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Evaluating the Sustainability of The Hydrogen Economy in Oman by Multi-Criteria Decision-Making Analysis

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Abstract

The sustainability of the hydrogen economy within Oman is achieved through a multi-criteria decision-making (MCDM) approach that targets the analytical hierarchy process (AHP). The methodology involves five major criteria, that are localization potential, technical feasibility, energy security, environmental impact, and economic impact. It ensures a detailed analysis of the strategic options of Oman for the development of hydrogen. Three alternatives have been considered gradual development, a balanced approach, and rapid scaling. The assessment of each of the strategies has been done against the given criterion to identify the best path forward. Energy security and economic impact have been given more priority in the analysis, showing the strategic focus of Oman on the improvement of energy independence and economic diversification. The results show that the balanced approach, involving different assertive targets of growth along with the growth of the supporting ecosystem, is the most sustainable method for the hydrogen economy of Oman. This approach ensures economic development while boosting technical advancements and sustainability in the long run. However, rapid scaling has been ranked at the second position, showing some support for an aggressive strategy, targeted at the capitalization on rising opportunities of the global hydrogen market. On contrary to this, the gradual development approach has got the lowest ranking, showing the preference of stakeholders to have a fast development. The research targets the significance of following an adaptable and nuanced strategy balancing rapid economic development with localization objectives of the country, technical feasibility, and environmental sustainability.

Keywords

Hydrogen economy**,** Sustainability, Multi-Criteria Decision-Making (MCDM), Analytic Hierarchy Process (AHP), Economic diversification.

1. Introduction

The requirement to transform the system of global energy to align with the 1.5°C objective has reached a good height. Current climate data has identified this requirement, with intensifying environmental influences and record-breaking temperatures:

- The hottest month was August 2023, which even surpassed July 2023.
- The influences of climate change are more intense in terms of both severity and frequency.
- Scientific warnings related to the present trajectory have become more alarming.

Because of the increasing climate concerns, the world is undergoing a shift in energy paradigms. Oman has risen as a major force setting a goal for the future of its energy (Alrawahi *et al.*, 2023). The Sultanate has provided a good initiative: acquiring carbon neutrality by the year 2050 (Anon., 2022). This commitment is in alignment with the goals of the Paris Agreement, and it positions Oman to be at the front of the green energy revolution. The sustainability objectives of Oman extend even beyond the environmental considerations. The nation is positioning itself strategically in the green hydrogen market. Through projections targeting the production levels of hydrogen from 1 to 8.5 million tons yearly by 2050, Oman is not only handling climate concerns but is also diversifying its economic portfolio (Anon., 2022). The path toward sustainability involves different sources of renewable energy. Tidal, geothermal, biomass, hydro, wind, and solar power each present some distinct challenges and opportunities. Interpreting the intricacies of the given technologies is important, specifically in the economic and geographical landscape of Oman.

The renewable energy sector is developing faster around the world. The International Energy Agency expects 107 GW of new capacity to be added in 2023 (IEA, 2023e). Solar power also leads the given charge, having both smaller installation and utility-scale projects acquiring momentum. At the same time, onshore wind is also expecting a resurgence and more cost-competitiveness. While Oman is making this transformation, a detailed analysis of the renewable integration is important. This analysis will shape the energy landscape of the nation, informing investment strategies and policy decisions. The commitment of the Sultanate to a green future does not only handle environmental issues but also gives it new avenues for global cooperation and economic development.

With the efforts of combatting climate change getting intense, Oman has now set a goal to acquire Net Zero Emissions by the year 2050, which is in alignment with the Paris Agreement. The strategy of the nation to transform into a major player within the green hydrogen market is central to this goal. This study aims to use Multi-Criteria Decision-Making Analysis to analyze the sustainability and viability of the hydrogen economy strategy of Oman. This research aims to give a detailed framework to stakeholders and policymakers to make informed decisions related to the transition of Oman towards low-carbon economy.

This research aims to provide a critical evaluation of the viability and sustainability of the hydrogen economy strategy of Oman in the context of the Net Zero Emission goal of 2050. Through using the Multi-Criteria Decision-Making Analysis, the research aims to provide a good assessment of different options for renewable energy and their contributions to the production of hydrogen. The research aims to evaluate the most appropriate pathways for the transition of Oman towards a hydrogen-based economy, considering the social, environmental, economic, and technical factors.

This research holds more significance in the context of the ambitious journey of Oman towards a low-carbon and sustainable future. As the nation targets to acquire Net Zero Emissions by the year 2050 and get positioned as the major player within the international green hydrogen market, a good evaluation of the sustainability of the hydrogen economy is needed. The significance of the research is in its potential to give evidence-based insights that can assist stakeholders, investors, and policymakers in making informed decisions. Through doing Multi-Criteria Decision-Making Analysis, this research provides a better interpretation of the complex interlink between different sources of renewable energy, environmental considerations, and economic factors that are specific to the unique context of Oman.

1.1. Objectives

To achieve the above aim, the following objectives have been set:

Objective 1: To assess the potential of various renewable energy sources for hydrogen production in Oman's specific geographic and economic context.

Objective 2: To develop a multi-criteria framework for evaluating the sustainability of hydrogen production methods in Oman.

Objective 3: To analyze the economic viability and environmental impact of scaling up hydrogen production to meet Oman's 2050 targets.

Objective 4: To identify potential challenges and opportunities in implementing a hydrogen economy in Oman and propose strategies to address them.

2. Literature Review

2.1. Green Hydrogen Economy

Low-emission hydrogen production could observe substantial development by the year 2030, with projects providing 38 Mt yearly. The given figure shows a 50 percent increment over the projections done in the Global Hydrogen Review 2022 of IEA. Considering this, it can be stated that around 17 Mt comes through projects that are still in the early phases of development. However, the challenges associated with the cost are a major threat to the progress, with only 4 percent of these projects reaching the final investment decision (FID), despite having double absolute terms since the previous year (IEA 2023a). Figure 1 contains Global Low-emission hydrogen production projects.

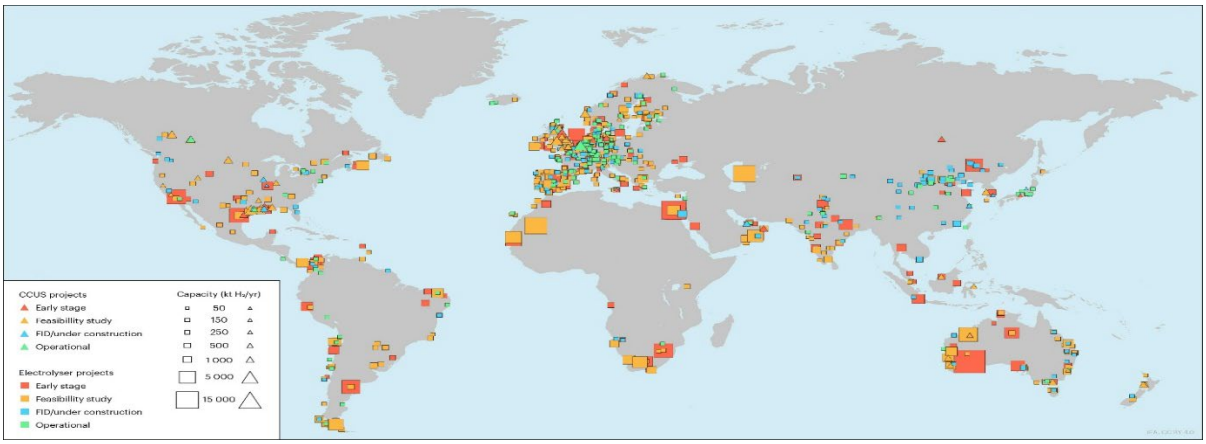

Figure 1. Global Low-emission hydrogen production projects(IEA, 2023b)

China is rising as the leader in the deployment of electrolyzers, with its capacity assumed to hit around 1.2 GW by 2023, making up around 50 percent of the global capacity. Governments in Europe and North America have started integrating initiatives like the UK Low Carbon Hydrogen Business Model, the EU Important Projects of Common European Interest, and the US Hydrogen Production Tax Credit. However, the slow process of these support schemes is resulting in a delay in the decisions of investment. The manufacturers of electrolyzers have some ambitious plans, with the capacity of manufacturing to reach around 155 GW every year by 2030.

2.2. Oman's Energy Landscape

Oman is a major international contributor to the export and production of natural gas and oil. Within 2020, it ranked 19th in the daily oil output, which accounts for 1.1 percent of the international supply. The gas and oil industry plays an important part in the economy of Oman, making around 70 percent of the government's annual income. The total final energy consumption (TFC) of Oman, involving electricity, natural gas, and oil products was 22 Mtoe. Figure 2 contains details regarding the energy balance of Oman.

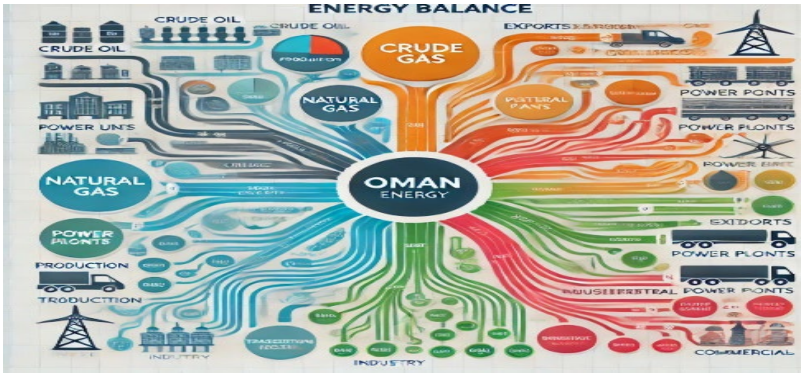

Figure 2. Energy Balance of Oman

Oman is a major player in the international gas and oil industry. It has committed to decreasing greenhouse gas (GHG) emissions by 7 percent by the year 2030 and to increase the renewable energy share to 30 percent by the year 2040. Oman has set the target to attain net-zero emissions by 2050, which is in alignment with the aim of the Paris Agreement to keep global warming below 1.5°C compared to the pre-industrial levels (Anon 2022a). The Sustainability Center of Oman is instrumental in the given process, being responsible to make and execute different strategies for acquiring carbon neutrality. Oman has set the goal for the production of renewable hydrogen, targeting to make around 1 million yearly by 2030.

3. Methods

Decision-making is an important part of human cognition, involving a complicated mental process that aims to solve issues and acquire the desired results. This cognitive function includes considering different factors, that range from biological and physiological influences to social and cultural dynamics. In the landscape of decision-making methodologies, Multi-Criteria Decision Making (MCDM), also termed as Multi-Criteria Decision Analysis (MCDA), has risen as a major revolutionary approach (Aruldoss, Lakshmi and Venkatesan, 2013; Mark Velasquez and Patrick T. Hester 2013). This method is considered more efficient for being more comprehensive and precise. A major strength of MCDM is its depth and versatility. It involves both quantitative and qualitative criteria, adapting flexibility to different decision scenarios. This detailed methodology helps decision-makers in handling the complicated choices with more clarity and confidence, and to finally reach the best solution. MCDM can be applied to different fields. In a current research by (Pramanik *et al.* 2021), a detailed review of different MCDM approaches was explored as given in Table 1.

Table 1. Applications of MCDM

Application Fields	Examples of the Application Focus
Healthcare	The assessment of COVID-19 regional safety, occupational health, and safety risk assessment
Energy sector	Ranking renewable energy sources, techniques for energy policy
Engineering and Production	Engineering, material selection for optimal design, Optimum Process Parameters
Career and Job	Occupational stressors among firefighters, personnel selection problems, Job Choice
Supply chain management	Supporting sustainable supplier selection, green supplier evaluation, and selection
Organizations and corporates	System Selection Process in Enterprises, corporate sustainability
Education	Contextual Learner Modelling in Personalized and Ubiquitous Learning, E-learning
Transportation	Urban passenger transport systems, integrated transportation systems
Civil Engineering	Flood disaster risk analysis
Finance/economics	Project portfolio management

3.1 Analytic Hierarchy Process (AHP)

Within decision-making theory, the Analytic Hierarchy Process (AHP), is a strategy made for the organization and analysis of complex decisions, utilizing the psychology and mathematics principles. AHP allows determining criteria importance through permitting decision-makers or experts to do the comparison of criteria. This comparative approach supports determining the most appropriate alternative (Fabianek *et al.* 2020).

AHP is designed for making group decisions (Saaty and Peniwati 2012). It is integrated into different fields like education, healthcare, industry, business and government (Saracoglu, 2013). Instead of talking about a “correct” decision, AHP helps decision-makers to look for the choice that is in best alignment with their goals and interpretation of the issue. Prominent organizations of information technology, involving those that use decision models from the Decision Drivers of Gartner Group, extensively use AHP.

The Analytic Hierarchy Process (AHP) provides a systematic framework to handle the complex issues related to decision-making following a structured approach. The generic steps of AHP are given below:

The first step in AHP includes dividing the complex issue into simpler sub-issues organized in the form of a hierarchy. This structure helps analyze every component independently, involving alternatives, sub-criteria, criteria, and objectives. Simplification of decision issues makes it easier to compare and evaluate various aspects.

After decomposition, the decision issue is changed into a hierarchy. This includes the arrangement of decision elements into different levels, initiating with the main objective at the top, followed by criteria, sub-criteria, and then the final alternatives. This hierarchical positioning assists in observing the links between various factors and helps to ensure that all the relevant aspects are considered systematically. Through having the hierarchy in place,

decision-makers evaluate different elements following pairwise comparisons. Each of the elements is compared two times, considering its influence on high-level elements and importance.

Evaluations through pairwise comparisons are then converted to numerical values. This step includes the assignment of numerical priorities or weights to every element of the hierarchy dependent on the comparisons. Finally, the numerical priorities for every element are used for calculating the priorities for decision alternatives. This synthesis assists in ranking the alternatives dependent on their effectiveness in acquiring the decision. The calculated priorities give a good base to evaluate and choose the optimal option among the given alternatives. Figure 3 contains generic steps for AHP.

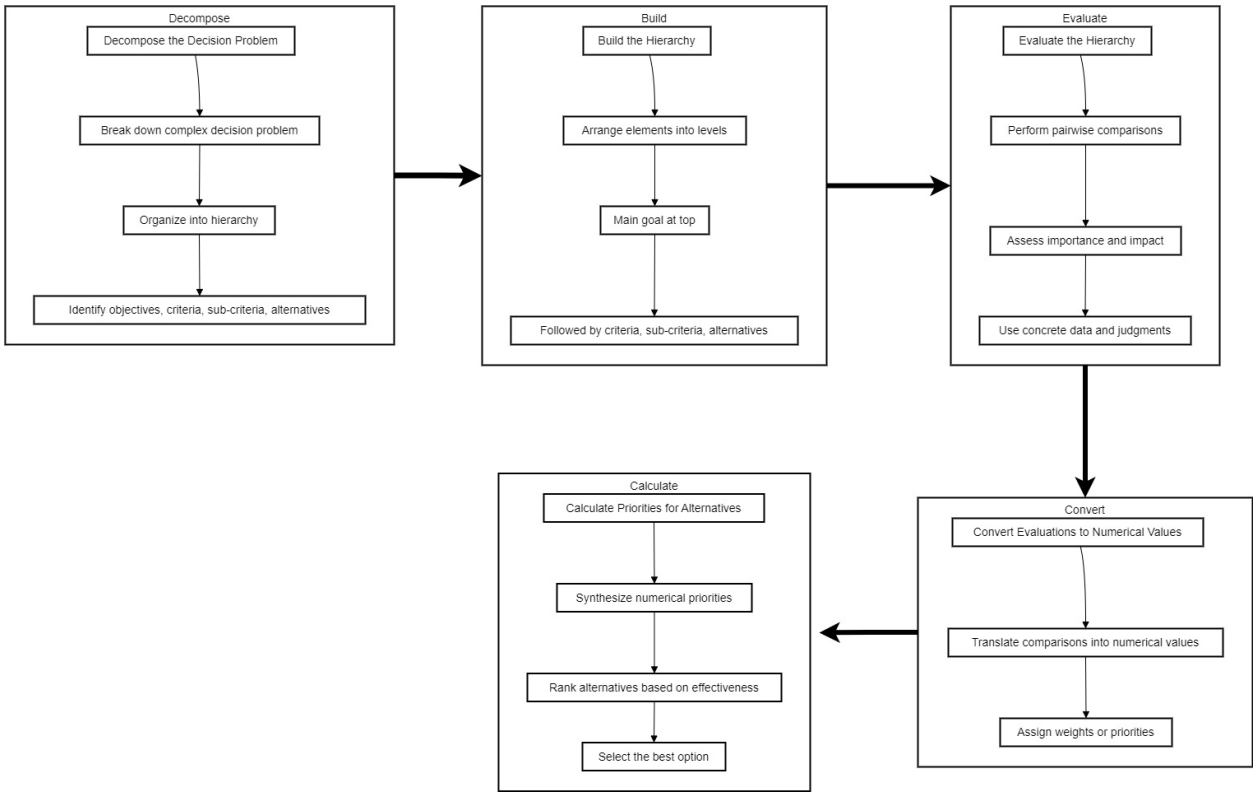

Figure 2. Generic Steps for AHP

4. Results and Discussion

4.1 Analytic Hierarchy Process

Step 1: Define the Problem and Goal
Problem: Evaluation of the hydrogen economy within Oman

Goal: To identify the most appropriate strategy to develop the hydrogen economy of Oman

This step provides the base for the whole analysis. The problem is clearly stated which is “the evaluation of hydrogen economy’s sustainability within Oman”. The objective is to identify the most sustainable technique for the growth of the economy.

Step 2: Identify the Criteria
The criteria are derived through the “Oman Green Hydrogen Strategy, May 2024” (Hydrom 2024)

Each criterion provides some aspect related to sustainability:
C1: Economic Impact – important for the economic diversification of Oman
C2: Environmental Impact – in alignment with the global objectives of sustainability
C3: Energy Security – significant for the long-term stability of Oman
C4: Technical Feasibility –ensures the attainment of strategy
C5: Localization Potential – focuses on developing local capabilities

These criteria involve different sustainable factors, helping in a detailed analysis.

Step 3: Identify the Alternatives
Three strategic approaches are identified:

A1: Rapid Scaling - aggressive expansion of hydrogen production

A2: Balanced Approach - moderate growth with ecosystem development

A3: Gradual Development - slower, more cautious expansion

These alternatives provide different types of development, helping to do a good comparison.

Step 4: Create The Hierarchical Structure
This step helps to organize the decision factors into one hierarchy, giving a better visual representation of the issue. It assists in interpreting the link between the objective, criteria, and other alternatives.

Level 1: Goal (Sustainable Hydrogen Economy in Oman)

Level 2: Criteria (C1, C2, C3, C4, C5)

Level 3: Alternatives (A1, A2, A3)

Figure 4 contains the hierarchical structure.

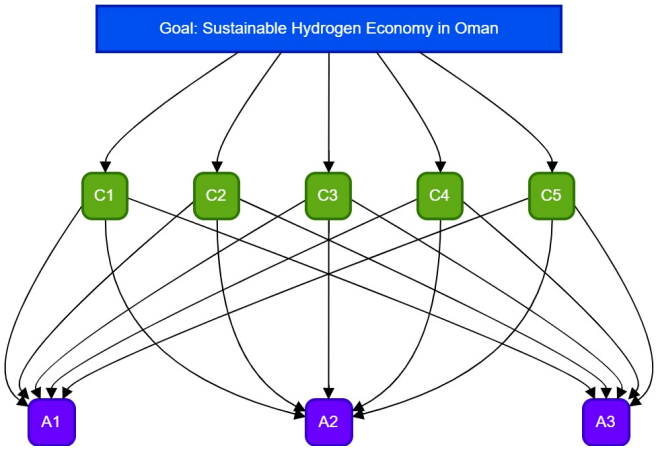

Figure 3. Hierarchical Structure

Step 5: Perform Pairwise Comparisons for Criteria
Table 2 contains the comparison of every criterion to the other one for determining the relative significance as given in Figure.

- C1 (Economic Impact) is given slightly higher importance (2) compared to C2 (Environmental Impact), likely reflecting Oman's focus on economic diversification.
- C1 is considered equally important (1) to C3 (Energy Security) and C5 (Localization Potential), suggesting a balanced approach.
- C1 is given moderately higher importance (3) than C4 (Technical Feasibility), possibly because economic outcomes are prioritized over technical challenges.
- C2, C3, and C5 are considered equally important (1) to each other, indicating a balanced consideration of environmental, security, and local development aspects.
- C4 is given slightly lower importance (1/2) compared to other criteria, suggesting that technical feasibility, while important, is not the primary concern.

The Consistency Ratio (CR) of 0.012 is well below the 0.1 threshold (i.e. Salty's Consistency Ratio condition) (Shyam Prasad *et al.* 2017), showing the reliability and consistency of judgments.

These assignments are dependent on the predicted priorities in the hydrogen strategy of Oman (Hydrom 2024). The economic impact has higher significance, showing the target of Oman over economic diversification.

Table 2. Pairwise Comparison Matrix

	Economic Impact	Environmental Impact	Energy Security	Technical Feasibility	Localization Potential	Priorities
Economic Impact	1	2	1	3	1	0.274
Environmental Impact	0.5	1	1	2	1	0.191
Energy Security	1	1	1	2	1	0.217
Technical Feasibility	0.333	0.5	0.5	1	0.5	0.1
Localization Potential	1	1	1	2	1	0.217

* Consistency Ratio calculated as 0.012

Step 6: Perform Pairwise Comparisons of Alternatives for Criteria
For each criterion, a pairwise comparison matrix has been created for all of the alternatives:

A1: Rapid Scaling

A2: Balanced Approach

A3: Gradual Development

We'll use the following scale for comparisons:

1 = Equal importance

3 = Moderate importance

5 = Strong importance

7 = Very strong importance

9 = Extreme Importance

2, 4, 6, 8 = Intermediate values

For every criterion, the comparison of alternatives has been done pairwise. The assigned values show how every alternative works related to the other ones. For instance:

For Economic Impact (C1), Rapid Scaling (A1) is strongly fevered over Gradual Development (A3), hence the value 7 in the A1-A3 cell.

For Technical Feasibility (C4), Gradual Development (A3) is strongly fevered over Rapid Scaling (A1), hence the value 7 in the A3-A1 cell.

The given comparisons are dependent on the logical assessments of how each of the strategies would act in every area. For example, rapid scaling can have more economic influence in the short term. On the other hand, growing slowly can be more feasible technically. The priority vectors for every criterion show which of the alternatives can be preferred for the given criterion. For instance, Rapid Scaling (A1) is given more preference for the Economic Impact. On the other hand, the Balanced Approach (A2) is targeted at Energy Security and Localization Potential. Table 3 contains economic impacts, Table 4 contains environmental impacts, Table 5 contains energy

security impacts Table 6 contains technical Feasibility Impacts, and Table 7 contains localization potential impacts from all options.

Table 3. Economic Impacts from all Options

Economic Impact 0.274	Rapid Scaling	Balanced Approach	Gradual Development	Priorities
Rapid Scaling	1	3	7	0.669
Balanced Approach	0.333	1	3	0.243
Gradual Development	0.143	0.333	1	0.088

* Consistency Ratio calculated as 0.0061

Table 4. Environmental Impacts from all Options

Environmental Impact 0.191	Rapid Scaling	Balanced Approach	Gradual Development	Priorities
Rapid Scaling	1	3	7	0.669
Balanced Approach	0.333	1	3	0.243
Gradual Development	0.143	0.333	1	0.088

* Consistency Ratio calculated as 0.0061

Table 5. Energy Security Impacts from all Options

Energy Security 0.217	Rapid Scaling	Balanced Approach	Gradual Development	Priorities
Rapid Scaling	1	0.333	3	0.243
Balanced Approach	3	1	7	0.669
Gradual Development	0.333	0.143	1	0.088

Table 6. Technical Feasibility Impacts from all Options

Technical Feasibility 0.1	Rapid Scaling	Balanced Approach	Gradual Development	Priorities
Rapid Scaling	1	0.333	0.143	0.088
Balanced Approach	3	1	0.333	0.243
Gradual Development	7	3	1	0.669

* Consistency Ratio calculated as 0.0061

Table 7. Localization Potential Impacts from all Options

Localization Potential 0.217	Rapid Scaling	Balanced Approach	Gradual Development	Priorities
Rapid Scaling	1	0.143	0.333	0.088
Balanced Approach	7	1	3	0.669
Gradual Development	3	0.333	1	0.243

* Consistency Ratio calculated as 0.0061

Step 7: Calculate Overall Priority Vector
This step links all of the priorities of alternatives under every criterion. The calculation gives weight to the performance of every alternative through the significance of each criterion. Table 8 contains priorities ranking whereas Figure 5 contains weighted attributes, attributes, and priorities

Table 8. Priorities Ranking

Option Name	Priorities
Rapid Scaling	0.392
Balanced Approach	0.428
Gradual Development	0.18

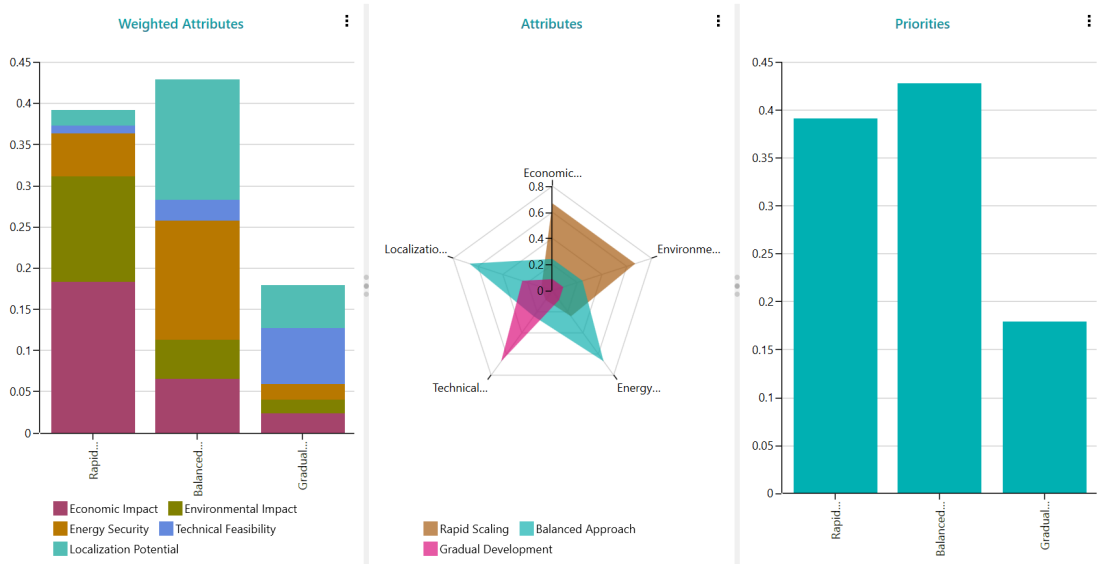

Figure 5. Weighted Attributes, Attributes, and Priorities

These values represent the overall preference for each alternative, considering all criteria and their relative importance.

The Analytic Hierarchy Process (AHP) analysis of the sustainability of the hydrogen economy of Oman has provided insights related to the significance of different criteria and the preferability of various strategic approaches.

4.2 Criteria Prioritization

The analysis identified the given priority vector for the criteria of evaluation:

- Economic Impact (C1): 0.274
- Environmental Impact (C2): 0.191
- Energy Security (C3): 0.217
- Technical Feasibility (C4): 0.100
- Localization Potential (C5): 0.217

This prioritization shows that economic considerations are important in the hydrogen strategy of Oman, which is followed through localization and energy security. Environmental impact is considered important but is still ranked at fourth, recommending a good balance between environmental and economic objectives. Technical feasibility was not given more priority, which shows more confidence in the ability of Oman to overcome different technical complexities.

4.3 Alternative Strategies Evaluation

For every criterion, the evaluation of three strategic alternatives was done:

- Economic Impact (C1): Rapid Scaling (0.669) > Balanced Approach (0.243) > Gradual Development (0.088)
- Environmental Impact (C2): Rapid Scaling (0.669) > Balanced Approach (0.243) > Gradual Development (0.088)
- Energy Security (C3): Balanced Approach (0.669) > Rapid Scaling (0.243) > Gradual Development (0.088)
- Technical Feasibility (C4): Gradual Development (0.669) > Balanced Approach (0.243) > Rapid Scaling (0.088)
- Localization Potential (C5): Balanced Approach (0.669) > Gradual Development (0.243) > Rapid Scaling (0.088)

4.4 Overall Strategy Prioritization

The final prioritization of different strategic alternatives, analyzing all of the criteria is given below:

- Balanced Approach (A2): 0.428
- Rapid Scaling (A1): 0.392
- Gradual Development (A3): 0.18

The Balanced Approach is the most suitable strategy, offering a narrow margin. This outcome recommends that a strategy combining ambitious development with proper consideration of ecosystem development is the most appropriate choice for the hydrogen economy of Oman. The ranking of the Gradual Development approach is lower, showing more preference for assertive techniques in making the hydrogen sector of Oman.

4.5 Discussions

The results acquired through the analysis of AHP give valuable insights related to the decision-making process for the growth of the hydrogen economy of Oman. The prioritization of criteria shows the strategic focus of Oman over energy security and economic diversification, while still showing a good commitment to local capacity building and environmental sustainability. The priority given to the economic impact (which is 0.274) is in alignment with the Vision 2040 of Oman, which focuses on economic diversification and decreasing dependency on oil revenues. The equal weighting of localization potential and energy security (both 0.217) shows the significance of making a self-sustaining hydrogen ecosystem. Giving less priority to environmental impact (0.191) should be noted as well. This ranking recommends that even when Oman is more committed to environmental sustainability, still it is balanced with security and economic considerations. This approach underlines the challenges of making the transition towards a green economy while maintaining good economic development. Evaluating the strategic alternatives shows a nuanced idea of the growth of the hydrogen economy of Oman. The top ranking of the Balanced Approach which is 0.411 shows that such a strategy is preferred that link ambitious

development with ecosystem development. This is in alignment with the "Oman Green Hydrogen Strategy May 2024", targeting both wider industrial growth and production targets. However, the second-ranking of the Rapid Scaling approach (0.394) shows support for an aggressive strategy of expansion. The Gradual Development approach has got lower rank of 0.195, which shows that stakeholders are at risk of moving slowly within the changing industry. These results imply that the current balanced strategy of Oman is in alignment with the sustainability considerations. However, the ranking of the Rapid Scaling approach shows the opportunities to speed up the growth in specific areas, specifically where Oman has competitive benefits.

4.6 Proposed Improvements

Moving forward, policymakers and industry leaders should consider:

- Regularly reassessing the balance between rapid scaling and ecosystem development as the global hydrogen market evolves.
- Investing heavily in technical capabilities and localization efforts to improve long-term sustainability.
- Identifying specific areas where rapid scaling could provide significant economic or strategic advantages.
- Continuing to monitor and mitigate environmental impacts to ensure long-term sustainability.

This AHP analysis provides a structured framework for decision-making, but it should be complemented with ongoing market research, stakeholder consultations, and flexibility to adapt to the changing global energy landscape.

5 Conclusion

The AHP analysis shows that such criteria have been given more priority which is important for the hydrogen economy of Oman, with energy security (0.217) and economic impact (0.274). This shows the strategic objective of Oman to decrease its dependency on oil while keeping its future secure. The lower ranking of 0.191 on the environmental impact shows that while there are some major environmental concerns, still security and economic factors are more alarming for Oman. The criterion of technical feasibility got a weight of 0.100 which is the lowest one, mainly because of the expectation that technological challenges can be handled with the maturity of industry. Among the strategic alternatives, the balanced approach scored 0.428, the most suitable one. It was followed by the rapid scaling option which is 0.392 and then the gradual development strategy to be 0180. It shows that it did not make advancements that were required in the advancing industry. The analysis facilitates the current strategy of Oman but shows that there can be opportunities to speed up the development, without making any compromise on the long-term objectives of sustainability.

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