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Leveraging aviation 4.0 for sustainable aviation fuel adoption towards net zero: – An integrated approach of cognitive mapping and analytical heuristic process

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Abstract: The Paris Agreement has had a substantial influence on industries worldwide, particularly the aviation sector, which is responsible for approximately 3% of global CO_2 emissions. As a high-energy-consuming industry, aviation faces mounting pressure to reduce its carbon footprint and align with international climate goals. Sustainable Aviation Fuel (SAF) has emerged as a viable solution to reduce greenhouse gas (GHG) emissions, offering a pathway toward achieving net-zero targets by 2050. This paper investigates the potential adoption of SAF within Oman's aviation industry, on how Aviation 4.0 principles and technologies can be leveraged to support SAF implementation. The study examines enablers, challenges, goals, and policies, highlighting the role of digitalization, automation, and data analytics in driving the transition to SAF. Advanced analytical methods, such as Fuzzy Cognitive Mapping (FCM) and the Analytical Hierarchy Process (AHP), will be employed to evaluate the impacts and rank the most suitable types of SAF for Oman. By addressing critical gaps in policy and practice, this study aims to provide actionable insights for aviation operators to transition toward sustainable fuel alternatives and meet long-term climate objectives.

1. Introduction

The Paris Agreement aims to reduce greenhouse gas emissions by half in 2030 and net zero emissions by 2050 [1] . The aviation industry faces significant pressure to meet these goals, with the industry responsible for producing almost 3% of CO2 emissions and 6% of GHG anthropogenic global emissions [2,3]. To reduce emissions, the International Civil Aviation Organization suggests improving technologies, adjustments in operation, carbon offsetting, and using Sustainable Aviation Fuel (SAF) [4]. SAF can reduce emissions until improvements in technologies like battery-powered aircraft, electric planes, or hydrogen-powered airplanes are commercially available and feasible [5] . European authorities propose a growth plan of SAF's share from 2% to more than 60% in 2050 [6] . Oman has joined the global effort to reach net zero by 2050, submitting its state action plan to ICAO [7] . The ministry of Energy in Oman is working with other partners to investigate the possibility of producing alternative fuels (SAF and e-gasoline) and scaling it up to a commercial-scale operation [8] .

Airlines like Oman Air face challenges in producing alternative aviation fuels, such as certification for additional channels, density similarity, and technical maturity. However, research

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indicates that it is possible to improve the supply chain for technological, social, and economic requirements with the right production, research, and organizational context. This study aims to assess how operators in Oman's aviation supply chain can implement SAF and other enablers to speed up the transition to Net-Zero and enhance their sustainable performance.

2. STATE OF THE ART

2.1 Types of Fuel in Aviation

The aviation sector currently uses kerosene fuel, with AvGas used mainly for old piston aircraft or sport planes [9]. Alternative fuels like hydrogen, SAF, and LCAF are being explored, with hydrogen being introduced as an alternative to CAF [10]. According to (ICAO), low-consumption aviation fuels (LCAF) are being considered for reducing greenhouse gas emissions. SAF based elements include Biofuel, recycled carbon fuel, and synthetic fuel, with recycled carbon fuel being adopted for commercial production between 2020-2030 [11] .

2.2 Net Zero Strategies in the Aviation Industry

The Paris Agreement aims for the aviation industry to achieve net zero emissions by 2050, despite its significant contribution to greenhouse gas (GHG) emissions. The industry, which contributes to 3% of CO2 emissions, has a significant share of GHG emissions in the transportation sector, with aviation accounting for close to 14% [12] . Decarbonizing aviation is challenging due to its high energy requirements and high-energy fuel density equipment [13]. To achieve net zero, airlines and manufacturers are adopting new approaches such as limited travel runs, fleet renewals, carbon offsetting, and hybrid fuel innovations [14]. However, these strategies may lead to higher taxes and lower demand due to the aviation industry's profit [15]. Advancements in aircraft technologies, such as electric or hydrogen batteries, are being developed to improve aircraft performance [16]. Alternative fuel systems like solar-assisted fuel (SAF) are crucial for decarbonization [17]. Strong policies and increased investment in renewable energy sources are needed to achieve this goal.

2.3 Aviation 4.0 Enabling Sustainable Fuel Adoption

Aviation 4.0, characterized by digitalization, automation, and data-driven decision-making, can accelerate the adoption of Sustainable Aviation Fuel (SAF) by integrating technologies like IoT, AI, and blockchain [18]. This can improve supply chain efficiency, optimize fuel production, and manage SAF adoption [19]. Real-time data analytics and blockchain technology can monitor production, distribution, and consumption, paving the way for net-zero aviation [20].

2.4 Enablers & Barrier of SAF in Aviation Industry

The adoption of sustainable aviation fuel (SAF) in the aviation industry faces challenges due to economic, environmental, fuel diversification, and social factors [21] . Enablers include new business opportunities, carbon reduction, policies, energy security, and economic and social drivers [22] . While energy economists view SAF as unfavorable, it opens new business opportunities due to limited companies in the sector [23] . SAF provides energy security and independency from a variable range of resources, with producers aiming to equal the current jet fuel's price [24] . Other enablers as discussed by [25] include corporate sustainability, economic viability, pricing differentials, consumer awareness, and increased demand for SAF globally. Authors have reviewed the previous literature and identified five main Net Zero related aviation strategies as mentioned in Table I. below.

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Table I. Main Net Zero related aviation strategies

Strategy	Explanations	Source
Travel Innovations	- Focus on Both Airline & Passengers Behavior - Adjustment on Demand of Travel - New Taxations Policies - Alternative Transportation Modes	(Takebayashi & Yamaguchi, 2024)
Fleet Renewable	- Adjustment on Current Planes (Aerodynamic) - Electric & Hydrogen Powered Planes - Routes Adjustments	(Muehlberger et al., 2024) (SEO, 2021)
Carbon Offset	- Carbon Storing & Capture - Plant Trees Projects for Reforestation & Afforestation	(Airbus, 2024) (Wozny *et al.*, 2022)
Fuel Innovations	- The main effective approach & the most expensive - Using Alternative Fuel System - Focus on SAF as alternative - R&D to Develop & Enhance SAF Pathways	(Muehlberger et al., 2024) (Uppink *et al.*, 2022) (Bergero *et al.*, 2023)

However, transitioning towards SAF faces barriers such as production costs, fewer investors, sustainable stock supply, logistics, quality control, and lack of stable policy [26] . Policies should provide assurance for manufacturers and investors to assign current capacity to SAF and build additional infrastructure.

2.5 Roadmap for SAF in Airline Industry

The European Commission aims for 5% Sustainable Alternative Fuels (SAF) contribution in the aviation industry by 2030, with projections of 32% and 63% by 2040 and 2050. Roadmaps for SAF production are essential for aligning business and government efforts [27] . Building infrastructure and legislative frameworks is crucial for integrating feedstocks into regional supply chains. The roadmap has three stages: immediate (2023-2025), medium term (2025-2035), and long term (2035+) [28] . The first stage focuses on creating investor confidence, second stage making biogenic feedstocks available, and final stage scaling up projects [29] .

2.6 SAF in Oman's Aviation Industry

The Civil Aviation Authority in Oman is promoting the use of Sustainable Aviation Fuels (SAF) for a sustainable and circular economy. Airbus is exploring commercial production of SAF,

recognizing its potential for green hydrogen, alternative fuels, and hybrid electricity [30] . The CAA emphasizes cooperation among stakeholders for feasibility studies and research [31] .

2.7 Integration of Cognitive Mapping and AHP Methods

Cognitive mapping and Analytic Hierarchy Process (AHP) methods are used in management to examine mental models and develop plans for Sustainable Air Fuels (SAF) development. Cognitive mapping helps identify obstacles and potential for increasing SAF usage among stakeholders, while AHP breaks down issues into a hierarchy of factors. For example, the AHP was used to choose the best aircraft for Philippine Airlines.

3. METHODS

This research uses abductive reasoning and analytical induction to generate new ideas using a mixed method approach [32,33] . Primary data was collected through interviews, group discussions, and online surveys. A hybrid approach was adopted using thematic analysis, cognitive fuzzy mapping, and AHP Analytical Hierarchy Process [34] . Thematic analysis was chosen due to its suitability for understanding people's viewpoints and experiences. The study involved six steps: understanding data, identifying significant themes, comparing them, and confirming findings' validity and reliability.

3.1 Cognitive Mapping & Fuzzy Cognitive Mapping (FCM)

The study utilized a Problem Structuring Method (PSM) to understand complex problems for the first objective, such as Strategic Choice Approach (SCA), Soft Systems Methodology (SSM), and Strategic Options Development and Analysis (SODA) [35] . SODA uses cognitive mapping, a mental model of decision-makers, to create action plans and achieve objectives. The second objective used Fuzzy logic of cognitive mapping, a digraph of nodes and edges connecting nodes [36] , to represent variable notions linked to problem attributes. FCM, which includes fuzzy-logic, computational conceptual relationships, and complex dynamic systems, was used for analysis. The research utilized Fuzzy Cognitive Mapping (FCM) Software, Mental Modeler.

3.2 The Analytical Hierarchy Process AHP

The Analytical Hierarchy Process (AHP) was used to rank enablers for Oman's zero emission goal. This method measures the ranking of alternatives based on decision-makers' judgment and emphasizes instinctive decisions and consistency in comparisons [37] . Participants were asked to compare importance and value within a logical framework and the consistency factor was calculated using the consistency ratio (CR) using the formula CR = CI/RI.

4. RESULTS

The study explores the potential of sustainable aviation fuel (SAF) in Oman through a comprehensive literature analysis and expert interviews. The research identified 19 themes, spanning technological, economic, environmental, and policy dimensions, providing a comprehensive understanding of SAF's potential in Oman. The following themes as mentioned below were identified

Theme 1: The net zero goal is a priority, with 12 out of 17 experts emphasizing its significance in aviation decarbonization, aligning with literature on the urgency of the transition. Theme 2: SAF as the main fuel is recognized as a key enabler, but an immediate 100% transition is not feasible. Blending SAF with conventional fuel is considered a viable short-term solution. Theme 3: Business opportunities presented by SAF are significant, but high costs remain a challenge. The long-term profitability potential of SAF is acknowledged, but cost remains a significant barrier. Theme 4: Consumer awareness and demand management are crucial in driving the transition to

sustainable aviation. Theme 5: There is strong support for carbon offset programs, particularly carbon capture and storage (CCS) technology, as an effective tool for achieving net zero. Theme 6: Efficiency improvements such as upgrading equipment and adopting advanced aircraft engines are emphasized to reduce emissions. Theme 7: Research and development (R&D) collaboration is seen as a critical factor in accelerating the transition to net zero. Theme 8: Airline sustainability practices are identified as key contributors to achieving net zero targets.

Theme 9: Taxation in aviation, including environmental taxes, is supported to incentivize sustainable practices and adjust consumer demand. Theme 10: There is a consensus on the need for shared costs among stakeholders, with strong support for government and fuel supply company contributions. Theme 11: Carbon quota systems, like CORSIA, are supported to accelerate the adoption of sustainable aviation practices. Theme 12: The enforcement of adoption through strong regulations is emphasized to drive SAF adoption and overcome obstacles, stimulating investment.

Theme 13: Capital investments remain a concern, as insufficient investment in aviation biofuel technology hinders progress. There are calls for increased government support to ease regulatory restrictions and attract investments. Theme 14: The environmental impact of the aviation industry is acknowledged, highlighting the benefits of biofuels in reducing the environmental footprint. Theme 15: There is a strong call for government support in funding research, easing regulations, and boosting investments in SAF technologies.

Theme 16: The cost feasibility of SAF remains a major barrier, as current costs are prohibitive. While the transition to clean energy is expensive, the long-term investment is seen as necessary for a sustainable future. Theme 17: There is emphasis on evaluating the effectiveness of enablers, particularly through tools like Life Cycle Assessment (LCA) to inform policy decisions. Theme 18: The social impact of SAF is significant, with a need to address public concerns and improve awareness regarding the safety and benefits of SAF. Theme 19: Technological advancements in SAF production are seen as essential to improving fuel quality, increasing production levels, and mitigating future uncertainties.

The expert consensus cognitive map is showing the Figure 1 below that was developed based on the thematic analysis of the literature review and the semi-structured interviews. The connections between the elements, and the level of impact of each connection were verified by the experts.

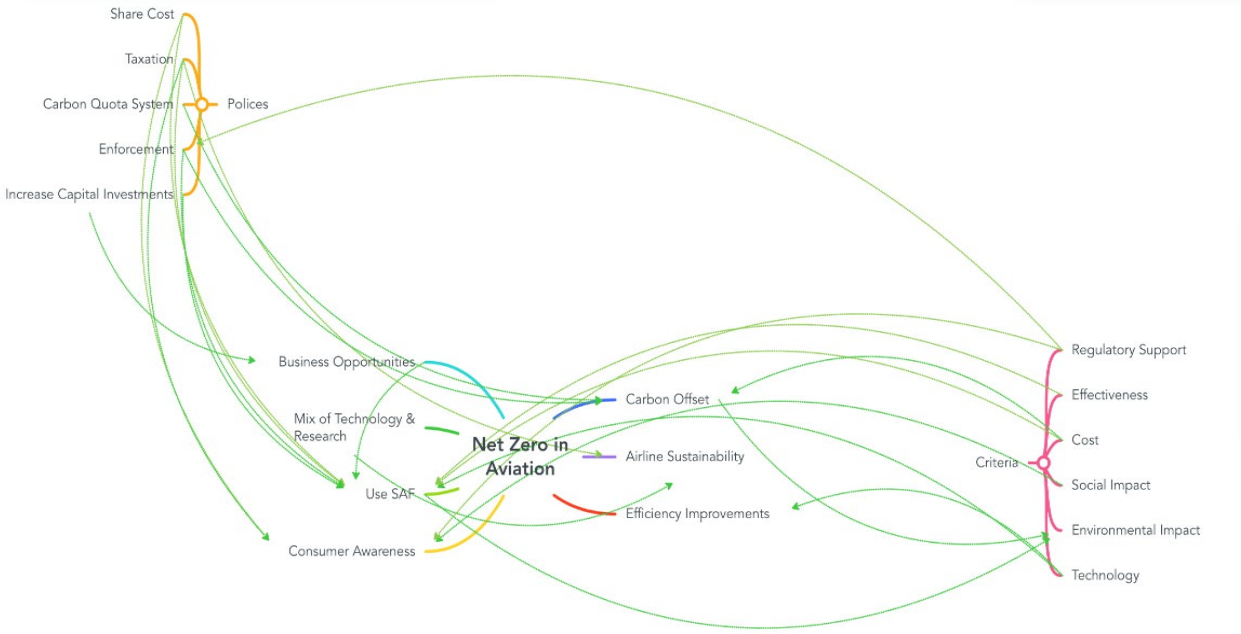


Figure 1. *Expert's Consensus Cognitive Map*

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Fuzzy Cognitive Mapping tool called Mental Modeler was used to model the overall thematic outcome in a better view as shown in the Figure 2 below.

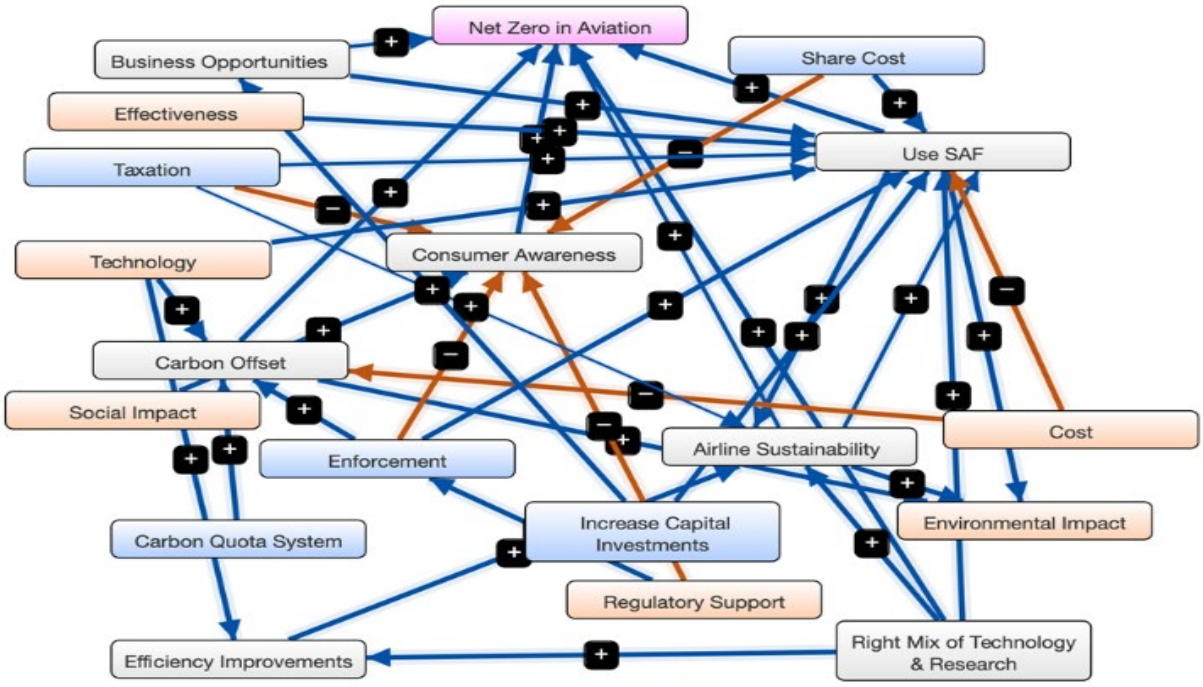


***Figure 2**. Fuzzy Cognitive Map of the Research*

Experts created a cognitive mapping process using Mental Modeler Software to identify dynamic interactions between elements for the net zero mission. The map displayed positive and negative relationships between components, with 19 themes and 37 connections recognized. The components were divided into driver, receiver, and ordinary categories, with a complexity score of 0.2 [38] . The map's density indicated potential for regulation. The details on the components, connections and density of the drivers, receivers are given below in Table II and indegree, outdegree, centrality are given in Table III.

***Table II.** Structural Metrics of the FCM*

Total Components	19
Total Connections	37
Density	0.108187
Connections per Component	1.947368
Number of Drivers	10
Number of Receivers	2
Number of Ordinaries	7
Complexity Score	0.2

Table 3 reveals the connections, centrality, and types of components in aviation. Use SAF has the highest centrality at 12, while Net zero in aviation has the highest centrality at 6, with Right Mix of Technology & Research having the highest centrality.

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Table III. *Details of Each Component*

Component	Indegree	Outdegree	Centrality	Type
Net Zero in Aviation	6	0	6	Receiver
Efficiency Improvements	2	1	3	Ordinary
Use SAF	9	3	12	Ordinary
Right Mix of Technology & Research	0	4	4	Driver
Carbon Offset	4	2	6	Ordinary
Airline Sustainability	3.25	2	5.25	Ordinary
Effectiveness	0	1	1	Driver
Environmental Impact	3	0	3	Receiver
Social Impact	0	1	1	Driver
Cost	0	2	2	Driver
Regulatory Support	0	2	2	Driver
Share Cost	0	2	2	Driver
Carbon Quota System	0	1	1	Driver
Enforcement	1	3	4	Ordinary
Taxation	0	1.75	1.75	Driver
Increase Capital Investments	0	2	2	Driver
Business Opportunities	1	1.5	2.5	Ordinary
Technology	0	3	3	Driver

4.1 AHP Reults

Table IV. *Aggregate Judgments of each Criterion*

Criteria	Cost Feasibility	Technology	Effectiveness	Social Impact	Regulatory	Environmental Impact	Weighted Sum
Cost Feasibility	0.0915	0.1104	0.0790	0.0888	0.1042	0.0783	0.5521
Technology	0.0430	0.0523	0.0564	0.0648	0.0537	0.0455	0.3157
Effectiveness	0.4445	0.3448	0.3761	0.4341	0.3255	0.3562	2.2812
Social Impact	0.0473	0.0523	0.0564	0.0648	0.0651	0.0859	0.3718
Regulatory	0.1436	0.1565	0.1880	0.1626	0.1628	0.1692	0.9827
Environmental Impact	0.2945	0.2836	0.2670	0.1885	0.2441	0.2526	1.5304

Table V. *Normalized and weighted sum Criteria*

Criteria	Cost Feasibility	Technology	Effectiveness	Social Impact	Regulatory	Environmental Impact	Weighted Sum
Cost Feasibility	0.0915	0.1104	0.0790	0.0888	0.1042	0.0783	0.5521
Technology	0.0430	0.0523	0.0564	0.0648	0.0537	0.0455	0.3157
Effectiveness	0.4445	0.3448	0.3761	0.4341	0.3255	0.3562	2.2812
Social Impact	0.0473	0.0523	0.0564	0.0648	0.0651	0.0859	0.3718
Regulatory	0.1436	0.1565	0.1880	0.1626	0.1628	0.1692	0.9827
Environmental Impact	0.2945	0.2836	0.2670	0.1885	0.2441	0.2526	1.5304

Table VI. *λmax (Criteria AHP)*

Weighted sum	Priority	Weighted Sum/ Priority
0.552	0.091	6.06593407
0.316	0.052	6.07692308
2.281	0.376	6.06648936
0.372	0.065	5.72307692
0.983	0.163	6.03067485
1.53	0.253	6.04743083
Averaged to get Lambda max		6.00175485

$$Consistency\ Index\ (CI) = (\lambda max - n)/(n-1) = (6.00175485 - 6)/5 = 0.001754851$$

$$Consistency\ Ratio\ (CR) = CI/RI = 0.001754851/1.24 = 0.0003$$

The purpose of run the calculations on Tables IV, V, and VI to find the consistency ratio to confirm the degree of consistency between the pairwise comparisons. The result of 0.0003 is below the reasonable standard level 0.1 which proves that the comparison is consistent.

Table VII. *Random Consistency Index (RI) adopted from [37]*

Matrix Size	Random Consistency Index (RI)
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Table VIII. *Rank of each Criterion*

Category	Priority	Rank
Cost Feasibility	9.10%	4
Technology	5.30%	6
Effectiveness	37.70%	1
Social Impact	6.50%	5
Regulatory	16.20%	3
Environmental Impact	25.30%	2

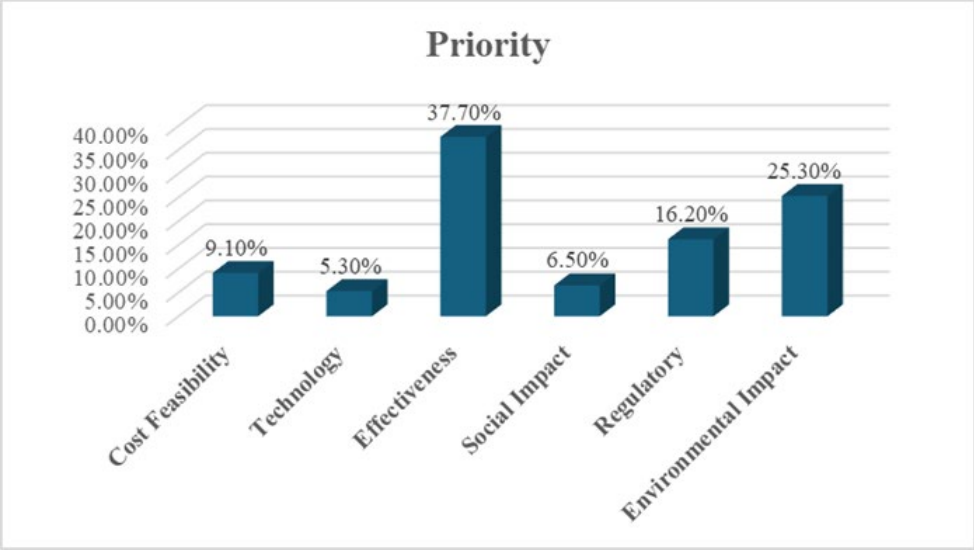


Figure 3. *Percentage of each Criterion*

Table IX. *Consistency index and ratio calculations for Alternatives based on each criterion*

Alternatives/ Criteria	Cost Feasibility	Technology	Effectiveness	Social Impact	Regulatory	Environmental Impact
	Weighted sum/Priority	Weighted sum/Priority	Weighted sum/Priority	Weighted sum/Priority	Weighted sum/Priority	Weighted sum/Priority
BioFuel	2.959322034	2.309796348	3.318947368	3.009603255	3.016893099	3.021388851
Recycled Carbon Fuel	3.058252427	3.316061689	2.398370385	3.017309963	3.016817548	3.027490676
Synthetic Fuel (PtL)	2.985971944	3.374572272	3.338993284	3.023666228	3.016696737	3.021939066
Averaged to get λmax	3.001182135	3.000143436	3.018770346	3.016859815	3.016802461	3.023606198
Consistency Index (CI)	0.000591	7.00E-05	0.00939	0.00842991	0.00840123	0.0118031
Consistency Ratio (CR)	0.00102	0.00012	0.02	0.01453432	0.01448488	0.02035017

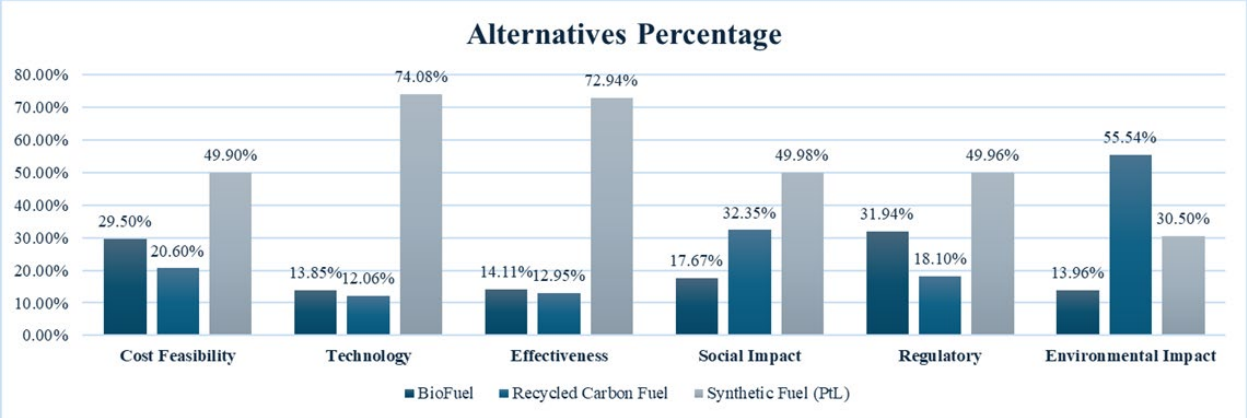


Figure 4. *Alternatives Percentage*

4.1.1 Cost

AHP findings based on cost criteria showed that Synthetic Fuel was ranked as the best alternative based on cost criteria with 49.9%. Figure 4 shows the rank in a pie chart, and the consistency ratio was 0.001. The consensus in evaluating the alternatives with reference to the criterion Cost Feasibility was 42.0%, and it is considered very low in agreement in their outcoming priorities.

4.1.2 Technology

AHP findings based on technology criteria showed that Synthetic Fuel was ranked as the best alternative based on technology criteria with 74%. Figure 4 shows the rank with percentage associated. In addition, the consistency ratio was close to 0. The consensus in evaluating the alternatives with reference to the criterion Technology was 96.1%, and it is considered very high in agreement in their outcoming priorities.

4.1.3 Effectiveness

AHP findings based on effectiveness criteria showed that Synthetic Fuel was ranked as the best alternative based on effectiveness criteria with 74%. Figure 4 shows the rank with percentage associated. It was found that the consistency ratio was close to 0.02. The consensus in evaluating the alternatives with reference to the criterion effectiveness was 96%, and it is considered very high in agreement in their outcoming priorities.

4.1.4 Social Impact

AHP findings based on social impact criteria showed that Synthetic Fuel was ranked as the best alternative based on effectiveness criteria with 50%. Figure 4 shows the rank with percentage associated. The consistency ratio was close to 0.014. The consensus in evaluating the alternatives with reference to the criterion effectiveness was 62%, and it is considered low in agreement in their outcoming priorities.

4.1.5 Legal/Judicial Support

AHP findings based on regulatory support criteria showed that Synthetic Fuel was ranked as the best alternative based on regulatory support criteria with 50.2 %. Figure 4 shows the rank with percentage associated. The consistency ratio was close to 0.0144. The consensus in evaluating the alternatives with reference to the criterion effectiveness was 54.3%, and it is considered low in agreement in their outcoming priorities.

4.1.6 Environmental Impact

AHP findings based on environmental impact criteria showed that Recycled Carbon Fuel was ranked as the best alternative based on environmental impact criteria with 55%. Figure 4 shows the rank with percentage associated. The consistency ratio was close to 0.0203. The consensus in evaluating the alternatives with reference to the criterion effectiveness was 54%, and it is considered low in agreement in their outcoming priorities.

4.2 Validity and Verification of Scenario

Experts simulated scenarios using FCM Mental Modeler, assessing impact of components on aviation's net zero goal, R&D, cost, taxation, shared cost, and enforcement.

5. DISCUSSION AND CONCLUSION

The FCM structural analysis identified 19 components and 37 causal connections, with a density value of 0.108, indicating a moderately complex but policy-sensitive system. The centrality analysis revealed “Use SAF” (centrality = 12) as the most influential node, followed by Net Zero in Aviation (6) and Right Mix of Technology & Research (4), confirming the dominance of fuel innovation and R&D-driven strategies. The AHP results ranked effectiveness (37.7%) and environmental impact (25.3%) as the most critical decision criteria, while cost feasibility ranked fourth (9.1%), reflecting expert prioritization of long-term sustainability over short-term cost. Synthetic fuel (PtL) achieved the highest rankings across cost, technology, effectiveness, social impact, and regulatory criteria, with consistency ratios below 0.02, validating the reliability of expert judgments. Recycled carbon fuel ranked highest for environmental impact (55%), indicating its role as a complementary pathway. These results collectively demonstrate that SAF adoption in Oman requires coordinated technological investment, regulatory enforcement, and Aviation 4.0–enabled decision support.

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