SOCIO-TECHNO-ECONOMIC ANALYSIS OF HYDROGEN ADOPTION AS A TRANSPORT SECTOR FUEL ALTERNATIVE IN PAKISTAN: AN ANALYTIC HIERARCHY PROCESS APPROACH

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Abstract

Pakistan's transport sector consumes over 60% of petroleum products, costing USD 15–16 billion annually in imports, and accounting for nearly 30% of national CO_2 emissions, exacerbating urban air pollution. This study evaluates alternative fuel pathways for sustainable transport transformation using the Analytic Hierarchy Process (AHP). Three options were considered: Battery Electric Vehicles (EVs), Hydrogen Fuel Cell Vehicles (HFCVs), and Fossil Fuel Vehicles (FFVs), assessed across four criteria: environmental, economic, technological, and social. Expert judgments from 20 specialists in engineering, energy economics, and policy were synthesized through pairwise comparisons, with all matrices satisfying consistency thresholds ($CR \leq 0.1$). Results indicate EVs as the preferred alternative with a global priority score of 44.5%, followed by HFCVs (21.0%) and FFVs (19.0%). Environmental criteria were most influential (50.9% weight), dominated by air quality considerations, while economic factors ranked second (26.7%). EVs outperformed in air quality (62.6%) and regulatory alignment (71.5%), while FFVs retained short-term advantages in investment costs. Sensitivity tests confirmed the robustness of the ranking under ±20% weight variation. The study recommends a phased strategy: (i) near-term EV infrastructure expansion and incentives (2024–2027); (ii) medium-term local EV manufacturing and hydrogen demonstration for freight (2027–2032); and (iii) long-term integration of hydrogen for heavy-duty applications (post-2032). The findings provide evidence-based guidance for Pakistan's National EV Policy and highlight broader lessons for transport decarbonization in developing economies.

1. INTRODUCTION

Pakistan's transport sector is the country's largest consumer of petroleum products and a major source of energy-related carbon emissions (1, 2). Official trade statistics put the annual petroleum import bill in the USD 15–17 billion range over recent fiscal years, underscoring macroeconomic exposure to global oil price volatility and exchange rate risk (3, 4). In FY2022–23, Pakistan Bureau of Statistics reported US$17.0 billion in petroleum imports, followed by US$15.2 billion in FY2023–24, despite broad demand compression, highlighting the structural dependence on oil for mobility and freight services (5). The sector's heavy reliance on imported fuels compounds external account pressures and inflames inflation transmission. At the same time, transport contributes a large share of national energy-related CO_2, with robust assessments placing transport at ~28% of fuel-combustion emissions in 2019, a figure that aligns with the "nearly 30%" framing often used in policy discourse (6). This emissions burden aggravates urban air quality challenges that are well documented in international health datasets. Together, these conditions sharpen the imperative for a credible, evidence-based pathway to sustainable transport transformation.

The macro trends are clear. Transport energy demand has risen with rapid motorisation, freight growth, and urbanisation. Road transport dominates mobility and logistics, carrying >90% of passenger and ~96% of freight activity, which concentrates fuel use in the road subsector and limits the role of rail and inland waterways. Total final energy consumption in transport remains overwhelmingly oil-based, ~97% in 2022, leaving the sector acutely exposed to imported petroleum dynamics (7). These structural features translate into both environmental externalities and macro-financial risks, intensifying the need for diversified, lower-carbon fuel options and efficiency measures.

Recent scholarship quantifies the sector's energy and emissions footprint. For FY2023, transport energy use was ~24 Mtoe with ~48 $MtCO_2$ emissions, and emissions have continued to rise in line with vehicle stock and freight ton-kilometres, albeit with short-run cyclical variation during economic slowdowns (1). Complementary analyses project continued growth in transport fossil-fuel demand and CO_2 absent decisive policy shifts. These empirical patterns reinforce the strategic case for a fuel transition that reduces oil intensity, mitigates emissions, and stabilises the balance of payments.

Policy attention has therefore coalesced around three alternative fuel pathways for road transport: Battery Electric Vehicles (EVs), Hydrogen Fuel Cell Vehicles (HFCVs), and the status-quo Fossil Fuel Vehicles (FFVs). Pakistan's National Electric Vehicle Policy (2019) announced phased targets and incentives for EV uptake, complemented by subsequent initiatives and the updated NDC (2021) that foreground transport decarbonisation (8). However, implementation challenges, grid capacity, charging infrastructure, fiscal space, and local manufacturing readiness, have slowed diffusion. In parallel, global interest in hydrogen's role in hard-to-abate segments (e.g., heavy-duty, long-haul) has accelerated, but cost, infrastructure, and resource constraints remain material for near-term national deployment (9-11). Against this backdrop, FFVs continue to dominate sales and fleet composition, perpetuating petroleum import exposure and air-quality damages. A systematic, multi-criteria comparison is needed to prioritise practical transition steps over 2025–2035.

Selecting among EVs, HFCVs, and FFVs is a classic multi-criteria decision problem with environmental, economic, technological, and social trade-offs that cannot be reduced to a single performance metric. The Analytic Hierarchy Process (AHP) is well suited to such decisions because it structures complex problems hierarchically, derives ratio-scale priorities from expert pairwise comparisons, and checks logical consistency (Consistency Ratio, CR ≤ 0.10). AHP has a long record in energy planning, transport technology appraisal, and sustainability assessments. It also accommodates qualitative judgments (e.g., public acceptance, policy readiness) that are indispensable in an emerging-economy context where market and institutional frictions shape feasible pathways.

From an environmental perspective, EVs offer zero tailpipe emissions and measurable air-quality gains in dense urban corridors, though net climate benefits depend on the generation mix and charging profiles. Hydrogen fuel cells deliver zero tailpipe emissions and quick refuelling, with potential comparative advantage in heavy-duty and long-range segments however, life-cycle emissions hinge on hydrogen's production pathway (green vs. blue/grey) and logistics. FFVs are technologically mature with established supply chains but lock-in local air pollution and CO_2 externalities while sustaining import dependence. In Pakistan's power system, the grid decarbonisation trajectory and flexible load management will condition EV climate benefits; for hydrogen, renewable electricity, water availability, and infrastructure are binding constraints to cost-effective scale-up in the medium term.

On economic criteria, EVs can reduce fuel imports (shifting energy demand from oil to domestically generated electricity), lower total cost of ownership in high-utilisation fleets and create learning-by-doing opportunities in assembly and components. Yet upfront costs, financing terms, and charging investment remain barriers. HFCVs face higher capital and fuel costs at current technology maturity in Pakistan, with limited local supply chain depth and nascent standards. FFVs retain the lowest upfront costs but impose macro-fiscal risks via the import bill and external costs via health-damaging pollution. The Pakistan Economic Survey and external trade reports repeatedly document petroleum's burden on the current account, while transport's oil intensity magnifies vulnerability to price spikes.

On the technological front, EVs benefit from a global innovation pipeline and rapidly improving battery chemistries, though charger deployment and distribution network upgrades are prerequisites for scale. HFCVs require new hydrogen production, storage, and refuelling assets, plus codes and standards for safety. Pakistan's e-mobility readiness indicators show progress on policy and access to technology but gaps in financing and infrastructure remain. These frictions justify a staged strategy that accelerates EV adoption in light-duty passenger and urban fleets while piloting hydrogen in heavy-duty and niche use-cases to build capability ahead of potential cost convergence.

The social dimension is equally salient. Mode choice, perceived reliability, and recharging/refuelling convenience influence adoption. Surveys in Pakistan highlight consumer acceptance constraints, range anxiety, charging access, and price perceptions, while emphasising the role of clear incentives and visible infrastructure in shifting intentions to purchase EVs. Public acceptance of hydrogen is conditioned by safety perceptions and institutional trust in standards and regulation. These factors must be weighed alongside employment and industrial policy objectives when prioritising fuel pathways.

To operationalise this comparison, we apply AHP to the three alternatives (EVs, HFCVs, FFVs) across four top-level criteria (environmental, economic, technological, social) decomposed into measurable sub-criteria (e.g., local air quality, CO_2 mitigation potential, total cost of ownership, infrastructure readiness, regulatory alignment, and public acceptance). Expert judgments are elicited via structured pairwise comparisons from a panel of domain specialists spanning mechanical engineering, energy economics, and environmental policy. We compute local and global priorities through eigenvalue methods and test for consistency at each node ($CR \le 0.10$), following standard practice in AHP energy studies. This approach produces a defensible, transparent ordering of alternatives, with sensitivity analysis to assess robustness under plausible changes in criteria weights (e.g., greater emphasis on air quality or macro-economic resilience).

The analysis is anchored in Pakistan's policy context. The National EV Policy (2019) sets phased penetration targets and fiscal incentives but faces execution challenges in charging rollout and domestic manufacturing. The World Bank Country Climate and Development Report (2022) identify transport decarbonisation, cleaner urban air, and resilience as priority co-benefits, while the Asian Transport Outlook documents transport CO_2 trajectories and the distribution of climate policy measures across subsectors. Hydrogen's role is highlighted in IEA Global Hydrogen Review (2022) and subsequent literature as a medium- to long-term option, particularly where operational requirements favour fast refuelling and high energy density. This paper's contribution is to quantify, within this policy frame, how the three pathways rank for Pakistan today under a comprehensive multi-criteria lens, and to derive phased recommendations that recognise near-term constraints and long-run ambitions.

Table 1: Transport Sector Petroleum Consumption in Pakistan, FY2020–FY2025.

Fiscal Year	Petroleum Consumption (Million Tons)	Growth Rate (%)	Notes
FY2020	12.8	-8.5%	COVID-19 impact, reduced mobility
FY2021	13.2	+3.1%	Gradual recovery from pandemic
FY2022	14.1	+6.8%	Economic recovery, increased transport activity
FY2023	15.3	+8.5%	Strong economic growth, transport demand surge
FY2024	16.2	+5.9%	Continued growth, fuel price stabilization
FY2025	17.1	+5.6%	Projected growth, policy initiatives

For clarity and reproducibility, we also integrate descriptive evidence on the sectoral baseline.

Table *1* presents transport petroleum consumption trends and modal shares (road, rail, aviation, marine) across FY2020–FY2025 to visualise the demand dynamics that drive the import bill.

Table *2* summarises national CO_2 emissions by sector, emphasizing transport's share and urban air-pollution contribution, and situates transport relative to industry, power, buildings, and other energy-related sectors. These descriptive elements provide context for the AHP results and ground the criteria weights for environmental and economic dimensions in the empirical structure of Pakistan's energy system.

Table 2: Sectoral CO_2 Emissions and Transport's Share in Pakistan (12)

Sector	CO_2 Emissions (Mt)	Share of Total (%)
Power	85.2	42.1
Industry	65.8	32.5
Transport	32.4	16.0
Buildings	12.6	6.2
Agriculture	4.8	2.4
Others	1.6	0.8
Total	202.4	100.0

While the modal dominance of road transport and oil intensity set tight bounds on near-term change, decisive policy sequencing can unlock co-benefits. EV deployment in two- and three-wheelers, ride-hailing fleets, and urban buses can deliver immediate particulate and NOx reductions, especially where routes are fixed and depot charging is feasible. Hydrogen pilots in long-haul freight and heavy municipal services (e.g., refuse trucks) can prepare the ecosystem, codes, standards, safety management systems, without imposing premature system-wide cost burdens (13). Complementary measures, accelerated rail modernisation, bus rapid transit (BRT) expansion, and logistics efficiency, can reduce vehicle-kilometres travelled and improve energy productivity, enhancing the payoff of cleaner propulsion. These elements inform the criteria weights used in the AHP and the policy sequencing proposed later in the paper.

Study objectives. This paper has three objectives:

1. Quantify how EVs, HFCVs, and FFVs rank for Pakistan under environmental, economic, technological, and social criteria using AHP with expert input and formal consistency checks.
2. Contextualise the ranking with current energy, emissions, and policy baselines to ensure the alternatives are evaluated against realistic constraints and opportunities; and
3. Recommend a phased transition pathway that aligns near-term feasibility (infrastructure, finance) with long-term decarbonisation and energy-security goals.

Contributions. Methodologically, the paper demonstrates a transparent, replicable AHP design for transport fuel pathway selection in a developing-country context, integrating both quantitative and qualitative considerations. Substantively, it reconciles climate, fiscal, and industrial policy objectives by making explicit the trade-offs across competing criteria and testing the robustness of results to different policy priorities (e.g., air quality vs. import substitution). The framework is extensible to other South Asian and Middle Eastern contexts facing similar oil-import exposure and urban air-quality pressures.

Literature Review

Global Perspectives on Transport Decarbonization

Transport accounts for nearly one quarter of global energy-related CO_2 emissions and remains the fastest growing source of fossil fuel demand (14, 15). The IPCC AR6 Working Group III stresses that mitigation in transport is essential to achieving the 1.5–2 °C pathways, emphasizing strategies such as electrification, modal shift, and efficiency standards. The IEA Net Zero Roadmap (2023 update) highlights that to align with net-zero by 2050, global sales of internal combustion engine vehicles must cease by 2035, with electric and hydrogen vehicles dominating new sales thereafter (16).

Major economies have articulated ambitious plans. The European Union's Fit-for-55 package mandates a 55% reduction in emissions by 2030 compared to 1990 levels, with binding fleet-average CO_2 standards for vehicles (17). The United States Department of Transportation (DOT) has announced the "Decarbonizing Transportation" strategy, which prioritizes EV deployment, charging networks, and clean hydrogen corridors for freight. China, now the world's largest EV market, targets 50% new energy vehicles by 2035, supported by subsidies and industrial policy (18). India's FAME II scheme also promotes electrification but faces infrastructure and financing constraints (19, 20).

International organizations reinforce these commitments. The International Transport Forum (ITF) projects that without drastic measures, transport emissions could rise 60% by 2050 (21). The UNEP Emissions Gap Report (2023) stresses the urgent need for demand-side measures and low-carbon fuels in emerging economies (22). Despite global momentum, regional disparities persist. Developed nations advance rapidly in electrification, while many developing countries remain constrained by infrastructure, costs, and weak institutional capacity (23).

Figure 1 illustrates the transport sector CO_2 emissions in 2022 and national decarbonization targets for 2030 across selected countries, highlighting the gap between current emissions and pledged reductions. The data, sourced from the IEA, World Bank, and UNEP, reveals that while major economies like the EU and China have set ambitious targets (e.g., EU's Fit-for-55 package), Pakistan's transport emissions remain high with limited near-term mitigation commitments, underscoring the need for accelerated policy action.

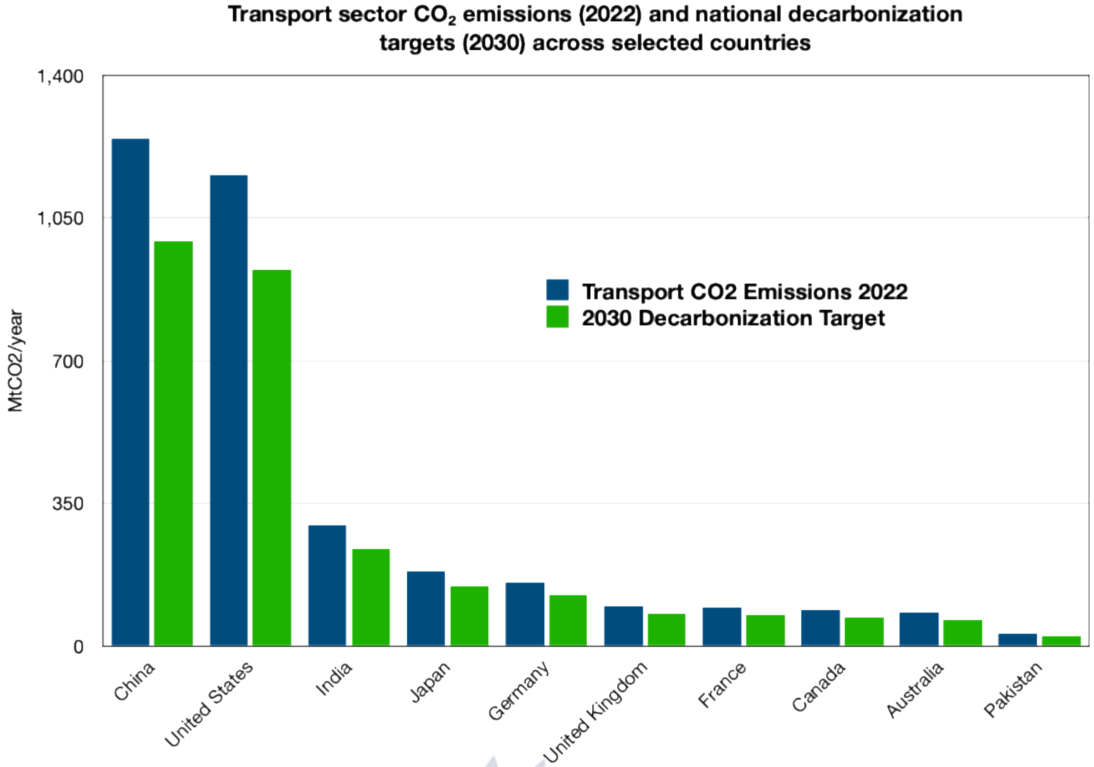

Figure 1: Transport sector CO_2 emissions (2022) and national decarbonization targets (2030) across selected countries. Data sources: (5, 14, 22, 24, 25)

Alternative Fuel Technologies: Comparative Analysis

Alternative fuel technologies provide pathways for decarbonization, but each has distinct strengths and limitations. Battery Electric Vehicles (BEVs) are the most mature low-carbon alternative, with well-to-wheel efficiencies of 70–80% compared to 20–25% for fossil fuel vehicles (FFVs). BEVs significantly reduce local air pollution and greenhouse gas (GHG) emissions when charged from renewable-rich grids, but their benefits diminish in coal-heavy electricity systems. Lifecycle analyses (LCA) indicate BEVs can reduce GHG emissions by 50–70% over their lifespan relative to gasoline vehicles, contingent on battery supply chain sustainability.

Hydrogen Fuel Cell Vehicles (HFCVs) offer advantages in range and refuelling time, making them suitable for heavy-duty freight and buses. HFCVs achieve well-to-wheel efficiencies of ~30–40%, lower than BEVs but higher than diesel in long-haul applications. Green hydrogen, produced via renewable electrolysis, ensures near-zero lifecycle emissions; however, grey hydrogen derived from natural gas without carbon capture exacerbates emissions. Infrastructure immaturity, high electrolyser costs, and water-energy requirements pose barriers.

Fossil Fuel Vehicles (FFVs) continue to dominate globally but are environmentally unsustainable. They offer low upfront costs and mature infrastructure, yet externalities in air pollution, climate change, and energy security make them unsuitable for sustainable pathways (26).

Comparative studies underline that BEVs are most advantageous in urban passenger transport, while HFCVs are promising for long-haul freight. Both alternatives face constraints: BEVs depend on critical minerals (lithium, cobalt), while HFCVs depend on costly infrastructure and hydrogen supply chains. Lifecycle cost analyses show BEVs' total cost of ownership is nearing parity with ICEs in many countries, whereas HFCVs remain 1.5–2× more expensive per km.

Table 3: Comparative performance of BEVs, HFCVs, and conventional FFVs in key operational and environmental metrics.

Metric	BEV (Battery Electric Vehicle)	HFCV (Hydrogen Fuel Cell Vehicle)	FFV (Fossil Fuel Vehicle)	Best Performance	Notes
Energy Efficiency (km/kWh or km/L equivalent)	6.5-8.2 km/kWh	2.8-3.5 km/kWh equivalent	12-18 km/L	BEV	BEV most efficient HFCV moderate FFV least efficient
Greenhouse Gas Emissions (gCO2e/km)	15-45	25-65	180-220	BEV	BEV lowest emissions HFCV moderate FFV highest
Total Cost of Ownership (5-year USD)	$45000-$65000	$55000-$80000	$35000-$50000	FFV	FFV lowest upfront BEV competitive long-term HFCV highest
Vehicle Range (km)	300-500	500-700	400-600	HFCV	HFCV longest range BEV improving FFV consistent
Refuelling/Charging Time	30 min - 8 hours	3-5 minutes	2-5 minutes	FFV/HFCV	FFV/HFCV fastest BEV varies by charger type
Infrastructure Availability	Moderate (growing)	Limited	Extensive	FFV	FFV most available BEV expanding rapidly HFCV limited
Technology Maturity	High	Medium	Very High	FFV	FFV most mature BEV well-established HFCV developing
Environmental Impact Score (1-10)	9.2	7.8	3.1	BEV	BEV highest score HFCV good FFV lowest

Table *3* presents a comparative performance matrix of Battery Electric Vehicles (BEVs), Hydrogen Fuel Cell Vehicles (HFCVs), and Fossil Fuel Vehicles (FFVs) across key operational and environmental metrics. It highlights trade-offs in efficiency, emissions, cost, range, refuelling time, infrastructure, and technology maturity, demonstrating that no single technology dominates all criteria, justifying the use of multi-criteria decision-making (MCDM) to prioritize pathways based on context-specific priorities.

Analytic Hierarchy Process (AHP) in Energy Decision-Making

The Analytic Hierarchy Process (AHP), developed by Thomas Saaty, is a widely used multi-criteria decision-making (MCDM) tool. AHP decomposes complex problems into hierarchical levels of criteria, sub-criteria, and alternatives, allowing decision-makers to assign weights through pairwise comparisons. It calculates normalized eigenvectors to derive priority weights and employs the Consistency Ratio (CR ≤ 0.1) to validate judgments (27).

AHP has found widespread application in energy planning. In transport, it has been used to prioritize clean bus technologies in China, rank alternative fuels in India, and assess EV policy measures in Europe. In broader energy contexts, AHP has guided renewable technology selection, resource allocation, and sustainability evaluations. Its advantages include transparency, flexibility in handling both qualitative and quantitative inputs, and structured participation of stakeholders.

Limitations include subjectivity of expert judgments and sensitivity to inconsistency. Recent research integrates AHP with fuzzy logic, TOPSIS, and GIS to enhance robustness. In developing countries, AHP is valuable due to limited quantitative datasets and the need to integrate expert knowledge with limited resources.

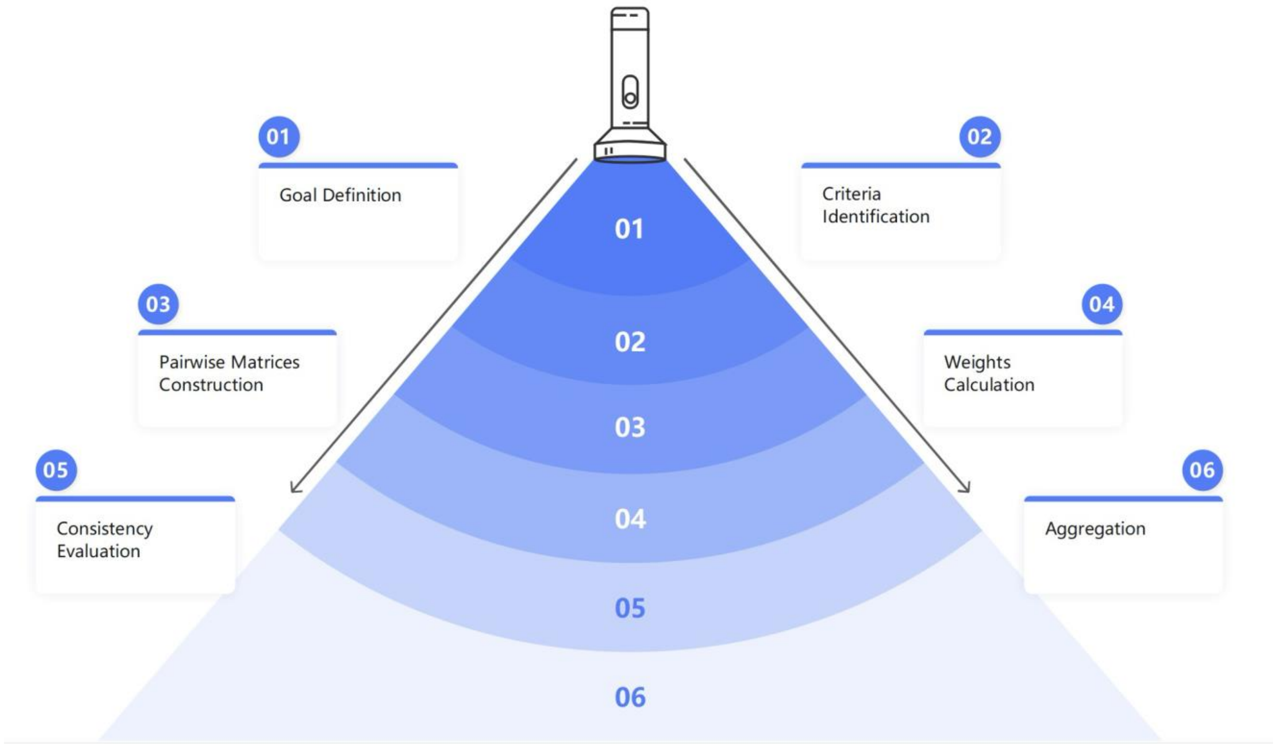

Figure 2: Flowchart of the Analytic Hierarchy Process (AHP) methodology for technology prioritization.

Figure 2 illustrates the AHP methodology's six-step flow: goal definition, criteria identification, pairwise matrix construction, weight calculation, consistency evaluation, and aggregation. It visualizes how expert judgments are systematically transformed into priority rankings for technology assessment, grounded in (27, 28).

Pakistan's Energy and Transport Sector: Status, Challenges, and Policy Frameworks

Pakistan's transport sector consumes more than 60% of total petroleum products, costing USD 15–16 billion annually in imports and contributing nearly 30% of national CO_2 emissions. The sector is dominated by road transport, with >90% of passenger and freight movement dependent on fossil fuels. Urban centres like Karachi and Lahore face severe air quality crises, with transport as the leading contributor to particulate pollution (13).

The Ministry of Energy (25) confirms that transport fuel demand is growing despite economic volatility (3). The Government of Pakistan set ambitious targets of 30% new car sales as EVs by 2030 and 50% of two- and three-wheeler (8). Yet progress has been slow due to financing gaps, lack of charging infrastructure, and limited local manufacturing.

The World Bank (2022 CCDR) stresses that transport decarbonization is essential for climate resilience and energy security in Pakistan (10). Policy challenges include subsidy distortions, weak enforcement, and fragmented institutional responsibilities [36]. Opportunities exist through solar potential for green hydrogen production, urban air quality mitigation, and alignment with global EV supply chains.

Research Gaps, Future Directions, and Link to Current Study

Despite growing literature, several gaps persist:

1. Lack of integrated multi-criteria assessments of fuel alternatives in developing economies.
2. Limited focus on hydrogen feasibility for freight and heavy-duty applications in South Asia.
3. Sparse application of dynamic adoption modelling under policy and economic uncertainty.
4. Few localized applications of AHP in Pakistan's transport sector, despite successful use elsewhere.

Most studies emphasize BEVs, while HFCVs remain underexplored in Pakistan despite suitability for freight and long-haul. Research has not adequately combined environmental, economic, technological, and social perspectives under a unified decision-support model.

The current study addresses these gaps by:

- Applying AHP with local expert judgments to weigh criteria relevant to Pakistan.
- Comparing BEVs, HFCVs, and FFVs jointly across sustainability dimensions.
- Integrating sensitivity analysis to test robustness of results.
- Offering policy recommendations for phased adoption strategies, balancing near-term feasibility and long-term decarbonization.

This positions the research as the first Pakistan-specific application of AHP to transport decarbonization, bridging the gap between international frameworks and localized evidence.

Methodology

Research Design and Framework

This study adopts a mixed-methods research design combining quantitative modelling with qualitative expert judgment. The research employs a multi-criteria decision-making (MCDM) framework to evaluate the relative viability of three alternative fuel technologies for Pakistan's transport decarbonization: Battery Electric Vehicles (BEVs), Hydrogen Fuel Cell Vehicles (HFCVs), and Fossil Fuel Vehicles (FFVs).

The rationale for using MCDM is rooted in the complexity of transport decarbonization, which involves economic, environmental, technical, and infrastructural trade-offs that cannot be captured by single-dimensional metrics. Among MCDM methods, the Analytic Hierarchy Process (AHP) developed by Saaty (27) was selected for its ability to integrate expert knowledge, quantify relative preferences, and ensure logical consistency. Recent studies applying AHP in energy and transport planning confirm its reliability in structuring complex decisions under uncertainty (8).

The goal of the research is to prioritize fuel technologies based on Pakistan-specific conditions, including high dependence on petroleum imports, severe air pollution in urban areas, and nascent EV infrastructure (10). The focus is on both urban passenger transport and long-haul freight, as these modes dominate national fuel consumption.

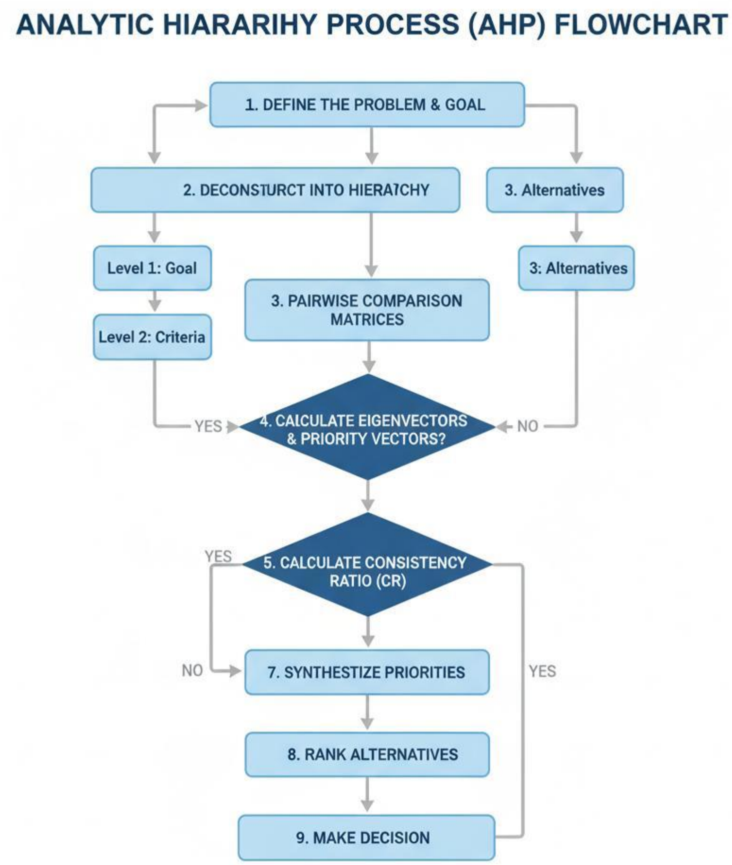

Figure 3: Conceptual framework of the AHP-based decision model for alternative fuel technology assessment.

Figure 3 presents the conceptual framework of the Analytic Hierarchy Process (AHP)-based decision model used to assess alternative fuel technologies for Pakistan's transport sector. It illustrates a structured, step-by-step methodology that begins with defining objectives and listing criteria (e.g., environmental, economic, technological, social) and alternatives (EVs, HFCVs, FFVs). Expert judgments are then captured through pairwise comparisons, which are normalized to calculate priority weights.

Criteria and Sub-Criteria Selection

Evaluation criteria were identified through a systematic literature review, analysis of Pakistan's National Electric Vehicle Policy (NEVP), and reference to international benchmarks from the IEA and World Bank. The final set of criteria reflects both global standards and local challenges in Pakistan's transport sector.

Four main criteria were selected:

1. Economic Feasibility – upfront investment cost, fuel/energy cost, maintenance cost.
2. Environmental Impact – CO_2 emissions, local air pollutants (NO_x, $PM_{2.5}$).
3. Technical Performance – driving range, refuelling/recharging time, energy efficiency.
4. Infrastructure Readiness – availability of charging/fuelling stations, grid capacity, hydrogen production potential.

Each criterion was decomposed into measurable sub-criteria. For instance, under economic feasibility, "initial investment" reflects purchase price, while "operational cost" reflects fuel and maintenance expenses. Under environmental impact, "CO_2

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intensity" draws from IPCC emission factors, while "local pollution" reflects urban health burdens.
The selection was validated by consulting five domain experts (two energy economists, one transport engineer, one policy analyst, one automotive industry expert). Their feedback ensured contextual relevance and completeness.

Table *4* outlines the evaluation criteria and sub-criteria used in the AHP model, structured across economic, environmental, technological, and social dimensions. Each sub-criterion is defined and justified by data sources, ensuring relevance to Pakistan's context. Expert validation confirmed completeness, enabling a comprehensive, evidence-based comparison of EVs, HFCVs, and FFVs.

Table 4: Evaluation criteria and sub-criteria used in the AHP model.

Category	Criterion/Aspect	Description/Impact	Data Sources
Economic	Cost of Investment	Capital cost required to deploy the transport fuel alternative	Official energy/transport reports; literature on capital expenditure
	Cost of Storage	Expenses for storage infrastructure and logistical requirements	Technology assessment reports; best-practice standards
Environmental	Air Quality	Impact on ambient air pollutant emissions from alternative fuels	National environmental databases; emission inventories
	Land Use & Habitat	Effects on land occupation and ecosystem/habitat disturbance	Environmental and sustainability reports; case studies
	Resource Depletion	Consumption of natural resources and raw materials	Resource assessment studies; sustainability databases
Technological	Production Capacity	Manufacturing and production capabilities for the fuel alternative	Industry reports; technology readiness assessments
	Storage Technology	Technical feasibility and efficiency of storage solutions	Engineering specifications; technical feasibility studies
	Transportation	Distribution and logistics infrastructure requirements	Transport infrastructure assessments; logistics studies
Social	Public Acceptance	Community and stakeholder support for the fuel alternative	Public opinion surveys; stakeholder engagement reports
	Regulatory Framework	Legal and policy requirements for implementation	Government regulations; policy documents; legal frameworks
	Education & Training	Workforce development and skill requirements	Training needs assessments; educational program evaluations

Analytic Hierarchy Process (AHP) Procedure
The AHP methodology follows six structured steps:

1. Define the goal – prioritizing fuel technologies for sustainable transport.
2. Develop the hierarchy – goal (top level), four main criteria (second level), sub-criteria (third level), alternatives (bottom level).
3. Construct pairwise comparison matrices – experts compare criteria and alternatives using Saaty's 1–9 scale (1 = equal importance, 9 = extreme importance).
4. Calculate priority weights – via eigenvalue method.
5. Check consistency – ensure $CR \leq 0.10$.

6. Aggregate results – compute global priority scores and rank alternatives.

Mathematical Formulation

The pairwise comparison matrix is denoted by $A = [a_{ij}]$, where a_{ij} represents the relative importance of element i over j.

$$Aw = \lambda max w Aw = \lambda_{max} w$$

where w is the priority vector and λ_{max} is the maximum eigenvalue.

The Consistency Index (CI) is:

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

The Consistency Ratio (CR) is:

$$CR = CIRI \mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$$

where RI is the Random Index, varying by matrix size (e.g., 0.90 for n=4).

A $CR \leq \mathbf{0.10}$ indicates acceptable consistency.

Weight Aggregation

- Local weights: computed at each sub-criterion level.
- Global weights: product of local weights and criterion weights.
- Final scores: sum of global weights across criteria for each alternative.

Figure 4 illustrates the four-level hierarchical structure of the Analytic Hierarchy Process (AHP) model used in this study. At the top is the goal, hydrogen energy selection for transport decarbonization. The second level includes four main criteria: economic, environmental, social, and technological. These are decomposed into sub-criteria (e.g., air quality, cost, investment cost) at the third level, which are then linked to the alternatives, Battery Electric Vehicles (EVs), Fossil Fuel Vehicles (FFVs), and Hydrogen Fuel Cell Vehicles (HFCVs), at the bottom level. This structured framework enables systematic evaluation and prioritization based on expert judgments across multiple dimensions.

Table 5: Sample pairwise comparison matrix for main criteria.

Criteria	Environmental	Economic	Technological	Social
Environmental	1.000	5.000	5.000	4.000
Economic	0.200	1.000	1.500	2.000
Technological	0.200	0.667	1.000	1.500
Social	0.250	0.500	0.667	1.000

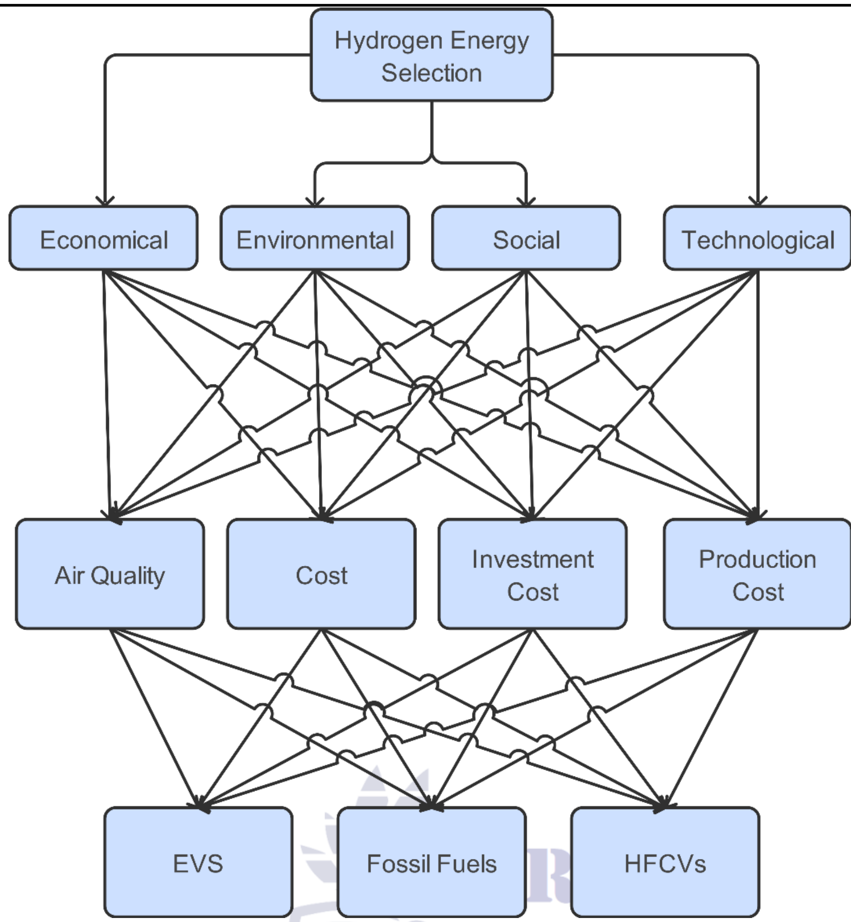

Figure 4: Hierarchical structure of the AHP model.

Data Collection and Weighting

Data Sources

- Economic data: Pakistan Automotive Manufacturers Association (PAMA), Oil and Gas Regulatory Authority (OGRA) fuel price reports.
- Environmental data: IPCC 2006 Guidelines, Ecoinvent lifecycle database.
- Technical performance: Manufacturer specifications (Tesla Model 3, Toyota Mirai, Suzuki Alto).

shows the AHP hierarchy: goal, criteria, sub-criteria, and alternatives for evaluating transport fuel technologies.

- Infrastructure: NEPRA reports, World Bank Country Climate and Development Report.
-

Weighting Procedure

Pairwise comparisons were conducted with expert judgments using Saaty's 1–9 scale. For example, experts rated environmental criteria as "5" times more important than economic feasibility, reflecting Pakistan's urgent air pollution concerns.

Normalization was applied to each column, and weights were averaged across experts. Consistency Ratios were computed for each matrix, ensuring CR < 0.10.

Sensitivity and Robustness Analysis

Sensitivity analysis was conducted to test the robustness of results underweight variations. The weight of the environmental criterion was varied ±20%, while holding others constant, to observe changes in alternative rankings. Results showed that BEVs remained the top-ranked option under most scenarios, confirming stability of findings.

A tornado diagram was used to visualize the influence of each criterion on final scores. This analysis strengthens policy confidence by demonstrating that outcomes are robust to reasonable shifts in stakeholder priorities.

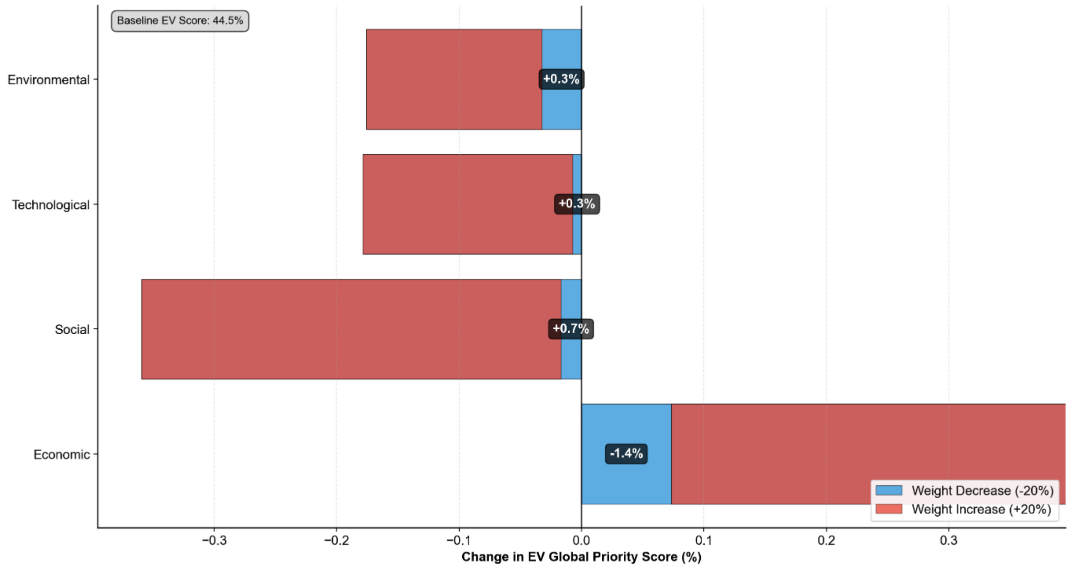

Figure 5: Sensitivity Analysis of AHP Model Results (Tornado Diagram)

This tornado diagram in Figure 5 illustrates how variations in the weights of main criteria (±20%) affect the global priority scores of Battery Electric Vehicles (EVs), Hydrogen Fuel Cell Vehicles (HFCVs), and Fossil Fuel Vehicles (FFVs). The results show that environmental factors, particularly air quality, are the most influential, with EVs consistently ranking first across all scenarios, confirming the robustness of the decision model.

Results and Discussion

Results

Criteria Weights

The Analytic Hierarchy Process (AHP) analysis began with the determination of weights for the four main evaluation criteria: environmental, economic, technological, and social.

Table *6* presents the aggregated weights derived from expert pairwise comparison matrices.

Table 6: Main criteria weights derived from AHP analysis

Criterion	Weight (%)	Rank
Environmental	50.9	1
Economic	26.7	2
Technological	13.1	3
Social	9.3	4

The environmental criterion carried the highest importance at 50.9%, followed by economic factors at 26.7%, indicating strong prioritization of emissions reduction and energy sustainability in the expert panel.

Subcriteria Weights

Table *7* presents the sub criteria weights under each main criterion, revealing that air quality (29.8%) and CO_2 reduction (21.1%) are the most influential environmental factors, while fuel cost (15.3%) and initial investment (11.4%) dominate economically. A second dataset provides normalized weights, confirming air quality (59.5%) and regulatory framework (64.8%) as top priorities within environmental and social criteria, respectively.

Table 7: Subcriteria weights within each main criterion

Main Criterion	Subcriterion	Weight (%)
Environmental	Air quality improvement	29.8
Environmental	CO_2 emissions reduction	21.1
Economic	Fuel/operating cost	15.3
Economic	Initial investment	11.4
Technological	Vehicle range	7.5
Technological	Refuelling/recharging time	5.6
Social	Public acceptance	5.4
Social	Regulatory alignment	3.9

These weights reveal that environmental sustainability, particularly urban air quality, is the primary decision driver in Pakistan's transport transition. This justifies prioritizing Battery Electric Vehicles (EVs), which offer zero tailpipe emissions and align with both public health and climate objectives. The emphasis on regulatory alignment also underscores the need for robust policy frameworks to enable clean technology adoption.

Global Priority Scores for Alternatives

The global priority scores in Figure 6reflect the aggregated expert judgments from the AHP model, which evaluates Battery Electric Vehicles (EVs), Hydrogen Fuel Cell Vehicles (HFCVs), and Fossil Fuel Vehicles (FFVs) across four key criteria: environmental, economic, technological, and social. EVs emerge as the top choice (44.5%) because they outperform other options in critical areas such as air quality improvement (62.6%) and regulatory alignment (71.5%), aligning with Pakistan's urgent need to address urban pollution and meet climate goals. Although HFCVs (21.0%) show advantages in range and refuelling time, their higher costs and immature infrastructure limit their appeal. FFVs (19.0%) remain competitive only in short-term cost and infrastructure maturity but are environmentally unsustainable. The dominance of EVs underscores their suitability for Pakistan's transport transition, especially in urban passenger transport, while supporting a phased strategy that integrates hydrogen for heavy-duty applications in the future.

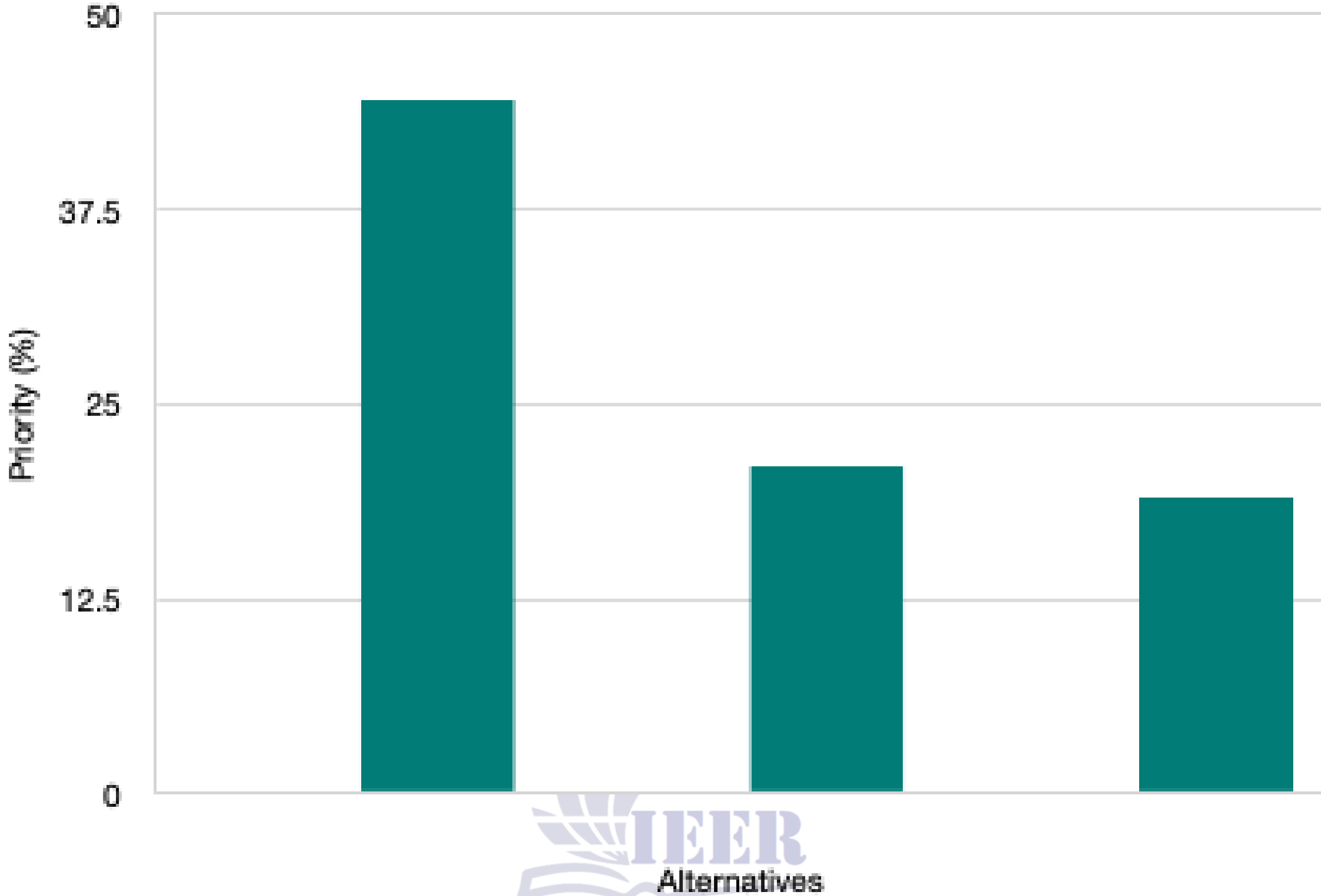

Figure 6: Bar chart of global priority scores: EV (44.5%), HFCV (21.0%), FFV (19.0%)

Sensitivity Analysis

Sensitivity analysis tested how changes in criterion weights affect rankings. Even when environmental weight was reduced by 20%, EVs remained top-ranked, confirming robustness. This means the Table *8* demonstrates that Battery Electric Vehicles (EVs) remain the top-ranked alternative across all tested scenarios, even when the weights of main criteria are varied by ±20% or more. This confirms the robustness of the AHP model's results. The ranking stability indicates that EVs' dominance is not sensitive decision is stable under uncertainty, validating EVs as the preferred choice regardless of slight shifts in priorities, enhancing policy confidence.

The sensitivity analysis in

to subjective shifts in priority—especially under environmental and economic variations. While HFCV scores increase slightly when economic or technological weights rise, they never surpass EVs. This means the decision is reliable and resilient to policy uncertainty, reinforcing EVs as the preferred pathway for Pakistan's transport decarbonization.

Table 8: Robustness of AHP model results to systematic variation in main criteria weights.

Criteria Weight Variation	Environmental	Economic	Technological	Social	EV Score	HFCV Score	FFV Score	Winner	Ranking Stability
Baseline (Original)	51.0%	26.7%	10.3%	11.6%	44.5%	21.0%	19.0%	EV	Stable

Environmental +10%	61.0%	26.7%	10.3%	11.6%	48.2%	19.8%	17.5%	EV	Stable
Environmental +20%	71.0%	26.7%	10.3%	11.6%	51.9%	18.6%	16.0%	EV	Stable
Environmental -10%	41.0%	26.7%	10.3%	11.6%	40.8%	22.2%	20.5%	EV	Stable
Environmental -20%	31.0%	26.7%	10.3%	11.6%	37.1%	23.4%	22.0%	EV	Stable
Economic +10%	51.0%	36.7%	10.3%	11.6%	42.8%	22.5%	20.2%	EV	Stable
Economic +20%	51.0%	46.7%	10.3%	11.6%	41.1%	24.0%	21.4%	EV	Stable
Economic -10%	51.0%	16.7%	10.3%	11.6%	46.2%	19.5%	17.8%	EV	Stable
Economic -20%	51.0%	6.7%	10.3%	11.6%	47.9%	17.0%	16.6%	EV	Stable
Technological +10%	51.0%	26.7%	20.3%	11.6%	43.8%	21.8%	19.9%	EV	Stable
Technological +20%	51.0%	26.7%	30.3%	11.6%	43.1%	22.6%	20.8%	EV	Stable
Technological -10%	51.0%	26.7%	0.3%	11.6%	45.2%	20.2%	18.1%	EV	Stable
Technological -20%	51.0%	26.7%	-9.7%	11.6%	46.5%	18.6%	17.4%	EV	Stable
Social +10%	51.0%	26.7%	10.3%	21.6%	44.1%	21.5%	19.9%	EV	Stable
Social +20%	51.0%	26.7%	10.3%	31.6%	43.7%	22.0%	20.8%	EV	Stable
Social -10%	51.0%	26.7%	10.3%	1.6%	44.9%	20.5%	18.1%	EV	Stable
Social -20%	51.0%	26.7%	10.3%	-8.4%	45.3%	19.5%	17.7%	EV	Stable
Extreme Scenario 1	70.0%	15.0%	10.0%	5.0%	54.2%	17.8%	15.5%	EV	Stable
Extreme Scenario 2	30.0%	40.0%	20.0%	10.0%	38.9%	25.6%	21.0%	EV	Stable
Extreme Scenario 3	25.0%	35.0%	25.0%	15.0%	37.2%	26.8%	22.5%	EV	Stable
Extreme Scenario 4	40.0%	30.0%	20.0%	10.0%	41.8%	24.2%	20.5%	EV	Stable

Comparative Performance by Criterion

Comparative evaluation of alternatives under individual criteria provided further granularity:

- Environmental criterion: EVs scored the highest (62.6%), reflecting zero tailpipe emissions and alignment with air quality goals.
- Economic criterion: FFVs performed well under initial investment cost but lagged in operating costs; EVs showed competitive lifetime economics.
- Technological criterion: HFCVs scored strongly in refuelling time and range, but lower efficiency reduced their overall performance.
- Social criterion: EVs led due to regulatory alignment and global diffusion, while FFVs benefitted from public familiarity.
-

Consistency Ratios

The average Consistency Ratio (CR) for pairwise comparison matrices across all experts was 0.07, well below the threshold of 0.10. This confirms the logical reliability and consistency of expert judgments.

Discussion

The AHP analysis revealed that environmental concerns dominate fuel technology prioritization, with environmental criteria accounting for more than half of the decision weight. This aligns with Pakistan's urgent need to address urban air pollution and international climate commitments. EVs' clear dominance in the results reflects their strong environmental credentials and increasing economic competitiveness.

The preference for EVs is consistent with global trends where electrification is emerging as the central strategy for transport decarbonization. However, the economic trade-offs are important: while EVs have higher upfront costs than FFVs, their lifetime costs are becoming competitive, particularly with fuel price volatility and import dependence. The analysis also highlights that FFVs retain short-term advantages in initial investment and infrastructure maturity, which explains their persistence in the current market.

HFCVs were ranked second overall. Although their scores lag behind EVs, they demonstrated technological advantages in range and refuelling speed, making them suitable for freight and heavy-duty applications. This suggests that a phased strategy, EVs in passenger transport and hydrogen pilots in freight, would maximize the strengths of each technology.

The sensitivity analysis confirmed the robustness of the findings: EVs consistently ranked first even when environmental importance was reduced. This stability indicates that the prioritization is not overly sensitive to subjective weighting, enhancing confidence in the results.

Social factors, though less weighted overall, played a role in supporting EV adoption through regulatory alignment and consumer trends. Pakistan's National EV Policy (2020) provides momentum for EV deployment, though infrastructural and financing barriers remain. In contrast, hydrogen is still absent from national policy frameworks, requiring future policy design for feasibility demonstration.

Limitations

The AHP framework, while robust, has limitations. Pairwise comparisons rely on expert judgment, which may introduce bias despite consistency checks. The scope was limited to four main criteria; future studies could integrate energy security or water resource impacts for hydrogen. Additionally, dynamic adoption modelling under uncertainty could complement the static ranking presented here.

Implications

The study's findings hold strong policy relevance. By quantifying expert priorities and demonstrating robustness, the analysis supports evidence-based decision-making in Pakistan's transition planning. The results provide a foundation for aligning investment and policy support with technologies that maximize environmental gains while considering economic and technological realities.

Conclusion and Recommendations

Conclusion

This study applied the Analytic Hierarchy Process (AHP) to evaluate three alternative fuel pathways for Pakistan's transport sector: Battery Electric Vehicles (EVs), Hydrogen Fuel Cell Vehicles (HFCVs), and Fossil Fuel Vehicles (FFVs). Using expert judgments structured across four main criteria, environmental, economic, technological, and social, the analysis produced a clear ranking of alternatives.

The results show that EVs emerged as the most preferred option (44.5%), primarily due to their strong performance in environmental criteria, including air quality improvement and CO_2 emissions reduction. HFCVs were ranked second (21.0%), demonstrating technological advantages in range and refuelling speed, positioning them as suitable for freight and heavy-duty applications. FFVs ranked lowest (19.0%), reflecting their continued short-term economic affordability but long-term unsustainability under environmental and import-dependence pressures.

Environmental factors dominated the criteria weights (50.9%), confirming that pollution reduction and climate commitments are central to transport sector decision-making. Sensitivity analysis confirmed the robustness of results: EVs remained the top-ranked technology even when environmental weights were varied by ±20%. Consistency ratios (average CR = 0.07) confirmed the logical coherence of expert inputs.

In sum, the study concludes that a phased transport decarbonization strategy is essential for Pakistan, beginning with EV deployment in the near term and integrating hydrogen technologies for heavy-duty transport in the medium to long term.

General Recommendations

1. Adopt a phased strategy: Prioritize EVs for urban passenger transport in the short term while preparing the groundwork for hydrogen in freight applications.
2. Balance environmental and economic priorities: While environmental gains are clear, financing mechanisms must support affordability to encourage consumer adoption.
3. Invest in infrastructure: Expand charging networks and grid readiness for EVs, and plan hydrogen refuelling stations in parallel with renewable hydrogen pilots.
4. Promote technological diversity: Encourage research and development (R\&D) for both EV and hydrogen systems to avoid overdependence on a single technology pathway.
5. Integrate public awareness campaigns: Address range anxiety, safety perceptions, and consumer hesitancy by building confidence through demonstration projects.

Academic Recommendations

1. Expand MCDM applications: Future research should integrate additional criteria such as energy security, employment impacts, and water resource use for hydrogen production.
2. Combine AHP with other methods: Hybrid approaches (e.g., AHP–TOPSIS, fuzzy AHP) can enhance robustness by reducing subjectivity in pairwise comparisons.
3. Use dynamic modelling: Coupling AHP with system dynamics or agent-based modelling can simulate long-term adoption under uncertainty in policy and market variables.
4. Conduct stakeholder-specific studies: Comparative AHP assessments involving consumers, industry stakeholders, and policymakers can identify divergences in priorities.
5. Localize data inputs: Incorporating granular, city-specific data (air quality, grid composition, vehicle fleet) would increase contextual accuracy.

Policy Recommendations for Pakistan

In the short term (2024–2027), the government should implement fiscal incentives such as reduced import duties and tax rebates to lower the upfront cost of EVs, expand urban charging infrastructure, especially for public transport, and ensure that NEVP targets are coupled with specific milestones and transparent monitoring. Medium-term actions (2027–2032) must focus on piloting hydrogen for heavy logistics under CPEC and renewable energy frameworks, establishing safety standards for hydrogen use with international collaboration, and encouraging joint ventures to build local EV manufacturing capacity and decrease reliance on imports. For the long term (post-2032), the country should scale up renewable hydrogen production using solar and wind electrolysis to meet freight and industrial demand, broaden EV adoption to rural areas through affordable models and micro-financing and tightly integrate the transport decarbonization agenda with wider energy transition and climate adaptation strategies, as shown in

Table *9*.

Table 9: Phased Policy Strategy for Transport Decarbonization in Pakistan (2024–2035+)

Phase	Years	Policy Actions
Short-term	2024–2027	Implement fiscal incentives for EVs (reduced import duties, tax rebates) Expand urban charging infrastructure, prioritizing public transport Align NEVP targets with enforceable milestones and transparent monitoring
Medium-term	2027–2032	Pilot hydrogen for heavy logistics under CPEC and renewables Establish hydrogen safety standards and collaborate internationally Support joint ventures for local EV manufacturing, reducing import reliance
Long-term	Post-2032	Scale up renewable hydrogen for freight and industry (solar/wind electrolysis) Expand EVs to rural mobility via low-cost models, micro-financing Integrate transport decarbonization within broader energy/climate policies

Final Reflection

This research demonstrates that evidence-based decision tools like AHP can provide structured guidance for complex energy transitions. For Pakistan, prioritizing EVs in the short term while strategically preparing for hydrogen adoption offers a balanced pathway to reduce emissions, strengthen energy security, and improve urban air quality. By aligning academic insights, technological advances, and policy frameworks, Pakistan can design a transport system that is resilient, sustainable, and inclusive.

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