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Overcoming barriers to fuel cell electric vehicles adoption: Greener environmental governance in the Indian subcontinent☆

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ABSTRACT

Fuel cell electric vehicles (FCEVs) are gaining global attention as a sustainable transportation solution, yet their adoption in emerging South Asian economies remains limited. This study addresses the research gap by identifying and prioritizing barriers to FCEV adoption in India, Pakistan, and Bangladesh, regions underrepresented in existing literature. A hybrid methodology integrating Exploratory Factor Analysis (EFA), Fuzzy Set Theory (FST), and Evidential Reasoning Approach (ERA) was applied to analyze responses from 221 experts across five stakeholder groups. The results reveal that high cost, inadequate infrastructure, and lack of skilled workforce are the most critical and stable barriers. The study also proposes a scenario-based stability analysis for targeted and adaptive policy design. The study offers practical implications for policymakers and industry leaders aiming to accelerate the FCEV transition in emerging markets by providing region-specific insights.

1. Introduction

The increasing need for automobiles and ongoing environmental issues have pushed the industry to adopt measures to manage demand and provide sustainable growth. Many sustainability issues are linked to the automobile industry, including Greenhouse gas (GHG) emissions. CO_2 (75 %) and Methane (11 %) are significant components of GHG [1]. The total global CO_2 eq emission of the transportation sector is 16.2 percent [2]. Moreover, CO_2e across industries is stable but still growing in the Transport Industry. This can be attributed to the growing economies and increasing urban populations [3]. Efforts are taken in this direction to limit further climatic changes threatening the planet's existence. Selected South Asian emerging countries, namely India, Pakistan, and Bangladesh (Group & Bank, 2023), are showing faster growth and contributing to the emission of GHG. In this study, "emerging economies" refers to nations with rapidly developing industrial bases, growing energy demands, and transitional policy frameworks—characteristics typical of countries like India, Pakistan, and Bangladesh. These economies differ from developed nations such as Germany, Japan, or the United States in several critical dimensions relevant to FCEV adoption: lower R&D investment in hydrogen technologies, limited domestic manufacturing capacity, underdeveloped infrastructure (e.g., hydrogen refueling stations), and fragmented or nascent policy ecosystems. These distinctions shape the nature and severity of adoption barriers, making it essential to analyze FCEV challenges in a region-specific context. Although they share the same neighborhood, India, Pakistan, and Bangladesh are different in infrastructure development, policy initiatives for clean energy, and economic capabilities to implement new technologies such as FCEVs. Despite these differences, India, Pakistan, and Bangladesh are grouped together in this study due to their shared characteristics as fast-growing South Asian economies facing comparable sustainability challenges. All three countries are urbanizing rapidly, have high fossil fuel dependence, and show rising vehicular emissions without fully developed EV ecosystems. While India has launched initiatives like the National Green Hydrogen Mission and pilot projects on FCEVs, Pakistan and Bangladesh are at nascent

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stages with exploratory projects and limited policy instruments. This combination of shared challenges and staggered policy maturity offers a meaningful basis for comparative analysis to identify common and unique barriers to FCEV adoption in the region. India has started with national hydrogen missions and pilot projects in this regard, while Pakistan and Bangladesh are in the preliminary stages of insufficient policy structures and industrial readiness. India is concerned about its emissions. India's GHG emissions of 3200 million metric tonnes of CO2 eq, 6.5 % of global emissions, have raised concern for policymakers. India committed at COP26 to make itself a net-zero country by 2070 [4]. This required control of gas emissions in various sectors. Transport is India's third most carbon-emitting industry [5]; controlling it can result in decarbonization goals. The other two emerging economies of South Asia are Pakistan and Bangladesh. Pakistan's contribution to GHG emissions is 1 % but it is the world's 20th most significant contributor [6]. Bangladesh's contribution to GHG is insignificant at 0.4 %, but its increasing population and growing economy indicate possible emission levels [7]. Sustainable development goals of the World Economic Forum are efforts in this direction. This is possible by adopting technologies that reduce harmful effects. As suggested by Ahi & Searcy [8] sustainability is considering long-term welfare by managing resources so that current needs are met without compromising the needs of future generations.

Introducing electric vehicles and hydrogen-powered FCEVs is a step in this direction. Compared to an internal combustion engine vehicle (ICEV), the electric vehicle produces 59 % less CO_2eq [9]. Khalili et al. [10] found that alternative energy sources have the potential to replace fossil fuels, contributing to almost 92 percent of transportation fleets/vehicles. FCEV and battery electric vehicles (BEV) are the most commonly used electric vehicles. BEVs are based on batteries and electricity, which dominate the market [11]. In contrast, FCEVs are based on hydrogen-generated electricity, with only 43000 vehicles in 2021 International Energy Agency [12]. Despite this, policymakers and manufacturers are interested in complementing BEV with FCEV for several reasons including mileage and quick refilling [13], no issues about recovery and recycling of used batteries [14], and reduced dependence on critical raw materials like cobalt and nickel as reserves of these materials are limited International Energy Agency [12].

This study focuses on three representative South Asian emerging economies—India, Pakistan, and Bangladesh—chosen for their comparable challenges in FCEV adoption and varying degrees of policy readiness. While not exhaustive of the entire South Asian region, these countries provide relevant insights into common and divergent barriers within this regional context.

This study formulated the following research questions.

1. What are the key barriers that restrict the sustainable adoption of FCEV in Selected South Asian emerging economies?
2. What are the priority rankings of barriers based on their importance?

The research has potentially contributed in many ways. The study's findings reveal multiple barriers to adopting FCEV, which can be used for strategy formulation by various stakeholders in emerging economies. The results highlight the most severe obstacles that need to be addressed as a priority. The study's unique contribution is in building multiple scenarios with a combination of various perspectives based on severity. This may be used as a ready reckoner by policymakers, manufacturers, environmentalists, and society for decision-making in emerging economies. The study contributed to the knowledge pool by identifying the barriers to FCEV adoption in emerging economies and ranking them based on severity. Also, unlike other studies, this work combines multiple perspectives of the TBL (Triple Bottom Line), namely, environmental, social, and economic, along with an additional perspective, operational. Furthermore, the changing severity behavior of the barriers is studied by building multiple scenarios based on the varying significance of each perspective.

The motivation for the study can be attributed to the following: The global need and utility of FCEVs are increasing manifold. Countries such as European nations, the US, Japan, South Korea, and China have increased efforts to fulfill their pledges under the Paris Agreement, with hydrogen being highlighted as a key component in establishing a low-carbon or even carbon-free energy system [15]. This trend indicates potential growth in hydrogen energy sources and investment prospects for developing economies. Between 2006 and 2017, the US Department of Energy (DOE) reported a significant decrease of 60 % in fuel cell costs, accompanied by a quadrupling in their durability in terms of hours. Between 2002 and 2017, the cost of creating hydrogen from renewable sources was reduced by up to 80 %[16]. Hydrogen-powered FCEVs have several significant benefits over battery-powered electric vehicles, including refueling duration, long-range mobility, operability in cold and hot weather conditions, etc. [15]. Considering the global demand, emerging economies can also be instrumental in serving developed economies in the form of low-cost production hubs and at the same time, large markets. The net-zero emission targets result in policymakers encouraging solutions like FCEV throughout the economy. Despite opportunities, the big question is, are the emerging economies prepared enough to adapt to the global demand in terms of FCEVs sustainably? The authors are interested in identifying the barriers faced by emerging economies in the South Asian region.

Selected South Asian emerging economies have shown growth better than the global average in the last decade. And India is a major driver of the economy of this subcontinent (C.[17]). Growing economies are seen as contributing more to CO_2 eq emissions [18]. The current study focuses on selected South Asian nations interested in studying the adoption of FCEV. In India, FCEV is in the nascent stage. However, the country considers green hydrogen efficient in decarbonizing various carbon-emitting sectors. India announced its first hydrogen policy in March 2022 to promote and store green hydrogen [19]. Also, the first plant of Toyota Mirai, a green hydrogen fuel cell electric vehicle (FCEV), was recently inaugurated (Ministry of Road, Govt of India). Other South Asian economies are also moving in the same direction, though slowly. For instance, Sindh will soon be home to Pakistan's first green hydrogen factory, which can create about 150,000 kg of fuel daily [20]. In Bangladesh, there are initiatives to investigate and utilize hydrogen energy and fuel cell electric vehicles (FCEVs), and the government has initiated pilot projects to develop research facilities, test facilities, and train scientists [21]. While FCEVs are viewed as a promising alternative, the adoption of FCEVs in Selected South Asian emerging economies faces multiple barriers similar to some issues discussed by Bögel et al. [22], such as investment in hydrogen refueling routes and vehicle manufacturing. These issues intrigued researchers to discover why the automobile industry was limited from focusing on FCEV. This study contributes original insights by applying a multi-method framework—FST, EFA, and ERA—to the underexplored context of Selected South Asian emerging economies. While the barriers to FCEV adoption have been studied in developed countries, this paper offers a region-specific perspective that captures the complex interplay of economic constraints, policy immaturity, and technological gaps typical of India, Pakistan, and Bangladesh. Including an "Operational" pillar expands the conventional TBL framework, and the stability analysis provides a policy-relevant lens not commonly used in FCEV literature.

This study contributes to the literature by (i) focusing on the under-researched Selected South Asian context, (ii) integrating multiple decision-support methodologies—EFA, FST, and FERA—to derive empirically validated and expert-prioritized barriers, and (iii) introducing an operational dimension to the Triple Bottom Line framework to reflect infrastructure and technological constraints specific to emerging markets.

2. Literature review

The study stands out as one of the first to focus on FCEV's theory and

Table 1
Comparative study of Existing Literature and Current Study.

	Context	Objective	Method	Theory	Findings
Existing Literature	Emerging-market strategies on energy saving, energy substitution, and carbon reduction	To explore the production elasticities and technological progress of energy/non-energy factors.	Ridge regression [18]	NA	Fuels can substitute for each other, and coal could be replaced by gas
	Regional Comprehensive Economic Partnership (RCEP) and CO_2 emissions	To investigate emerging nations' participation in the RCEP on global industrial CO_2 emissions.	Quantitative analysis using a multi-regional input-output [26]	NA	Emerging economies are contributing more to CO_2 emissions
	Electricity consumption, CO_2 emissions in rising economies	To investigate the key driving factors for CO_2 emissions in Pakistan	Decomposition and decoupling methods, logarithmic mean Divisia index [27]	NA	Increasing electricity consumption increases CO_2 eq emissions
	Energy substitution effect on the transport sector	To establish a trans-log production function model for the transport sector	Output elasticity, ridge regression [26]	NA	A trans-log production function model for the transport sector
	Korea's FCEV development	To study the significance of the Korean government's National R&D Programme in FCEV development	Comparative Analysis [28]	NA	Government initiatives for the success of FCEVs.
	Best practices for using hydrogen fuel-cell electric vehicles in public transport	Investigate best practices used in small- to medium-sized European cities and regions.	Comparative analysis of regions[29]	NA	Regions with similar geographies, economics, weather, and terrain face identical barriers to FCEV adoption.
	Implementation of Electric Vehicles	To investigate the strategies of the stakeholders in the development of EVs and charging infrastructure.	Primary data collection through interviews and analysis [24]	Stakeholders theory	Financial incentives, charging infrastructure, and the presence of manufacturing facilities are significant.
	Hydrogen-fueled freight transportation	To identify, categorize, and prioritize essential success elements for hydrogen-powered cars.	EFA grey–ordinal priority approach [30]	Critical success factor theory	Operational and environmental factors are the most significant perspectives determining the success of FCEVs.
Current study	Overcoming Barriers to Fuel Cell Electric Vehicle Adoption	To identify and prioritize barriers and develop a spectrum of scenarios from multiple perspectives for overcoming the barriers to the sustainable adoption of FCEV in emerging economies	Severity analysis using the Fuzzy Evidential Reasoning Algorithm (FERA) methodology	Stakeholders theory, Triple Bottom Line Theory, Fuzzy Set Theory	The severity of barriers to FCEV varies with the changes in the weights of each perspective.

TBL aspects to thoroughly understand stakeholders' perspectives. According to Freeman [23], any entity, including groups or individuals, that can influence or be influenced by the outcomes of an organization's goals or objectives can be considered a stakeholder. The commitment fulfillment of stakeholders is essential to the success of environment-friendly products like FCEV [24]. Further, the government, industry, and academia are focused on integrating economic, social, and environmental goals to reduce emissions and waste [25]. This is seen in TBL theory, which balances the organization's goals. This section presents a comparative analysis of the existing literature and the current study, summarised in Table 1.

Various authors conducted different categorizations for barriers. For instance Ref.[9], considered four significant barriers: market, technical, policy, and infrastructure [31], which can be regarded as demand-side, supply-side, institutional, and infrastructure barriers. The study presents extant literature in four categories, namely market barriers, supply barriers, infrastructure barriers, and policy barriers. In a study on barriers to adopting BEV and FCEV in Japan, a developed economy, Trencher et al. [32] highlighted supply-side, demand-side, institutional and infrastructure preparation as the key barrier categories. Another study in developed economies by Van de Kaa et al. [33] compared the barriers to Battery electric vehicles with the FCEV using only the multi-criteria decision-making (MCDM) method. Also, Li & Kimura, (2021), studied the adoption challenges and potential in the south-east Asian countries. While studies are available for developed countries, limited studies are available that assess developing or underdeveloped economies. While Weiss et al. [34] have forecasted the need of FCEV as an alternative to electric vehicles for developing economies in 2012 itself, the work by Harichandan & Kar [35] assessed the potential for the FCEV adoption and consumer perception towards such solutions. While another study Kar et al. [4] tested the intentions of the public in developing economy, India, towards acceptance of FCEVs. A study by Rawat et al. [36] identified the barriers to the Hydrogen vehicle adoption, but focused only on India, and that too from the technical perspective. A study understanding the challenges in penetration of electric vehicles in developing economies like Nepal was carried out by Mali et al. [37]. However, no explicit study about the barriers to adopting FCEVs in South Asian economies was found. Also, most of the studies are based on single methodologies and not an integration of multiple methods like MCDM or Structural Equation Modelling.

This study, however, fills the research gap from a methodology as well as a contextual perspective by studying the barriers through a stakeholder-driven perspective with an additional 'Operational' approach, and by implementing a novel combination of multiple studies of EFA-FST-FERA that is not used by earlier studies for the South Asian economies.

2.1. Market barriers

The market is controlled by several factors, with customers at the center. As far as FCEV is concerned, customers are currently not satisfied with many parameters. The first and significant barrier to the adoption of FCEV is higher pricing. Despite less carbonization and pollution, consumers are unwilling to pay higher prices [38]. Additionally, higher battery costs discourage customers. The inconvenience caused by the lack of a refueling station is another concern. Without trained personnel for repairing work, customers are demotivated to consider switching to FCEV technology [39]. Customers are also wary about the on-road performance of these vehicles [40]. As a new technology, very few options(models/variants) are available to customers compared to traditional automobiles. Also, FCEV requires stringent safety measures for handling hydrogen storage, electrical systems, and crashworthiness [31]. Lastly, limited familiarity and public cognizance of environmental issues [41] and fuel cell mobility's economic benefits impede market growth [42]. As the production is low, limited vehicle ply on roads results in poor public awareness in comparison to battery counterparts

[39].

2.2. Supply barriers

Supply and operations-related factors also hinder the adoption of FCEV. For manufacturers of FCEV, there are some significant challenges. As production is limited, achieving economies of scale is difficult [43]. Trencher & Edianto [31] observed that establishing component supply chains is difficult for FCEV, which further demotivates manufacturers. Nevertheless, there is a beacon of hope in GCC countries, where significant initiatives for green hydrogen projects have been launched. Selected South Asian countries may have the opportunity to import hydrogen from neighboring GCC nations [44]. The required inputs for the production of FCEV are fuel cells and hydrogen tanks. These inputs are expensive [45] and not mass-produced [46]. From the FCEV user's perspective, the higher cost of hydrogen and the non-green source of hydrogen may become another impediment [42]. The vicious cycle of low demand and production demotivates stakeholders to focus on FCEV [41].

2.3. Infrastructure barriers

Supportive infrastructure is significant in the growth of the automobile sector. The significant barrier is in the form of establishing refueling stations[47]. These stations require heavy investment, and considering a significantly smaller number of such vehicles [48] on road stations, developers will visualize it as a low or negative return on investment project [38]. Less government support (in the form of subsidies) also hinders the establishment of refueling centers [42]. The absence of refueling stations affects consumers [49], and in turn, manufacturers are discouraged, and overall market attractiveness is compromised [50].

2.4. Policy barriers

A country's institutional framework supports or limits the growth of a particular industry[51]. The automobile industry, being capital-intensive, requires the support of policymakers. The policymakers are also less interested in the absence of quantity (number of vehicles), and the required infrastructure remains undeveloped [41]. For FCEV, most of the government is lethargic [52]. The hindrances from the government may come in many ways. Stringent safety standards for refueling stations [32] or institutions disinterested/problematic/lethargic towards hydrogen production and refueling stations. This can also happen if lobbying activities are absent for FCEV [31]. As the FCEV industry is new, the absence of collaborative support from the government or other partnering institutions may hinder its development [53]. Overall, the impact could be observed as significant automobile producers have postponed their FCEV production [52]. Based on the above literature review, 21 barriers were identified and presented in Table 2.

2.4.1. Research gaps and limitations of previous studies

The research papers available focused on one of the barrier categories mentioned above. The current research attempts to address the gap by including all the barriers in the study. The research papers reviewed focused on barriers and drivers to the adoption of FCEV in European countries [52] or related to specific problems about transporters [48] or power trains[66]. Some were focusing on electric vehicles generally, i.e., including all types [67]. Some studies proposed a theoretical framework [9]. Many others explored the landscape of hydrogen fuel application [46] and its future [45]. Studies by Ref. [68, 68] highlighted the challenges encountered by the aviation industry concerning fuel cell energy. Limited papers have attempted to study hydrogen fuel cell possibilities [19] in selected South Asian countries. The literature discusses CO_2 emissions in different sectors, but no

Table 2
Identified barriers to FCEV's sustainable adoption.

SN	Barriers	Description	Source
1	Higher Cost	Higher input costs include materials, fuel station setup, operating costs, technology, etc.	Trencher & Wesseling [52]
2	Limited subsidies and awareness	Limited aid from the government in terms of subsidies for producers and buyers, incentives for producers and suppliers	Trencher & Wesseling [52]
3	Lack of awareness and demand	Lack of awareness about the benefits of FCEV, availability of FCEV, subsidies, and desire to buy	Trencher & Edianto [31]
4	Limited availability of models	Fewer producers and fewer models of FCEVs	Rosales-Tristancho et al. [54]
5	Strict environment-related laws	H2 fuel handling, manufacturing, and usage laws, and norms, Emission norms	Trencher & Edianto [31]
6	Government support and political will	Lack of Support from the local government for the setup and operations of fuelling stations and production facilities	Lee et al. [55]
7	Limited variety and volumes	Fewer producers, operating with limited variety and volumes	Trencher et al. [32]
8	Complex technology adaptation	Complex imported technology adoption by producers, machinery, workers, and additional costs.	Kelley et al. [56]; Lopez Jaramillo et al. [40]
9	Underdeveloped supply chain	Transformation in the existing supply chains is required	Shamsi et al. [57]
10	A limited number of refueling stations	Limited refueling stations due to the nascent stage of the industry	Tostado-Véliz et al. [58]
11	Carbon-emitting sources of Hydrogen	Carbon emissions from fossil fuel-generated Hydrogen	An et al. [59]
12	A limited number of automakers	The nascent stage of the industry has a limited number of producers	Wood [60]
13	Lack of visible goals	The FCEVs would require a long-term focus for their successful implementation.	Browne et al. [61]
14	Lack of indigenous technology	FCEV technology, not available domestically, needs to be adopted from developed nations	Khan et al. [62]
15	Lack of service facilities	Lack of Training on new-to-market technology regarding maintenance and repairs of FCEVs	Trencher & Edianto [31]
16	Absence of tax holidays	Availability of Tax holiday schemes for fuel and FCEV producers to encourage the production	Brey et al. [63]
17	Lack of associations and collaboration	Lack of knowledge and information-sharing collaborative platforms	Aaldering et al. [64]
18	Lack of skilled workforce	Human resources with the required technical skills are limited in number	Trencher & Wesseling [52]
19	Lack of clarity on the design and aesthetics of FCEV	Unavailability of design, prototypes of FCEVs for visualization, and demand creation	Wood [60]
20	Environmental Impact of FCEV Manufacturers	The Vehicle manufacturing factories increase the GHG emissions factories	Isabel Kreiβig & Franziska Bocklisch [65]
21	Limited digital and physical infrastructure	The provision of digital and physical infrastructure by governments is limited.	Trencher & Wesseling [52]

comprehensive study has been conducted to address the barriers to adopting hydrogen vehicles in selected South Asian economies. This work addresses the issues concerning barriers to the adoption of hydrogen fuel in emerging economies, considering at the same time the perspective of stakeholders. This paper has adopted a balanced approach in methodology following the Triple Bottom Line theory.

While several studies have investigated FCEV barriers in developed economies, very few have systematically analyzed these in the context of Selected South Asian emerging economies. Moreover, existing research often applies a single MCDM technique or lacks integration with stakeholder sensitivity. This study addresses these limitations through a multi-method, regionally focused analysis. This study contributes original insights by applying a multi-method framework—FST, EFA, and ERA—to the underexplored context of South Asian emerging economies. While the barriers to FCEV adoption have been studied in developed countries, this paper offers a region-specific perspective that captures the complex interplay of economic constraints, policy immaturity, and technological gaps typical of India, Pakistan, and Bangladesh. Including an "Operational" pillar expands the conventional TBL framework, and the stability analysis provides a policy-relevant lens not commonly used in FCEV literature. These elements enhance both the methodological rigor and contextual relevance of the study.

3. Methodologies and data

This section explains the study's data collection techniques and the adoption of various methodologies. This study develops a framework by integrating multiple theories and methods like Fuzzy Set Theory (FST), Exploratory Factor Analysis (EFA), and Evidential Reasoning Approach (ERA), as presented in Fig. 1. A self-administered questionnaire with 26 items was initially developed based on a comprehensive review of academic and policy literature on FCEV adoption barriers. These items were then subjected to expert validation. Based on relevance, redundancy, and clarity, five items were removed, resulting in a final validated set of 21 items. These 21 items are presented in Table 2 and form the basis for data collection and subsequent exploratory factor analysis. Expert stakeholders from the FCEV sector and allied areas, including manufacturers, battery suppliers, government officials, and environmentalists with more than 15 years of experience, were selected using the snowball method. The data was collected using a self-administered online questionnaire distributed via email and professional networks, including LinkedIn and domain-specific forums. The survey was open for two months, and participants were identified through purposive and snowball sampling. Before full distribution, a pilot survey was conducted with 15 experts to test for the items' clarity, consistency, and relevance, resulting in minor refinements. Participation was voluntary and anonymous, and expert profiles were verified to ensure domain relevance and professional diversity.

Data was collected from experts representing India, Pakistan, and Bangladesh. These countries were selected due to their active but evolving interest in FCEV technology, providing a meaningful basis for cross-national comparison within the South Asian context. Two hundred twenty-one valid responses were collected from various stakeholders (for respondents' profiles, refer to Appendix A), and 17 items were retained after performing EFA for further analysis. The sample of 221 expert respondents was designed to represent a cross-section of key stakeholders involved in the FCEV ecosystem. The respondents included 70 from vehicle manufacturers (owners, managers, and technical experts), 20 battery suppliers, 20 government officials involved in energy and transport policy, 20 environmental professionals, and 81 customers/end users with knowledge of clean energy technologies. This occupational distribution, presented in Table A, ensured that insights were gathered across the value chain—from policy and production to end-use. The snowball sampling method was used to identify informed participants with at least 10 years of experience, enhancing the responses' sectoral and professional diversity.

Previous studies examining FCEV or EV adoption barriers have commonly relied on the analytic hierarchy process (AHP), decision-making trial and evaluation laboratory (DEMATEL), or qualitative comparative analysis (QCA) techniques. However, such methods often lack the statistical rigor or the ability to handle linguistic vagueness and uncertainty in stakeholder-driven data. In contrast, the present study

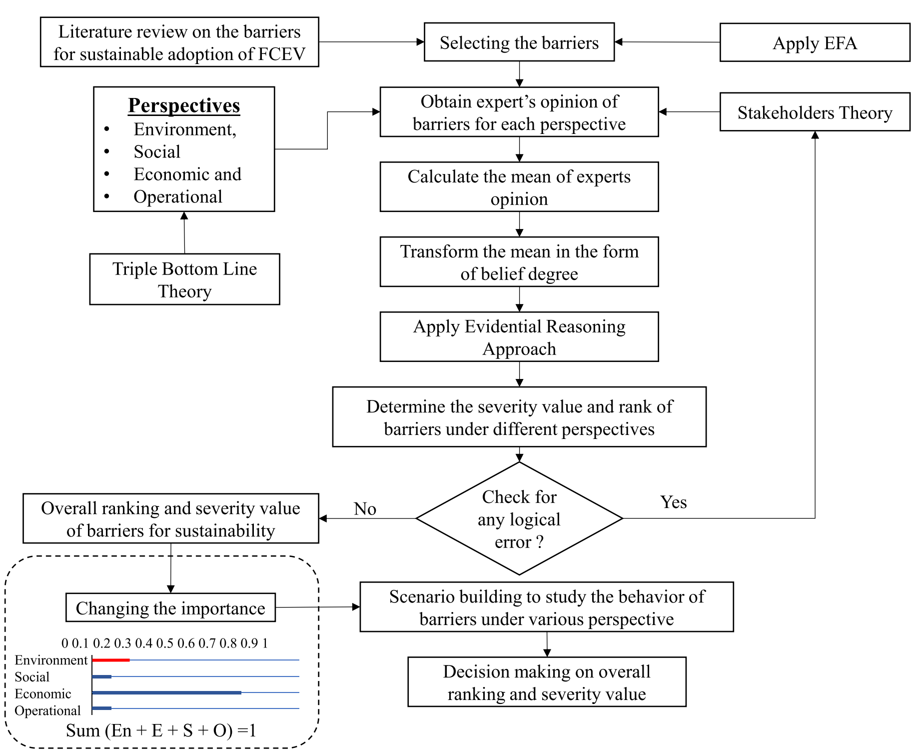

Fig. 1. Research Flow.

combines data reduction via Exploratory Factor Analysis (EFA) with Fuzzy Evidential Reasoning Approach (FERA), guided by the theoretical underpinnings of Stakeholder Theory and the Triple Bottom Line (TBL). This integration allows for a more grounded, multi-perspective, and uncertainty-aware evaluation of adoption barriers in the complex socio-economic environment of South Asian countries.

3.1. Application of exploratory factor analysis (EFA)

The EFA technique is applied in this research to explore interrelationships among 21 variables on responses given by 221 respondents, and the related variables are grouped as factors [69]. The SPSS 26 computer application was used for this purpose. Firstly, the adequacy of the sample was examined using the Kaiser-Meyer-Olkin (KMO) measure. The correctness of the data collected for factor analysis was analyzed using Bartlett's sphericity test. This test ensures that the data does not produce an identity matrix and is correct for factor analysis. Factor analysis was done using principal component analysis (PCA) for data reduction.

Furthermore, Varimax rotation was applied. It maximizes the sum of the variances of the squared loadings, thereby leading to low factor loadings for the remaining variables and high factor loadings for a smaller number of variables. For the collected data, factors with eigenvalues of more than one and factor loadings of more than 0.40 were retained. The Kaiser-Meyer-Olkin (KMO) test is considered "middling to meritorious," indicating that the sample was adequate for factor analysis [70]. Bartlett's Test of Sphericity was significant at $p < 0.001$, confirming that the variables are sufficiently correlated and the data is not an identity matrix, thus validating the suitability of the dataset for EFA. A factor loading threshold of **0.4** was used in this study based on the recommendation of [71], who note that in exploratory studies with moderate sample sizes ($N \approx 200$), loadings above 0.4 are considered meaningful for factor interpretation.

The study has followed certain suggested conventions. The number of respondents in the sample was ten times the number of items included in the research instrument, as indicated by Hair et al. [71] for conducting exploratory factor analysis. The expert stakeholders were selected using the snowball sampling method, coming from the FCEV ecosystem and related areas such as automobile manufacturers, battery providers, environmentalists, and government representatives. The selection criteria were a minimum of 15 years of work experience. The self-administered questionnaire with 26 items was floated, of which 21 were kept for preliminary analysis after expert validation. Later, these experts provided 221 valid responses, and 17 essential items were retained using Exploratory Factor Analysis (EFA). Appendix A contains a detailed profile of respondents, including their professional background and affiliation.

Further, only those factors where factor loading was more than 0.4 were considered for further analysis. The reliability coefficient(Cronbach's alpha) of these factors was more than 0.7, which could be considered satisfactory [72]. The results are presented in Section 4.1.

3.2. Fuzzy Evidential Reasoning Approach (FERA)

The FERA methodology is an integration of FST and ERA. This study further integrates ST and TBL to encompass multiple perspectives of sustainability. The ST is used to assess the severity of identified barriers, the ERA provides the ranking based on the severity values (SV), and the FST is applied to eliminate the vagueness and subjectivity in the study. The Fuzzy Evidential Reasoning Approach (FERA) was selected as this study's primary multi-criteria decision-making tool due to its suitability for handling vague, uncertain, and conflicting information, which is common in expert-driven assessments of emerging technologies. Unlike traditional MCDM methods such as AHP, which requires crisp pairwise comparisons, or TOPSIS, which assumes complete and comparable numerical data, FERA can integrate qualitative linguistic assessments across multiple perspectives (environmental, social, economic, and operational). Moreover, it accommodates incomplete belief structures, making it robust when expert opinions vary in detail or certainty. These features align well with this study's exploratory and interdisciplinary nature and enhance the rigor of barrier prioritization in the South Asian FCEV context.

3.2.1. Application of Fuzzy Set Theory (FST)

The FST has evolved from the dual logic and classical set theory that later got its fuzzy mathematical model developed [73]. The theory emerged as a solution to study vague, imprecise, and subjective phenomena in a practical and certain way. The functions are converted into membership values that range between 0 and 1. This study applied the linguistic terms converted to triangular fuzzy membership values provided by Sarkar et al. [74]. TFNs (Triangular Fuzzy Numbers) were generated for each perspective. Five expert groups were formed, each consisting of four senior experts with a minimum of 15 years of experience in their respective domains. The selection was based on demonstrated expertise and active involvement in FCEV-related policymaking, research, or technology deployment. The groups included: (i) senior managers and R&D heads from vehicle manufacturing firms, (ii) policy advisors from transport and energy ministries, (iii) consultants and analysts working in hydrogen infrastructure projects, and (iv) environmentalists affiliated with sustainability-focused NGOs. Efforts were made to ensure diversity across both public and private sector organizations, enhancing the credibility of linguistic assessments used in the FERA framework. The linguistic terms and their fuzzy membership functions used in the study are presented in Appendix B. The experts and their responses in terms of linguistic terms were recorded on five-point membership functions of Very High (VH), High (H), Medium (M), Low (L), and Very Low (VL) and presented in Appendix C. A total of 340 opinions were collected in five groups with four experts. The linguistic responses help register the vague and ambiguous responses of the stakeholders [74]. Appendix D presents the mean of the triangular fuzzy membership values.

3.2.2. Application of belief degree

A belief degree is an assessment of the value of the opinion that is believed to be true. The values obtained in the form of TFNs cannot be used for the ERA analysis [75]. Thus, the TFNs are converted into the five belief degree values (FCEVB) as per their severity.

$$\mathrm{FCEVB} = \{\mathrm{FB}_1, \mathrm{FB}_2, \mathrm{FB}_3, \mathrm{FB}_4, \mathrm{FB}_5\} \tag{1}$$

$$= \{\ \mathrm{VL}, \mathrm{L}, \mathrm{M}, \mathrm{H}, \mathrm{VH}\ \}$$

Initially, the TFNs are calculated using the mean values of the opinion of stakeholders (Appendix D). The TFNs are plotted to the corresponding membership functions. The triangular pattern is formed as shown in Fig. 2. For example, the TFN values mean for FVB_1 under an environmental perspective are (0.35, 0.6, 0.85). These values are plotted as [VL, L, M, H, VH]. The outcome was [0, 0.3, 0.8, 0.7, 0.2], and the sum of the values is 2, which is non-normalized. Next, these non-normalized values are converted into normalized values. Thus, the importance of FCEVB was obtained by normalizing the previous results, obtaining FCEVB = [0, 0.15, 0.4, 0.35, 0.1]. In the same way, the normalized values for all the barriers were obtained.

These calculated FCEVB values are presented in Appendix E.

3.2.3. ERA application for the severity value

Evidential reasoning theory, developed by Dempster [76], was later adopted by Shafer in 1976 and is now known as the Dempster-Shafer Theory [76,77]. The ER approach deals with less precise data with private or uncertain information. Let "FB" represent the barriers in fuzzy linguistics. When the views of two different expert groups, FB_1 and FB_2, are aggregated, FB, FB_1, and FB_2 are represented as:

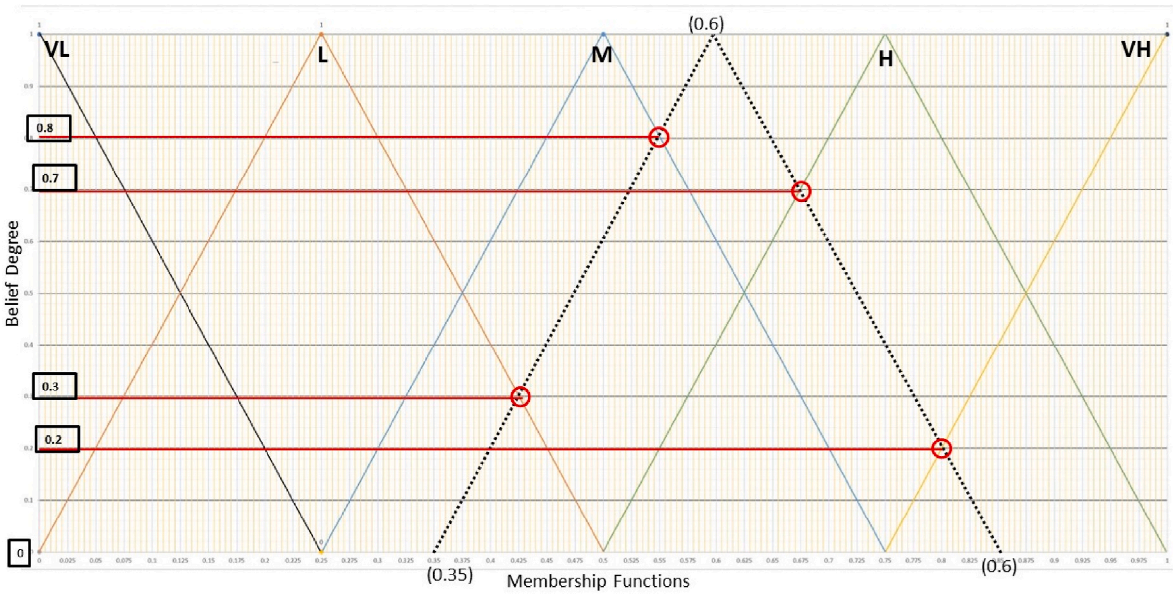

Fig. 2. Formulating belief degrees from TFNs.

$$FB = \{VL \text{“}\alpha^{1}\text{”}, L \text{“}\alpha^{2}\text{”}, M \text{“}\alpha^{3}\text{”}, H \text{“}\alpha^{4}\text{”}, VH \text{“}\alpha^{5}\text{”}\}$$

$$FB_1 = \{VL \text{“}\alpha_1^{1}\text{”}, L \text{“}\alpha_1^{2}\text{”}, M \text{“}\alpha_1^{3}\text{”}, H \text{“}\alpha_1^{4}\text{”}, VH \text{“}\alpha_1^{5}\text{”}\}$$

$$FB_2 = \{VL \text{“}\alpha_2^{1}\text{”}, L \text{“}\alpha_2^{1}\text{”}, M \text{“}\alpha_2^{3}\text{”}, H \text{“}\alpha_2^{4}\text{”}, VH \text{“}\alpha_2^{5}\text{”}\}$$

The linguistic expressions are paired with their degrees of belief. The total weight of perspectives should be 1 ($wt_1+wt_2+ \ldots +wt_n = 1$). Perspective-wise normalized weights e is wt_1, wt_2, and wt_3 ($wt_1+wt_2+wt_3 = 1$). Consider X_{jn} (j = 1 or 2; n = 1 to 5), where “j” denotes the number of expert groups and “n” denotes the grades for evaluation. As a result, the computation of the barrier's belief structure is as follows:

$$X_1^n = wt_1 * \alpha_1^n \tag{2}$$

$$X_2^n = wt_2 * \alpha_2^n$$

Bld_1 and Bld_2 are the belief degrees associated with X_1^n and X_2^n. According to Liu et al. [78] Bld_1 & Bld_2 are computed as:

$$Bld_1 = \widetilde{Bld}_1 + \overline{Bld}_1 \tag{3}$$

$$Bld_2 = \widetilde{Bld}_2 + \overline{Bld}_2$$

Where, $\widetilde{Bld}_n$ represents the incompleteness in FB_1 and FB_2. The other perspectives in the evaluation process $\overline{Bld}_n$ is represented as:

$$\widetilde{Bld}_1 = wt_1 \left(1 - \sum_{i=1}^{5} \alpha_1^n\right) \tag{4}$$

$$\widetilde{Bld}_2 = wt_2 \left(1 - \sum_{i=1}^{5} \alpha_2^n\right)$$

$$\overline{Bld}_1 = 1 - wt_1 = wt_2 \tag{5}$$

$$\overline{Bld}_2 = 1 - wt_2 = wt_1$$

where α^n denotes non-normalized degree of barriers derived from the sum of five linguistic terms assessments. $\overline{Bld}_U$ denotes the non-normalized belief degrees that are not assigned to the linguistic terms. As a result, a modified ERA is presented [73]:

$$\alpha^n = P^*\left(X_1^n * X_2^n + X_1^n * Bld_2 + X_2^n * Bld_1\right) \tag{6}$$

$$\overline{Bld}_U{}' = P(\overline{Bld}_1 * \overline{Bld}_2)$$

$$\overline{Bld}_U{}' = P^*(\widetilde{Bld}_1 * \widetilde{Bld}_2 + \widetilde{Bld}_1 * Bld_2 + \widetilde{Bld}_2 * Bld_1) \tag{7}$$

$$P = \left[1 - \sum_{a=1}^{5} \sum_{\substack{b=1 \\ b \neq a}}^{5} X_1^a * X_2^b\right]^{-1}$$

Now, α_U and α^n are calculated as follows, where “α_U” denotes overall incompleteness in the computation, “α^n” denotes combined belief degree [79]

$$\alpha^n = \alpha^{n'} / (1 - \overline{Bld}_U{}')\ (n = 1 \text{ to } 5) \tag{8}$$

$$\alpha_U = \widetilde{Bld}_U{}' / (1 - \overline{Bld}_U{}')$$

This is a union of two subsets. If multiple subsets are synthesized, the cumulative result of any two subsets can be coupled with the other subset using these steps.

Based on their variation, the framework classified the barriers into three categories: stable - showing lesser variations in different scenarios - changes in weights are observed to have little or no impact on most of the barriers; moderately stable - showing moderate variations in different scenarios - exhibiting the barriers whose severity changes moderately due to the weight change; and unstable - showing more significant variations in different scenarios - their severity largely varies with the changes in the weights of the perspectives. The unstable barriers are the most severe and require maximum attention by the stakeholders, followed by moderately stable and stable barriers. Each barrier was classified based on rank variation across the nine weight scenarios to assess the sensitivity of barriers to varying stakeholder priorities. A barrier was considered stable if its rank fluctuated by no more than two positions across all scenarios (i.e., Range ≤ 2), moderately stable if the rank varied between 3 and 4 positions (Range = 3–4), and unstable if it shifted by more than four ranks (Range >4). This classification helps identify which barriers consistently rank high (or low) regardless of decision context, and which are more volatile based on stakeholder weightings. Range was used as the criterion due to its direct interpretability for ordinal rankings in scenario-based analysis.

4. Result and analysis

This section initially presents the results of EFA and FERA based on different perspectives, namely, environmental, social, economic, operational, and overall rankings.

4.1. EFA outcome

To conduct the study, responses were collected from 221 respondents. They responded on 21 identified barriers. This was meeting desired and widely accepted ratio of respondents to items i.e. 10:1 [80]. The factor analysis was applied to the barriers (items) using principal component analysis of data reduction and varimax rotation. Kaiser-Meyer-Olkin (KMO) measure for sampling adequacy of collected data was 0.807 and could be classified as meritorious [72]. Bartlett's sphericity test result with a value below 0.05 confirms the fitness of data for factor analysis. The factor loading of items is given in Table 3. A total of 17 factors with eigenvalue of more than one and factor loadings of more than 0.40 were retained. The barriers weeded out due to lesser factor loading were the Lack of visible goals, the Absence of tax holidays, and the Lack of clarity on the design and aesthetics of FCEV.

Items dropped from futher analysis included Limited Availability of models, lack of visible goals, absence of tax holidays, and lack of clarity on design and aesthetics of FCEV owing to poor factor loadings (less than 0.4) Extracted 17 items (barriers) are shown in Table 4.

The analysis in Table 4 is based on factors with a threshold factor loading of over 0.4, meeting the specified conditions. The table displays the extracted factors along with their respective construct labels.The first factor, EC, accounts for 41 % of the variance, with a Cronbach's alpha value of 0.672. This factor is constructed from three variables: high cost, limited subsidies and awareness, and limited variety and volumes, with factor loadings ranging from 0.733 to 0.964. The second factor, EV, explains 13 % of the variance, with a Cronbach's alpha value of 0.639. This factor is constructed from three variables: strict environment-related laws, carbon emitting sources of hydrogen, and environmental impact of FCEV manufacturers, with factor loadings ranging from 0.839 to 0.895. The third factor, OP, accounts for 12 % of the variance, with a Cronbach's alpha value of 0.802. This factor is constructed from six variables: complex technology adaptation, underdeveloped supply chain, limited number of automakers, lack of indigenous technology, lack of service facilities, and limited digital and physical infrastructure, with factor loadings ranging from 0.816 to 0.936. The fourth factor, SC, explains 10 % of the variance, with a Cronbach's alpha value of 0.736. This factor is constructed from five variables: lack of awareness and demand, government support and political will, limited number of refueling stations, lack of associations and collaboration, and lack of skilled workforce, with factor loadings ranging from 0.801 to 0.974. While the Cronbach's alpha values for the Economic (0.672) and Environmental (0.639) constructs are slightly below the generally accepted threshold of 0.70, they are within the acceptable range for exploratory research [71]. These values indicate moderate internal consistency. However, future research could refine the measurement items further or conduct confirmatory factor analysis to strengthen construct reliability in larger or more targeted samples.

Table 3
Factor loading (FL) of 17 barriers to FCEV.

Barriers	F L	Barriers	F L
Higher Costs	0.887	Carbon emitting sources of Hydrogen	0.861
Limited subsidies and awareness	0.762	A limited number of automakers	0.830
Lack of awareness and demand	0.843	Lack of visible goals	−0.567
Limited availability of models	−0.646	Lack of Indegenious technology	0.875
Strict environment-related laws	0.894	Lack of service facilities	0.877
Government support and political will	0.837	Absence of tax holidays	−0.603
Limited variety and volumes	0.855	Lack of associations and collaboration	0.884
Complex technology adaptation	0.837	Lack of skilled manpower	0.877
Underdeveloped supply chain	0.644	Lack of clarity on the design and aesthetics of FCEV	−0.643
A limited number of refueling stations	0.613	Environmental impact of FCEVmanufacturers	0.887
		Limited digital and physical infrastructure	0.892

Table 4
Loadings of selected barriers along with the constructs.

Barriers with Nomenclature	F L	Cronbach's Alpha	Construct Labelling
Higher Costs (FVB_1)	0.964	0.672	EC
Limited subsidies and awareness (FVB_2)	0.733		
Limited variety and volumes (FVB_3)	0.856		
Strict environment-related laws (FVB_4)	0.895	0.639	EV
Carbon emitting sources of Hydrogen (FVB_5)	0.839		
Environmental Impact of FCEV Manufacturers (FVB_6)	0.891		
Complex technology adaptation (FVB_7)	0.809	0.802	OP
Underdeveloped supply chain (FVB_8)	0.837		
A limited number of automakers (FVB_9)	0.816		
Lack of Indegenious technology (FVB_{10})	0.936		
Lack of service facilities (FVB_{11})	0.877		
Limited digital and physical infrastructure (FVB_{12})	0.898		
Lack of awareness and demand (FVB_{13})	0.834	0.736	SC
Government support and political will (FVB_{14})	0.839		
A limited number of refueling stations (FVB_{15})	0.801		
Lack of associations and collaboration (FVB_{16})	0.974		
Lack of skilled manpower (FVB_{17})	0.875		

* FVB – FCEV Barriers.

4.2. Results of FERA

This section presents the outcomes of FERA from various perspectives. While some severity values (SVs) given in Table 5 appear close in magnitude, it is essential to note that these values are derived from fuzzy belief structures and are used primarily for relative ranking, not for inferential statistical comparison. Due to the nature of FERA, which relies on linguistic and expert-driven input, traditional significance testing is not directly applicable. To verify the reliability of these rankings, a stability analysis was conducted across nine weighted scenarios (Section 4.3). The results indicate that barriers such as high cost, lack of infrastructure, and limited skilled workforce consistently ranked high, confirming the robustness of these findings despite narrow SV margins.

4.2.1. Environmental perspective

The acceptance and implementation of FCEVs in emerging economies face multiple challenges from different perspectives. The prime objective in accepting FCEV lies in its environmental merits. However,

Table 5
Ranking and severity values (SV) of the barriers.

	ENVIRONMENTAL		SOCIAL		ECONOMICAL		OPERATIONAL	
Codes	SV	Rank	SV	Rank	SV	Rank	SV	Rank
FVB_1	0.6	3	0.8693	1	0.7726	1	0.7726	4
FVB_2	0.45	4	0.7972	3	0.65	6	0.65	9
FVB_3	0.1298	15	0.5513	9	0.3982	12	0.3982	13
FVB_4	0.2023	11	0.3982	12	0.35	13	0.65	9
FVB_5	0.3982	5	0.5513	9	0.6741	5	0.43	12
FVB_6	0.1298	15	0.5762	8	0.5513	10	0.3982	13
FVB_7	0.1298	15	0.2361	15	0.3003	15	0.7887	2
FVB_8	0.1708	14	0.2023	17	0.5513	10	0.6872	8
FVB_9	0.3557	6	0.8302	2	0.6	8	0.7887	2
FVB_{10}	0.8693	1	0.2456	13	0.35	13	0.35	16
FVB_{11}	0.2456	8	0.65	5	0.2361	17	0.3982	13
FVB_{12}	0.3003	7	0.45	11	0.7726	1	0.7972	1
FVB_{13}	0.2023	11	0.7972	3	0.3003	15	0.35	16
FVB_{14}	0.2096	9	0.2361	15	0.7	4	0.7	7
FVB_{15}	0.2096	9	0.65	5	0.65	6	0.7726	4
FVB_{16}	0.8693	1	0.6	7	0.6	8	0.5513	11
FVB_{17}	0.1751	13	0.2456	13	0.7726	1	0.7726	4

from the environmental perspective, as presented in Table 5, a few barriers may discourage the acceptance of the FCEVs. As an outcome of the study, the "Carbon emitting sources of Hydrogen" is assumed to be the most severe barrier with an SV of 0.87. As supported by Shardeo & Sarkar [30], if the Hydrogen fuel comes from a source with a negative carbon footprint, the purpose of accepting FCEVs gets defeated. Thus, it is essential to verify the source of the hydrogen fuel. Another severe barrier for FCEVs with the same SV of 0.87 is "GHG emission by FCEV manufacturers." Though the fuel is claimed to be green, the companies manufacturing cars would emit GHG during the production process of FCEVs. Thus adding to the environmental concerns. These were followed by "Higher Costs" (0.6), "Limited subsidies and their awareness" (0.45), and "Government support and political will" (0.398) barriers as per the environmentalists' opinions. Government subsidies should be anticipated only on a limited basis due to their potential lack of longevity. Similar results were noted by Rosales-Tristancho et al. [54]. Thus, the success of FCEVs in emerging economies largely depends on overcoming environmental barriers by creating awareness, providing additional subsidies, reducing costs [38], and controlling the emission of GHG during the production of FCEVs and Hydrogen fuels.

4.2.2. Social perspective

The acceptability of the FCEVs largely depends on the masses' social acceptance of them in emerging economies. From the study, multiple social barriers emerged. With an SV of 0.869, the "higher cost" is at the top from a social perspective, as presented in Table 5. As the FCEV technology, products, and fuels belong to the higher cost range, it may hinder the acceptability of the masses in emerging economies. This barrier is followed by the "limited number of refueling stations" with an SV of 0.83. As the FCEV industry is at its nascent stage, the infrastructure in refueling stations needs to be developed for the convenience of the masses. The third severe social barrier is "limited subsidies and their awareness" and "lack of service facilities," each with an SV of 0.797. Along with similar barriers to these, Asif & Schmidt [45] also mentioned lobbying as a significant barrier to FCEVs. The lack of awareness or availability of subsidies increases the cost of FCEVs, thus making them less attractive. Similar observations were reported by Whiston et al. [81]. Also, being a new technology, the limited presence of service stations and the availability of spares raise concerns for the general public. The buyers of FCEVs may have limited choices due to the barrier "limited number of automakers" with an SV of 0.65, thus discouraging the purchase of FCEVs.

4.2.3. Economical perspective

For the sustainable implementation of FCEVs in emerging economies, it is necessary to ensure economic viability. The most severe form of economic perspective with an SV of 0.772 is the "higher costs," as presented in Table 5. The FCEV technology, manufacturing process, distribution, fuel, refueling stations, etc., incur higher costs, making it less economically viable. Also, with the same SV of 0.772, "lack of indigenous technology" is an equally severe barrier as the technology acquired from foreign countries adds up to the cost of the product and its operations. "limited digital and physical infrastructure" is an equally severe barrier as it limits the sector's rapid growth and results in lesser outputs, depriving economies of scale. The "lack of associations and collaboration" barrier with SV of 0.7 reduces the negotiation power of the operators in the sector and the opportunities for sharing technology, information, and facilities. Also, as reported by Ref. [54], "government support and political will" is a severe barrier with a value of 0.674. The regulators and policymakers should be optimistic about an industry flourishing and becoming sustainable. Thus, the economic feasibility of FCEVs is hindered because of higher costs due to a lack of indigenous technology, limited infrastructure, regulator's support, and lack of collaborations within the sector. Similar results were disclosed by Ref. [31].

4.2.4. Operational perspective

From the operational perspective, as presented in Table 5, the most severe barrier is the "lack of indigenous technology," with an SV of 0.797, as the adoption of foreign technology adds to several challenges, including the intellectual property acquisition, setting up physical and digital infrastructure, seamless implementation, and adoption in the local markets. These additional tasks inflate the costs incurred and the time required and may hamper operational efficiency. With a SV of 0.789, "complex technology adaptation" and "limited number of refueling stations" barriers are ranked second, which were also noted as significant barriers by Kowalska-Pyzalska et al. [82]. Adapting complex technology in the current automotive sector is an operational challenge, and the limited number of refueling stations would provide higher-efficiency vehicles to consumers. At the same time, it increases the difficulty of convincing consumers to switch to FCEVs. The "limited digital and physical infrastructure" along with the "lack of skilled manpower" results in "higher costs," with SV of 0.7726, creating operational difficulties hampering the operational effectiveness and efficiency.

4.2.5. Overall ranking

When the overall ranking of barriers under multiple perspectives is presented in Table 6, the "higher costs" emerged as a significant barrier with an 8.9 % severity. This is followed by the "GHG emission by FCEV manufacturers" [30], which is 7.72 % severity. Thus, though higher

Table 6
Overall ranking of barriers under multiple perspectives.

Codes	SV	Rank	Normalized SV	Percentage
FVB_1	0.7582	1	0.089325055	8.93
FVB_{16}	0.6549	2	0.077155076	7.72
FVB_9	0.6492	3	0.076483548	7.65
FVB_2	0.6386	4	0.07523474	7.52
FVB_{12}	0.5831	5	0.068696175	6.87
FVB_{15}	0.577	6	0.067977521	6.80
FVB_5	0.5142	7	0.060578928	6.06
FVB_{17}	0.4916	8	0.057916377	5.79
FVB_{14}	0.4597	9	0.054158174	5.42
FVB_{10}	0.4443	10	0.05234387	5.23
FVB_6	0.4162	11	0.049033353	4.90
FVB_{13}	0.4045	12	0.047654952	4.77
FVB_8	0.3998	13	0.047101236	4.71
FVB_4	0.3974	14	0.046818487	4.68
FVB_{11}	0.3776	15	0.04448581	4.45
FVB_3	0.3695	16	0.043531532	4.35
FVB_7	0.3523	17	0.041505166	4.15
	8.4881		**1**	**100**

acquisition costs and operations are a concern, automotive manufacturers' environmental impact is also a concern. "Limited number of refueling stations" and "limited subsidies and its awareness" follow the top two barriers with a severity of 7.65 % and 7.52 %, respectively. With a severity of 6.87 %, the "lack of indigenous technology" [82] is ranked 5th, which is a tedious task from the operational perspective. With an equivalent severity of 6.8 %, "lack of skilled manpower" would hinder the adoption of FCEVs in emerging economies and thus is ranked at the sixth position. The top 6 most severe barriers amount to 46 % of the total barriers to FCEV. These barriers combine economic, environmental, social, and operational perspectives. "Government support and political will," "limited digital and physical infrastructure," "lack of associations and collaboration, "limited variety and volumes," and "carbon emitting sources of hydrogen" stand from 7th to 11th position as barriers to the FCEV adoption that comprise over 27 % of the barriers. These barriers indicate the need for more policymaker support regarding infrastructure, support, and opportunities from the regulators' point of view. As reported by Asif & Schmidt [45], the need for policymakers' support in developing conducive policies is a major barrier to FCEV adoption. The rest of the barriers, comprising 27 %, include "lack of service facilities," "underdeveloped supply chain," "strict environment-related laws," "limited number of automakers," "lack of awareness and demand," and "complex technology adaptation."

5. Discussion

A spectrum of scenarios was created to understand the impact of changes in the weightage of each perspective on the barrier's severity. A framework based on the spectrum was created for each perspective separately. Various weights from 0.1 to 0.9 were applied to the selected perspective and presented in Appendix F. The balance value was distributed equally among the other three perspectives. Thus creating various scenarios for each perspective. It identified the severity of each barrier under different scenarios. The steps involved in analyzing the dynamics among the barriers are presented in Fig. 3.

For instance, the environmental perspective scenarios were built to assess the severity of various barriers. The ranking under each perspective was converted into graphs to understand the variations in the severity of each barrier. Based on their variation, the framework classified the barriers into three categories: stable - showing lesser variations in different scenarios - changes in weights are observed to have little or no impact on most of the barriers; moderately stable - showing moderate variations in various scenarios - exhibiting the barriers whose severity changes moderately due to the weight change; and unstable - showing more significant variations in different scenarios - their severity largely varies with the changes in the weights of the perspectives. The unstable barriers are the most severe and require maximum attention by the stakeholders, followed by moderately stable and stable barriers.

Table 7
Analysis of barriers from the Environmental perspective.

	Weightage of Environmental Perspective								
Codes	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
FVB_1	1	1	1	2	2	3	3	3	3
FVB_2	3	3	4	3	4	4	4	4	4
FVB_3	14	16	16	16	16	15	16	16	16
FVB_4	13	14	13	12	13	11	11	11	11
FVB_5	8	7	7	7	6	5	5	5	5
FVB_6	10	10	11	14	15	15	15	15	15
FVB_7	16	17	17	17	17	15	17	17	17
FVB_8	11	12	14	15	14	14	14	14	14
FVB_9	2	2	3	4	5	6	6	6	6
FVB_{10}	17	13	8	4	3	1	2	2	2
FVB_{11}	15	15	15	13	11	8	9	8	8
FVB_{12}	5	5	5	6	7	7	7	7	7
FVB_{13}	12	11	12	11	12	11	12	12	12
FVB_{14}	9	9	10	10	9	9	10	10	10
FVB_{15}	4	6	6	8	8	9	8	9	9
FVB_{16}	6	4	2	1	1	1	1	1	1
FVB_{17}	7	8	9	9	10	13	13	13	13

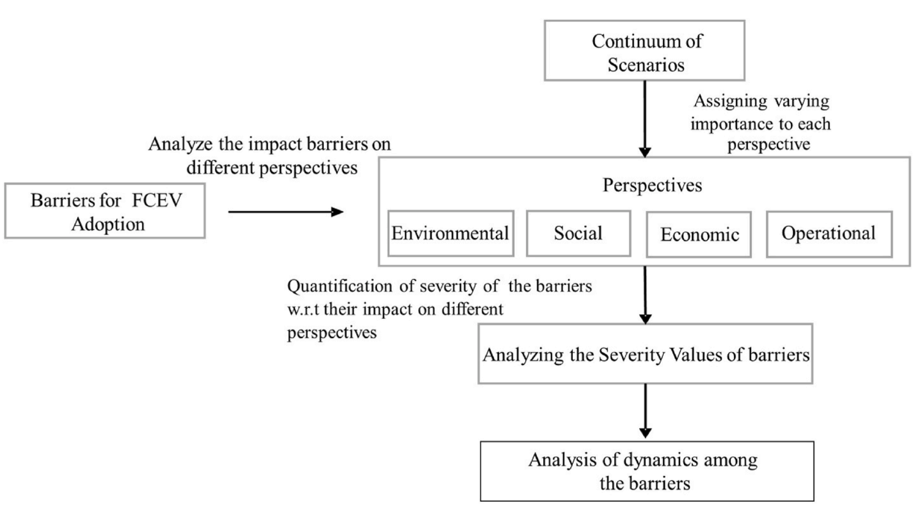

Fig. 3. Analysis of dynamics among the barriers.

Table 7 represents the analysis of the barriers from an Environmental perspective. The classification of barriers appears as follows.

From the environmental perspective, it is observed that some of the barriers are stable for varying levels of weightage; hence, their severity remains constant. These barriers include higher costs, limited subsidies and awareness, lack of awareness and demand, complex technology adaptation, lack of indigenous technology, lack of service facilities, and lack of associations and collaboration. Similar observations were noted by Whiston et al. [81] in their study about FCEV. The high severity assigned to cost-related barriers in this study aligns with the findings of Li et al. (2020) and Ehsani et al. (2021), who noted that capital cost and hydrogen production expenses significantly impede FCEV diffusion globally. However, unlike in Germany or Japan, where state subsidies offset initial costs (IEA, 2023), selected South Asian economies show higher sensitivity due to weaker policy support and import dependence, making this barrier more structurally entrenched. The barriers classified as moderately stable from an environmental perspective are strict environment-related laws, government support and political will, limited variety and volumes, an underdeveloped supply chain, a limited number of refueling stations, a lack of skilled workforce, and GHG emissions by FCEV manufacturers. These barriers show moderate variation in their severity due to changes in the weightage of the environmental perspective. The study by Rosales-Tristancho et al. [54] and Shardeo & Sarkar [30] revealed similar findings, mentioning government policies as the most significant barrier. The class unstable consists of carbon-emitting sources of hydrogen, a limited number of automakers, and limited digital and physical infrastructure barriers. This severity is primarily affected by the varying weights of perspectives. The study by Trencher [83] about barriers to the distribution of FCEVs in California stressed the limited number of automakers, whereas Cano et al. [38] highlighted the limited digital and physical infrastructure as an unstable barrier. Consistent with studies by Kim et al. (2018) and Wang and Wu (2021), inadequate hydrogen refueling infrastructure emerged as a significant constraint. However, the issue is magnified in South Asia, where even basic EV charging infrastructure is still underdeveloped. This further validates the contextual need to prioritize hydrogen infrastructure as a foundational investment. The barriers like carbon emitting sources of hydrogen, a limited number of automakers, and limited digital and physical infrastructure vary primarily with the changing weights of the environmental perspective; thus, it is suggested that for sustainable adoption of FCEVs in emerging markets, the policymakers and the auto manufacturers should focus upon ensuring usage of green sources of hydrogen, provide the adequate infrastructure that fosters the benefits at a large scale enabling environmental protection at large. The moderately stable barriers also highlight the government's role in policymaking and providing infrastructure to the automakers and fuel stations.

The severity analysis from the social perspective (refer to Appendix G1) revealed that the stable barriers include limited subsidies and awareness, strict environment-related laws, government support, and political will, limited number of refueling stations, and lack of skilled workforce. The barrier's severity did not change slightly with the changing weights of the perspectives. The barriers whose severity changes moderately due to the weight change are limited variety and volumes, complex technology adaptation, and carbon-emitting hydrogen and GHG emission sources by FCEV manufacturers. It is also supported by the research work of Trencher et al. [32]. The unstable barriers concerning the perspective weights are a lack of awareness and demand, an underdeveloped supply chain, a limited number of automakers [82], a lack of indigenous technology, a lack of service facilities, a lack of associations and collaboration, and limited digital and physical infrastructure. Lack of awareness, ranked highly in this study, is rarely emphasized in developed-country contexts where public education campaigns and demonstration projects are common (Zhou et al., 2019). This highlights a unique regional barrier that merits direct policy intervention through outreach and stakeholder education. The social perspective highlights the importance of providing digital and physical infrastructure, creating awareness and demand, developing supply chains, and enabling associations and collaborations to ensure better social benefits and sustainable adoption of FCEVs in emerging economies.

The economic perspective changes in weights have little or no impact on most of the barriers, making the economic perspective barriers the most significant (Appendix G2). The barriers classified under the stable category are higher costs [45], limited subsidies and awareness, lack of awareness and demand, strict environment-related laws, government support and political will, limited variety and volumes, complex technology adaptation, carbon emitting sources of hydrogen, limited number of automakers, lack of indegenious technology and lack of skilled workforce. In their study, Cano et al. [38] stressed the importance of strict environment-related laws, complex technology adaptation, carbon-emitting sources of hydrogen, and higher costs. Only two barriers, underdeveloped supply chains and a limited number of refueling stations, have moderate variation in SV due to the change in the perspective weights. Lack of service facilities, lack of associations and collaboration, GHG emissions by FCEV manufacturers [81], and limited digital and physical infrastructure fall into the unstable class. Underdeveloped supply chains and limited refueling stations are moderately stable barriers. In contrast, lack of service facilities, lack of associations and collaboration, GHG emissions by FCEV manufacturers, and limited digital and physical infrastructure are unstable barriers from an economic perspective. Thus, policymakers and automakers should focus on overcoming these barriers to ensure the financial viability of FCEV adoption.

The operational perspective severity analysis (Appendix G3) highlights higher costs, lack of awareness and demand, limited variety and volumes, limited number of refueling stations, limited number of automakers, and lack of skilled workforce as stable barriers. Limited subsidies and awareness, strict environment-related laws, lack of indigenous technology, lack of associations and collaboration, and restricted digital and physical infrastructure [54] are the barriers classified as moderately stable.

The barriers falling in the unstable class are government support and political will [82], complex technology adaptation, an underdeveloped supply chain, carbon-emitting sources of hydrogen, a lack of service facilities, and GHG emissions [81] by FCEV manufacturers. From an operational perspective, government support and conducive policies, along with well-developed supply chains by the manufacturers, help in the sustainable adoption of FCEVs in emerging markets. The stakeholders should focus on developing indigenous technologies, building associations, and ensuring conducive policies and environmental laws are in place.

While subsidies are a short-term enabler for FCEV approval, long-term cost savings must be obtained through native competence building. Within the South Asian situation, there is at present negligible domestic manufacture of FCEVs, with most vehicles either imported or locally assembled from imported parts. Initiatives such as India's National Hydrogen Mission and forthcoming R&D from companies are moving towards within-state manufacturing. Policy incentives for indigenous component production, public-private research and development partnerships, tax holidays, and early adoption in commercial fleets may provide more sustainable and region-specific solutions to overcome cost barriers. Also, when compared with the developed economies, the obstacles like high cost and infrastructure are common. Still, their severity is mitigated drastically by the existence of the hydrogen ecosystems, more substantial government incentives, and higher consumer awareness. Substantial investments in hydrogen refueling stations support this and offers long-term purchase incentives (*Global EV Outlook 2023 – Analysis - IEA*, n.d.). While in developed economies several car manufacturers produce FCEVs catering to the increasing consumer demands of FCEV, the selected South Asian market lacks inherent awareness and demand for FCEV, coupled with the lack of indigenous technology and production, resulting in a greater import dependence and higher cost burdens [50].

The sensitivity analysis using a spectrum of scenarios gives an in-depth understanding of the sensitivity and severity of barriers to the changing scenarios. The stakeholders and decision-makers can use this information for rational decision-making about overcoming the barriers to ensure sustainable adoption of FCEVs.

While this study identifies cost, infrastructure, and awareness as the most severe barriers to FCEV adoption in South Asia, future technological advancements may alter these rankings. For instance Ref. [84], highlight how ongoing patent-driven innovations in proton exchange membrane fuel cells (PEMFCs) are reducing rare material dependence and improving energy density, both of which can lower production costs over time. Similarly [85], emphasizes the role of eco-design in solid oxide fuel cells (SOFCs), where prospective life cycle improvements may lead to significantly reduced environmental burdens. If such advancements continue and reach commercialization, the severity of economic and environmental barriers identified in this study may decline, potentially elevating the relative importance of softer barriers such as policy gaps or social acceptance. This underlines the importance of regularly updating barrier assessments in light of rapidly evolving technology landscapes.

6. Conclusion

The study proposes a framework to assess the influence of identified barriers on the sustainable adoption of FCEVs in emerging economies. The FERA methodology was implemented to rank the barriers per their SV. The significance of each perspective would be different for different stakeholders. In light of this, a spectrum of scenarios was formulated to examine the dynamics of the barriers and the changing significance of each perspective.The severity-based ranking of barriers for each perspective was obtained. The overall ranking of barriers under multiple perspectives resulted in "higher costs" emerging as the significant barrier, followed by "GHG emission by FCEV manufacturers." though higher acquisition costs and operations are a concern, automotive manufacturers' environmental impact is also significant. "a limited number of refueling stations," "limited subsidies and its awareness," and "lack of indigenous technology" are significant barriers from an operational perspective. The top 6 most severe barriers amount to 46 % of the total barriers to FCEV. These barriers combine economic, environmental, social, and operational perspectives.

The results reveal that high cost, underdeveloped infrastructure, and lack of skilled manpower are the most critical and consistently ranked barriers across stakeholder scenarios, emphasizing systemic and long-term constraints in the FCEV adoption landscape. The study's contribution lies in contextualizing global FCEV challenges within South Asia's unique industrial, infrastructural, and policy landscape. It further advances methodological application by combining EFA, FST, and FERA in a novel framework and introduces scenario-based stability analysis to inform dynamic policy formulation—both of which are underutilized in this research domain.

The theoretical implications of the study lie in the novel approach to identifying and analyzing the barriers. Previous literature has studied the FCEVs from a single domain by only considering the barriers in developed countries [52] or only from the environmental perspective. Some studies have used only the ST [24] or the TBL theory [86]. However, a study of FCEV barriers by integrating multiple theories was unavailable. This study adds to the existing literature by integrating the ST and TBL theories to identify the barriers to the sustainable adoption of FCEVs in emerging economies. The TBL theory's application in previous works has considered the traditional perspectives of environmental, economic, and social. However, this study has added a new dimension of operation to the traditional perspectives of TBL. There have been studies to identify barriers by application of various multi-criteria decision-making methods, but unlike previous studies, this study has adopted the ERA. ERA has been integrated with the FST to eliminate the vagueness and subjectivity in the responses by the stakeholders.

Managerial implications of the study enable decision makers towards sustainable adoption of FCEVs. From an environmental viewpoint, manufacturers and policymakers should ensure that the hydrogen used in FCEVs comes from clean sources and that the production processes of FCEVs follow carbon emission norms. The social perspective barriers study suggests that to ensure social acceptability, the producers and policymakers should provide affordability by the masses, adequate refueling stations and servicing facilities, and the availability of subsidies and incentives to encourage people to adopt FCEVs, at least for initial purchases. From an economic perspective, the government and corporate houses should develop indigenous technology, facilitate the required infrastructure, encourage collaborations to ensure reduced costs and smoothen the process of FCEV adoption. From the operational perspective, the decision-makers can ensure facilities develop a skilled workforce, develop technologies, and improve infrastructure to facilitate better adoption of FCEVs. The severity analysis would help the stakeholders prioritize their focus over the most severe barriers. The manufacturers and service providers better understand the societal expectations of the FCEVs to make the FCEVs more attractive from environmental and social perspectives and improve the efficiency and effectiveness. These findings offer a practical roadmap for regional policymakers and industry leaders. Interventions should focus on capacity building, localized manufacturing, and targeted infrastructure development to reduce dependency on imports and improve cost-effectiveness in deployment.

The policy implications enable policymakers to decide their focal area of priority. The results of this study suggest that long-term policy commitments should be directed toward addressing stable and high-severity barriers such as high cost, lack of infrastructure, and shortage of skilled manpower. Instead of recommending general subsidies, targeted interventions are proposed, such as capital subsidies for hydrogen refueling station infrastructure—particularly in urban freight corridors—production-linked incentives (PLI) for domestic manufacturers of fuel cell components to reduce import dependence, and national-level vocational training programs in collaboration with technical institutes to build a skilled hydrogen and fuel cell workforce. For dynamic or unstable barriers, such as a limited number of automakers or weak consumer awareness, more adaptive policy instruments are needed, including temporary tax holidays or co-financed R&D schemes for early-stage FCEV manufacturers entering the Selected South Asian market, public–private demonstration projects showcasing FCEV buses or logistics fleets in metro areas, and coordinated awareness campaigns to educate consumers and fleet operators about the safety and benefits of hydrogen mobility. These policy suggestions are directly informed by barrier ranking and stability analysis and are designed to tackle the root causes of adoption challenges in a regionally relevant and actionable manner. The stability analysis offers an important lens for guiding policy design. Barriers identified as stable—such as higher costs, underdeveloped hydrogen infrastructure, and lack of skilled manpower—remain critical across varying stakeholder priorities. These barriers warrant long-term, foundational policy responses, such as investment in hydrogen production infrastructure, tax credits or subsidies for domestic manufacturing, and skill development programs. Conversely, unstable or moderately stable barriers—such as the limited number of automakers or low public awareness—may vary in salience depending on policy context or market evolution. The scenario-based stability analysis equips decision-makers to distinguish between structural barriers requiring foundational investment, and variable barriers that can be addressed through adaptive, time-bound strategies. These require more flexible and adaptive interventions, such as targeted incentive schemes, public-private demonstration pilots, or awareness campaigns that can be scaled or reoriented as the industry matures. This alignment of barrier stability with policy agility enhances strategic resource allocation and policymaking effectiveness in emerging Selected South Asian markets.

The study has a few limitations. The study is based on stakeholders from only four different perspectives which are: Economic, Environmental, Social and Operational. A few more perspectives can be added in further research. The study is based on the opinion of a limited number of stakeholders from each perspective; this number can be increased in future work. The study is based on the expert's views and may have biased fallacies. As with most self-administered questionnaires, this study is subject to potential response biases. These may include over- or underestimation of barrier severity, misinterpretation of linguistic scales, or self-selection bias among participants with higher interest or awareness. Although a pilot test was conducted and detailed instructions were provided, these limitations are acknowledged as inherent to expert-based survey methodologies. As the study is exploratory and relies on expert responses from diverse stakeholders, the use of EFA was appropriate for identifying the underlying barrier dimensions. However, the study does not incorporate confirmatory factor analysis (CFA), composite reliability (CR), or common method bias (CMB) testing. These techniques, while valuable, are typically applied in large-sample, theory-testing studies. Future research could incorporate these additional psychometric tools to strengthen construct validity and measurement precision. The study is limited to FCEVs and can be extended to multiple similar products. Only emerging economies from South Asia are considered for barrier identification, but a comparative study of emerging and developed economies can be conducted in the future. Also, for the sensitivity analysis, the study used hypothetical weight combinations without anchoring them in empirical data from stakeholders. Though it covers all scenarios, it does not reflect the stakeholder's priorities.

Future research could apply this integrated framework to additional emerging economies or expand the analysis by incorporating longitudinal data on policy impact. Further exploration into behavioral adoption drivers, comparative FCEV vs. BEV (Battery Electric Vehicle) challenges, and real-time techno-economic modeling would strengthen predictive capabilities and policy alignment.

CRediT authorship contribution statement

Prasad Vasant Joshi: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bishal Dey Sarkar:** Writing – original draft, Visualization, Validation, Software, Resources, Investigation, Formal analysis, Data curation. **Vardhan Mahesh Choubey:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Fadi Sibai:** Writing – original draft, Visualization, Validation, Software, Resources, Formal analysis. **Sandeep Jagtap:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table
Respondent's Profile

Category	Subcategory	Number
Respondents	Manufacturers (owners, managers, and technical experts)	70
	Battery Suppliers	20
	Government officials	20
	Customers	81
	Environmentalists (NGOs)	20
Age (in years)	20–30	50
	30–40	66
	40–50	50
	Above 50	45
Gender	Male	149
	Female	72
Total Experience	5–10 years	24
	10–20 years	84
	Above 20 years	111

Appendix B

Table
Linguistic Terms with the membership functions

Linguistic Terms	Consequence of Enablers	Notations	Membership functions		
Very Low	Negligible	VL	0	0	0.25
Low	Moderate	L	0	0.25	0.5
Medium	Somewhat Important	M	0.25	0.5	0.75
High	Important	H	0.5	0.75	1
Very High	Highly Important	VH	0.75	1	1

Appendix C

Table
Responses in terms of linguistic terms

		EXPERT 1				EXPERT 2				EXPERT 3				EXPERT 4				EXPERT 5			
Code	Barriers	En	S	E	O	En	S	E	O	En	S	E	O	En	S	E	O	En	S	E	O
FVB1	Higher Costs	M	VH	VH	H	H	VH	H	VH	M	H	H	H	M	VH	H	H	H	VH	H	H
FVB2	Limited subsidies and awareness	H	VH	H	H	M	H	H	H	M	VH	H	H	L	H	M	M	L	H	M	M
FVB3	Lack of awareness and demand	VL	L	M	L	VL	H	L	L	VL	L	L	L	VL	H	M	M	L	H	M	H
FVB4	Strict environment-related laws	VL	L	L	H	VL	L	L	H	L	L	M	H	L	H	L	L	L	M	M	H
FVB5	Government support and political will	M	H	H	H	L	M	VH	VH	L	L	VH	M	L	M	M	L	H	H	L	L
FVB6	Limited variety and volumes	VL	VH	H	L	VL	L	H	M	VL	M	L	L	L	M	L	M	VL	H	H	M
FVB7	Complex technology adaptation	VL	VL	M	VH	L	L	L	VH	VL	L	L	VH	VL	L	L	H	VL	L	L	M
FVB8	Underdeveloped supply chain	L	VL	M	H	VL	L	M	H	VL	L	M	VH	VL	L	H	M	L	VL	M	M
FVB9	A limited number of refueling stations	H	VH	M	VH	M	H	M	H	L	VH	M	M	L	H	H	VH	VL	VH	H	VH
FVB10	Carbon emitting sources of Hydrogen	H	VL	L	M	VH	VL	L	M	VH	VL	L	L	VH	M	M	L	VH	M	M	L
FVB11	A limited number of automakers	M	H	VL	M	VL	H	L	L	VL	M	L	M	M	M	L	M	VL	H	L	L
FVB12	Lack of Indegenious technology	L	L	H	VH	M	M	H	H	L	M	H	H	L	M	VH	VH	L	M	H	H
FVB13	Lack of service facilities	VL	VH	M	L	L	VH	L	M	VL	H	L	L	L	H	L	L	L	H	L	M
FVB14	Lack of associations and collaboration	VL	VL	H	H	VL	VL	H	H	VL	L	H	M	M	M	M	H	L	L	H	H
FVB15	Lack of skilled manpower	VL	H	L	VH	L	M	H	H	VL	M	H	H	M	H	H	H	VL	H	H	H
FVB16	Greenhouse gas emissions by FCEV manufacturers	H	H	M	M	VH	M	M	M	VH	H	M	M	VH	M	H	H	VH	M	H	M
FVB17	Limited digital and physical infrastructure	VL	L	VH	H	VL	VL	H	H	VL	VL	H	H	VL	VL	H	VH	M	H	H	H

Appendix D

Table
Averaged- TFNs of the responses

	Average											
Code	Env			S			E			O		
FVB1	0.35	0.6	0.85	0.7	0.95	1	0.55	0.8	1	0.55	0.8	1
FVB2	0.2	0.45	0.7	0.6	0.85	1	0.4	0.65	0.9	0.4	0.65	0.9
FVB3	0	0.05	0.3	0.3	0.55	0.8	0.15	0.4	0.65	0.15	0.4	0.65
FVB4	0	0.15	0.4	0.15	0.4	0.65	0.1	0.35	0.6	0.4	0.65	0.9
FVB5	0.15	0.4	0.65	0.3	0.55	0.8	0.45	0.7	0.85	0.1875	0.4375	0.6875
FVB6	0	0.05	0.3	0.35	0.6	0.8	0.3	0.55	0.8	0.15	0.4	0.65
FVB7	0	0.05	0.3	0	0.2	0.45	0.05	0.3	0.55	0.6	0.85	0.95
FVB8	0	0.1	0.35	0	0.15	0.4	0.3	0.55	0.8	0.45	0.7	0.9
FVB9	0.15	0.35	0.6	0.65	0.9	1	0.35	0.6	0.85	0.6	0.85	0.95
FVB10	0.7	0.95	1	0.1	0.2	0.45	0.1	0.35	0.6	0.1	0.35	0.6
FVB11	0.1	0.2	0.45	0.4	0.65	0.9	0	0.2	0.45	0.15	0.4	0.65
FVB12	0.05	0.3	0.55	0.2	0.45	0.7	0.55	0.8	1	0.6	0.85	1
FVB13	0	0.15	0.4	0.6	0.85	1	0.05	0.3	0.55	0.1	0.35	0.6
FVB14	0.05	0.15	0.4	0.05	0.2	0.45	0.45	0.7	0.95	0.45	0.7	0.95
FVB15	0.05	0.15	0.4	0.4	0.65	0.9	0.4	0.65	0.9	0.55	0.8	1
FVB16	0.7	0.95	1	0.35	0.6	0.85	0.35	0.6	0.85	0.3	0.55	0.8
FVB17	0.05	0.1	0.35	0.1	0.2	0.45	0.55	0.8	1	0.55	0.8	1

Appendix E

Table
Normalized Values of Belief Degrees

	Environmental					Social					Economic					Operational				
Codes	VL	L	M	H	VH	VL	L	M	H	VH	VL	L	M	H	VH	VL	L	M	H	VH
FVB1	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000	0.0000	0.0654	0.3922	0.5425	0.0000	0.0000	0.2128	0.4840	0.3032	0.0000	0.0000	0.2128	0.4840	0.3032
FVB2	0.0500	0.3000	0.4500	0.2000	0.0000	0.0000	0.0000	0.1714	0.4686	0.3600	0.0000	0.1000	0.3500	0.4000	0.1500	0.0000	0.1000	0.3500	0.4000	0.1500
FVB3	0.5455	0.3896	0.0649	0.0000	0.0000	0.0000	0.2000	0.4450	0.3050	0.0500	0.1005	0.3518	0.4020	0.1457	0.0000	0.1005	0.3518	0.4020	0.1457	0.0000
FVB4	0.3642	0.4624	0.1734	0.0000	0.0000	0.1005	0.3518	0.4020	0.1457	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000	0.0000	0.1000	0.3500	0.4000	0.1500
FVB5	0.1005	0.3518	0.4020	0.1457	0.0000	0.0000	0.2000	0.4450	0.3050	0.0500	0.0000	0.0552	0.3315	0.4751	0.1381	0.0700	0.3200	0.4300	0.1800	0.0000
FVB6	0.5455	0.3896	0.0649	0.0000	0.0000	0.0000	0.1604	0.4278	0.3583	0.0535	0.0000	0.2000	0.4450	0.3050	0.0500	0.1005	0.3518	0.4020	0.1457	0.0000
FVB7	0.5455	0.3896	0.0649	0.0000	0.0000	0.2778	0.5000	0.2222	0.0000	0.0000	0.2010	0.4472	0.3015	0.0503	0.0000	0.0000	0.0000	0.1786	0.4881	0.3333
FVB8	0.4410	0.4348	0.1242	0.0000	0.0000	0.3642	0.4624	0.1734	0.0000	0.0000	0.0000	0.2000	0.4450	0.3050	0.0500	0.0000	0.0524	0.3141	0.4660	0.1675
FVB9	0.1443	0.3918	0.3608	0.1031	0.0000	0.0000	0.0000	0.1235	0.4321	0.4444	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000	0.0000	0.1786	0.4881	0.3333
FVB10	0.0000	0.0000	0.0654	0.3922	0.5425	0.2486	0.5202	0.2312	0.0000	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000
FVB11	0.2486	0.5202	0.2312	0.0000	0.0000	0.0000	0.1000	0.3500	0.4000	0.1500	0.2778	0.5000	0.2222	0.0000	0.0000	0.1005	0.3518	0.4020	0.1457	0.0000
FVB12	0.2010	0.4472	0.3015	0.0503	0.0000	0.0500	0.3000	0.4500	0.2000	0.0000	0.0000	0.0000	0.2128	0.4840	0.3032	0.0000	0.0000	0.1714	0.4686	0.3600
FVB13	0.3642	0.4624	0.1734	0.0000	0.0000	0.0000	0.0000	0.1714	0.4686	0.3600	0.2010	0.4472	0.3015	0.0503	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000
FVB14	0.3413	0.4790	0.1796	0.0000	0.0000	0.2778	0.5000	0.2222	0.0000	0.0000	0.0000	0.0500	0.3000	0.4500	0.2000	0.0000	0.0500	0.3000	0.4500	0.2000
FVB15	0.3413	0.4790	0.1796	0.0000	0.0000	0.0000	0.1000	0.3500	0.4000	0.1500	0.0000	0.1000	0.3500	0.4000	0.1500	0.0000	0.0000	0.2128	0.4840	0.3032
FVB16	0.0000	0.0000	0.0654	0.3922	0.5425	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000	0.1500	0.4000	0.3500	0.1000	0.0000	0.2000	0.4450	0.3050	0.0500
FVB17	0.4268	0.4459	0.1274	0.0000	0.0000	0.2486	0.5202	0.2312	0.0000	0.0000	0.0000	0.0000	0.2128	0.4840	0.3032	0.0000	0.0000	0.2128	0.4840	0.3032

Appendix F

Table
Developing a continuum of scenarios by changing the weights

Environmental	Social	Economical	Operational
0.1	0.3	0.3	0.3
0.2	0.26	0.26	0.26
0.3	0.23	0.23	0.23
0.4	0.2	0.2	0.2
0.5	0.163	0.163	0.163
0.6	0.133	0.133	0.133
0.7	0.1	0.1	0.1
0.8	0.066	0.066	0.066
0.9	0.033	0.033	0.033

Appendix G1

Table
Analysis of Barriers under the Social Perspective

	Weightage of Social Perspective								
Codes	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
FVB1	1	1	1	1	1	1	1	1	1
FVB2	5	4	3	3	3	3	3	3	3
FVB3	15	17	15	11	11	11	10	10	10
FVB4	12	13	14	13	12	12	12	12	12
FVB5	9	8	7	7	7	8	9	9	9
FVB6	14	12	11	9	10	9	8	8	8
FVB7	13	15	17	17	17	16	16	16	16
FVB8	11	11	16	16	16	17	17	17	17
FVB9	4	3	2	2	2	2	2	2	2
FVB10	10	10	12	15	15	14	14	14	13
FVB11	17	16	13	10	9	7	7	6	6
FVB12	3	5	6	6	8	10	11	11	11
FVB13	16	14	9	8	6	4	4	4	4
FVB14	8	9	10	14	14	15	15	15	15
FVB15	6	6	5	5	5	5	5	5	5
FVB16	2	2	4	4	4	6	6	7	7
FVB17	7	7	8	12	13	13	13	13	14

Appendix G2

Table
Analysis of Barriers from an Economic Perspective

	Weightage of Economical Perspective								
Codes	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
FVB1	1	1	1	1	1	1	1	1	1
FVB2	4	4	4	2	3	4	5	6	6
FVB3	16	16	15	14	13	12	12	12	12
FVB4	12	13	14	13	14	14	14	14	14
FVB5	7	7	7	8	8	8	6	5	5
FVB6	14	12	11	10	10	10	10	10	10
FVB7	15	17	17	17	16	16	16	16	16
FVB8	17	15	12	11	11	11	11	11	11
FVB9	3	3	3	5	6	9	9	8	8
FVB10	8	9	10	12	12	13	13	13	13
FVB11	11	14	16	16	17	17	17	17	17
FVB12	6	6	5	4	2	2	2	2	2
FVB13	9	11	13	15	15	15	15	15	15
FVB14	13	10	9	9	9	6	4	4	4
FVB15	5	5	6	6	7	5	7	7	7
FVB16	2	2	2	3	5	7	8	8	9
FVB17	10	8	8	7	4	3	3	3	3

Appendix G3

Table
Analysis of barriers from the Environmental perspective

	Weightage of Operational Perspective								
Codes	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
FVB1	1	1	1	1	1	1	1	3	4
FVB2	3	4	4	4	5	7	8	9	9
FVB3	14	16	17	17	16	15	15	15	14
FVB4	15	13	12	12	11	11	10	10	10
FVB5	5	7	8	9	12	12	12	12	12
FVB6	10	11	13	14	13	13	13	13	13
FVB7	17	17	15	11	9	6	6	4	3
FVB8	16	14	11	10	10	9	9	8	8
FVB9	4	3	2	2	2	2	2	2	2
FVB10	8	9	10	13	14	16	16	16	16
FVB11	13	15	16	16	15	14	14	14	15
FVB12	6	5	5	3	3	3	3	1	1
FVB13	11	12	14	15	17	17	17	17	17
FVB14	12	10	9	8	8	8	7	7	7
FVB15	7	6	6	5	4	4	4	5	5
FVB16	2	2	3	6	7	10	11	11	11
FVB17	9	8	7	7	6	5	5	6	6

Data availability

Data will be made available on request.

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