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A Delphi Analysis on the Barriers of Battery Swapping in Indian Electric Vehicle Battery Infrastructure

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Abstract

Battery swapping is a critical component of the operational framework underpinning the Battery-as-a-Service (BaaS) model. It enables electric vehicle (EV) users to replace near-depleted batteries with fully charged ones at designated battery swapping stations, ensuring minimal downtime and continuous driving range. While several studies have explored the technological development of battery swapping, limited research has focused on identifying and prioritizing the key enablers influencing its adoption—particularly within the Indian Electric Vehicle Battery (EVB) infrastructure. This study adopts a three-stage approach to address this gap. First, relevant factors influencing battery swapping adoption are identified through an extensive literature review. Next, a frequency-based mapping technique is used to shortlist the most frequently cited enablers. Finally, these enablers are validated and prioritized using a structured questionnaire survey based on a Likert scale, followed by expert evaluation using the Delphi method. The findings highlight the most significant enablers of battery swapping in the Indian context and offer practical implications at both policy and managerial levels. The study concludes with a discussion on its limitations and suggests directions for future research.

Keywords
Battery Swapping Method, Indian Electric Vehicle Battery Infrastructure, Delphi Technique, Firm-Based Perspective, Demand-Side Economics

1. Introduction

Battery swapping has emerged as a viable alternative to conventional EV charging methods, offering a faster and more space-efficient solution. Unlike plug-in charging, which requires vehicles to remain stationary for extended periods, battery swapping involves replacing a depleted battery with a fully charged one in just a few minutes. This method has garnered attention worldwide, particularly for its ability to mitigate challenges related to limited land availability and constrained grid capacity in densely populated urban areas.

While the establishment of plug-in charging stations demands significant capital and space, battery swapping stations (BSSs) offer a more adaptable and cost-efficient option. They can be seamlessly integrated into existing infrastructure, and support the standardization of battery packs across vehicle platforms. Recognizing its strategic value, NITI Aayog proposed a draft battery swapping policy in 2022 to promote its adoption in India. The policy emphasizes three major benefits over plug-in charging: faster turnaround, better use of space, and improved cost efficiency when battery usage remains high (Aayog, 2022).

Battery swapping complements other charging technologies such as fast, slow, and wireless charging. The latter methods, often referred to as point chargers (PCs), require vehicles to be immobile during charging. By contrast, swapping reduces charging time to approximately 2–3 minutes, significantly cutting vehicle downtime (Vallera et al., 2021). It also addresses concerns about battery wear and promotes grid-friendly, off-peak energy consumption—an important consideration in a country like India, where electricity demand can be highly variable (Zhu et al., 2023). However, the model faces hurdles such as the lack of universal battery standards, the complexity of automation in swapping systems, and the initial setup costs (Patel et al., 2024; Zhan et al., 2022).

Though the technology has progressed from early trials to commercially viable systems, the deployment of BSSs in India remains nascent. Empirical studies on fully operational swapping networks are limited (Revankar & Kalkhambkar, 2021). Additionally, the potential for BSSs to generate revenue through integrated renewable energy sources—like solar or wind—remains underexplored. Utilizing such systems could reduce environmental impact while improving operational margins (Patel et al., 2024).

Economically, battery swapping is proving competitive across multiple vehicle categories, especially for two-wheelers and four-wheelers, where operational costs are lower than those of plug-in systems. Government subsidies have bolstered its appeal, extending its feasibility to three-wheelers and buses in commercial fleets. These financial incentives help reduce the cost disparity with plug-in charging and enhance key performance indicators such as internal rate of return (IRR) and net present value (NPV) (Patel et al., 2024).

The Battery-as-a-Service (BaaS) model has received particular support from the Indian government. Under BaaS, consumers purchase EVs without batteries, significantly reducing upfront costs, and instead subscribe to battery services throughout the vehicle's lifecycle. This approach enhances affordability and widens access to EVs for price-sensitive segments of the population (Murugan & Marisamynathan, 2024).

Despite these advancements, the adoption of battery swapping in India still faces policy and implementation challenges. To encourage uptake at fuel stations and other public points, there must be cohesive frameworks that address infrastructure readiness, regulatory compliance, safety standards, and financial viability. Experts recommend introducing tax benefits for users, ensuring interoperability between stations, offering loyalty incentives, and developing insurance mechanisms to mitigate operational risk (Murugan & Marisamynathan, 2024).

Several business models for BSSs have emerged, varying in investment structure, revenue strategy, and service delivery. Major OEMs like Renault, Tesla, and Nio have tested different models, including subscription-based and pay-per-swap options, tailored to market maturity (Shareef et al., 2016; Liang et al., 2021; Setiawan et al., 2023; Z. Yang et al., 2022). Research, including from California, suggests that swapping can yield greater economic and societal benefits than plug-in stations offering similar services (Liang & Zhang, 2018).

Nonetheless, current business models often overlook key revenue opportunities such as battery leasing and fail to account for variable pricing based on battery type and user profile (Hu et al., 2023; Z. Yang et al., 2022; Zhan et al., 2022). Forecasting methods also tend to inadequately capture the full life cycle of a vehicle or differentiate between commercial and personal use scenarios (Lidicker et al., 2011).
While global studies frequently compare plug-in charging to internal combustion engine vehicles, few examine battery swapping across all vehicle segments. In India, research indicates that for commercial two-wheelers, battery swapping is more economical—even without subsidies (Lévay et al., 2017). Although the 2022–23 Union Budget acknowledged battery swapping and interoperability, policy gaps persist. For instance, while electric two-

and three-wheelers can now be sold without batteries, there remains no clear directive on battery-related subsidies (Aayog, 2022; Murugan & Marisamynathan, 2024).

Despite policy efforts and growing industry interest, academic research on the enablers of battery swapping tailored to the Indian context remains scarce. Addressing this gap is essential for accelerating India's transition to net-zero emissions and establishing sustainable mobility solutions.

1.1 Objectives

The objective of this study is to identify and prioritize the key barriers influencing the adoption of battery swapping in the context of the Indian Electric Vehicle Battery (EVB) infrastructure. Specifically, the study aims to:

- Identify the factors challenging the adoption of battery swapping through a comprehensive review of existing literature.
- Map and shortlist these factors using frequency analysis to determine their relevance and prevalence in prior studies.
- Determine the most critical barriers from a firm-level perspective within the Indian EVB ecosystem by employing expert surveys and the Delphi method.

2. Literature Review

Infrastructure

Infrastructure-related barriers are among the most pressing challenges facing the battery swapping ecosystem. A major concern is the limited number of battery swapping stations (BSSs), which restricts widespread access to this service, especially in non-urban areas where deployment is slower due to logistical and investment constraints (Ahmad et al., 2020). Accessibility issues further complicate adoption. Battery swapping stations often require large physical footprints, making it difficult to find suitable urban locations. The presence of underground utilities and regulatory hesitations from landowners exacerbate this problem (Ahmad et al., 2020; Thangaraj et al., 2022; Li et al., 2021; Ramesan et al., 2022). In addition to space and availability, the adequacy of electrical infrastructure presents another serious challenge. Insufficient power generation and a fragile grid system hinder the ability to supply consistent electricity to swapping stations. This has led to instances where diesel generators are used as a fallback, undermining the sustainability goals of electric mobility (Saxena et al., 2014). The growing availability of fast-charging alternatives and public transportation options also reduces the attractiveness of battery swapping, creating competitive barriers (Ahmad et al., 2020; Murugan & Marisamynathan, 2024; Kang et al., 2015). Moreover, the integration of BSSs with the national grid remains complex due to grid instability and the lack of centralized load management, making scaling difficult (Steinhilber et al., 2013; Zhan et al., 2022).

Economic

Financial concerns significantly influence the scalability of battery swapping systems. One key issue is the high cost of electricity, which raises the per-unit cost for users and affects the overall operating margins of service providers (Chakraborty et al., 2019; Melliger et al., 2018; Saxena et al., 2014; Ramesan et al., 2022). Subscription-based models, while innovative, often come with high recurring fees that deter middle- and lower-income consumers (Chakraborty et al., 2019; Murugan & Marisamynathan, 2024). Additionally, the operation and maintenance of BSSs involve significant costs, including battery replacement and inventory management, which pose ongoing financial burdens for operators (Ahmad et al., 2020; Helander & Ljunggren, 2023). Consumers also face barriers due to the high upfront costs associated with battery swapping services and EV ownership. These costs include not only the price of the vehicle but also the infrastructure required to access battery swapping, making it feasible primarily for higher-income groups (Murugan & Marisamynathan, 2024). Furthermore, setting up a BSS demands substantial capital investment in infrastructure, batteries, and technology. Providers must maintain a buffer stock of batteries, which increases inventory and upfront costs (Schmidt, 2021; Ramesan et al., 2022). Finally, uncertainty around future battery prices and technological advances creates financial unpredictability. Providers find it difficult to estimate long-term costs due to rapidly evolving technologies and shifting consumer behavior (Gonzalez-Salazar et al., 2023; Zhou et al., 2023).

Technical and Standardization

The technical complexity of battery swapping is another key barrier to its broader implementation. One major issue is the lack of standardization in battery design. Differences in battery size, chemistry, and capacity across manufacturers make universal swapping stations difficult to implement (Murugan & Marisamynathan, 2024). The supporting software infrastructure is also underdeveloped. Many BSSs lack integrated digital platforms for managing bookings, payments, and energy flows efficiently (Mæland, 2024; Li et al., 2024; Adegbohun et al., 2019). Operationally, battery swapping involves challenges in scheduling and demand prediction. The unpredictable arrival of vehicles and variation in battery state-of-charge complicate planning, making inventory and electricity demand harder to manage (Lai & Li, 2024; Zhang et al., 2023). Users may also experience delays due to long queues or the need to travel to distant BSSs, further reducing convenience (Li et al., 2024; Huang et al., 2024). Concerns around data safety have also emerged. Because battery swapping systems rely heavily on connected infrastructure, risks of cyberattacks and data breaches are significant (Chen et al., 2024). Finally, the lack of real-time data, transparency, and seamless integration between hardware and software systems limits the efficiency and reliability of current BSS networks.

Regulatory and Strategic
Policy and strategic planning are crucial enablers of any emerging technology, and battery swapping is no exception. A significant regulatory barrier is the absence of a comprehensive legal framework. The lack of standard rules around liability, operations, and safety regulations creates uncertainty for investors and slows down implementation (Mæland, 2024; Rizos et al., 2016). Additionally, government support through subsidies, tax incentives, or R&D grants is perceived as insufficient. This limited financial encouragement discourages stakeholders from investing in the development and expansion of battery swapping systems (Patyal et al., 2021; Ramesan et al., 2022).

Market and Consumer
Consumer behavior and market acceptance are vital to the success of battery swapping. One of the primary obstacles is a widespread lack of awareness about how the system works and its potential environmental benefits. Many consumers remain unfamiliar with battery swapping and often confuse it with traditional EV charging (Ahmad et al., 2020; Goel et al., 2021; Bobanac et al., 2018). Another critical barrier is the lack of trust in new technologies. Consumers worry about the quality and lifespan of swapped batteries, and fear being provided with substandard or incompatible units. These concerns are compounded by the absence of standardized quality checks and third-party oversight (Patyal et al., 2021; Goel et al., 2021).

3. Methods
To address challenges in electric vehicle (EV) battery swapping infrastructure, this study adopts a three-phase exploratory framework. Phase I involves a systematic literature review to identify factors which are critical to the adoption of electric vehicle battery swapping infrastructure cross components such as battery specifics, infrastructure, time, stakeholder and economic dimensions, drawing on peer-reviewed studies from databases such as Scopus and Web of Science. Based on the literature review, Phase II mapped out the most frequently used barriers to the adoption of battery swapping infrastructure. According a close ended questionnaire was prepared for a pilot fuzzy Delphi study. Phase III employs a fuzzy Delphi method, engaging 27 experts ranging from 2 policy maker, 4 industry and 21 academic experts to refine and validate the factors. Thus, concluding with the most relevant factors that challenge the adoption of electric vehicle battery swapping infrastructure particularly in the Indian context.

The Fuzzy Delphi Method (FDM) is a hybrid decision-making technique that integrates the traditional Delphi method with fuzzy logic to address ambiguity and subjectivity in expert judgments. Developed to overcome limitations in handling uncertain or imprecise human evaluations, FDM efficiently consolidates expert opinions while reducing the need for multiple survey rounds (Zhao & Li, 2016). A structured questionnaire was developed using a modified Saaty scale, ranging from 1 (extremely irrelevant) to 5 (extremely relevant) (Table 1). Each scale point was mapped to a corresponding linguistic variable and then to a fuzzy triangular number (FTN), reflecting the inherent vagueness in human judgment.

Table 1. Measurement scale for the FDM survey

Linguistic variable	Rating	Corresponding TFN	p	q	r
Extremely irrelevant	1	(0.1, 0.1, 0.3)	0.1	0.1	0.3
Irrelevant	2	(0.1, 0.3, 0.5)	0.1	0.3	0.5
Normal	3	(0.3, 0.5, 0.7)	0.3	0.5	0.7
Relevant	4	(0.5, 0.7, 0.9)	0.5	0.7	0.9
Extremely relevant	5	(0.7, 0.9, 0.9)	0.7	0.9	0.9
Source: Own elaboration					

Interviewers evaluate factors using an adapted Saaty linguistic scale (1–5), where each score corresponds to a fuzzy triangular number (FTN). Results are expressed through FTNs assigned to each linguistic variable. These FTNs are constructed by partitioning the interval into five values aligned with the triangular format (p, q, r). The fuzzy triangular numbers (FTNs) are generated by distributing the scale across the five comparison indices. Each index is assigned an FTN structured in the (p, q, r) triangular format, where:

p = Lower bound (minimum value)
q = Peak (most likely value)
r = Upper bound (maximum value)
This partitions the 0–1 continuum into overlapping fuzzy sets that mathematically represent the linguistic importance levels. For example, "extremely relevant" is represented as (0.7, 0.9, 0.9), while "Extremely irrelevant" is (0.1, 0.1, 0.3) (Table 1). The aggregated fuzzy values were converted into crisp scores using defuzzification techniques, such as centroid or weighted average methods. The resulting factor weights were analyzed to establish a prioritized list of variables. Reliability and validity were assessed.

4. Data Collection

Relevant factors challenging the adoption of battery swapping infrastructure was shortlisted for the fuzzy DELPHI analysis in three phases. In phase I, based on reviewed literatures published in databases such as Scopus and Web of Science, an exhaustive list of 570 variables were short listed. In phase II, based on review of literature and mapping, barriers to the adoption of battery swapping infrastructure were short listed and after removing for duplicate factors a finalized list of 24 barriers were shortlisted. Table 2 represents the short-listed barriers along with references and description of the factors

Table 2. List of Barriers for DELPHI analysis.

Sl. No.	**Battery Swapping Barriers**	**Description**
B1	Lack of availability of battery swapping stations (Ahmad et al., 2020)	Limited Number of Battery Swapping Stations. Building a large-scale nationwide offering takes time. Piping and electrical wiring underneath the ground are also reasons for experiencing difficulties while building.
B2	Lack of accessibility of battery swapping stations (Ahmad et. al., 2020; Thangaraj et al., 2022, Li et al., 2021; Ramesan et al., 2022)	Finding suitable places for battery-swapping stations: The swapping stations are large constructions that need a lot of space. At the same time, the technology is not yet very established, making the landowners and government more reluctant to open the station building.
B3	Inability to meet electricity demand for charging infrastructure (Saxena et al., 2014)	If the electricity generated is insufficient to charge EVs, more diesel generators must meet the demand.

		In the long run, the solution mentioned above contradicts the concept of sustainable transportation
B4	Availability of alternative options (Ahmad et. al., 2020; Murugan & Marisamynathan, 2024; Kang et al., 2015)	Greater access to charging or fast charging (charging infrastructure) or availability of cheaper alternative transportation options reduces the need for battery swapping and discourages the wider implementation
B5	Lack of electrical infrastructure for charging station (Schmidt, 2021; Saxena et al., 2014; Mæland, 2024; Steinhilber el al., 2013; Ramesan et al., 2022; Zhan et al., 2022)	These barriers address the challenges related to power supply and electrical infrastructure necessary for battery swapping.
B6	Difficulties integrating /associated with the national grid (Steinhilber el al., 2013; Zhan et al., 2022)	Difficulties integrating /associated with the national grid
B7	Lack Charging facility (Mæland, 2024; Steinhilber el al., 2013; Zhan et al., 2022)	Lack of charging facilities within the battery swapping station
B8	High electricity rates (Chakraborty et al., 2019; Melliger et al. 2018; Saxena et al., 2014; Ramesan et al., 2022)	Captures the high cost of electricity
B9	High subscription fees (Chakraborty et al., 2019; Melliger et al. 2018; Murugan & Marisamynathan, 2024)	Captures additional cost for lease or rent on the battery
B10	High infrastructure maintenance costs (Ahmad et. al., 2020; Chakraborty et al., 2019; Melliger et al. 2018; Helander & Ljunggren, 2023)	Battery degradation cost, Annual maintenance cost of BSS, Battery replacement cost, Operation cost
B11	High cost for the consumer (Chakraborty et al., 2019; Melliger et al. 2018; Murugan & Marisamynathan, 2024; Schmidt, 2021; Wang et al.,2020)	Only high-income household afford the services (Social constructs that negatively influence the decision of adopt battery swapping)
B12	High initial investment (Schmidt, 2021;]Wang et al.,2020; Ramesan et al., 2022; Shashank et al., 2020)	High Battery Swapping Station (BSS) Construction costs, High Battery and charger Cost, High initial Inventory cost, High infrastructure cost. The battery technologies for EVs are evolving. The present technology related to lithium-ion batteries is costly as well as unsafe. Infrastructure needed to complete the swapping also needs to have more batteries on hand to ensure the provider consistently can deliver a new charged battery to the customer.
B13	Uncertain future cost estimation (Li et al., 2021; Gonzalez-Salazar, 2023; Zhou et al., 2023)	(a) The marginal rent for a provider with a BaaS depends on the battery's price. Prices have also decreased since battery technology moves quickly. This creates uncertainty in the future as to whether a BaaS will be economically beneficial for both the provider and the consumers, since the model cannot predict the future value of the battery. (b) It is clear that since the driver's behaviour and the technology development are changing and challenging to predict accurately, it creates uncertainty for the providers. The cost during the lifetime is the cost the provider takes responsibility for. Therefore, future cost estimation is vital for a BaaS implementation.
B14	Battery pack heterogeneity (Murugan & Marisamynathan, 2024)	Battery size, Battery chemistry, Battery capacity (Non-standard battery design in terms of type, size, capacity and brand; Compatibility issues with vehicles for different manufacturers, which will be very difficult to standardize)
B15	Lack of software implementation (Mæland, 2024; Li et al., 2024; Adegbohun et al., 2019)	Challenges to software and app implementation

B16	Complications with Scheduling for Swapping (Mæland, 2024; Steinhilber el al., 2013; Lai & Li, 2024)	Depending on the state of health of the battery and the state of charge the charging time for a battery is uncertain. Additionally the unpredictable nature of demand for swap makes electricity consumption rate also variable
B17	Queueing time (Li et al., 2024; Huang et al., 2024)	Lack of information or access to real time data to train models
B18	Risk of Data safety and privacy (Li et al., 2024; Chen et al., 2024)	Malicious attacks; Risk of hacking
B19	Lack of historical data, Access to real-time data (Li et al., 2024; Chen et al., 2024)	Lack of information to train models
B20	Integration challenges between hardware and software for monitoring purposes (Li et al., 2024; Chen et al., 2024)	Integration challenges between hardware and software for monitoring purposes
B21	Nascent legal framework (Mæland, 2024; Steinhilber el al., 2013; Rizos et al., 2016)	Complex legal framework, Lack of legal framework
B22	Lack of government optimum incentives (Ramesan et al., 2022; Patyal et al. 2021)	Lack of Tax concession, Lack of Subsidy (In spite of various efforts by government departments underway to promote research relevant to EVs, the automotive industry may wish for more government funding to support their own R&D effort, as the industry is still suffering from the recent financial and economic crisis.)
B23	Lack of public awareness (Ahmad et. al., 2020, Schmidt, 2021; Ramesan et al., 2022; Patyal et al. 2021; Goel et al.,2021; Bobanac et al.; 2018)	Lack of education/awareness about EV battery swapping [1][5], Lack of knowledge about environmental benefits of battery swapping
B24	Lack of trust to acceptance of new technologies (Ahmad et. al., 2020, Patyal et al. 2021; Goel et al.,2021)	Non-reliable range of the swapped battery accurately; Life of batteries might be different; The EV batteries might be replaced with fake batteries; Chances of damaging components of the vehicle

In Phase III, the target group of experts including academicians and researchers across engineering and interdisciplinary departments, industry experts and policy makers were chosen for their expertise in EV battery swapping infrastructure. A list of 55 experts was prepared. Respondents were engaged via email, phone, and in-person visits. 33 experts agreed for the survey. However, 27 completed responses were finalized of which 7 experts (4 industry, 2 academician and 1 policy maker) submitted responses online while the remaining 20 experts (19 academicians, 1 policy maker) were interviewed in person. Based on the response, a fuzzy DELPHI analysis was implemented. Based on a cut off score of 0.56 from the fuzzy triangular numbers mentioned in Table 3 final factors were concluded.

5. Results and Discussion

The results are sub divided into two sub sections, numerical results, and graphical results. A detailed analysis of the Fuzzy DELPHI output is given in these two sub sections. In addition, the results are further sub divided into high impact enablers, weak enablers and policy level improvement under the subheading of proposed improvement.

5.1 Numerical Results

To identify the critical barriers impeding the adoption of battery swapping infrastructure, the study employed the Fuzzy Delphi Method with inputs from domain experts. A defuzzified mean score threshold of 0.56 was adopted to determine the inclusion of barriers in subsequent analysis. Based on this criterion, twelve out of twenty-four initially identified barriers were accepted, signifying that they surpassed the threshold and reflect a high degree of expert consensus regarding their importance.

Table 3. Fuzzy Delphi Result

Codes	Barrier Names	Mean Score	Accept/Reject
B1	Lack of availability of battery swapping stations	0.60471672	**Accept**
B2	Lack of accessibility of battery swapping stations	0.58044208	**Accept**
B3	Inability to meet electricity demand for charging infrastructure	0.55399648	**Reject**
B4	Availability of alternative options	0.52778616	**Reject**
B5	Lack of electrical infrastructure for charging station	0.57177502	**Accept**
B6	Difficulties integrating /associated with the national grid	0.61864336	**Accept**
B7	Lack Charging facility	0.52955109	**Reject**
B8	High electricity rates	0.52894075	**Reject**
B9	High subscription fees	0.5503448	**Reject**
B10	High infrastructure maintenance costs	0.55392692	**Reject**
B11	High cost for the consumer	0.64962746	**Accept**
B12	High initial investment	0.64958754	**Accept**
B13	Uncertain future cost estimation	0.5619818	**Accept**
B14	Battery pack heterogeneity	0.59609815	**Accept**
B15	Lack of software implementation	0.55837475	**Reject**
B16	Complications with Scheduling for Swapping	0.54903037	**Reject**
B17	Longer Queueing time	0.54345297	**Reject**
B18	Risk of Data safety and privacy	0.5215514	**Reject**
B19	Lack of historical data, Access to real-time data	0.51852377	**Reject**
B20	Integration challenges between hardware and software for monitoring purposes	0.54480007	**Reject**
B21	Nascent legal framework	0.63097794	**Accept**
B22	Lack of government optimum incentives	0.55255573	**Reject**
B23	lack of public awareness	0.5748808	**Accept**
B24	Lack of trust to acceptance of new technologies	0.57330369	**Accept**

The results reveal that some of the most critical barriers relate to financial and infrastructural constraints. For instance, high cost for the consumer (B11) and high initial investment (B12) emerged as the top two concerns, both recording a mean score of approximately 0.650. These barriers reflect the prevailing apprehensions surrounding the economic feasibility of battery swapping from both user and investor perspectives. Additionally, difficulties associated with integration into the national grid (B6) and the nascent state of the legal framework (B21) were also rated highly, suggesting a lack of structural preparedness and regulatory clarity in the Indian context. Other notable barriers included the lack of availability and accessibility of battery swapping stations (B1 and B2), and the presence of battery pack heterogeneity (B14), which poses challenges for standardization and interoperability.

Conversely, twelve barriers failed to meet the minimum threshold and were excluded. These include concerns such as high subscription fees (B9), high infrastructure maintenance costs (B10), lack of historical or real-time data (B19), and risk of data safety and privacy (B18). The relatively lower mean scores for these barriers may indicate either limited current relevance or insufficient awareness among stakeholders. It is also possible that these concerns are considered less immediate compared to the structural and economic barriers identified, and may become more salient as the industry matures (Figure 1).

5.2 Graphical Results

The results of the Fuzzy Delphi analysis were further visualized using a bar chart, with each barrier's mean score plotted alongside a horizontal line representing the acceptance threshold of 0.56. The chart provides a clear visual demarcation between accepted and rejected barriers, where green bars represent barriers with significant expert consensus and red bars indicate those that were not supported for further consideration.

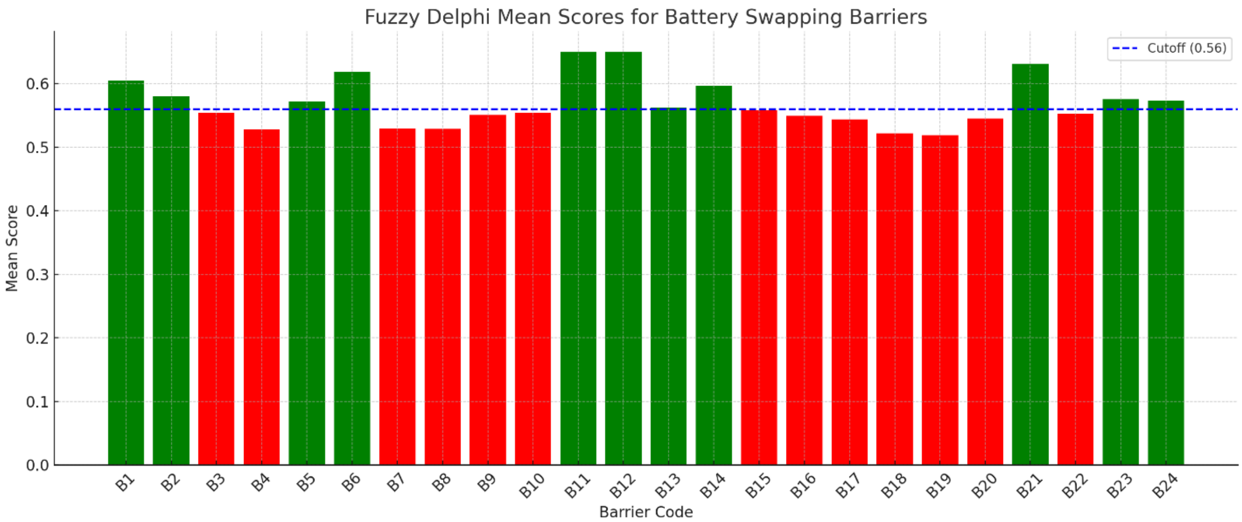

Figure 1. Fuzzy DELPHI Output

Visualization highlights a concentration of high-scoring barriers that are clearly perceived as pressing. Barriers such as B11, B12, and B6 stand out with scores significantly above the threshold, illustrating the dominance of cost and infrastructure-related issues. These are followed by barriers like B21 and B14, which further emphasize the importance of a supportive regulatory environment and standardized technical configurations. A cluster of barriers, such as B13, B23, and B24, hover just above the cutoff, suggesting a moderate but sufficient level of agreement among experts regarding their inclusion. These could be considered emerging issues that may gain more importance as the market evolves.

On the other hand, a notable number of barriers fall marginally below the threshold, including B3, B9, B10, and B22. Their proximity to the cutoff suggests that while they are not currently prioritized, they are not entirely irrelevant and could gain salience in specific contexts or future scenarios. The bar chart thus serves as a valuable tool to visually communicate expert consensus, enabling policymakers and stakeholders to easily identify the barriers requiring immediate attention.

5.3 Proposed Improvements

The findings from the Fuzzy Delphi analysis underscore the need for targeted policy and strategic interventions to address the validated barriers. The consistently high scores for economic challenges, such as consumer costs and capital investment requirements, suggest that the financial model for battery swapping must be re-evaluated. Policymakers and service providers should consider the introduction of capital subsidies, operating cost incentives, and interest-free or low-interest credit mechanisms to make the business model more financially attractive for both providers and users.

The presence of infrastructure-related barriers, including the lack of station availability and the complexity of grid integration, calls for immediate expansion of charging and swapping networks, especially in high-density urban and peri-urban areas. Strategic infrastructure development must be aligned with grid capacity planning and the use of smart grid technologies to ensure stability and scalability. Additionally, the issue of battery pack heterogeneity highlights the urgency for developing and enforcing industry-wide standards that can enable interoperability and reduce technology fragmentation.

The high rating assigned to the nascent legal framework points to the need for comprehensive policy formulation. A dedicated regulatory roadmap specifically addressing battery swapping, encompassing safety norms, operational guidelines, and licensing frameworks, would instill confidence among investors and operators. Moreover, moderate support for barriers such as lack of public awareness and trust in new technologies reflects the importance of continuous public engagement and demonstration projects to improve user perception and foster behavioral shifts.

Overall, the results suggest that while technical and digital concerns are currently perceived as secondary, the foundational challenges related to cost, infrastructure, and governance must be prioritized to create an enabling environment for battery swapping adoption. These insights form a crucial input for designing integrative solutions and coordinated stakeholder actions in future phases of battery swapping policy and implementation.

6. Conclusion

In conclusion, this study provides a comprehensive, evidence-based roadmap for overcoming the critical barriers to electric vehicle battery swapping infrastructure in India. By systematically combining literature review, expert consultation, and the Fuzzy Delphi Method, the research identifies eleven high-priority barriers, with financial and infrastructural challenges—such as high consumer costs, substantial initial investments, limited station availability, and complex grid integration—emerging as the most pressing concerns. The findings highlight the necessity for targeted policy interventions, including financial incentives, capital subsidies, and regulatory reforms, to enhance the economic feasibility and operational scalability of battery swapping networks. Furthermore, the study underscores the importance of developing standardized technical protocols to address battery pack heterogeneity and the urgent need for a robust legal framework to provide clarity and confidence for investors and operators. While digital and data-related challenges are currently seen as less critical, their relevance may increase as the sector matures. Ultimately, the validated barriers and proposed solutions offer actionable insights for policymakers, industry stakeholders, and researchers, ensuring that future battery swapping initiatives are grounded in consensus and aligned with India's broader sustainability and mobility goals. These findings lay the groundwork for integrative, stakeholder-driven strategies and future research on interdependencies among enablers.

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