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Swapping Ahead: Key Enablers of Battery Swapping in India's Electric Vehicle Ecosystem

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Abstract

Battery swapping is a critical component of the operational framework underpinning the Battery-as-a-Service business model. It enables electric vehicle 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 and infrastructural 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 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 these 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, Supply-Side Economics

1. Introduction
Establishing plug-in charging stations typically involves significant capital investment, both in terms of technology and physical space. Battery swapping is one of several available Electric Vehicle (EV) charging methods, alongside fast charging, slow charging, and wireless options. The latter two are generally referred to as point chargers (PCs), as they require the vehicle to remain stationary during charging. In contrast, battery swapping enables a depleted battery to be replaced with a fully charged one in approximately 2 to 3 minutes, significantly reducing the downtime associated with EV recharging (Vallera et al. 2021). This approach has gained global attention due to its potential to overcome key limitations of fixed charging infrastructure, particularly in urban environments where land availability and grid capacity are major constraints.

That is, battery swapping stations (BSSs) are comparatively more viable and can be more easily integrated into the existing EV ecosystem. Their deployment supports manufacturers and service providers in delivering standardized, swappable battery packs across a variety of vehicles. The Government of India has shown strong support for battery swapping under the broader *Battery-as-a-Service* (BaaS) business model. Under BaaS, EV users can purchase vehicles without batteries and instead pay a regular subscription fee to access battery services throughout the vehicle's lifetime (Murugan and Marisamynathan 2024). Recognizing its potential, the Government of India's policy think tank, NITI Aayog, introduced a draft battery swapping policy in 2022 to promote this model. The policy highlights three primary advantages over traditional charging: time efficiency, space optimization, and cost-effectiveness, particularly when battery utilization remains high (Aayog 2022).

This system also reduces concerns about battery degradation for users and allows for grid-friendly, off-peak charging practices, which is particularly beneficial in countries like India with fluctuating electricity demand (Zhu et al. 2023). However, battery swapping does face technical and financial challenges, including the absence of universal battery standards, the need for advanced swapping automation, and the relatively high initial cost of setting up a BSS (Patel et al. 2024; Zhan et al. 2022).

Battery swapping systems have evolved from early experimental models to more commercially viable platforms. Recent studies have demonstrated that battery swapping is economically viable across multiple vehicle segments, particularly two-wheelers (2Ws) and four-wheelers (4Ws), due to its lower per-kilometre operational cost when compared with plug-in charging. The introduction of government subsidies has further strengthened its competitive advantage, even making it feasible for commercial vehicles and public transport, such as three-wheelers (3Ws) and buses. These incentives not only narrow the cost gap between battery swapping and traditional charging but also improve financial metrics such as internal rate of return (IRR) and net present value (NPV). This makes battery swapping an appealing option for private and commercial users alike (Patel et al. 2024).

To improve user adoption at existing refuelling stations, well-formulated policies must be in place to support both users and service providers. Key considerations include infrastructure readiness, financial incentives, safety protocols, and regulatory frameworks. Recommendations from recent studies suggest the need for tax benefits for battery swapping users, enhanced station interoperability, loyalty-based incentives for frequent users, and comprehensive insurance frameworks to mitigate operational risks (Murugan and Marisamynathan 2024).

Various business models have emerged for BSSs, each offering different approaches to infrastructure investment, cost recovery, and service delivery (Liang et al. 2021; Setiawan et al. 2023; Z. Yang et al. 2022). Leading manufacturers such as Renault, Tesla, and Nio have piloted different battery swapping solutions (Shareef et al. 2016). These include subscription-based models, where users pay monthly or yearly fees, and pay-per-swap options that cater to more mature markets (Hu et al. 2023). A review of the existing literature reveals that, there is a lack of studies on battery swapping facilitators tailored to the Indian context. Addressing this is critical for supporting India's net-zero emissions target and scaling sustainable mobility solutions.

1.1 Objectives

The objective of this study is to identify and prioritize the key enablers 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 influencing 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 enablers from a firm-level perspective within the Indian EVB ecosystem by employing expert surveys and the Delphi method.

2. Literature Review

Time and Convenience

Time efficiency and user convenience are central enablers driving the adoption of battery swapping in electric mobility. One of the most significant advantages of battery swapping is its *remarkably short replacement time*. Unlike conventional EV charging, which can take from 30 minutes to several hours depending on the charging type, battery swapping can be completed in just a few minutes, allowing vehicles to return to the road much faster (Boti et al. 2024; Huang et al. 2024; Juvvala and Sarmah, 2021; Mæland 2024; Sayarshad and Mahmoodian 2021; S. Yang et al. 2019; Zhang et al. 2023). This rapid turnaround offers substantial time savings, particularly for commercial operators such as taxi services and freight companies, where minimizing downtime directly translates into increased operational efficiency and revenue. In these contexts, the opportunity cost of time is critical, and battery swapping helps maximize the time spent in active service rather than waiting for a charge (Lai and Li 2024; Li et al. 2023).

This high-speed process also contributes to reducing *range anxiety*, a common concern among EV users about running out of battery power before reaching a charging station. By providing a quick and reliable method of energy replenishment, battery swapping increases the practicality of EVs for daily use and long-distance travel (Adu-Gyamfi et al. 2022; Deng et al. 2023; Hemmati 2023; Mæland 2024; Raeesi and Zografos 2022; Sindha et al. 2023). The ability to maintain a consistent driving experience without long interruptions makes battery swapping a more attractive solution for consumers accustomed to the convenience of internal combustion engine vehicles.

Additional enablers supporting the convenience of battery swapping include the *affordability of battery rental models*, which can lower financial barriers for users by separating battery costs from vehicle ownership. This model not only reduces the upfront cost but also simplifies maintenance responsibilities, further enhancing the ease of EV adoption. Moreover, some systems implement *penalties for excessive wait times*, which incentivize service providers to maintain efficient operations and ensure prompt battery replacement services (Anderhofstadt and Spinler 2019; Juvvala and Sarmah 2021; S. Yang et al. 2019). This mechanism helps uphold service standards and reinforces the time-saving promise of battery swapping, ultimately contributing to a more reliable and user-friendly infrastructure.

In summary, the enablers related to time and convenience significantly enhance the appeal of battery swapping by reducing delays, easing user concerns about range, and enabling continuous vehicle operation with minimal interruption. These factors are particularly valuable in high-usage or commercial contexts and represent a strong complement to other technical and economic benefits of the swapping model.

Financial Benefits

The financial benefits of BaaS represent a crucial set of enablers that contribute to its growing adoption. One of the most significant economic advantages of the battery swapping model is the separation of battery ownership from vehicle ownership, which reduces the upfront cost for EV buyers. This approach lowers the initial financial barrier, making EVs more accessible to a wider market (Gonzalez-Salazar et al. 2023). Various *financial incentives*, including tax breaks, government grants, and subsidies, further support this model by encouraging both consumers and providers to participate in the ecosystem (Annarelli et al. 2020; Isaksson et al. 2011).

For service providers, battery swapping introduces new and stable sources of revenue. Instead of relying solely on one-time vehicle sales, providers can generate *recurring income* through battery subscriptions and swapping services, which has been shown to enhance profitability and revenue predictability (Sindha et al. 2023). Additionally, integrating battery swapping stations with the power grid allows providers to sell electricity back, creating *secondary income streams* through vehicle-to-grid (V2G) applications (Bobanac et al. 2018; Gonzalez-Salazar et al. 2023; Mæland 2024; Sindha et al. 2023).

From the customer perspective, the model leads to *reduced maintenance costs*, as the battery is owned and serviced by the provider (Helander and Ljunggren 2023; Hemmati 2023; Mæland 2024; Raeesi and Zografos 2022). This arrangement eliminates the need for the consumer to handle battery warranties or replacements, as any technical issues are managed by the service provider (Isaksson et al. 2011; Annarelli et al. 2020). Furthermore, customers benefit from *easier access to newer battery technologies*, as the ability to swap batteries allows them to adopt technological improvements without additional investment or depreciation concerns.

Lastly, the battery swapping model enables *economies of scale* by centralizing battery maintenance and standardizing infrastructure, which reduces marginal costs and enhances operational efficiency (Mæland 2024). These financial enablers collectively position battery swapping as a viable and attractive model for both consumers and service providers, playing a pivotal role in the broader adoption of electric vehicles.

Environmental and Sustainability

The environmental and sustainability-related enablers of battery swapping are central to advancing green mobility and responsible resource use. Battery swapping contributes to environmental sustainability by streamlining battery recycling and reuse, thereby minimizing pollution and promoting environmental awareness (Gonzalez-Salazar et al. 2023; Sindha et al. 2023). Through centralized management and ownership of batteries, the system supports a circular economy by enhancing the efficient use of materials and facilitating proper end-of-life handling.

A significant environmental benefit of battery swapping is its capacity to *promote the adoption of renewable energy sources*. Swapping stations can be integrated with solar photovoltaic systems and wind power, allowing the electricity used for charging batteries to come from clean energy sources (Ban et al. 2020; Helander and Ljunggren 2023; Mæland 2024; Shao et al. 2017; Vallera et al. 2021; Xu et al. 2022). This not only reduces dependency on fossil fuels but also aligns with global sustainability goals focused on carbon reduction and energy transition.

In addition, battery swapping supports *second-life battery applications*, allowing batteries that are no longer optimal for vehicle use to be repurposed for stationary storage or other less demanding applications (Borgosano et al. 2024; Helander and Ljunggren 2023; Hu et al. 2024; Lee et al. 2024; Marchesano et al. 2023). Centralized battery ownership in the swapping model makes it easier to identify and manage batteries suitable for reuse, creating new business opportunities while extending the lifespan of battery assets (Borgosano et al. 2024; Marchesano et al. 2023).

Battery swapping also enables *more effective battery health management and increased operational efficiency*. Since batteries are charged, monitored, and maintained at centralized swapping stations, service providers can apply optimized charging strategies and regularly assess key performance metrics such as State of Charge (SOC) and temperature. This proactive approach helps maintain battery health, extends lifecycle, and improves performance over time (Adegbohun et al. 2019; Mæland 2024). Such practices also encourage manufacturers and operators to focus on high-quality, durable battery technologies, which further contributes to environmental preservation.

Overall, battery swapping serves as a key enabler of environmental sustainability by integrating renewable energy, maximizing resource efficiency, and supporting the reuse and recycling of batteries. It represents a practical and scalable solution for reducing the environmental footprint of electric mobility while supporting the broader transition toward circular energy systems.

Infrastructure and Accessibility

Infrastructure and accessibility are critical enablers in the adoption and scalability of battery swapping systems. One of the key advantages of battery swapping lies in its potential to overcome the infrastructure limitations associated with conventional EV charging. Swapping stations can be more readily established in densely populated urban areas, offering a practical solution where space for fixed charging infrastructure is constrained (Bailey et al. 2015; Gonzalez-Salazar et al. 2023; Hardman et al. 2018; Murugan and Marisamynathan 2024).

The *proximity of swapping stations to users' everyday locations*, such as residential neighbourhoods, workplaces, and public spaces—plays an essential role in promoting EV adoption. Bailey et al. (2015) found that the visible presence of energy infrastructure in public areas positively influences perceptions of EV viability and convenience. Locating battery swapping stations in high-traffic zones thus contributes to increased user confidence and a stronger sense of accessibility.

Moreover, *the limitations of existing EV charging infrastructure* further highlight the appeal of battery swapping. Traditional fast-charging stations often face deployment challenges, including long installation timelines, grid constraints, and land-use conflicts, especially in urban centers. In addition, extended charging times and range anxiety persist as significant barriers to EV adoption (Boti et al. 2024; Helander and Ljunggren 2023). Battery swapping directly addresses these issues by offering a faster and more predictable alternative to recharging, thereby reducing user concerns about vehicle downtime and range limitations.

Another important enabler is the *ease of service delivery* that battery swapping systems can provide. In addition to fixed stations, mobile swapping solutions such as battery swapping vans offer a flexible approach to supporting EV users in areas with limited infrastructure (Adegbohun et al. 2019; Helander and Ljunggren 2023). These vehicles are equipped with mechanisms for quickly exchanging depleted batteries for fully charged ones, providing convenience and operational efficiency. Personnel operating these mobile units further enhance the accessibility of the service, ensuring that battery replacement is available where and when it is needed.

Additionally, emerging technologies such as the Internet of Things (IoT) play a supporting role in enhancing infrastructure efficiency. IoT integration allows real-time monitoring, scheduling, and optimization of battery inventory and station usage, further streamlining the user experience and supporting the scaling of battery swapping networks.

In sum, the infrastructure-related enablers of battery swapping not only address the physical and logistical barriers of traditional EV charging systems but also provide flexible, user-oriented alternatives that enhance accessibility, reduce anxiety, and facilitate broader adoption of electric vehicles.

3. Methods

To address the enablers in EVB 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 enablers 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 enable 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 and 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 enabling 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, enablers to the adoption of battery swapping infrastructure were short listed and after removing for duplicate factors a finalized list of 22 enablers were shortlisted. Table 2 represents the short-listed barriers along with references and description of the factors. 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 1 final factors were concluded.

Table 2. Enablers of Battery Swapping in Indian EVB Infrastructure

#	Enablers	Description	Sources
1	Quick battery replacement (low swapping time)	Switching batteries currently takes six minutes. This ability to go from 0% charge to 100% quickly benefits people in a hurry. (OPPORTUNITY COST OF TIME) Eg. For taxis, the ability to drive as much as possible without wasting time charging., Factors that reduce time for swapping increases time to earn (esp freight vehicles. Very low/Less waiting time compared to charging a vehicle	Mæland (2024); Zhang et al. (2023); Sayarshad and Mahmoodian (2021); Yang et al. (2019); Juvvala and Sarmah (2021); Huang et al. (2024); Anderhofstadt and Spinler (2019); Lai and Li (2024); Zhang et al. (2024); Zhang et al. (2024); Boti et al. (2024)
2	Convenient method to adopt which reduces range anxiety	Range anxiety refers to the fear or concern that an EV will not have enough battery charge to reach its intended destination, potentially leaving the driver stranded.	Mæland (2024); Raeesi and Zografos (2022); Hemmati (2023); Adu-Gyamfi et al. (2022); Deng et al. (2023); Sindha et al. (2023)
3	Low rent of battery	Battery swapping requires payment of battery rent instead of owning the battery. Paying rent is relatively cheaper than owning a battery by paying an upfront cost for ownership	Mæland (2024)
4	Penalty for wait time	Penalty cost imposed for the violation of the customer satisfaction due to longer time window for battery swapping	Yang et al. (2019); Juvvala and Sarmah (2021); Anderhofstadt and Spinler (2019)
5	Tax incentives	Financial incentive	Murugan and Marisamynathan (2024); Isaksson et al. (2011); Ralston and Nigro (2011); Annarelliet et al. (2020); Helander and Ljunggren (2023)
6	Grants	Financial incentive	Murugan and Marisamynathan (2024); Isaksson et al. (2011); Ralston and Nigro (2011); Annarelliet et al. (2020); Helander and Ljunggren (2023)
7	Subsidy	Financial incentive	Murugan and Marisamynathan (2024); Isaksson et al. (2011); Ralston and Nigro (2011); Annarelliet et al. (2020); Helander and Ljunggren (2023)
8	Stable source of income from battery swapping services	With a BaaS, a company will lower the upfront revenue from a sale of battery subscriptions but raise the recurring revenue via swapping facilities, which will be more stable. Stability makes planning and estimating future revenue possible, and it was found beneficial	Gonzalez-Salazar et al. (2023); Mæland (2024)
9	Secondary source of income vis V2G	Ability to attach the battery swapping stations to the grid for electricity in both directions. Consequently, they can sell electricity back to the grid. This	Gonzalez-Salazar et al. (2023); Mæland (2024); Bobanac et al. (2018); Sindha et al. (2023)

		imposes a new opportunity due to utilizing BaaS and battery swapping.	
10	Reduced maintenance cost to customers	The battery is a high cost for the consumer; in a BaaS, the ownership is with the provider, removing maintenance costs and bringing a new one if the battery breaks. In addition, it may result in upselling. Since the customers upfront cost is lower because they don't pay for the battery, many can afford a larger car and a larger battery	Gonzalez-Salazar et al. (2023); Mæland (2024); Raeesi and Zografos (2022); Hemmati (2023); Helander and Ljunggren (2023)
11	No warranty needed	Lowering purchasing barriers. Customers know their provider will take care of the typical services they would otherwise coordinate and purchase separately. This removal of responsibility can increase the competitive advantage by being more convenient for the customer. Since the customer does not own the battery, it does not depreciate. It does not need warranty.	Gonzalez-Salazar et al. (2023); Mæland (2024); Raeesi and Zografos (2022); Hemmati (2023) Helander and Ljunggren (2023)
12	Easier adoption of advanced battery technology	Battery technology is evolving quickly, and by having the possibility to switch, a customer can get better battery technology as it evolves.	Gonzalez-Salazar et al. (2023); Mæland (2024); Raeesi and Zografos (2022); Hemmati (2023); Helander and Ljunggren (2023)
13	Economies of scale	Lowered marginal costs due to scale advantage (can leverage large-scale advantages like standardization and centralization)	Mæland (2024)
14	Promotes environmental sustainability	Reduce pollution, promotes environmental awareness; green energy	Gonzalez-Salazar et al. (2023); Sindha et al. (2023)
15	Pushes towards renewable energy sources	Tap the potential of renewable energy sources for generating electricity, Increase used of photo photovoltaic cell, Increased use of wind power, Increase use of other sustainable sources of energy. Incentives to use other renewable sources of energy for battery swapping	Mæland (2024); Xu et al. (2022); Shao et al. (2017); Ban et al. (2020); Vallera et al. (2021); Helander and Ljunggren (2023)
16	Facilitates a second life batteries (and battery reuse)	Centralized ownership of the batteries opens significant potential in creating new business opportunities for second-life battery applications	Lee et al. (2024); Hu et al. (2024); Borgosano et al. (2024); Helander and Ljunggren (2023); Marchesano et al. (2023)
17	Better battery Management and Efficiency	The battery at the Battery swap station will be monitored and analysed to keep it fresh and in good health. Additionally, it incentivises the company to focus on high-quality products. Preserves health of battery, improves battery lifecycle, Increases efficiency in resource utilization	Mæland (2024); Adegbohun et al. (2019)
18	Centralised charging	Increases efficiency in resource utilisation	Li et al. (2024); Asadi and Pinkley (2021)
19	Proximity to users' locations	The visible presence of charging stations in public spaces can positively influence users' perceptions of EVs and contribute to their adoption	Murugan and Marisamynathan (2024); Gonzalez-Salazar et al. (2023); Hardman et al. (2018); Bailey et al. (2015)
20	Limited charging infrastructure (promotes battery swapping)	The scarcity in the availability of recharging stations, extended charging delay, coercion by underlying utility grid, and the most important is the inherent EV range anxiety (EVRA) problem	Boti et al. (2024); Helander and Ljunggren (2023)
21	Ease of service delivery	Battery swapping van, Battery swapping personnel. Battery swapping vans represent a mobile solution	Mæland (2024); Shao et al. (2017); Raeesi and Zografos (2022); Zhan et

		for battery replacement in EVs, offering flexibility and convenience compared to fixed swapping stations. These vans are equipped with specialized mechanisms to replace depleted batteries with fully charged ones, enabling quick and efficient service for EV users.	al. (2022); Helander and Ljunggren (2023); Adegbohun et al. (2019)
22	Adoption of digital technologies like IoT	Adoption of digital technologies like IoT to supervise and automate the services provided	Li et al. (2024)

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

The Fuzzy Delphi Method (FDM) was employed to validate and prioritize enablers relevant to the adoption of battery swapping services in the Indian electric mobility ecosystem. Experts were asked to rate each enabler on a five-point fuzzy linguistic scale. The final decision on the inclusion of enablers was based on the calculated defuzzified mean score, with a cutoff value set at 0.56, in line with expert consensus (Table 3).

Table 3. Fuzzy DELPHI Result

Codes	Enabler Names	Mean Score	Accept/Reject
E1	Quick battery replacement (low swapping time)	0.67676801	Accept
E2	Convenient method to adopt which reduces range anxiety	0.57806505	Accept
E3	Low rent of battery	0.55392692	Reject
E4	Penalty for wait time	0.51205618	Reject
E5	Tax incentives	0.57650604	Accept
E6	Grants	0.56948136	Accept
E7	Subsidy	0.57416687	Accept
E8	Stable source of income from battery swapping services	0.5820661	Accept
E9	Secondary source of income via (VV2G)	0.51674235	Reject
E10	Reduced maintenance cost to customers	0.58366075	Accept
E11	No warranty needed	0.52948924	Reject
E12	Easier adoption of advanced battery technology	0.64480888	Accept
E13	Economies of scale	0.55981751	Reject
E14	Promotes environmental sustainability	0.64324938	Accept
E15	Pushes towards renewable energy sources	0.63859208	Accept
E16	Facilitates a second life batteries (and battery reuse)	0.65205205	Accept
E17	Better battery Management and Efficiency	0.57255727	Accept
E18	Centralised charging	0.5561041	Reject
E19	Proximity to users' locations	0.58684142	Accept
E20	Limited charging infrastructure (promotes battery swapping)	0.49533402	Reject
E21	Ease of service delivery	0.6488112	Accept
E22	Adoption of digital technologies like IoT	0.63475414	Accept

As shown in Table 1, a total of 15 enablers out of 22 met the threshold and were therefore retained for further analysis. These include both technological and policy-driven enablers, such as Quick Battery Replacement (E1, mean = 0.677), Easier Adoption of Advanced Battery Technology (E12, mean = 0.645), Ease of Service Delivery (E21, mean = 0.649), and Subsidies and Grants (E6, E7). The relatively high scores of these enablers suggest strong expert agreement on their critical role in facilitating battery swapping adoption.

Conversely, 7 enablers were excluded for failing to meet the minimum threshold. These include Low Rent of Battery (E3, mean = 0.554), Penalty for Wait Time (E4, mean = 0.512), and Secondary Income via Vehicle-to-Grid (E9, mean = 0.517). Their lower scores reflect perceived uncertainty in economic viability or limited policy clarity, indicating they are currently less influential in shaping battery swapping deployment.

5.2 Graphical Results

To enhance the interpretability of the Fuzzy Delphi results, a bar chart visualization was created (see Figure 1). This chart plots the mean scores of all 22 enablers and includes a horizontal cutoff line at 0.56, visually distinguishing accepted enablers (green bars) from rejected ones (red bars).

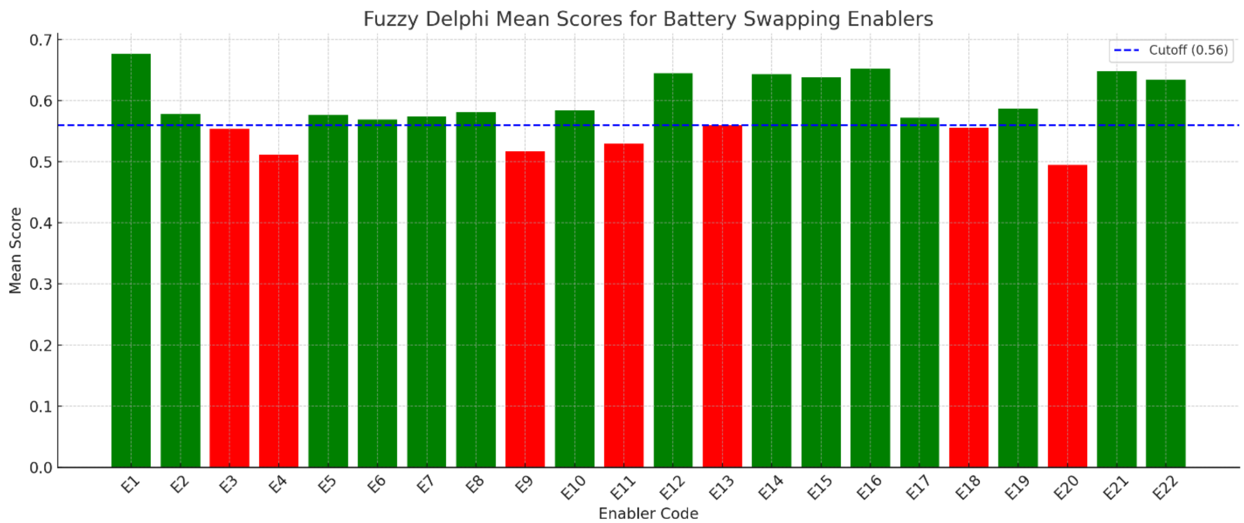

Figure 1. Fuzzy DELPHI Output

This visualization clearly demonstrates the distribution of expert consensus. High-scoring enablers such as E1, E12, E16, and E21 significantly exceed the cutoff, indicating strong alignment among experts regarding their importance. Notably, several enablers cluster just above the threshold (e.g., E5, E6, E7, E17), suggesting areas of moderate agreement that may require further exploration or reinforcement through policy incentives or industry dialogue.

The rejected enablers, clustered below the 0.56 line, show a sharper drop-off in mean scores, emphasizing a clear divergence in perceived relevance. This sharp contrast reinforces the utility of the cutoff-based decision rule and the effectiveness of the Fuzzy Delphi process in filtering marginal enablers.

The chart also supports rapid stakeholder communication by summarizing complex expert consensus in a simple visual, making it especially useful for policymakers and industry practitioners seeking to understand which drivers warrant strategic focus.

5.3 Proposed Improvements

5.3.1 Strengthen High-Impact Enablers

The Delphi analysis confirmed 15 enablers as critical for battery swapping adoption. To capitalize on these insights, the following strategic improvements are proposed:

Fast Infrastructure Deployment: Given that Quick Battery Replacement (E1) and Ease of Service Delivery (E21) scored the highest, investment in standardized, modular, and automated battery swapping stations must be accelerated. Policies should support fast-track approvals and land use for such infrastructure.

Enhance Financial Incentives: Subsidies (E7), Grants (E6), and Tax Incentives (E5) were strongly validated. Governments should streamline access to these schemes and make them applicable to both providers and end users to encourage broad participation.

Leverage Advanced Battery Tech (E12): Public-private partnerships can co-invest in R&D and testing labs for new battery chemistries compatible with swapping, reducing technological uncertainty and encouraging innovation.
Boost Environmental Messaging: Sustainability-related enablers, E14 (Environmental Sustainability), E15 (Renewable Energy Push), and E16 (Battery Reuse), received strong support. These should be integrated into marketing campaigns and ESG compliance policies to attract environmentally conscious users and investors.
Promote Digitalization: IoT-based monitoring (E22) and centralized battery management (E17) need greater emphasis through smart platforms and mobile apps that enable real-time battery health tracking, performance analytics, and location-based swapping availability.

5.3.2 Address Weak or Underemphasized Areas
The Delphi process also revealed enablers with limited consensus or low perceived relevance. Instead of discarding them outright, the following steps are suggested to improve their future utility:

Redesign Low-Rated Economic Models: Low Rent of Battery (E3) and Secondary Source of Income (E9) were rejected, possibly due to unclear financial models. Stakeholders should re-evaluate pricing strategies and battery ownership models to make them more appealing and sustainable.

Improve User Experience Insights: Enablers such as Penalty for Wait Time (E4) and Warranty Exclusion (E11) were rated low. These issues likely reflect user behavior concerns. More behavioral studies or user trials are needed to refine these propositions for practical relevance.

Clarify the Role of Economies of Scale (E13): Though theoretically important, E13 was rejected, suggesting limited current applicability. Industry associations or coalitions may be formed to share resources and scale swapping services, making this enabler more viable over time.

5.3.3 Policy and Governance Improvements
Integrated Policy Framework: A unified policy that bundles battery leasing, swapping, and recycling under a single regulatory umbrella would help operationalize many of the accepted enablers (e.g., E1, E6, E16). Targeted Incentive Structures: Policies could differentiate support based on business models (fleet-based, private, logistics, last-mile delivery), ensuring enablers like Proximity to Users (E19) and Stable Income Sources (E8) are tailored to specific market segments.

6. Conclusion
In conclusion, this study systematically identified, validated, and prioritized the key enablers for the adoption of EV battery swapping infrastructure in India using a rigorous three-phase framework anchored by the FDM. By engaging a diverse panel of experts and leveraging a structured, quantitative approach, the research distilled a comprehensive list of 570 variables down to 15 critical enablers, spanning technological, economic, policy, and environmental dimensions. High-impact factors such as quick battery replacement, ease of service delivery, advanced battery technology adoption, ease of service delivery and adoption of digital technologies like IoT emerged as central to accelerating infrastructure deployment and user acceptance. The findings underscore the necessity for targeted policy support, streamlined financial schemes, and the integration of advanced digital and environmental practices to foster a sustainable and scalable battery swapping ecosystem. Furthermore, the study highlights areas requiring further attention, including the redesign of economic models and the need for greater user experience insights, ensuring that even less-emphasized enablers are not overlooked. The adoption of an integrated policy framework and differentiated incentive structures will be vital for addressing market-specific needs. Ultimately, the validated enablers and proposed strategic improvements provide a robust foundation for policymakers and industry stakeholders to drive the widespread adoption of battery swapping in India, supporting the nation's transition to clean and efficient electric mobility.

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References

Aayog, Niti., Battery swapping policy, Available: https://www.niti.gov.in/sites/default/files/2023-03/20220420_Battery_Swapping_Policy_Draft_0.pdf, Accessed on May 30, 2025.

Adegbohun, F. Von Jouanne, A. and Lee, K. Y., Autonomous battery swapping system and methodologies of electric vehicles, *Energies*, vol. 12, no. 4, pp. 667, 2019.

Adu-Gyamfi, G. Song, H. Asamoah, A.N. Li, L. Nketiah, E. Obuobi, B. Adjei, M. and Cudjoe, D., Towards sustainable vehicular transport: Empirical assessment of battery swap technology adoption in China, *Technological Forecasting and Social Change*, vol. 184, pp. 121995, 2022.

Anderhofstadt, B. and Spinler, S., Factors affecting the purchasing decision and operation of alternative fuel-powered heavy-duty trucks in Germany – A Delphi study, *Transportation Research Part D: Transport and Environment*, vol. 73, pp. 87-107, 2019.

Annarelli, A. Battistella, C. and Nonino, F., Competitive advantage implication of different Product Service System business models: Consequences of 'not-replicable' capabilities, *Journal of Cleaner Production*, vol. 247, pp. 119121, 2020.

Asadi, A. and Pinkley, S. N., A stochastic scheduling, allocation, and inventory replenishment problem for battery swap stations, *Transportation Research Part E: Logistics and Transportation Review*, vol. 146, pp. 102212, 2021.

Ban, M. Yu, J. and Yao, Y., Joint optimal scheduling for electric vehicle battery swapping-charging systems based on wind farms, *CSEE Journal of Power and Energy Systems*, vol. 7, no. 3, pp. 555-566, 2020.

Bailey, J. Miele, A. and Axsen, J., Is awareness of public charging associated with consumer interest in plug-in electric vehicles?, *Transportation Research Part D: Transport and Environment*, vol. 36, pp. 1-9, 2015.

Bobanac, V. Pandzic, H. and Capuder, T., Survey on electric vehicles and battery swapping stations: Expectations of existing and future EV owners, *IEEE International Energy Conference (ENERGYCON),* pp. 1-6, 2018.

Borgosano, S. Martini, D. and Longo, M., Electric mobility: analyzing the role of battery swap stations in addressing range anxiety and grid impact, *CIRED 2024 Vienna Workshop,* vol. 2024, pp. 1-4, 2024.

Boti, A. M. Eashwar, M. V. Shekar, H. and Swathika, O. G., Battery Swapping for Electric Vehicles: Assessing Its Viability as an Alternative or Complement to Fast Charging, *3rd Odisha International Conference on Electrical Power Engineering, Communication and Computing Technology (ODICON),* pp. 1-6, 2024.

Deng, Y. Chen, Z. Yan, P. and Zhong, R., Battery swapping and management system design for electric trucks considering battery degradation, *Transportation Research Part D: Transport and Environment*, vol. 122, pp. 103860, 2023.

Gonzalez-Salazar, M. Kormazos, G. and Jienwatcharamongkhol, V., Assessing the economic and environmental impacts of battery leasing and selling models for electric vehicle fleets: A study on customer and company implications, *Journal of Cleaner Production*, vol. 422, pp. 138356, 2023.

Hardman, S. Jenn, A. Tal, G. Axsen, J. Beard, G. Daina, N. Figenbaum, E. Jakobsson, N. Jochem, P. Kinnear, N. Plötz, P. Pontes, J. Refa, N. Sprei, F. Turrentine, T. and Witkamp, B., A review of consumer preferences of and interactions with electric vehicle charging infrastructure, *Transportation Research Part D: Transport and Environment*, vol. 62, pp. 508-523, 2018.

Helander, H. and Ljunggren, M., Battery as a service: Analysing multiple reuse and recycling loops, *Resources, Conservation and Recycling*, vol. 197, pp. 107091, 2023.

Hemmati, R., Dynamic expansion planning in active distribution grid integrated with seasonally transferred battery swapping station and solar energy, *Energy*, vol. 277, pp. 127719, 2023.

Hu, X. Yang, Z. Sun, J. and Zhang, Y., Optimal pricing strategy for electric vehicle battery swapping: Pay-per-swap or subscription?, *Transportation Research Part E: Logistics and Transportation Review*, vol. 171. 2023.

Hu, X. Zhang, X. Xu, L. Feng, J. and Luo, S., The battery swapping service network deployment problem: Impact of driver range anxiety and impatience, *Computers & Industrial Engineering*, vol. 192, pp. 110189, 2024.

Huang, Y. Tianci, L. I. Xinyu, W. A. N. G. and Bingquan, W. U., A Consumer Expectation-Based Multiple Satisfaction Model for Battery-Swapping Station Deployment, *Economic Computation & Economic Cybernetics Studies & Research*, vol. 58, pp. 3, 2024.

Isaksson, O. Larsson, T. C. and Johansson, P., Towards a framework for developing product/service systems, *Functional Thinking for Value Creation: Proceedings of the 3rd CIRP International Conference on Industrial Product Service Systems,* pp. 44-49, Berlin, 2011.

Juvvala, R. and Sarmah, S. P. Evaluation of policy options supporting electric vehicles in city logistics: a case study, *Sustainable Cities and Society*, vol. 74, pp. 103209, 2021

Lai, Z. and Li, S., Towards a multimodal charging network: Joint planning of charging stations and battery swapping stations for electrified ride-hailing fleets, *Transportation Research Part B: Methodological*, vol. 183, pp. 102928, 2024.

Lee, G. Lee, J.S. and Park, K.S. Battery swapping, vehicle rebalancing, and staff routing for electric scooter sharing systems, *Transportation Research Part E: Logistics and Transportation Review*, vol. 186, pp. 103540, 2024

Lévay, P. Z. Drossinos, Y. and Thiel, C., The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership, *Energy Policy*, vol. 105, pp. 524–533, 2017

Li, L. Li, Y. Liu, R. Zhou, Y. and Pan, E., A Two-stage Stochastic Programming for AGV scheduling with random tasks and battery swapping in automated container terminals, *Transportation Research Part E: Logistics and Transportation Review*, vol. 174, 2023.

Li, X. Cao, Y. Hu, Z. Zhang, X. Lin, H. and Liu, Z. An Integrated Framework on Autonomous Valet Parking and Battery Swapping Service Considering Malicious False Data Injection Attack, *IEEE Transactions on Transportation Electrification*, 2024.

Liang, Y. Cai, H. and Zou, G., Configuration and system operation for battery swapping stations in Beijing, *Energy*, vol. 214, pp. 118883, 2021.

Liang, Y. and Zhang, X., Battery swap pricing and charging strategy for electric taxis in China, *Energy*, vol. 147, pp. 561–577, 2018.

Lidicker, J. Lipman, T. and Williams, B., Business model for subscription service for electric vehicles including battery swapping for San Francisco Bay Area, California, *Transportation Research Record*, vol. 2252, pp. 83–90, 2011.

Mæland, J. T., *Drivers and Barriers for implementing a Battery as a Service Business Model,* NTNU, 2024.

Marchesano, M. G. Guizzi, G. Vespoli, S. and Ferruzzi, G., Battery swapping station service in a smart microgrid: A multi-method simulation performance analysis, *Energies*, vol. 16, no. 18, pp. 6576, 2023.

Murugan, M. and Marisamynathan, S., Investigating the potential of a battery swapping method at refuel stations for electric vehicle: A case study of India, *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 107, pp. 254-274, 2024.

Patel, M. Arora, P. Singh, R. Mahapatra, D. Chaturvedi, V. and Kumar Saini, S., Impact of battery swapping in the passenger sector: EV adoption, emissions, and energy mix, *Energy*, vol. 298, 2024.

Raeesi, R. and Zografos, K. G., Coordinated routing of electric commercial vehicles with intra-route recharging and en-route battery swapping, *European Journal of Operational Research*, vol. 301, no. 1, pp. 82-109, 2022.

Rahman, M. A. Sarker, B. R. and Escobar, L. A., Peak demand forecasting for a seasonal product using Bayesian approach, *Journal of the Operational Research Society*, vol. 62, pp. 1019-1028, 2011.

Ralston, M. and Nigro, N., *Plug-in electric vehicles: literature review*., *Pew Center on Global Climate Change*, Arlington, VA, USA, 2011.

Reimer, D. Islam, T. and Ali, A., Engineering education and the entrepreneurial mindset at Lawrence Tech, *Proceedings of the 12th Annual International Conference on Industrial Engineering and Operations Management*, vol. 20, pp. 3-6, Istanbul, Turkey, July 3-6, 2012.

Reimer, D., *Entrepreneurship and Innovation*, Available: http://www.ieomsociet.org/ieom/newsletters/, Accessed on May 30, 2025.

Revankar, S. R. and Kalkhambkar, V. N., Grid integration of battery swapping station: A review, *Journal of Energy Storage*, vol. 41, 2021.

Sayarshad, H. R. and Mahmoodian, V., An intelligent method for dynamic distribution of electric taxi batteries between charging and swapping stations, *Sustainable Cities and Society*, vol. 65, pp. 102605, 2021.

Setiawan, A. D. Zahari, T. N. Anderson, K. Moeis, A. O. and Hidayatno, A., Examining the effectiveness of policies for developing battery swapping service industry, Energy Reports, vol. 9, pp. 4682–4700, 2023.

Shao, S. Guo, S. and Qiu, X., A mobile battery swapping service for electric vehicles based on a battery swapping van, *Energies*, vol. 10, no. 10, pp. 1667, 2017.

Shareef, H. Islam, M. M. and Mohamed, A., A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles, *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 403–420, 2016.

Shetty, D. Ali, A. and Cummings, R., A model to assess lean thinking manufacturing initiatives, *International Journal of Lean Six Sigma*, vol. 1, no. 4, pp. 310-334, 2010.
Sindha, J. Thakur, J. and Khalid, M., The economic value of hybrid battery swapping stations with second life of batteries, *Cleaner Energy Systems*, vol. 5, pp. 100066, 2023.
Vallera, A. M. Nunes, P. M. and Brito, M. C., Why we need battery swapping technology, *Energy Policy*, vol. 157, pp. 112481, 2021.
Xu, X. Hu, W. Liu, W. Du, Y. Huang, Q. and Chen, Z., Robust energy management for an on-grid hybrid hydrogen refueling and battery swapping station based on renewable energy, *Journal of Cleaner Production*, vol. 331, pp. 129954, 2022.
Yang, S. Cheng, P. Li, J. and Wang, S., Which group should policies target? Effects of incentive policies and product cognitions for electric vehicle adoption among Chinese consumers, *Energy Policy*, vol. 135, pp. 111009, 2019.
Yang, Z. Lei, Q. Sun, J. Hu, X. and Zhang, Y., Strategizing battery swap service: Self-operation or authorization?, *Transportation Research Part D: Transport and Environment*, vol. 110, 2022.
Zhan, W. Wang, Z. Zhang, L. Liu, P. Cui, D. and Dorrell, D. G., A review of siting, sizing, optimal scheduling, and cost-benefit analysis for battery swapping stations, *Energy*, vol. 258, pp. 124723, 2022.
Zhao, H. and Li, N., Optimal siting of charging stations for electric vehicles based on fuzzy Delphi and hybrid multi-criteria decision making approaches from an extended sustainability perspective, *Energies*, vol. 9, no. 4, pp. 270, 2016.
Zhang, T. Y. Yao, E. J. Yang, Y. Pan, L. Li, C. P. Li, B. and Zhao, F., Deployment optimization of battery swapping stations accounting for taxis' dynamic energy demand, *Transportation Research Part D: Transport and Environment*, vol. 116, pp. 103617, 2023.
Zhang, Y. He, P. Ren, W. Jiao, J. Long, Z. and Jian, Y. A customer satisfaction-based optimization model for the charging and discharging path and battery swapping stations' site selection of electric vehicles, *Frontiers in Energy Research*, vol. 12, pp. 1353268, 2024.
Zhu, F. Li, L. Li, Y. Li, K. Lu, L. Han, X. Du, J. and Ouyang, M., Does the battery swapping energy supply mode have better economic potential for electric heavy-duty trucks?, *ETransportation*, vol. 15, 2023.

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