Prioritizing Battery-as-a-Service Operational Strategies using Fuzzy Delphi: Sustainable Mobility Lessons with India-Centric findings and Global EV Implications

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Abstract

Operational strategy is the "engine room" of Battery-as-a-Service (BaaS), it transforms raw assets (packs, bays, chargers, sites) into reliable, low-cost, low-carbon service through sensing, optimization, and coordinated execution. BaaS succeeds or fails in operations: how batteries are monitored, queued, charged, rotated, and priced in real time. This study develops an operational priority map for BaaS in India using a three-phase design: (i) systematic mapping of ~550 strategy signals down to 47 operational strategy variables; (ii) expert elicitation with a fuzzy linguistic scale; and (iii) Fuzzy-Delphi aggregation and defuzzification against a pre-defined acceptance threshold. Nine variables cleared the cut, revealing an "operations-first" capability stack. In contrast, structure-centric levers (ownership/topology without strong digital/optimization layers) systematically underperformed. The resulting priority map gives OEMs, operators, and regulators a concrete, interoperable target for improving utilization, compressing wait times, extending battery life, and lowering carbon intensity in India's BaaS roll-out. The results offer actionable priorities for operators, OEMs, and regulators to raise utilization, compress wait times, extend battery life, and reduce carbon intensity, while outlining policy hooks (interoperability codes, telemetry minima, dynamic tariffs) to scale BaaS reliably in the Indian context.

Keywords
Battery-as-a-Service, Operational Strategy, Fuzzy Delphi, Digital Battery Management, Indian EV ecosystem.

1. Introduction
Operational strategy is the spine of BaaS: it orchestrates how batteries circulate through a city-scale network of swap stations, how energy is procured and scheduled, how queues are controlled, and how digital intelligence aligns asset health with real-world demand. Mature deployments converge on a few core principles: fast, standardized swaps; centralized slow charging; network-aware siting; and health-aware battery allocation delivering refuel-like

convenience while extending asset life and lowering total cost of ownership (S. Yang et al., 2020; Rodemann et al., 2023). Empirical programs report sub-5-minute swaps and even ≈3-minute automated exchange in commercial stations, with station capex and national deployment plans explicitly accounted for, evidence that operational choices (automation level, interface standardization, staffing model) compress downtime and stabilize service quality at scale (Yang et al., 2020; Rodemann et al., 2023).

At the network layer, station siting and capacity planning are framed as facility-location and flow problems that balance user detours, expected waiting time, and infrastructure cost. Mixed-integer linear programs (MILP) provide exact baselines for small instances, while metaheuristics such as Large Neighbourhood Search (LNS) scale solutions to realistic city sizes; both embed user-centric objectives like minimizing detours and maximizing accessibility (Zeng et al., 2025). In practice, planning integrates demand analysis, B2C/B2B segment needs (e.g., delivery and taxi fleets), and local partnerships (e.g., rickshaw manufacturers) to ensure coverage and utilization (Rodemann et al., 2023). Queue-aware metrics including Expected Waiting Time for Switch (EWTS) enter both design and daily dispatch, keeping "right battery, right place, right time" as an operational invariant.

Day-to-day service levels are stabilized by reservation-centric control and edge intelligence. Reservation timing, time-slot estimation windows, and data freshness are coordinated between EVs (clients), station operators, and a global controller; Mobile Edge Computing (MEC) nodes (e.g., on buses) aggregate telemetry to reduce communication overhead and enable decentralized decisions (Cao et al., 2021; Gorityala & Radhika, 2024). In operation, EVs independently select stations using predicted status signals EWTS and expected battery numbers (EBN) while station controllers prioritize charge queues with policies such as "Shortest Charging Time First" to accelerate turnaround (Gorityala & Radhika, 2024). The net effect is reduced infrastructure burden per served vehicle, lower waiting times, and higher battery reuse rates.

Battery inventory is treated as a pooled, health-aware fleet. Real-time battery monitoring via cloud-connected BMS and IoT streams informs swap authorizations, triggers condition-based maintenance, and guides module-level refurbishment choices pushing life extension through controlled cycling and targeted repairs (Shi, n.d.). Scheduling and swap decisions explicitly consider battery state (e.g., SoC thresholds) to protect quality while meeting service commitments a cornerstone for circular operations (Yang et al., 2017). Modular swapping further enhances maintainability and circularity by enabling component-level repair/refurbish without removing entire packs from service.

The energy layer closes mobility with power-system economics. Centralized slow charging at hubs often co-located with swap stations reduces degradation and extends battery life by ad-hoc fast charging, while also enabling off-peak charging, renewable integration (e.g., solar), and grid-aligned dispatch (Yang et al., 2020; Rodemann et al., 2023). For prosumers and community energy contexts, operational control arbitrages flat/dynamic tariffs and day-ahead or imbalance markets under device constraints (capacity, round-trip efficiency, cycle limits), with linear programming horizons that co-schedule charge/discharge for cost and autonomy (Pocola, n.d.; Cao et al., 2021). These practices systematically lower energy cost per swap and carbon intensity per kilometre without compromising station-level service guarantees.

Digital service design anchors customer experience and utilization. Platforms expose reservation, live station availability, and health-aware allocation; they also bundle swap allowances (e.g., 4–6 free swaps/month in premium models) and upgrade pathways that influence load profiles and asset rotation (Zeng et al., 2025). In premium ecosystems, alliances with fuel retailers (e.g., CNPC/Sinopec in China) expand the spatial footprint of swap infrastructure, while branded service hubs (e.g., NIO House) smooth logistics and after-sales operations. Combined with rapid swap times and national deployment plans, this platform-plus-infrastructure logic underpins perceived reliability and long-distance usability for EVs (Zeng et al., 2025; S. Yang et al., 2020).

Economics and pricing are embedded in operations, not bolted on. BaaS decouples vehicle and battery balance sheets, lowering entry cost for users while preserving centralized lifecycle control for automakers and operators (S. Yang et al., 2020). At the same time, pricing levers battery lease, swap fee, energy cost pass-through must clear heterogeneous participation incentives across manufacturers, leasing firms, and station operators; price sensitivity and subsidy design directly shape demand elasticity and optimal operating points (Pocola, n.d.). In practice, pooling reduces capex per user, and ROI analyses for retrofit-plus-swap cases show payback horizons within a year in specific service niches, conditioned by fuel and maintenance savings (Rodemann et al., 2023).

Contextual tailoring matters. In India, integrating swap services with the dense fuel-station network can lift accessibility while avoiding redundant build-outs; demand-responsive planning and load-management via swapping (e.g., time-of-day pricing) adapt operations to local grid and mobility patterns (Murugan & Marisamynathan, 2024). More broadly, flexible ownership (subscription and hybrid pay-per-use) and MaaS integrations help match diverse user archetypes while reinforcing circularity via reuse/refurbish cycles (Huang et al., 2021; Shi, 2023.; Zhong, 2024).

Finally, the operating system of BaaS is analytical. Predictive models ranging from regression and ARIMA/LSTM to reinforcement learning forecast demand, routes, and maintenance events; game-theoretic and stacked revenue formulations coordinate pricing and energy market participation across stakeholders; and PESTEL/marketing frameworks explain why policy support and premium positioning can accelerate early uptake (Rodemann et al., 2023; Li & Yuan, 2025; S. Yang et al., 2020). Together, these tools institutionalize a loop of measure-decide-adapt that keeps swap networks reliable, economically viable, and progressively greener.

1.1 Objectives:

This study aims to identify and prioritize the key operational strategies for adopting Battery-as-a-Service in the context of the Indian Electric Vehicle Battery (EVB) infrastructure. Specifically, the study aims to:

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

2. Literature Review:

Operational strategies in Battery-as-a-Service (BaaS) ecosystems are critical for enabling scalability, efficiency, and circularity across electric vehicle infrastructures. This study categorizes these strategies under distinct operational models - location, cost, flexibility, and time/value-based, reflecting varied dimensions of infrastructure deployment, service delivery, and resource optimization. The following analysis provides a theoretical interpretation of these models with relevant author-specific citations.

Location-Based Operational Models

Location-based models focus on the physical placement and architectural design of battery swapping stations, charging infrastructure, and mobility platforms. A major trend is the adoption of standardized modular battery packs and swapping infrastructure, enabling interoperability and reuse across vehicle types (Bege & Tóth., 2024; Zhou et al., 2025). These systems reduce idle infrastructure and promote asset sharing through centralized battery pools and swappable platforms (Cao et al., 2021; Jiang et al., 2024). Strategic placement of BSS through optimization models such as LNS + MILP further enhances accessibility and minimizes infrastructure redundancy (Rodemann et al., 2023). Advanced integration with renewable energy sources like solar-assisted microgrids supports *Reduce, Recover,* and *Reuse* imperatives by aligning battery charging with decarbonization goals (Marchesano et al., 2023; Patel et al., 2024). Additionally, the rise of mobile swap vehicles and dynamic routing logistics provides on-demand services in low-density regions, thus enhancing operational flexibility without duplicating physical infrastructure (Shao et al., 2017). Emerging models also integrate smart Battery Management Systems (BMS) and IoT platforms to enable real-time monitoring, State-of-Health (SoH)-based allocation, and predictive maintenance, improving battery lifespan and reducing lifecycle emissions (Kim et al., 2023; Zeng et al., 2025).

Cost-Based Operational Models

Cost-based models emphasize economic sustainability, balancing investment in infrastructure with pricing incentives and service efficiency. *Government subsidies and incentive-driven investments* are fundamental to expanding BSS networks, especially in capital-intensive regions (Yang & Xianye., 2024). These support frameworks lower the upfront burden on operators and enable widespread reuse through shared access (Setiawan et al., 2023). Simultaneously, *green premium pricing mechanisms* reward users who opt for durable, low-carbon batteries, encouraging eco-conscious behaviour and reducing overuse (He et al., 2025). Operators increasingly use *predictive revenue and leasing optimization* to match service pricing with battery lifecycle expectations, as seen in (Hui et al., 2022). This approach

mitigates financial risks while enhancing reuse and performance management. Strategies such as *peer-to-peer energy trading and real-time pricing response* foster local energy sharing and flexible tariff models that maximize grid efficiency (Al-Alawi et al., 2022; Jiang et al., 2024). Digital tools also enable *SoH-based service pricing and centralized monitoring*, optimizing repair cycles and aligning incentives with sustainability outcomes (Hui et al., 2022; Jiang et al., 2024).

Flexibility-Based Operational Models

Flexibility-focused models center on dynamic deployment, condition-based battery use, and digital integration to enable circular usage and intelligent decision-making. Interoperable and *standardized modular battery designs*, such as Honda's Mobile Power Pack, ensure swappability across vehicle platforms and simplify refurbishment (Rodemann et al., 2023; Yang & Xianye., 2024). *AI and BMS-enabled predictive maintenance systems* dynamically allocate batteries based on real-time SoH and usage data, preventing premature degradation and promoting *Repair* and *Reuse* (Bege & Tóth., 2024; Zhou et al., 2025). Digital battery allocation systems not only balance resource use but also extend service life through targeted deployments (Cao et al., 2021). *Smart fleet routing, reverse logistics optimization*, and *intelligent battery matching* allow for seamless circulation of batteries, reducing underutilization and enhancing second-life viability (Chen et al., 2022; Sindha et al., 2023). Additionally, *cloud-based platforms and mobile apps* play a pivotal role in scheduling, swapping, and performance tracking leading to better demand matching and reduced infrastructure strain (Ding et al., 2025; Pisano et al., 2023). These models collectively advance *Refurbish*, *Recover*, and *Repurpose* strategies by integrating technological intelligence into the operational lifecycle.

Time/Speed/Value-Based Operational Models

These models optimize operational value by focusing on minimizing user wait time, energy replenishment delays, and infrastructure inefficiencies. Fast battery exchange stations such as those operated by NIO enable battery swaps within 3–5 minutes, dramatically reducing downtime and increasing battery rotation efficiency (Kader., 2022; Zhu et al., 2024). *Hybrid models*, where vehicles retain fixed batteries for short-range and swappable units for long-range needs, combine flexibility with operational effectiveness (Tahara et al., 2020). Real-time fleet *telematics and route optimization* tools enhance dispatch decisions, promote energy conservation, and support battery longevity (India EV Landscape EMaaS-Revolutionizing the Mobility Space, 2022). Time-sensitive operations also benefit from *centralized certification and SoH evaluation* for second-life deployments, ensuring safety and reuse suitability (McCrossan & Shankaravelu., 2021). Additionally, models incorporating *time-of-use charging and grid-integrated energy storage* contribute to energy load balancing and reduce strain on infrastructure during peak hours (Davis & Hiralal., 2016; Mominul Hasan., 2020) .Strategic franchising and integration with existing fuel station networks further reduce deployment time and maximize infrastructure utilization (Murugan & Marisamynathan., 2024; Zhao & Jiang., 2021).

So, the operational strategies underpinning BaaS systems, whether location-based, cost-driven, flexibility-oriented, or time-optimized, demonstrate a strong alignment with circular economy principles. By integrating modular infrastructure, predictive analytics, dynamic pricing, and intelligent routing, these models collectively enhance battery utilization, reduce waste, and promote sustainable electric mobility.

3. Methods

To address the different operational strategy variables in EV BaaS infrastructure, this study adopts a three-phase exploratory framework. Phase I involves a systematic literature review to identify operational strategy variables which are critical to the adoption of Baas infrastructure across 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 strategy variables. Accordingly, a closed-ended questionnaire was prepared for a pilot fuzzy Delphi study. Phase III employs a fuzzy Delphi method, engaging 50 experts ranging from 10 policy makers, 25 industry professionals, and 15 academic experts to refine and validate the factors. Thus, we conclude 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 or operation strategy variables enabling the adoption of BaaS infrastructure were shortlisted for the fuzzy DELPHI analysis in three phases. In phase I, based on the reviewed literature published in databases such as Scopus and Web of Science, an exhaustive list of 550 variables were shortlisted. In phase II, based on a review of literature and mapping, factors related to the adoption of operational strategies were shortlisted, and after removing duplicate factors, a finalized list of 47 factors was shortlisted. Table 2 represents the short-listed strategy variables along with references and descriptions 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 60 experts was prepared. Respondents were engaged via email, phone, and in-person visits. 55 experts agreed to the survey. However, 55 completed responses were finalized, of which 30 experts (20 industry, 2 academicians and 10 policy makers) submitted responses online, while the remaining 20 experts (15 academicians, 4 industries, 1 policy maker) were interviewed in person. Based on the response, a fuzzy DELPHI analysis was implemented. Final factors were concluded based on a cut-off score of 0.6 from the fuzzy triangular numbers mentioned in Table 2.

Table 2. Procurement Strategy adoption variables in Indian EVB Infrastructure

Sl. No.	Strategy Variables	Detail Description	Key References
S1	Heavy Asset Risk via Battery Operators	Battery operators bear the entire financial and operational risk of owning large fleets of EV batteries. They face asset depreciation, uncertain utilization rates, and exposure to rapid technological obsolescence, making financing, partnerships, or leasing essential to reduce the burden.	(Hui et al., 2022)
S2	Two-Level Swap Station Network	A hierarchical approach with central hubs on highways and distributed local stations in urban areas. This structure improves accessibility, minimizes congestion, and balances supply-demand of charged batteries across regions.	(S. Yang et al., 2020)
S3	Infrastructure-as-a-Service	Swapping infrastructure is provided as a shared service, managed by OEMs or third parties. It reduces capital barriers for small operators and ensures efficient lifecycle management, maintenance, and scalability of infrastructure.	(Toorajipour et al., 2022)
S4	BSS Without Government Support	Battery swapping networks built without subsidies face challenges of high investment costs and uncertain demand. Financial sustainability becomes dependent on innovative revenue models and partnerships rather than direct policy incentives.	(L. Yang & Xianye, 2024)
S5	Incentive-Driven BSS Investment	Government credits, tax incentives, and subsidies encourage investment in BSS networks. High credit or subsidy levels significantly improve financial viability, reducing risk for private investors and OEMs.	(L. Yang & Xianye, 2024)
S6	Collaborative Ecosystem Models	An approach where OEMs, utilities, financiers, and governments jointly develop battery swapping ecosystems. It distributes risks, enhances interoperability, and supports sustainable adoption of BaaS.	(Toorajipour et al., 2022)
S7	Franchised Charging Infrastructure	OEMs or large firms partner with smaller operators to run swap or charging facilities under franchise agreements. This model accelerates network expansion without requiring OEMs to directly finance all infrastructure.	(Zhao & Jiang, 2021)
S8	BSS-led Procurement by EV Manufacturers	EV manufacturers directly procure and manage batteries and swap stations. This ensures control over lifecycle, quality, and compatibility, while reducing consumer battery ownership burden.	(Zhong, 2025)
S9	Renewable-Energy Linked Swapping Network	Integration of renewable energy sources like solar or wind into swapping stations. It reduces carbon intensity, enhances sustainability, and stabilizes grid operations by charging during low-demand periods.	(Patel et al., 2024)
S10	Decentralized Ownership	Battery ownership is distributed among smaller or local providers. This reduces dependence on single operators, but raises challenges of standardization and coordination among diverse owners.	(Zhou et al., 2025)
S11	Centralized Ownership	Battery ownership is concentrated with a single entity (OEM or operator). This central control simplifies quality management but increases the capital risk borne by one firm.	(Zhou et al., 2025)

Sl. No.	Strategy Variables	Detail Description	Key References
S12	Dual Ownership with Platform Coordination	Ownership of batteries and infrastructure is shared between OEMs and service providers, coordinated through a platform. It balances risk, improves efficiency, and enables multi-stakeholder participation.	(Zhong, 2025)
S13	Battery Purchase (Sell-and-Buy)	Traditional ownership-based model where consumers purchase, use, and dispose of the battery themselves. It often results in higher upfront cost and limited lifecycle optimization.	(Gonzalez-Salazar et al., 2023)
S14	BSS Ownership by Battery Producers	Battery producers directly manage swapping stations and lease batteries to consumers. This aligns incentives for producers to design long-lasting batteries and ensures recurring revenue streams.	(Zhong, 2025)
S15	Autonomous Battery Swapping Stations	Automated stations perform battery swaps with robotic mechanisms, reducing human involvement. This minimizes labour costs, improves safety, and enables 24/7 operation with high precision.	(X. Chen et al., 2022)
S16	Peer-to-Peer Energy Trading	Consumers exchange stored energy with peers via community or digital platforms. It enhances grid flexibility, reduces costs, and supports decentralized renewable energy integration.	(Al-Alawi et al., 2022)
S17	IoT + BMS-driven Condition-Based Maintenance	Internet of Things (IoT) and Battery Management Systems (BMS) monitor battery health in real-time, triggering condition-based servicing. This prevents premature disposal and extends lifecycle through timely maintenance.	(Bege & Tóth, 2024)
S18	Location-Agnostic Swapping via App	A mobile app directs users to nearby swap stations or dispatches mobile swap vehicles. It enhances convenience, reduces downtime, and allows flexible deployment in urban and rural areas.	(Shao et al., 2017)
S19	Digital Monitoring & Control	Advanced digital platforms monitor battery use, track lifecycle data, and manage swaps. Blockchain and smart metering systems ensure transparency, trust, and optimized allocation of battery resources.	(Al-Alawi et al., 2022)
S20	Swapping Platform Optimization	Optimization models determine battery allocation, swap station logistics, and pricing to minimize costs and maximize carbon savings. Such platforms improve service efficiency and adapt dynamically to demand variations.	(He et al., 2025)
S21	SoH-Based Deployment	Cloud-based BMS monitors SoH and usage. Supports Repair, Reduce (failure risk), and Recover Flexibility. SoH-Based Deployment allocates batteries by state of health across vehicles. Extends service life; enables Reuse and Refurbish Time-Speed	(Zhou et al., 2025)
S22	Smart Battery Management	Mandated interoperable BSSs with unique IDs, cross-OEM compatibility, and CAN-based communication protocols. Enables Reuse, Refurbish, Reduce – avoids duplication, ensures compatibility, Flexibility Smart Battery Management Use of IoT-based BMS and CMS to monitor health, optimize charge/discharge, and schedule swaps Recover, Reduce – enhances operational efficiency and lifetime management Location	(Tripathi et al., 2023)
S23	Condition-Based Swapping (BMS-Driven)	Real-time app facilitates nearest station discovery, swap reservations, and status updates. Reduce / Optimize – Minimizes time and transport waste, improves energy	(Ding et al., 2025)

Sl. No.	Strategy Variables	Detail Description	Key References
		and route efficiency. Flexibility Condition-Based Swapping (BMS-Driven) AIoT-enabled BMS recommends swap timing and matches the battery based on SoH. Repair / Reuse prevents premature degradation and promotes predictive maintenance Flexibility	
S24	Digital Battery Management	Encourages optimization across vehicle-battery lifecycle Reduce, Recover Flexibility Digital Battery Management Use of Battery Management Systems (BMS) to track SoH, charge cycles, and optimize usage Enhances ease of second-life transition and parts recovery Reuse, Recycle	(Shi & Hu, n.d.)
S25	Green Premium Pricing Mechanism	Extends battery lifespan; minimizes overuse & waste. Reduce, Repair Cost Green Premium Pricing Mechanism BaaS operators charge premium for low-carbon or longer-lifecycle batteries Encourages eco-conscious behaviour (Reduce); rewards durability Flexibility	(He et al., 2025)
S26	Modular Procurement	Implementation of modular, swappable battery packs across platforms. Reuse, Refurbish – Simplifies reuse, promotes interoperability, and reduces complexity in refurbishment and logistics. Location Modular Procurement Standardized and swappable battery acquisition Enhances Refurbish and Reuse through interoperability Cost-Based	(Zhou et al., 2025)
S27	Battery Pooling	Interoperable battery banks for fleet or public access Maximizes usage intensity; supports Reduce and Reuse. Location Battery Pooling Shared battery fleets and swapping infrastructure. Reduces idle inventory; enables Reuse and Refurbish Flexibility	(Zhou et al., 2025)
S28	Static Allocation	Managed charging profiles, slow charging policies, reduced degradation; supports Repair and Reduce Flexibility Static Allocation Single User Through Battery Lifetime Risk of under/overutilization by user profile Use-as-is (linear), low resource efficiency	(Gonzalez-Salazar et al., 2023)
S29	Service Price Adjustment Linked to Battery Flow	BSS stations are strategically aligned with renewable energy availability and grid decarbonization goals. Recover / Reduce carbon intensity of battery recharge cycles through smart energy alignment. Cost Service Price Adjustment Linked to Battery Flow SPs vary prices based on service volume and battery flow efficiency. Reduce / Optimize Incentivizes high utilization, efficient inventory rotation, and minimizes idle asset time Cost	(Hu et al., 2024)
S30	Dynamic Allocation	Risk of under- or over-utilisation by user profile. Use-as-is (linear), low resource efficiency, Flexibility, Dynamic Allocation, Random Redistribution Across User Profiles. Balances usage patterns, but requires minimal operational overhead Reuse, Reduce	(Gonzalez-Salazar et al., 2023)
S31	All-Swap Battery (Fully Swappable)	Studies Leasing Battery Leasing All-Swap Battery (Fully Swappable) Users do not own a battery; swap at stations; reduces downtime, but needs more infrastructure. Leasing Battery Leasing	(Tahara et al., n.d.)
S32	Minimum-Cost Flow	Time-Speed Network Optimization, Minimum-Cost Flow Optimization, ILP-based optimization of charging	(Tahara et al., n.d.)

Sl. No.	Strategy Variables	Detail Description	Key References
		and swapping logistics across multiple stations. Fixed battery for daily needs + swappable for extended trips; cost-effective and operationally flexible. Location User-Centric Scheduling	
S33	Dedicated Swap Infrastructure	Real-time monitoring of SoH, SoC, and operational data via BMS; ensures availability and lifecycle optimization Reduce, Recover – enables performance-based servicing, lowers premature failure Location Dedicated Swap Infrastructure Wide deployment of swap stations with high utilization rates (~10–20 swaps/day/station) Reuse, Recover – high turnover infrastructure reduces per capita resource consumption flexibility.	(Zhang & Rao, 2016)
S34	Standardized Swapping Infrastructure	Optimizes performance and limits degradation Reduce, Reuse, Time-Value Standardized Swapping Infrastructure. Modular and interoperable battery swapping stations across OEMs or regions. Reduces waste and enable battery compatibility across platforms Reuse, Refurbish	(Tripathi et al., 2023)
S35	Mobile Swap Vehicle Deployment	Location Mobile Swap Vehicle Deployment Procurement of mobile units equipped for on-demand battery delivery and exchange Reduce – Reduces need for fixed infrastructure in low-density areas; promotes lean, demand-responsive resource use flexibility.	(Shao et al., 2017)
S36	Subscribed Access	Limits EoL control; weak Recycle and Recover enforcement Leasing Leasing/Subscribed Access Batteries accessed via monthly/usage-based fee Supports Reduce (material use) and Refuse (ownership) Owner-Operator A third-party BaaS provider procures and manages battery assets, reducing per-user ownership cost and ensuring standardized battery quality.	(Zhou et al., 2025)
S37	Partially Swappable Battery (BaaS)	Owner-Operator Hybrid Ownership Partially Swappable Battery (BaaS) Combines fixed (owned) and swappable (shared) batteries; cost-efficient; improves utilization. Users purchase EVs with a full battery, high upfront cost, and poor flexibility for varying range demands. Outsourcing OEM-Owned Battery Procurement	(Tahara et al., n.d.)
S38	High-Frequency Battery Swapping	Collaborations with partners to operate supercharging or franchised stations Reduce – Limits need for multiple duplicate infrastructures by sharing access to fewer, higher-utilization stations. Time High-Frequency Battery Swapping EVs use battery swapping instead of home or public charging; reduces charging downtime Reuse / Optimize – Maximizes battery utility through faster rotation and standardized energy cycles Location	(Patel et al., 2024)
S39	Standardized Battery Design	Standardized Battery Design Collaborate with other OEMs for cross-brand compatibility and scale up economies of modular battery units. Upgrade to faster, more efficient swap tech; reduce maintenance time and increase automation levels. Subscription Model Flexibility provides tiered subscription plans (e.g., mileage-based), enabling temporary upgrades and pause options. App-Based Integration Enhance UX/UI for real-time swap scheduling, battery health tracking, and loyalty rewards via the app.	(Rodemann et al., 2023)

Sl. No.	Strategy Variables	Detail Description	Key References
S40	Delay-Minimized Operation	Location User-Centric Scheduling Delay-Minimized Operation Reduces attach-detach, quick-charge, and swap time to improve user experience and system efficiency. ILP-based optimization of charging and swapping logistics across multiple stations. Flexibility Predictive Maintenance Systems	(Tahara et al., n.d.)
S41	Smart BSS Energy Dispatching	Wide deployment of swap stations with high utilization rates (~10–20 swaps/day/station) Reuse, Recover – high turnover infrastructure reduces per capita resource consumption. Flexibility Smart BSS Energy Dispatching Simulation of BSS energy dispatch using real-time state of charge, demand, and grid capacity Reduce, Recover – optimizes resource use and reduces operational energy wastage location.	(Marchesano et al., 2023)
S42	Flexible Swapping Infrastructure	Batteries are sorted and assigned to EVs or energy storage based on state-of-health (SoH) Repair, Refurbish – Maximizes utility by condition-based use allocation and lifecycle extension Location Flexible Swapping Infrastructure Stations support both mobility (EVs) and stationary (energy storage) services Reuse, Recover – Facilitates dual use scenarios, improving circularity of infrastructure and batteries' flexibility.	(Sindha et al., 2023)
S43	Distributed Smart Swap Stations	AIoT-enabled BMS recommends swap timing and matches battery based on SoH Repair / Reuse – Prevents premature degradation and promotes predictive maintenance. Distributed Smart Swap Stations Modular stations placed based on heatmaps and mobility density Reduce – Avoids overbuilding, ensures infrastructure is based on real need flexibility.	(Ding et al., 2025)
S44	Multi-type Station Infrastructure Procurement	Access to EVs through short- or long-term shared mobility platforms like car clubs or peer-to-peer sharing Reuse, Reduce – High turnover per asset, lowers total units required for mobility. Outsourcing Multi-type Station Infrastructure Procurement. Procurement of charging-only, swapping-only, and hybrid stations to address diverse urban demand Reduce, Recover – Flexible infrastructure avoids overbuilding and enables energy recovery systems Outsourcing	(J. Yang et al., 2017)
S45	Dual-Model Service Offering	Operation strategy involves maximizing leasing income while minimizing battery degradation and returns Reuse, Repair – prioritizes optimal usage duration before refurbishing or replacement Location Dual-Model Service Offering Offering both vehicle leasing and vehicle sales to different market segments Reduce, Repurpose – helps align resource flow with user preference and lifecycle flexibility Flexibility	(Wu & Li, 2024)
S46	Partnership with Battery Lessors	Subsidy and policy support for infrastructure co-investment between state and private players Reduce – Shared infrastructure models reduce duplicative investments and resource consumption Outsourcing Partnership with Battery Lessors Battery Swap Station Providers (SPs) lease batteries from third-party lessors to reduce upfront capital cost Refuse / Reuse – Avoids	(Hu et al., 2024)

Sl. No.	Strategy Variables	Detail Description	Key References
		individual asset ownership, increases battery utilization via shared access Outsourcing	
S47	Centralized Battery Dispatch	Maximizes utilization rates; reduces idle time and wastage Reuse, Reduce Flexibility Centralized Battery Dispatch Optimization algorithm dispatches charging/discharging at the community level ensures maximum efficiency and lifetime extension Reduce, Optimize.	(Al-Alawi et al., 2022)

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 strengthening high impact factors, weakness of the rejected factors and policy level improvement under the subheading of proposed improvement. The result is shown in Table 3.

Table 3. Fuzzy DELPHI Result

Codes	Strategy Variables	Mean Score	Accept/Reject
S1	Heavy Asset Risk via Battery Operators	0.527116	Reject
S2	Two-Level Swap Station Network	0.529239	Reject
S3	Infrastructure-as-a-Service	0.671569	Accept
S4	BSS Without Government Support	0.448813	Reject
S5	Incentive-Driven BSS Investment	0.524242	Reject
S6	Collaborative Ecosystem Models	0.527165	Reject
S7	Franchised Charging Infrastructure	0.537706	Reject
S8	BSS-led Procurement by EV Manufacturers	0.49882	Reject
S9	Renewable-Energy Linked Swapping Network	0.665918	Accept
S10	Decentralized Ownership	0.472346	Reject
S11	Centralized Ownership	0.53234	Reject
S12	Dual Ownership with Platform Coordination	0.514395	Reject
S13	Battery Purchase (Sell-and-Buy)	0.481399	Reject
S14	BSS Ownership by Battery Producers	0.515361	Reject
S15	Autonomous Battery Swapping Stations	0.526186	Reject
S16	Peer-to-Peer Energy Trading	0.491081	Reject
S17	IoT + BMS-driven Condition-Based Maintenance	0.656326	Accept
S18	Location-Agnostic Swapping via App	0.538796	Reject
S19	Digital Monitoring & Control	0.54997	Reject
S20	Swapping Platform Optimization	0.670128	Accept
S21	SoH-Based Deployment	0.535594	Reject
S22	Smart Battery Management	0.664506	Accept
S23	Condition-Based Swapping (BMS-Driven)	0.665918	Accept
S24	Digital Battery Management	0.670128	Accept
S25	Green Premium Pricing Mechanism	0.531284	Reject
S26	Modular Procurement	0.520173	Reject
S27	Battery Pooling	0.52117	Reject
S28	Static Allocation	0.496199	Reject
S29	Service Price Adjustment Linked to Battery Flow	0.645769	Accept
S30	Dynamic Allocation	0.539999	Reject

Codes	Strategy Variables	Mean Score	Accept/Reject
S31	All-Swap Battery (Fully Swappable)	0.520126	Reject
S32	Minimum-Cost Flow	0.528299	Reject
S33	Dedicated Swap Infrastructure	0.534521	Reject
S34	Standardized Swapping Infrastructure	0.5534	Reject
S35	Mobile Swap Vehicle Deployment	0.54997	Reject
S36	Subscribed Access	0.534521	Reject
S37	Partially Swappable Battery (BaaS)	0.529239	Reject
S38	High-Frequency Battery Swapping	0.530233	Reject
S39	Standardized Battery Design	0.546376	Reject
S40	Delay-Minimized Operation	0.52526	Reject
S41	Smart BSS Energy Dispatching	0.546485	Reject
S42	Flexible Swapping Infrastructure	0.660384	Accept
S43	Distributed Smart Swap Stations	0.529239	Reject
S44	Multi-type Station Infrastructure Procurement	0.53234	Reject
S45	Dual-Model Service Offering	0.515361	Reject
S46	Partnership with Battery Lessors	0.515268	Reject
S47	Centralized Battery Dispatch	0.535491	Reject

5.1. Numerical Results

The Fuzzy Delphi Method (FDM) was employed to validate and prioritize the strategy variables relevant to the adoption of BaaS 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.

As shown in Table 1, a total of 9 operational strategy variables out of 47 met the threshold and were therefore retained for further analysis.

The evidence from the analysis table indicates a decisive preference for digitally orchestrated, condition-aware operations layered on flexible infrastructure, with the highest mean score achieved by Infrastructure-as-a-Service (S3, 0.6716) and a compact acceptance cluster comprising Renewable-Energy Linked Swapping Networks (S9), IoT + BMS-driven Condition-Based Maintenance (S17), Swapping Platform Optimization (S20), Smart Battery Management (S22), Condition-Based Swapping (BMS-Driven) (S23), Digital Battery Management (S24), Service Price Adjustment Linked to Battery Flow (S29), and Flexible Swapping Infrastructure (S42). Thematically, these nine accepted levers cohere around an operations-first paradigm: (i) pervasive digital visibility of battery condition and usage (S17, S22, S23, S24), (ii) intelligent optimization of charge/swap logistics and dispatch (S20), (iii) platformization of capital assets (S3) so smaller actors can participate without prohibitive CapEx, (iv) carbon-aligned siting and energy coupling (S9) that reduces lifecycle intensity and stabilizes grid interactions, (v) flexible, modular physical plant (S42) capable of serving volatile spatial-temporal demand, and (vi) dynamic pricing linked to actual battery flow efficiency (S29) to internalize operational frictions and nudge behaviour. Collectively, their mean scores (≈0.646–0.672) separate clearly from the broad rejection cluster, signalling that operational intelligence, platform delivery, RE-coupling, and flexibility form the panel's "minimum efficient stack" for BaaS competitiveness.

In contrast, levers that emphasize ownership structure, franchise models, or purely structural network design without an equally strong digital/optimization layer tended to underperform. The ownership/financing family Heavy Asset Risk via Battery Operators (S1), BSS-led Procurement by EV Manufacturers (S8), Decentralized Ownership (S10), Centralized Ownership (S11), Dual Ownership with Platform Coordination (S12), Battery Purchase (Sell-and-Buy) (S13), BSS Ownership by Battery Producers (S14), Modular Procurement (S26), Battery Pooling (S27), Subscribed Access (S36), Partially Swappable Battery (BaaS) (S37), Dual-Model Service Offering (S45), and Partnership with Battery Lessors (S46) largely scored below the acceptance band. The panel's implicit message is that who owns the assets (centralized, decentralized, or hybrid) is less decisive than how intelligently those assets are observed, optimized, and priced in day-to-day operations. Similarly, policy/finance signalling in isolation was insufficient: BSS

Without Government Support (S4) posted the lowest score (0.4488), reflecting perceived sustainability challenges without supportive mechanisms, while Incentive-Driven BSS Investment (S5) also remained below the cut, suggesting that incentives are enablers, not substitutes, for the digital-optimization core. Even Green Premium Pricing (S25) did not clear the bar, whereas S29's operationally grounded pricing (tied to throughput and flow) did underscoring the panel's preference for performance-linked, not purely normative, price instruments.

The infrastructure group shows the same logic. Designs that primarily scale the shape of the network Two-Level Swap Station Network (S2), Franchised Charging Infrastructure (S7), Dedicated Swap Infrastructure (S33), Standardized Swapping Infrastructure (S34), Mobile Swap Vehicle Deployment (S35), Distributed Smart Swap Stations (S43), Multi-type Station Infrastructure Procurement (S44), and High-Frequency Battery Swapping (S38) clustered below acceptance, whereas Flexible Swapping Infrastructure (S42) was accepted. This pattern signals that adaptability (S42) matters more than a priori fixed blueprints (S2, S33, S34, S44): the panel rewards reconfigurability and multi-use readiness when paired with the digital stack that knows when, where, and how to reconfigure. Even product-level standardization. Standardized Battery Design (S39) scored mid-pack, again implying that standardization without active orchestration offers diminishing returns relative to analytics-driven flexibility. A similar story holds for the operations-algorithms subset: Minimum-Cost Flow (S32), Dynamic Allocation (S30), Static Allocation (S28), Delay-Minimized Operation (S40), Smart BSS Energy Dispatching (S41), and Centralized Battery Dispatch (S47) all trailed Swapping Platform Optimization (S20). The panel seems to penalize narrow or static formulations (e.g., S28) and single-objective framings (e.g., S40), favouring the broader, system-integrating optimization of S20 that explicitly coordinates inventory, routing, charge windows, and station utilization under demand variability and carbon constraints.

Finally, digitally adjacent but lighter-weight applications Location-Agnostic Swapping via App (S18) and Digital Monitoring & Control (S19) performed better than purely structural levers but still fell short of acceptance, which aligns with the thesis that data visibility must be paired with prescriptive intelligence (the accepted S17/S20/S22/S23/S24 cluster). R&D-oriented or horizon levers like Autonomous Battery Swapping Stations (S15) and Peer-to-Peer Energy Trading (S16) garnered interest but remained below the cut, likely reflecting implementation risk and ecosystem prerequisites not yet widely met. Taken together, the distribution of scores paints a coherent picture: a winning BaaS configuration is less about an idealized ownership pattern or a monolithic network blueprint and more about instrumented assets (S17, S22–S24), system-level optimization (S20), flexible plant (S42), carbon-integrated siting (S9), and performance-linked pricing (S29) executed atop platformized infrastructure (S3). Ownership and topology still matter, but their value is mediated by the intelligence and adaptivity of the operating stack; without that stack, they rarely cross the acceptance threshold.

5.2 Graphical Results

The bar chart depicts a clear stratification of BaaS operational strategy variables, with a compact accepted cluster (S3, S9, S17, S20, S22, S23, S24, S29, S42) concentrated near the upper tail of the distribution (~0.65–0.67) and a broad rejected mass centered in a mid-band (~0.52–0.55). The prominence of S3 (≈0.672) and the weakness of S4 (≈0.449) establish the spread and signal that panel judgments systematically reward strategies that convert digital observability of batteries (BMS/DBM, condition-based maintenance/swapping) into prescriptive coordination (platform optimization and flow-linked pricing) executed on flexible, renewable-aligned infrastructure (Figure 1). In theoretical terms, the accepted set embodies an operations-centric capability stack where information quality (continuous SoH/SoC telemetry) and optimization (inventory/queue/dispatch decisions) jointly reduce uncertainty, lower transaction and coordination costs, and unlock higher asset utilization advantages that ownership patterns, static network shapes, or generic pricing mechanisms alone cannot replicate. The dense mid-band of rejections thus reflects strategies that are necessary but not sufficient: they may offer structural or governance benefits, yet, without being anchored in data-driven control and adaptive plant, they fail to shift system performance to the frontier. Consequently, the chart provides empirical support for a contingency view of BaaS: competitive advantage emerges from instrumented assets + system optimization + infrastructural flexibility, rather than from financing or topology choices in isolation.
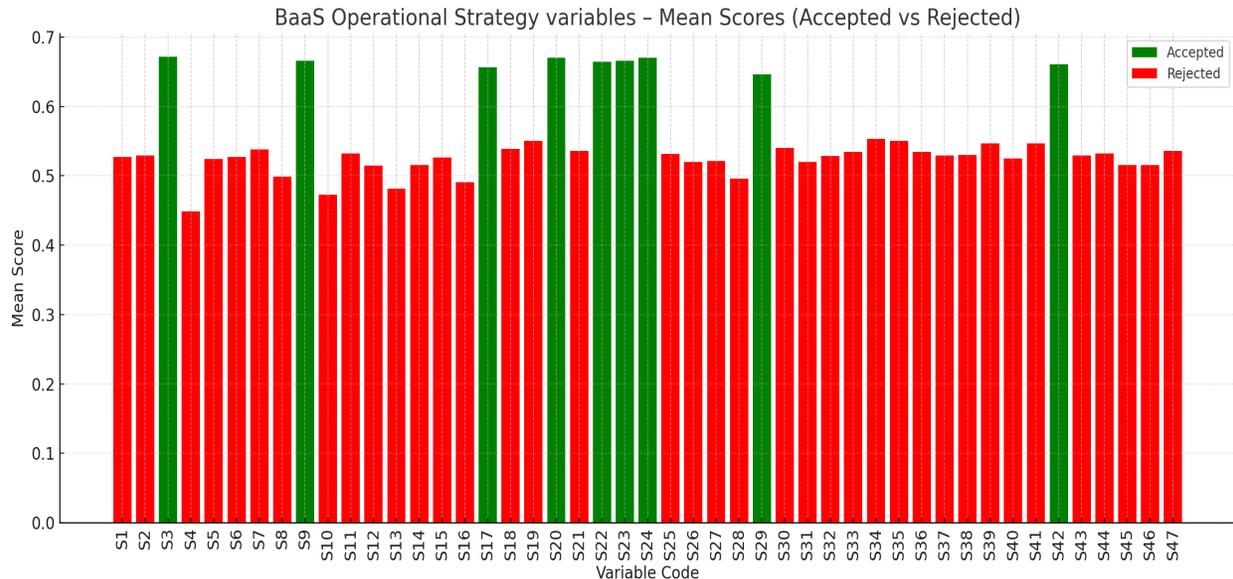
Figure 1. Fuzzy DELPHI Output

5.3 Proposed implementation policies for the accepted variables:

5.3.1 Strengthen High-Impact Factors

BaaS succeeds when operations are treated as a data-driven service, not just hardware deployment. The accepted variables together form a compact stack instrumented assets, prescriptive optimization, flexible RE-aligned infrastructure, and flow-sensitive pricing that jointly lift reliability, cost efficiency, and carbon performance. The following subsections briefly formalize each lever in that stack.

Infrastructure-as-a-Service (S3)

In an Infrastructure-as-a-Service configuration, the swapping network is conceived as a platform layer that abstracts ownership and concentrates lifecycle responsibilities with the operator, thereby reducing heterogeneous transaction costs across OEMs and fleets. Theoretically, IaaS internalizes asset-specific risks (depreciation, technology churn) and transforms them into service obligations governed by SLAs, while enabling scale economies in maintenance, inventory pooling, and grid interfacing. By separating vehicle purchase from battery access, the model shifts capital intensity from end users to a specialized asset manager, which improves adoption elasticity and allows dynamic capacity right-sizing. The platform logic also creates positive network externalities: every additional participant increases utilization, shortens queue times through shared buffers, and enhances the value of operational data used for system-wide optimization.

Renewable-Energy Linked Swapping Network (S9)

Linking station operations to renewable generation embeds carbon and price signals directly into dispatch rules. Theoretically, aligning swap-charging windows with solar/wind availability lowers marginal emissions and hedges wholesale volatility through temporal arbitrage, while nodal siting near RE capacity minimizes distribution losses. When operators prioritize green windows in their objective function, the system converges toward a joint optimum in which energy cost, carbon intensity, and station utilization are co-optimized. This coupling also strengthens policy coherence: credits, time-of-day tariffs, and grid flexibility services become monetizable levers that reinforce clean, reliable BaaS.

IoT + BMS-driven Condition-Based Maintenance (S17)

Condition-based maintenance treats the battery as a cyber-physical asset whose health state (SoH, temperature, impedance, fault codes) is continuously estimated by the BMS and IoT telemetry. Theoretical gains arise from replacing periodic maintenance with probabilistic failure prevention, thus reducing unexpected downtime and extending residual life through timely interventions. CBM reduces information asymmetry in warranties and secondary markets, because health trajectories are observable and auditable. Systemically, CBM decreases spare

ratios, compresses mean time to repair, and dampens variance in station throughput, all of which elevate service reliability at lower lifecycle cost.

Swapping Platform Optimization (S20)

A swapping platform's "brain" is a multi-objective optimizer coordinating inventory positioning, charging queues, dispatch priorities, and repositioning flows across stations under stochastic demand. Theoretically, embedding these decisions in a unified optimization (with cost-carbon-SLA trade-offs) converts local heuristics into a global policy that minimizes total system cost while satisfying service constraints. Such optimization exploits convexity in energy tariffs, submodularity in shared buffers, and queuing dynamics to reduce wait times and idle inventory simultaneously. As the state space is high-dimensional, algorithmic governance (ILP/rolling horizon/MDP) becomes a persistent capability rather than a one-off tool.

Smart Battery Management (S22)

Smart Battery Management extends the BMS into a cloud-orchestrated control layer where data fusion, diagnostics, and remote configuration inform operational decisions. Theoretically, this capability upgrades the operator's information set from reactive metering to predictive control, allowing degradation-aware assignment, safe fast-charging envelopes, and anomaly isolation at fleet scale. By standardizing data schemas and control APIs, SBM reduces interface frictions between stations, OEMs, and grid counterparts, enabling modular upgrades (software-defined batteries) and continuous improvement loops driven by real-world telemetry.

Condition-Based Swapping (BMS-Driven) (S23)

Condition-based swapping uses health-aware rules to trigger and route swaps, moving from user-initiated events to system-initiated interventions. Theoretically, matching packs to vehicles based on SoH/thermal history equalizes ageing across the pool and suppresses tail-risk failures. This policy creates a feedback loop: better health estimation yields better assignment; better assignment slows degradation; slower degradation stabilizes capacity forecasts, which in turn improves station planning. The outcome is a self-reinforcing improvement in availability and lifecycle economics.

Digital Battery Management (S24)

Digital Battery Management formalizes the battery's digital twin traceable across manufacturing, swapping, second-life, and recycling—so that every operational decision is made against a verified, longitudinal data record. Theoretically, DBM reduces measurement error and moral hazard by making states and transitions transparent; it also enables causal learning about degradation under different duty cycles, which refines operating envelopes over time. In market terms, DBM creates credible signals of quality that support residual-value pricing, insurance, and circularity credits, thereby unlocking financing at lower spreads.

Service Price Adjustment Linked to Battery Flow (S29)

Pricing linked to battery flow operationalizes congestion and utilization into economic signals. The theoretical mechanism is straightforward: when price reflects throughput, users are nudged toward off-peak times and less congested stations, flattening demand and improving social welfare under capacity constraints. Flow-indexed pricing internalizes queue externalities and accelerates inventory rotation, which reduces calendar ageing and balancing losses. Coupled with time-of-use electricity tariffs, it propagates grid-friendly behavior from the operator to the end user, aligning private incentives with system optima.

Flexible Swapping Infrastructure (S42)

Flexibility at the station, multi-format trays, hybrid charge-swap bays, and modular power blocks act as a real-options hedge against technology uncertainty and volatile demand. Theoretically, such a design increases the option value of waiting and adapting: capacity can be scaled in discrete steps; formats can be reconfigured as ecosystems standardize; and assets can be repurposed between mobility and stationary services. Flexibility complements digital orchestration: the optimizer can only realize its prescribed policy if the physical plant is capable of reconfiguration. Together, they deliver robustness, maintaining service levels across shocks without permanent overbuild.

Taken together, the accepted variables describe a coherent operating system for BaaS: instrumented assets (S17, S22, S24) feed prescriptive optimization (S20) that executes on flexible, RE-aligned infrastructure (S3, S9, S42), while

flow-sensitive pricing (S29) aligns user behaviour with system constraints. This stack shifts BaaS from a capital-heavy infrastructure play to a data-driven service platform where reliability, cost, and carbon are jointly optimized.

5.3.2 Proposed analysis of weakness of the rejected BaaS Operational Strategy Variables:

The rejected BaaS operational strategy variables largely emphasize structure (ownership, topology, form factor) over operational intelligence. Absent the triad of health-aware telemetry, multi-objective optimization, and flow-aligned pricing, these levers tend to relocate bottlenecks, misprice congestion, and underutilize assets rather than improve system performance.

(S1) concentrates CapEx and obsolescence risk on the operator without guaranteeing higher turns, so utilization-adjusted ROI and WACC remain unfavourable; (S2) reshuffles topology but, without predictive dispatch and flow-aware tariffs, merely relocates bottlenecks; (S4) faces valley-of-death economics before utilization crosses breakeven; (S5) can misallocate capital when subsidies aren't tied to uptime, carbon, or SLA KPIs; (S6) adds coordination overhead absent shared telemetry, enforceable SLAs, and optimization primitives; (S7) scales footprint rather than intelligence, yielding inconsistent SOPs and performance variance; (S8) locks capital to single-OEM demand cycles and weakens cross-OEM network effects; (S10) fragments standards/incentives, hindering SoH governance, rotation, and unified pricing; (S11) overconcentrates risk and becomes capital-bound without platform economics; (S12) introduces legal/settlement frictions unless backed by common data rails and strict platform rules; (S13) divorces lifecycle control from the service, eroding pooling, rotation, and circularity compliance; (S14) risks lock-in and misaligned incentives, limiting interoperability without robust standards; (S15) carries high CapEx/integration and reliability/safety burdens that undercut unit economics without very high, stable throughput; (S16) suffers metering/settlement complexity and thin local liquidity, limiting near-term operational impact; (S18) improves wayfinding but, without flow-linked pricing and inventory logic, simply steers demand to the next bottleneck; (S19) yields dashboards rather than performance unless fused with BMS/DBM signals and prescriptive optimization; (S21) is an informative signal but a partial policy that cannot by itself resolve queueing, carbon, or cost trade-offs; (S25) is normative rather than operative, failing to internalize congestion and rotation externalities; (S26) adds hardware options without responsiveness when not governed by granular SoH data and system-wide optimization; (S27) invites free-riding and adverse selection unless pricing/SoH governance are explicit; (S28) forfeits pooling gains and slows degradation equalization; (S30) can thrash under noise unless disciplined by multi-objective cost-carbon-cycle terms; (S31) raises infrastructure burden that only pays back with high rotation and CBM/DBM discipline; (S32) optimizes a narrow objective, underweighting service and emissions constraints; (S33) is brittle under volatile demand and lacks option value; (S34) is necessary but insufficient interoperability without optimization still misallocates capacity; (S35) is costly per swap, with routing/staffing overheads eroding benefit; (S36) dulls demand signals when tariffs ignore congestion/flow; (S37) complicates logistics and dilutes pooling benefits unless tightly orchestrated; (S38) accelerates ageing and queue externalities if not coupled to SoH and congestion signals; (S39) reduces variant complexity but can ossify innovation and still yields uneven ageing without health-aware assignment; (S40) over-targets a single KPI, risking unsafe envelopes or staff misallocation; (S41) optimized in isolation can starve swap SLAs unless coupled with inventory/queue control; (S43) remains locally smart but globally uncoordinated without cross-network inventory control; (S44) increases planning complexity absent demand forecasting, rotation rules, and rebalancing; (S45) splits managerial attention and creates shared-resource bottlenecks without prioritization logic; (S46) shifts CapEx but leaves health/risk information asymmetry unresolved; and (S47) introduces latency and single-point fragility unless complemented by hierarchical (central–local) control together indicating that structural or financial change without health-aware telemetry, multi-objective optimization, and flow-aligned pricing fails to convert capacity into reliable, low-carbon, high-utilization service.

Individually, these strategies are necessary but insufficient; they gain efficacy only when embedded in a data-driven stack that couples BMS/DBM visibility with prescriptive dispatch and incentive-compatible tariffs. Recasting them within that stack backed by open standards, enforceable SLAs, and carbon-aware objectives can convert structural change into reliable, low-cost, low-carbon BaaS outcomes.

5.3.3 Policy and Governance Improvements

To operationalize Infrastructure-as-a-Service (S3), formalize an interoperability code (form-factor, connectors, swap protocol, data schema), recognize batteries/stations as a regulated asset class (SPVs/PPPs, concessional debt, accelerated depreciation), and require open, audited operator–OEM–grid APIs with vendor-neutral access and SLA enforcement; align dispatch with clean power via Renewable-Energy Linked Swapping Network (S9) by tying

operations to time-of-day/real-time tariffs, enabling green open access/virtual PPAs and net-metering, and permitting ancillary-services participation with clear metering/settlement and per-swap carbon disclosure; make reliability endogenous through IoT + BMS-driven Condition-Based Maintenance (S17) by mandating a minimum telemetry set (SoH/SoC, temperature, cycles, fault codes), predictive programs, standardized calibration/certification, and cybersecurity/secure-OTA tied to warranty governance; then coordinate the whole system with Swapping Platform Optimization (S20) by licensing multi-station optimization (inventory, queues, charge windows, repositioning) against KPI targets and granting regulated access to anonymized traffic/grid data under algorithm auditability/fairness and a supervised sandbox; elevate control with Smart Battery Management (S22) cloud analytics with standardized schemas and digital-passport fields for second-life/recycling, secured by role-based APIs, logging/retention/consent, and audited OTA/change-control; convert health signals into actions via Condition-Based Swapping (S23) by codifying SoH-gated allocation/timing (thermal/health gates, anomaly flags), requiring periodic third-party calibration, publishing priority/equity logic with audit/appeals, and enforcing privacy via minimization/pseudonymization; preserve provenance through Digital Battery Management (S24) with near-real-time operator–OEM–grid exchange over versioned open APIs (time-stamped), data-quality SLAs (latency, completeness, accuracy) and independent integrity audits, plus guaranteed portability across operators; steer user behaviour using Service Price Adjustment Linked to Battery Flow (S29) by authorizing dynamic, flow-indexed tariffs (throughput, congestion, rotation) within consumer protections (caps/floors, notice, transparency), coupling prices to grid signals, and piloting with equity/elasticity reporting; and, finally, ensure the physical plant can execute these prescriptions through Flexible Swapping Infrastructure (S42) by updating codes for modular/hybrid bays and multi-format trays with fast-track expansions, enforcing performance-based safety (fire, HVAC, isolation) and resilience (backup, islanding), and allowing dual-use so off-peak capacity supports stationary storage and grid services.

6. Conclusion

This study establishes that competitive BaaS operations cohere around a minimum efficient stack: instrumented assets (S17, S22, S24) feeding system-level optimization (S20), executed on renewable-coupled, reconfigurable infrastructure (S3, S9, S42), and reinforced by flow-linked pricing (S29). Within this stack, condition-aware allocation and swapping (S23) stabilizes service levels, slows degradation, and equalizes ageing across the pool, unlocking higher turns with lower lifecycle cost. Strategies centered purely on ownership form, franchising, or static topology do not, by themselves, move the utilization and reliability frontiers; they become effective only when layered atop health telemetry, prescriptive dispatch, and congestion-sensitive tariffs.

For practice, the findings translate into four imperatives: (1) Codify interoperability and data rails (telemetry minima, digital passports, secure OTA) so SoH signals are trustworthy, portable, and auditable; (2) License and audit optimization engines that jointly minimize total cost, carbon, and expected wait time across stations; (3) Design flexible physical plant (multi-format trays, hybrid charge-swap bays, dual-use with stationary storage) to give the optimizer real options; and (4) Adopt throughput-indexed, ToU-aware tariffs that nudge demand off-peak and accelerate inventory rotation, aligning operator economics with grid stability and decarbonization.

Limitations include the scope and composition of the expert panel and a single-country operational context. Future work should (i) validate these priorities via large-N Delphi/BWM weighting and sensitivity analysis; (ii) embed the accepted variables in city-scale simulation (demand stochasticity, grid signals, thermal constraints); and (iii) run field pilots that couple dynamic pricing with condition-based swapping to quantify causal gains in wait time, turns-per-pack, and emissions per kilometre. By centring operations not just assets, the roadmap here provides a concrete path to scale BaaS that is reliable, economical, and progressively greener.

Future scope includes sensitivity and robustness, re-run FDM with expanded panels and cutoff/weighting sensitivity (e.g., alternative defuzzification, BWM/AHP overlays). City-scale simulation embeds the nine accepted variables into stochastic, queueing-aware, grid-constrained network models to quantify effects on expected wait time, turns-per-pack, capex/opex, and emissions. Controlled field pilots test condition-based swapping + flow-indexed pricing bundles, measuring causal impacts on service levels and battery ageing. Data/standards operationalize digital battery management (data schemas, digital passports) and RE-linked dispatch contracts to enable multi-operator interoperability and grid services. These steps move from expert consensus to validated operating envelopes for reliable, economical, and lower-carbon BaaS at scale.

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