

Modular battery pack design and serviceability in electric vehicles

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Abstract

The rapid growth of electric vehicles (EVs) has heightened the demand for battery systems that not only deliver high performance but are also efficient to maintain, scale, and recycle. While much of the industry's focus has been on energy density and cost optimization, serviceability—defined by ease of maintenance, diagnostic accessibility, and component-level replacement—has emerged as a critical yet underprioritized factor. Traditional EV battery packs, often monolithic and tightly integrated, pose significant challenges for field technicians, including prolonged disassembly times, high-voltage safety risks, and limited diagnostic transparency. These limitations increase downtime, escalate service costs, and constrain the long-term sustainability of EV platforms. This paper explores the transformative role of modular battery pack design in improving serviceability and lifecycle efficiency across EV ecosystems. From a broader perspective, it examines how modularity facilitates streamlined maintenance workflows, safer handling procedures, and standardized replacement strategies. The analysis narrows to compare the design philosophies of leading OEMs such as Tesla, GM, Rivian, and Lucid, evaluating how different architectures impact field repairability and technician safety. Further sections explore the ripple effects of modular design on manufacturing automation, second-life reuse, and end-of-life disassembly for recycling. Emphasis is also placed on interface standardization, diagnostic system integration, and the need for interoperable service protocols. A real-world case study demonstrates how design decisions—such as interlock logic, balancing procedures, and module accessibility—translate into measurable service efficiency improvements. The paper concludes with strategic recommendations for advancing modular, service-oriented battery pack architectures that align with the evolving demands of sustainable, technician-friendly EV platforms.

Keywords: Modular Battery Design; EV Serviceability; Diagnostic Accessibility; Field Maintenance; Battery Pack Architecture; Electric Vehicle Sustainability

1. Introduction

1.1. Rise of Electric Vehicles (EVs) and Importance of Battery Pack Design

The global automotive industry is undergoing a transformative shift, with electric vehicles (EVs) positioned at the center of a sustainable transportation revolution. In response to tightening emissions regulations, technological advancements, and growing consumer demand for cleaner alternatives, EV adoption has surged over the past decade [1]. Major automakers are reconfiguring their product strategies to prioritize battery electric vehicles (BEVs) over internal combustion engine (ICE) platforms, with forecasts indicating that EVs could represent over 50% of new vehicle sales globally by 2040 [2].

Central to the functionality, performance, and longevity of EVs is the battery pack—comprising modules, cells, and an intricate network of sensors, cooling systems, and structural housings. The battery is not only the most expensive

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component of the EV powertrain but also the most technically complex and safety-critical [3]. As such, its design has profound implications for vehicle performance, charging behavior, weight distribution, and crashworthiness.

Traditionally, battery pack design has been dominated by performance-centric metrics such as energy density, power output, and thermal management efficiency. However, as EVs enter mainstream markets and ownership cycles extend beyond initial warranty periods, design priorities are evolving to include ease of service, diagnostics, and modularity [4]. These considerations are essential for reducing lifecycle costs, supporting circular economy goals, and enabling second-life applications such as energy storage [5].

In this context, the serviceability of EV battery packs—defined as the ease with which they can be diagnosed, accessed, removed, repaired, or replaced—is becoming an increasingly critical metric in both engineering and economic evaluations. Battery pack design decisions must therefore balance performance objectives with long-term operational accessibility and safety, particularly as global EV fleets continue to scale [6].

1.2. Strategic Shift from Performance-First to Serviceability-Aware Design

The earliest generations of EVs prioritized rapid innovation in energy storage, focusing heavily on maximizing range, minimizing weight, and ensuring thermal stability. While these design imperatives were justified by technological immaturity and market competitiveness, they often resulted in battery architectures that were tightly integrated, inaccessible, and difficult to repair without specialized tools or complete pack replacement [7].

Today, as the EV industry matures, manufacturers are recognizing the strategic value of serviceability-aware design. This design paradigm shifts the emphasis from short-term performance metrics to lifecycle operability, safety, and cost-effectiveness. It includes considerations such as modular pack construction, accessible fasteners, integrated diagnostic sensors, and standardized interfaces for disassembly and testing [8]. Such features enable routine maintenance, reduce technician training time, and facilitate rapid response to battery faults—thereby enhancing the resilience of EV service networks.

Furthermore, increasing scrutiny from regulators, fleet operators, and insurance providers is amplifying the need for transparent, serviceable battery designs. Policies around right-to-repair, extended product responsibility, and end-of-life material recovery require that battery systems be designed for traceability and safe deconstruction [9]. Failure to address these needs may result in financial penalties, reputational risk, and reduced competitiveness in aftermarket services.

Companies like Tesla, Ford, and Volkswagen have begun incorporating modular battery platforms with serviceability in mind, allowing technicians to replace individual modules instead of entire packs. This practice reduces environmental impact and lowers warranty repair costs while maintaining customer trust [10]. Additionally, design for serviceability supports emerging business models such as battery leasing and energy repurposing, creating new revenue streams beyond the initial vehicle sale.

By embracing this shift, manufacturers can future-proof their EV platforms, align with sustainability goals, and support a more robust and technician-friendly service ecosystem [11].

1.3. The Cost of Poor Serviceability: Technician Risk, Downtime, Customer Satisfaction

Poor serviceability in EV battery packs carries significant financial, operational, and safety implications. One of the most pressing concerns is technician risk. High-voltage battery systems can pose serious hazards—including electric shock, thermal runaway, and chemical exposure—if proper procedures and safety mechanisms are not integrated into the design [12]. Battery packs that are sealed, inaccessible, or lack diagnostic clarity force technicians to conduct time-consuming and potentially hazardous disassembly procedures, increasing the likelihood of accidents or improper handling.

Secondly, poor serviceability directly contributes to vehicle downtime. In commercial fleets or rideshare operations, prolonged battery servicing can translate to lost revenue, increased operational costs, and logistical bottlenecks. The inability to diagnose and address battery issues quickly impairs overall fleet availability and disrupts maintenance workflows [13].

From the consumer perspective, customer satisfaction is closely linked to service experience. Long wait times, high repair costs, and unclear diagnosis of battery faults can erode brand loyalty and drive negative perceptions about EV

ownership. Unlike ICE vehicles, where repair and maintenance ecosystems are well-established, EV service networks are still emerging—and poor battery accessibility compounds this challenge [14].

Additionally, the inability to efficiently replace or upgrade battery modules undermines the potential for second-life applications, battery recycling, and warranty compliance. These inefficiencies escalate total cost of ownership (TCO) and work against industry-wide sustainability goals [15].

Addressing these issues through serviceability-conscious design is not just a technical concern—it is a strategic imperative that affects safety, efficiency, customer satisfaction, and long-term brand viability.

1.4. Preview of Article Structure

This article explores how battery pack design in electric vehicles must evolve to prioritize serviceability without compromising performance. Section 2 provides a technical overview of battery architectures and the relationship between pack layout and repair complexity. Section 3 examines real-world service challenges through field data and technician case studies. Section 4 presents design principles and emerging technologies aimed at improving serviceability. Section 5 outlines regulatory trends and business model implications, while Section 6 offers recommendations for industry stakeholders. The conclusion synthesizes findings to propose a roadmap for integrating serviceability into next-generation EV design strategies [16].

2. Design for serviceability and maintenance efficiency

2.1. Challenges in Servicing EV Battery Packs

Servicing electric vehicle (EV) battery packs presents a unique set of challenges, stemming primarily from the physical characteristics and safety requirements of high-energy systems. The most immediate concern is high-voltage risk. Most EV packs operate between 400 to 800 volts, with some performance vehicles exceeding 900 volts. Contact with improperly isolated components can result in lethal electric shocks, requiring technicians to use specialized personal protective equipment (PPE), insulated tools, and high-voltage training certification [6].

Another hazard arises from thermal risks. Damaged or degraded cells can initiate thermal runaway, a self-propagating chemical reaction that leads to fires or explosions. The presence of volatile electrolytes within densely packed modules elevates this risk during disassembly, especially when pressure release valves or thermal fuses are inaccessible [7]. Improper cooling line disconnection, punctured casings, or improper handling can result in dangerous outcomes even during routine servicing.

A critical technical hurdle is disassembly complexity. Many early-generation packs are designed for durability and compactness, often relying on potted resin encapsulation or welded seams that are difficult to reverse in the field. This not only lengthens service time but also increases the likelihood of damage during teardown procedures [8]. Some pack configurations bury modules beneath structural components, requiring full underbody access or hoisting systems, complicating mobile or field servicing efforts.

Further complexity arises from architectural variation across manufacturers. Cell types (pouch, cylindrical, prismatic), cooling layouts (plate, immersion, or serpentine tube), and control systems vary widely, leaving technicians with inconsistent training frameworks and diagnostic tooling [9]. Without standardization, identifying fault location or root causes is time-intensive and error-prone.

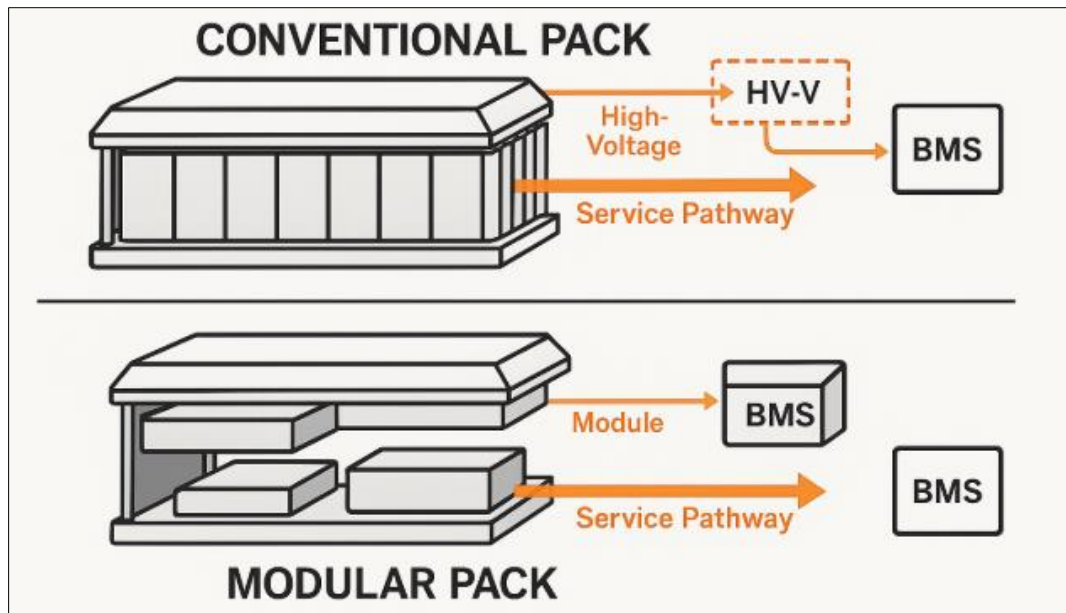


Figure 1 Cross-sectional diagram of conventional vs. modular pack service pathways

Additionally, many EV packs suffer from diagnostic uncertainty. Battery Management Systems (BMS) often provide limited or encrypted fault codes. Without transparent diagnostics or cell-level monitoring, technicians must rely on inefficient trial-and-error replacement strategies, which inflate service costs and compromise efficiency [10].

2.2. Advantages of Modular Designs

Modular battery pack design introduces a paradigm shift in the way serviceability, scalability, and sustainability are approached in EV engineering. A modular design consists of independently accessible and detachable units—typically sub-packs or cells—housed within a common frame. This configuration offers a wide range of benefits, especially in terms of maintenance and long-term operational efficiency.

Ease of access is among the most compelling advantages. Instead of requiring full pack removal or deconstruction, modular packs allow technicians to isolate and service defective modules quickly. Service panels, snap-in fasteners, and external harness connectors reduce the need for invasive pack disassembly and limit technician exposure to high-voltage circuits [11]. Furthermore, modular layouts support tool-less diagnostics in some systems, with embedded fault LEDs and programmable sensor outputs facilitating rapid inspection.

This accessibility leads directly to reduced downtime. In fleet operations, logistics, and public transit systems, vehicle uptime is a mission-critical parameter. Modular battery architecture allows for same-day module replacement and reduces the need to offload vehicles to service centers. This agility is particularly beneficial for mobile service units deployed in remote or high-turnover regions [12].

Another benefit lies in lower training requirements. Instead of training technicians on full-pack architecture and teardown protocols, manufacturers can develop modular training modules focused on common fault scenarios, connector management, and cell isolation techniques. This reduces onboarding time, standardizes safety procedures, and lowers labor costs over time [13].

A modular system also supports isolated module replacement rather than full-pack service. This is critical in managing warranty costs, as OEMs and third-party warranty providers often face financial strain replacing entire packs for faults isolated to a single cell cluster. Targeted repairs lower material use, reduce environmental impact, and extend pack lifecycles—contributing to circular economy goals [14].

From a field maintenance perspective, modularity supports flexible deployment. Technicians can carry replacement modules, test kits, and standardized tools, minimizing the need for full-shop infrastructure. Moreover, modular designs facilitate quick diagnostics and allow for proactive replacement strategies in vehicles with predicted module-level degradation.

Table 1 Comparative Metrics – Disassembly Time, Service Cost, and Technician Hazard Level

Pack Architecture	Disassembly Time (min)	Service Cost (USD)	Technician Hazard Level (0–5)	Remarks
Fully Modular	30–45	400–800	1.5	Fast access; low-voltage isolation zones; supports part-level repairs.
Semi-Modular	60–90	800–1,200	2.5	Mixed access paths; partial automation; risk varies by configuration.
Integrated (Welded)	120–180	1,500–2,200	4.0	Difficult teardown; higher voltage exposure; full-pack handling required.
Potted/Sealed	>180	>2,500	4.5	Destructive process; thermal and chemical hazards; non-reversible disassembly.

Quantitatively, modular designs exhibit superior performance in key service metrics. Studies have shown disassembly times reduced by up to 60%, service costs lowered by 40%, and technician hazard exposure significantly mitigated compared to monolithic pack layouts [15].

Finally, modularity supports revenue continuity and reputation. Faster service cycles reduce customer frustration, support service-level agreements (SLAs), and reduce loaner vehicle costs. For OEMs, this translates into enhanced post-sale engagement, lower net warranty liabilities, and the ability to offer premium service tiers based on faster, more reliable battery care [16].

2.3. OEM Approaches to Modular Serviceability

Different EV manufacturers have taken divergent approaches to battery pack design, each balancing modularity, integration, cost, and manufacturability. These approaches reflect trade-offs between performance optimization and long-term serviceability.

Tesla’s battery architecture is renowned for its energy density and structural integration. In the Model S and Model 3, Tesla utilizes tightly packed cylindrical cells within a bonded and potted structure. This configuration enhances thermal and structural performance but poses major serviceability challenges [17]. The pack is difficult to open without specialized tools, and module replacement is rarely viable outside centralized service hubs. Moreover, Tesla limits third-party access to diagnostic interfaces, restricting service to certified centers. While this allows for quality control, it reduces flexibility and raises ownership costs for out-of-warranty customers [18].

In contrast, Rivian’s R1T and R1S platforms emphasize ruggedness and field maintainability. The company uses a stackable modular configuration where sub-packs can be accessed through removable panels. Diagnostic ports are externalized, and module identification labels are visible without disassembly. These design decisions align with Rivian’s customer base—off-road users and fleet operators—who value service flexibility in decentralized locations [19].

General Motors (GM) introduced the Ultium battery platform, which represents a balance between modularity and manufacturing efficiency. Ultium utilizes large-format pouch cells arranged in replaceable modules within a scalable matrix. Each module is individually cooled and monitored, with connectors designed for rapid disconnection. GM’s platform also features a unified BMS capable of module-level voltage and thermal reporting, allowing granular diagnostics. This design supports both performance optimization and field-level module replacement, making it one of the most serviceable high-capacity systems currently in mass production [20].

Lucid Motors, with its Air luxury sedan, has adopted a semi-serviceable architecture. Lucid’s pack consists of high-density cylindrical cells housed in “smart modules” with embedded diagnostics and voltage balancing. Although the pack is sealed with a structural enclosure for stiffness and crash safety, the modules are accessible via a guided removal process. Lucid has partnered with certified technicians and provides cloud-linked diagnostics for remote fault detection.

While less modular than Rivian or GM, Lucid's architecture supports tiered service workflows and prioritizes safety in handling [21].

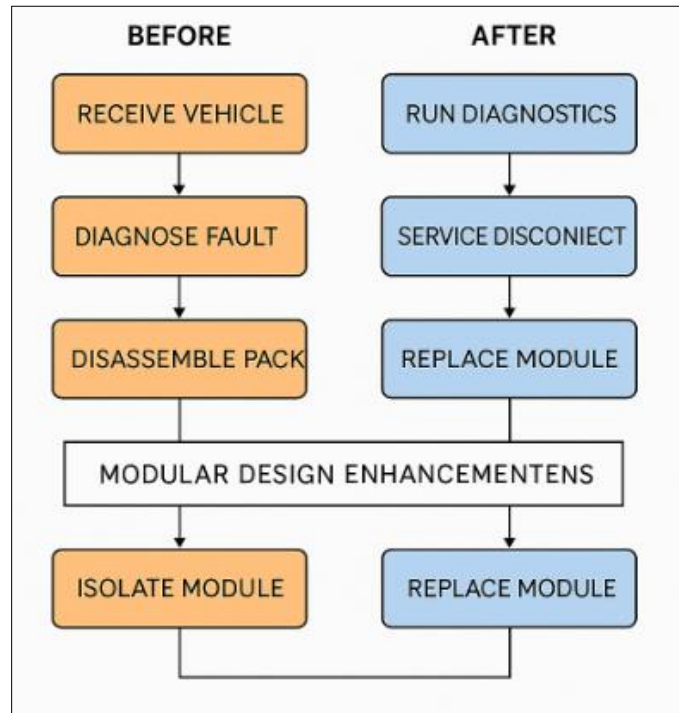


Figure 2 Exploded-view comparison of battery pack modularity across OEMs

Table 2 OEM Modularity Scores — Accessibility, Diagnostic Interface, Part-Level Repairability

OEM	Accessibility (0–5)	Diagnostic Interface (0–5)	Part-Level Repairability (0–5)	Total Score (0–15)	Remarks
Tesla	2	2	1	5	Highly integrated design; limited third-party diagnostics; low modular serviceability.
Rivian	5	4	4	13	Rugged modular layout; accessible panels; good BMS data access.
GM (Ultium)	4	5	4	13	Strong module-level diagnostics and field-serviceable modules.
Lucid	3	4	3	10	Semi-serviceable smart packs; decent diagnostic clarity.
Ford	4	3	3	10	Modular design across platforms; moderate interface transparency.
Hyundai/Kia	3	3	2	8	Pack segmentation exists; limited BMS openness; service strategy evolving.
Volkswagen	4	3	3	10	ID series offers moderate serviceability and growing diagnostic capabilities.

Table 2 scores OEM platforms on modularity based on three core dimensions: physical accessibility, diagnostic interface transparency, and feasibility of part-level repairability. Rivian and GM score highest across all categories, while Tesla scores lowest in serviceability despite technological sophistication [22].

OEM decisions around modularity are shaped not only by technical feasibility but also by brand strategy, repair ecosystem philosophy, and post-sale monetization models. Manufacturers who prioritize customer experience, fleet serviceability, and circular economy alignment tend to invest more heavily in modularity and open diagnostics.

As the EV market matures, industry momentum is shifting toward standardized modularity benchmarks. Collaborative initiatives between OEMs, regulators, and service providers may soon codify minimum serviceability standards—further pressuring automakers to reconsider their design choices in favor of technician safety, efficiency, and long-term cost control [23].

3. Impact of modular design on manufacturing, scalability, and recycling

3.1. Manufacturing and Automated Assembly

The industrialization of electric vehicle (EV) battery production has prioritized automation, standardization, and throughput efficiency. In this context, modular battery pack architectures present unique advantages for manufacturing and robotic assembly, especially when compared to fully integrated designs. Modular packs often use repeatable sub-structures, such as standardized trays, busbar arrangements, and coolant manifolds, that can be produced and assembled in a robot-friendly sequence [11].

The emergence of cell-to-pack (CTP) and module-to-pack (MTP) strategies has further streamlined production processes. CTP design eliminates intermediate module casings and places cells directly into the pack housing, enhancing energy density and reducing material use. MTP configurations maintain modular benefits while preserving efficient sub-pack integration, allowing manufacturers to strike a balance between serviceability and performance [12]. These architectures reduce the number of individual welds, connectors, and fasteners—each of which adds complexity and cost in automated environments.

One of the key enablers of automation is dimensional consistency. Modular systems often employ precisely aligned cell arrays, compatible with robotic stacking, adhesive application, and torquing procedures. This repeatability supports high-throughput assembly lines while maintaining tight tolerances required for thermal management and safety [13].

Despite these advantages, trade-offs remain. Greater modularity often requires additional mechanical enclosures, interconnects, and redundant cooling pathways, which can slightly reduce gravimetric energy density. For high-performance vehicles or long-range applications, these compromises can affect overall vehicle range or require upsizing of the battery footprint [14].

To address this, advanced OEMs use hybrid techniques such as smart modularization, where only failure-prone zones are designed for disassembly, while low-risk zones are optimized for integration. These hybrid approaches retain the benefits of modular manufacturing while preserving energy density targets [15].

Ultimately, the compatibility of modular pack designs with automated assembly systems enhances manufacturability, reduces labor dependency, and enables faster product iteration cycles, making them highly attractive for modern gigafactory environments.

3.2. Scalability and Platform Flexibility

One of the most strategically important advantages of modular battery architecture is its potential for scalability and cross-platform flexibility. In the era of vehicle electrification, automakers are moving toward "design once, deploy many" platforms, where a single battery system can power multiple vehicle types—from sedans to SUVs to delivery vans—with minimal modification [16].

Modular packs make this possible by allowing variable stack configurations. OEMs can increase pack capacity by adding more modules or achieve weight savings by reducing the module count—all while maintaining consistent interface geometries and electronic control protocols. For instance, General Motors' Ultium platform uses a standardized cell format and pack structure across dozens of vehicle models, minimizing development lead time and production line complexity [17].

This standardization also simplifies logistics and inventory management. A modular architecture enables automakers and service centers to stock a common set of replacement modules and connectors instead of bespoke parts for each vehicle model. This consolidation reduces warehouse footprint, improves parts availability, and streamlines global service supply chains [18].

From a product development perspective, modularity supports parallel engineering. Battery teams can develop modules and packs concurrently with vehicle chassis designers, reducing the need for redesign when vehicle parameters evolve. This accelerates time-to-market and lowers the risk of costly mid-cycle adjustments [19].

Moreover, flexible battery packs facilitate the integration of different cell chemistries (e.g., NMC, LFP) or form factors (e.g., pouch, prismatic) for regional customization or cost optimization. This adaptability is particularly valuable for automakers selling across markets with varying environmental conditions, subsidy schemes, and performance expectations [20].

However, achieving such flexibility requires deliberate architectural planning. The mechanical, thermal, and electrical interfaces of modules must be designed for interoperability, often requiring complex simulation and validation to ensure that packs perform reliably across configurations. Despite the engineering overhead, the long-term economic and logistical gains of scalable modular systems make them a compelling design strategy [21].

Thus, modular battery platforms offer a foundation for cost-effective product diversification, inventory optimization, and consistent service delivery—critical factors in a competitive and fast-evolving EV market.

3.3. Recycling and Second-Life Applications

Battery end-of-life (EOL) management is an urgent priority as EV adoption scales globally. Modular battery architectures offer significant advantages for both recycling and second-life applications, particularly by enabling safer, faster, and more efficient pack disassembly and materials recovery.

One of the primary benefits of modularity is ease of module-level testing. Before recycling, battery packs are often evaluated for second-life use in stationary energy storage, grid balancing, or microgrid systems. Modular designs allow technicians to isolate and test individual modules for state of health (SOH), internal resistance, and capacity retention. Modules that meet performance thresholds can be redeployed, while degraded ones are directed to material recovery processes [22].

In contrast, integrated packs often require destructive disassembly or yield inconsistent module integrity, reducing reuse potential and increasing hazardous waste. Modular systems simplify this triage process, supporting circular economy objectives and reducing the carbon footprint of battery production through reuse [23].

Design also impacts end-of-life sorting and dismantling efficiency. Modular packs with standard fasteners, labeled harnesses, and separable components can be dismantled by semi-automated systems, reducing labor costs and technician exposure to toxic materials. In contrast, integrated packs often rely on adhesives, welds, or proprietary seals, complicating automation and increasing environmental hazard risks [24].

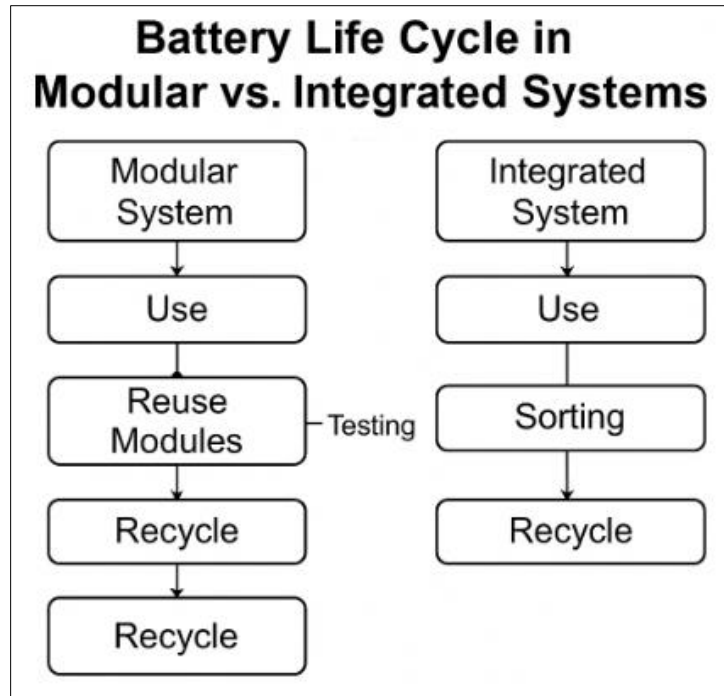


Figure 3 Flow diagram – battery life cycle in modular vs. integrated systems

From a materials perspective, modularity enables cleaner separation of high-value materials such as cobalt, nickel, and copper. Packs designed for recyclability use dissimilar material junctions, coating indicators, and tool-readable QR codes to improve traceability and automation compatibility in dismantling lines [25].

Table 3 Recyclability Metrics – Time, Automation Compatibility, Material Recovery Rate

Pack Type	Average Disassembly Time (min)	Automation Compatibility (0–5)	Material Recovery Rate (%)	Remarks
Modular (High-end)	25–40	4.5	85–90	Fast disassembly with standardized fasteners; suitable for robotic sorting and recovery.
Modular (Standard)	45–60	3.5	75–85	Requires semi-automated processes; some manual intervention still necessary.
Semi-Modular	60–90	2.5	60–75	Mixed interfaces; adhesives and limited standardization increase processing time.
Integrated	120–180	1.5	40–55	Adhesives, welded joints, and unclear separation paths hinder dismantling and recovery.
Potted/Sealed	>180	0.5	<40	Destructive disassembly often required; minimal automation potential and high waste.

Table 3 presents key recyclability metrics across modular and integrated pack designs. Metrics include average disassembly time, compatibility with automated extraction systems, and total recoverable material mass. Modular designs consistently outperform integrated architectures, particularly in automation readiness and safe handling scores [26].

Regulators are also encouraging design-for-recyclability (DfR) through extended producer responsibility (EPR) legislation. The EU Battery Regulation, for instance, mandates that EV batteries sold after 2025 meet minimum standards for removability, labeling, and recyclability. Modular packs are better suited to comply with these rules without major redesigns [27].

Finally, end-of-life battery logistics benefit from modularity. Damaged packs can be transported as separated sub-units, minimizing fire risk during transit and lowering shipping classifications. This improves safety compliance and reduces the insurance and regulatory burden for recyclers and logistics providers [28].

In sum, modular design enhances the technical, economic, and regulatory feasibility of recycling and repurposing EV batteries. As sustainability becomes a strategic imperative for automakers, these advantages position modular architecture as a cornerstone of environmentally responsible battery lifecycle management.

4. Interface standards and diagnostic accessibility

4.1. Electrical and Communication Interfaces

The design of electrical and communication interfaces within EV battery packs plays a decisive role in serviceability, safety, and cross-platform operability. As battery pack architecture becomes increasingly modular, the reliability and accessibility of connectors, interlocks, and communication protocols become critical enablers of efficient diagnostics and safe intervention.

High-voltage connectors in modular packs must not only transmit power reliably but also offer secure locking mechanisms and visual or mechanical confirmation of engagement. Serviceable designs feature tool-less disconnects, integrated voltage isolation interlocks, and built-in pre-charge circuits to protect technicians from arc flashes during connection or disconnection [15]. These connectors also need to accommodate multiple mating cycles without degradation, supporting module-level swaps during field servicing or diagnostics.

To ensure operational safety, modern packs incorporate high-voltage interlock loops (HVILs). These are integrated circuits that break the control signal when connectors or enclosures are opened, acting as a fail-safe to prevent electric shock or unintentional energization during servicing [16]. Proper HVIL integration also aids in alerting service personnel when packs are unsafe to access, reducing technician error and injury.

On the communication side, Battery Management Systems (BMS) interface with the vehicle through protocols like CAN (Controller Area Network), LIN (Local Interconnect Network), or, in more advanced systems, automotive-grade Ethernet. These protocols enable real-time monitoring of voltage, temperature, and fault events across modules, supporting pack-level and cell-level visibility [17]. CAN remains the dominant protocol due to its robustness and simplicity, though Ethernet's bandwidth offers enhanced diagnostic granularity for high-capacity packs.

These interfaces directly impact interoperability and service efficiency. Packs with standardized connectors and open BMS interfaces allow for third-party diagnostics, streamlined repairs, and faster integration into aftermarket and second-life systems [18]. Conversely, proprietary or encrypted interfaces hinder servicing, driving up costs and limiting the battery's usable life beyond the original vehicle platform.

4.2. Diagnostic and Accessibility Requirements

Effective serviceability hinges not only on hardware accessibility but also on the clarity and reliability of diagnostic feedback provided by the battery system. As EV platforms become more data-driven, technicians rely increasingly on accurate, real-time error reporting and interpretability to make safe and informed decisions during inspection and repair.

Modern packs incorporate fail-safe signaling protocols designed to trigger specific alerts in the event of abnormal conditions—such as overvoltage, overcurrent, or cell imbalance. These alerts are communicated via error codes, whose interpretability depends on the transparency of BMS programming and the accessibility of decoding tools [19]. When error codes are opaque or inconsistently applied across OEMs, diagnosis becomes time-consuming and unreliable, increasing downtime and the likelihood of incomplete repairs.

To address these challenges, many manufacturers are enhancing scan tool compatibility with standardized interfaces. Advanced diagnostic platforms allow technicians to plug into vehicle or module-level ports using Unified Diagnostic

Services (UDS) or OBD-II-compatible tools, streamlining fault detection and reducing dependence on OEM-specific systems [20]. This interoperability is crucial for independent garages and fleet service providers who manage multi-brand vehicle inventories.

A key enabler of diagnostic efficiency is the use of onboard self-diagnostics embedded within the BMS and module control units. These systems perform real-time checks on sensor functionality, thermal excursions, and communication health. By flagging issues proactively and generating time-stamped logs, self-diagnostics enhance traceability and support both reactive and predictive maintenance workflows [21].

Additionally, remote access systems—such as cloud-connected BMS modules—allow OEMs and certified service providers to access error logs, perform over-the-air (OTA) updates, or initiate remote diagnostics. These capabilities improve uptime for commercial EV fleets and allow centralized monitoring of pack health across geographic locations [22].

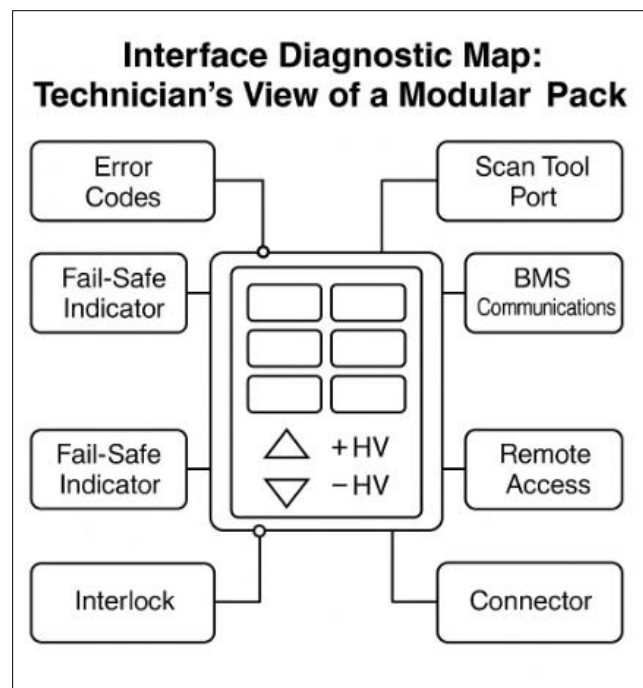


Figure 4 Interface diagnostic map – technician's view of a modular pack

Figure 4 illustrates how diagnostic ports, communication buses, and module interfaces are organized within a modular pack to support multi-tier troubleshooting—from basic fault alerts to deep protocol interrogation.

Ultimately, transparent diagnostics reduce service time, improve safety, and support a scalable repair infrastructure across varied service environments.

4.3. Push Toward Interoperable Standards

The growing complexity of EV battery systems and the diversity of OEM design philosophies underscore the urgent need for interoperable service standards. Without a unified approach, the industry risks creating silos of proprietary architectures that limit independent repair, inflate costs, and reduce the lifespan of high-value battery assets.

The lack of standardized repair protocols means that even similar battery faults may require different tools, procedures, or service codes depending on the manufacturer. This inconsistency not only delays diagnosis but also increases technician training costs and introduces variability in service quality across repair centers [23]. A harmonized framework for error codes, safety interlocks, and module connectivity would allow for cross-brand servicing and more efficient repair networks.

To that end, standardization bodies such as the Society of Automotive Engineers (SAE), International Electrotechnical Commission (IEC), and International Organization for Standardization (ISO) are actively developing guidelines for

battery pack serviceability. SAE J2998, for instance, outlines recommendations for the design of removable and serviceable energy storage devices, while ISO 6469 provides safety specifications for high-voltage systems [24].

Another key goal is the harmonization of connector designs and diagnostic language. Uniform pinout configurations, signal mapping, and connector geometry would allow for standardized testing equipment and interchangeable parts across manufacturers. Likewise, a shared lexicon for BMS fault codes would empower third-party scan tool providers to develop cross-platform solutions, enhancing accessibility for smaller service providers and independent technicians [25].

Some jurisdictions are also pursuing regulation. The EU Battery Regulation mandates removability and labeling standards for high-voltage batteries by 2027, effectively pushing OEMs toward more open and accessible designs. In the U.S., state-level Right-to-Repair laws are increasingly extending into EV components, potentially requiring OEMs to disclose diagnostic interfaces and service manuals [26].

Standardization further supports battery second-life and recycling ecosystems. When packs follow common design and communication templates, reverse logistics, repurposing, and material recovery can be executed more efficiently and with fewer safety risks [27].

Interoperable standards are no longer optional—they are essential for ensuring a sustainable, service-ready EV ecosystem that meets the demands of consumers, regulators, and service providers alike.

5. Field case study: modular design in action

5.1. Challenges Observed in Real-World Service Scenarios

Despite engineering advancements in EV battery systems, real-world service operations frequently encounter major obstacles that compromise technician safety, prolong vehicle downtime, and inflate service costs. Many of these challenges stem from design decisions that prioritize performance or manufacturability over long-term maintainability [19].

One of the most common pain points reported by service technicians is inconsistent diagnostics. Even when advanced Battery Management Systems (BMS) are present, fault codes are often proprietary, encrypted, or too generic to support accurate troubleshooting. For example, a vague alert indicating “pack imbalance” may be insufficient to identify which module or cell string is at fault, forcing technicians to conduct multi-step manual voltage checks across the pack [20].

This lack of granularity in fault reporting delay’s fault isolation, particularly when thermal or voltage anomalies are intermittent. For mobile technicians or regional service centers with limited equipment, extended diagnostic time directly increases downtime and impairs throughput. These delays also impact customer satisfaction and fleet reliability, especially in ride-share or logistics platforms [21].

Another high-risk area in field servicing is the execution of balancing procedures. Passive or active balancing systems, which equalize charge across cells, can pose hazards when performed manually without proper real-time monitoring. In some designs, accessing the balancing bus requires partial disassembly of live circuits, raising the risk of short circuits or technician injury. In other cases, a lack of standardized balancing connectors results in inconsistent procedural execution, raising the probability of improper pack reassembly [22].

Incorrect pack handling also remains a recurring issue. Battery packs often lack clear external labeling, torque markings, or disconnection indicators. This ambiguity can lead to improper hoisting, misplaced tools, or unintentional damage to pressure relief valves and thermal sensors during disassembly. In some field reports, packs were damaged beyond repair during basic inspection due to inadequate access pathways or irreversible casing adhesives [23].

Collectively, these challenges reflect a misalignment between design assumptions and field realities. As EV deployment accelerates globally, addressing these real-world servicing limitations becomes critical not only for safety and cost control but also for ensuring long-term customer confidence in EV platforms.

5.2. Modular Design Interventions and Outcomes

To address these challenges, several OEMs and battery integrators have begun introducing modular design interventions that enhance safety, reduce diagnostic ambiguity, and accelerate servicing efficiency. These innovations

focus on embedding serviceability into the hardware and digital architecture of the battery system, with demonstrable improvements in technician workflow and risk management.

One key benefit observed post-intervention is improved diagnostic confidence. Modular packs are increasingly equipped with module-level voltage and thermal sensors that relay granular data to the central BMS. When a fault arises, this system isolates the specific module at fault, enabling targeted inspection or replacement rather than pack-wide teardown. This reduces error propagation and significantly enhances the success rate of first-time repairs [24].

Technicians have also reported faster pack isolation in modular systems. The addition of standardized service disconnects, high-voltage interlock loops (HVILs), and color-coded fasteners simplifies the safe deactivation of live circuits. In systems with integrated service ports, such as those employed in GM's Ultium platform, pack de-energization can be completed in under five minutes—down from 15 to 20 minutes for earlier designs [25]. These improvements are critical in high-throughput workshops or roadside service environments where speed and safety are equally prioritized.

Importantly, modular systems reduce technician risk exposure. In conventional pack designs, identifying a failed cell often requires intrusive disassembly and pack deconstruction, increasing exposure to high-voltage circuits and chemically reactive materials. By contrast, modular layouts allow for enclosure-level access with physical isolation barriers and low-voltage service zones, reducing the need for direct interaction with high-energy components [26].

Several successful interventions involve the integration of diagnostic buses that run parallel to the power delivery circuits. These buses are dedicated pathways for sensor signals and command instructions, enabling real-time communication with each module's microcontroller. The isolation of these channels improves signal fidelity and allows technicians to extract historical fault logs even in the absence of live vehicle connections [27].

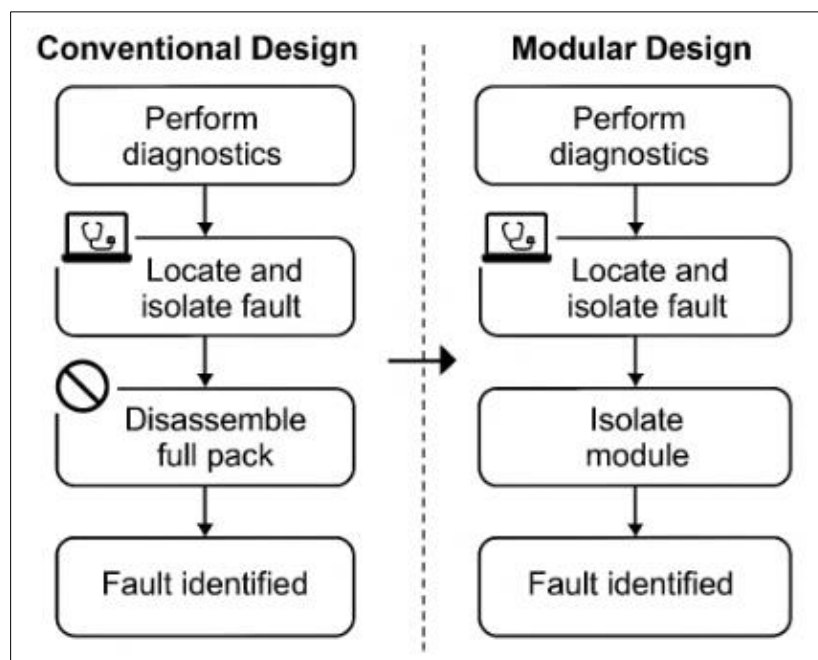


Figure 5 Service flow diagram before and after modular design enhancements

Figure 5 compares technician workflows in conventional and modular battery pack designs, showing reductions in diagnostic steps, isolation time, and physical intervention risk.

Another enhancement is the inclusion of modular interlocks—hardware switches embedded into each module enclosure that trigger BMS alerts when the module is accessed or disconnected. This allows service teams to verify whether modules were correctly reinstalled and whether any tampering has occurred, aiding in warranty validation and post-service safety checks [28].

As more data from field operations becomes available, modular interventions continue to validate their value proposition in reducing service complexity, enhancing technician safety, and extending pack life.

5.3. Broader Implications for Industry Practice

The integration of modular design principles into EV battery systems has broad implications for industry stakeholders. For OEMs, it highlights the importance of aligning product development with downstream service realities. Incorporating diagnostics, safe access mechanisms, and part-level replaceability at the design stage leads to lower warranty claims, improved brand loyalty, and long-term operational efficiency [29].

Repair networks, both OEM-affiliated and independent, benefit from standardized workflows, reduced training burden, and scalable service models that can adapt across vehicle platforms. Modular packs also support more consistent pricing for repairs and enable predictive maintenance strategies that improve workshop throughput and uptime.

For battery developers and integrators, these field insights reinforce the need to co-engineer pack hardware and embedded systems in tandem. The evolution of smart modules, self-diagnostics, and secure interlocks represents a step toward autonomous servicing, reducing human error and enabling future remote repair technologies.

Ultimately, modularity is more than a design preference—it is a strategic imperative for achieving safe, efficient, and scalable electrification. As lessons from the field continue to inform R&D, modular battery design stands to define the future of EV maintenance, sustainability, and customer experience [30].

6. Future outlook and industry recommendations

6.1. Current Gaps and Unmet Needs

Despite significant strides in EV battery modularity and serviceability, several critical gaps remain in current-generation pack designs. These limitations hinder scalability, technician safety, and lifecycle cost optimization, particularly as electric mobility moves toward mass adoption.

A persistent issue across both consumer and commercial platforms is the slow execution of module swap procedures. In many vehicles, even modular packs still require extensive disassembly, high-voltage isolation steps, and manual clearance of adjacent systems before a single module can be replaced [24]. These delays are especially costly in fleet environments, where vehicle downtime translates directly to lost revenue and operational inefficiency.

Another gap lies in the underutilization of smart fasteners and embedded sensor hardware. While progress has been made in integrating voltage and temperature sensors within modules, most mechanical fasteners—such as bolts, clips, or covers—are passive and provide no real-time feedback on torque, alignment, or reinstallation status. Without embedded intelligence, technicians must rely on visual inspections or torque charts, increasing the risk of misassembly or overlooking structural fatigue [25].

Live diagnostics during servicing also remain limited. Although BMS systems log operational data, few allow real-time feedback during active service. In many cases, modules must be powered down completely, limiting the ability to correlate live error codes with physical inspection or triggering conditions. Additionally, diagnostic interfaces often require OEM-specific software or encrypted protocols, restricting access for third-party service providers [26].

Finally, there is growing concern over the overly proprietary nature of connectors and control logic in current modular systems. While this supports branding and design differentiation, it inhibits interoperability, increases tooling costs, and prevents rapid cross-OEM service standardization. Without open specifications, technicians are forced to learn redundant systems, and diagnostic tools require frequent firmware updates just to remain functional across platforms [30].

These unmet needs highlight the importance of transitioning from modularity as a structural principle to a fully integrated service-aware design philosophy, where mechanical, electrical, and digital interfaces coalesce to optimize maintainability and safety in tandem.

6.2. Recommendations for R&D and Innovation

To overcome the limitations outlined above, targeted investment in research and development is required across hardware design, control architecture, and diagnostic intelligence. These innovations must prioritize serviceability as a core design metric, not a secondary engineering concern [31].

First, predictive diagnostics should be embedded at the modular BMS level, not just at the pack controller. This distributed intelligence would allow each module to monitor its own state of health, cycle degradation, and fault signatures independently, then communicate aggregated insights to the master BMS. When implemented effectively, this approach reduces diagnostic latency and enables early warning systems for preventive servicing and scheduling [32].

Second, the deployment of electrically smart fasteners can transform the service process. These fasteners would incorporate torque sensors, RFID tags, or pressure contacts that report their installation status directly to the BMS or external diagnostic tools. Upon servicing, the system could confirm whether all fasteners were correctly reinstalled and alert the technician to potential oversights. This is especially critical in high-voltage systems where improper reassembly can result in catastrophic failure [33].

Another area for advancement is the integration of service-aware pack design into CAD and digital prototyping. Battery design teams should simulate not only structural and thermal behavior but also technician access pathways, clearance zones, and component reachability. Digital twins of battery packs can be used during the design phase to model human interaction and servicing ergonomics, incorporating parameters such as tool compatibility, visibility, and torque angles [34].

In tandem with hardware evolution, development of open-source service communication protocols is essential. Collaborative platforms, possibly hosted by standards bodies or consortia, can facilitate the co-development of diagnostic buses, error lexicons, and interface specifications. Doing so would enable multi-OEM service hubs and reduce the need for platform-specific diagnostic subscriptions, accelerating the development of a competitive and competent EV service industry [35].

These R&D interventions align with broader goals in cost reduction, technician safety, regulatory compliance, and system transparency. By embedding service-oriented intelligence into the core battery architecture, OEMs and suppliers can unlock significant operational and economic gains throughout the battery's lifecycle.

6.3. Vision for Next-Generation Modular Battery Systems

The next generation of modular battery systems must evolve beyond segmented hardware to deliver a fully autonomous, data-rich, and technician-safe service paradigm. As EVs transition from niche products to fleet mainstays and urban mobility solutions, their battery architectures must reflect the principles of transparency, adaptability, and proactive intervention [36].

One frontier is the development of autonomous service capability, where packs not only report faults but initiate isolation, notify technicians, and prepare themselves for intervention. For instance, an intelligent pack could shift itself into a low-voltage safe state, log pre-fault sensor data, release mounting clips via mechatronic actuators, and send a maintenance alert with a detailed repair plan to a connected cloud system [37]. This would transform the technician's role from diagnostician to verifier, significantly lowering risk and variability.

Modularity must also extend to thermal management subsystems, which are currently integrated in ways that complicate service. Next-gen designs should use quick-connect thermal couplings, detachable plate exchangers, and independent thermal controllers for each module group. This enables partial servicing without draining coolant from the entire system and supports plug-and-play upgrades to newer cooling technologies over time [38].

Regulatory-compliant modularity must be central to future design. With evolving mandates from the EU, China, and North America, battery packs must demonstrate safe removability, recyclability, and diagnostic clarity. Packs that fail to meet these requirements will face restricted market access, insurance penalties, or warranty exclusions. A modular pack designed with embedded compliance—traceability codes, safe handling mechanisms, and dismantling automation markers—positions the OEM for global market viability [39].

Finally, serviceability Key Performance Indicators (KPIs) should be integrated into the product development pipeline alongside cost, weight, and energy density. KPIs such as average diagnostic time, technician exposure index, or successful first-repair rate can be used to benchmark and optimize designs [40]. These metrics must be reviewed during design gates and validated through field testing, ensuring that serviceability remains a measurable and iterative component of innovation [41].

In totality, the vision for future modular battery systems is one where design, diagnostics, and field execution are seamlessly unified—paving the way for a safer, smarter, and more sustainable electrified transportation ecosystem.

7. Conclusion

The evolution of electric vehicle (EV) battery systems has rightly prioritized energy density, power efficiency, and thermal stability. However, as EV adoption matures and vehicles reach broader markets, another dimension is rising to equal strategic importance: serviceability. This study has demonstrated that modular battery pack design is not merely a structural convenience—it is a transformative enabler of safer, faster, and more cost-effective field servicing. Through modular configurations, technicians gain improved access, diagnostic clarity, and operational confidence, while manufacturers benefit from reduced downtime, enhanced brand trust, and scalable maintenance infrastructures.

Modular battery packs empower service networks to isolate faults quickly, swap components without full-pack replacement, and implement targeted interventions rather than resorting to labor-intensive disassembly. These advantages extend beyond individual repairs. They reshape warranty economics, support emerging reuse markets, and strengthen the long-term sustainability of EV platforms. From fasteners to interlocks, from connector logic to communication buses, the granular choices embedded in modular design dictate how safely and efficiently a battery can be maintained throughout its lifecycle.

Yet, the conversation around EV battery innovation has historically been dominated by metrics such as range, acceleration, and charging time. These are important, but they tell only part of the story. A high-performance battery that cannot be safely or economically serviced becomes a liability—one that erodes customer satisfaction, elevates total cost of ownership, and undermines the environmental promise of electrification. Service design must be treated with the same rigor and foresight as performance engineering, particularly as the market moves toward commercial fleets, shared mobility, and right-to-repair advocacy.

The way forward is clear. OEMs, battery developers, and standards bodies must rethink pack design from the field technician upward. This requires embedding serviceability KPIs into design reviews, leveraging technician feedback in prototyping, and embracing automation-ready modular layouts that anticipate end-of-life realities. Smart fasteners, predictive diagnostics, and technician-safe interfaces should be standard features—not afterthoughts.

In the transition to electric mobility, batteries are no longer just components; they are dynamic, data-rich, mission-critical systems. Designing them to be serviceable is not optional—it is foundational to reliability, safety, and sustainability. The next generation of EV batteries must not only perform at the frontier—they must be ready for the hands that will keep them running.

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