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Some Critical Thinking on Electric Vehicle Battery Reliability: From Enhancement to Optimization

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Abstract: Electric vehicle (EV) batteries play a crucial role in sustainable transportation, with reliability being pivotal to their performance, longevity, and environmental impact. This study explores battery reliability from micro (individual user), meso (industry), and macro (societal) perspectives, emphasizing interconnected factors and challenges across the lifecycle. A novel lifecycle framework is proposed, introducing the concept of "Zero-Life" reliability to expand traditional evaluation methods. By integrating the reliability ecosystem with a dynamic system approach, this research offers comprehensive insights into the optimization of EV battery systems. Furthermore, an expansive Social–Industrial Large Knowledge Model (S-ILKM) is presented, bridging micro- and macro-level insights to enhance reliability across lifecycle stages. The findings provide a systematic pathway to advance EV battery reliability, aligning with global sustainability objectives and fostering innovation in sustainable mobility.

Keywords: system reliability enhancement; reliability system optimization; EV battery; "zero"-life reliability; sustainable transportation; social–industrial large knowledge model (S-ILKM)

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1. Introduction

In the transformative era of sustainable transportation, electric vehicles (EVs) stand at the forefront of an eco-conscious e-mobility revolution, which is not just about replacing fossil-fuel-driven vehicles with electric ones; it is about fostering a sustainable, efficient, and environmentally friendly transportation system that aligns with broader goals of reducing emissions, conserving energy, and promoting public health and economic growth [1–5].

EVs distinguish themselves from traditional vehicles by featuring a novel and crucial electrical system, which include battery packs, charging mechanisms, and power distribution systems. This battery system serves as the primary power source for propulsion. Not only is the battery system economically significant, accounting for up to 40% of the total cost of EVs [6], but it also fundamentally influences the EV's driving range, performance, efficiency, and environmental impact. Despite technological advancements [4], including lithium battery technology, the next challenge lies in making these batteries more sustainable, high-performing, and durable [7].

Reliability, fundamentally defined as the ability of a system to perform its required functions under specific conditions for a designated period, plays a pivotal role in making EV batteries more sustainable, high-performing, and durable by ensuring consistent and safe operation over an extended lifespan, which reduces the need for frequent maintenance and eventual replacement. This long-term dependability is crucial for sustaining high performance under various conditions, minimizing environmental impact through less frequent resource extraction and waste, and ultimately supporting the durability of the batteries, making them a more sustainable choice for electric mobility [8].

Current state-of-the-art reviews indicate that efforts to enhance EV battery reliability predominantly focus on isolated solutions, including but not limited to (1) battery design, encompassing material selection, uniformity, and degradation characters among battery cells and packs [9–13]; (2) power density optimization [14]; (3) environmental impact factors such as temperature, moisture, and road conditions [15–17]; (4) driving behaviors, including driving schedule, speed, acceleration, and braking patterns [18]; and (5) charging and discharging strategies [19–23]. In these research studies, an efficient battery management system (BMS) for condition monitoring, thermal management, balance management, fault diagnosis and prediction [24–29], and metrics such as Battery State-of-Health (SOH), State-of-Charge (SOC), State-of-Energy (SOE), and Remaining Useful Life (RUL) are commonly utilized to gauge operational reliability (Operational reliability = inherent reliability + use reliability. Reliability is a birth-to-death concern, where the inherent reliability of a product is decided in the stages of concept and definition, design and development, manufacture and installation, while the use reliability of a product is decided in the stage of operation and maintenance. For more details, see Section 3) [30–34].

The reliance on isolated solutions for enhancing EV battery reliability, although beneficial for targeted issues, can fall short in a broader context. This approach often has a limited scope, addressing specific components or aspects without considering the intricate interdependencies within the battery and vehicle systems. Such a narrow focus can lead to *short-term* solutions that fail to tackle underlying systemic challenges, potentially leading to recurring problems. For instance, improvements in battery materials for increased capacity might adversely affect thermal management, highlighting how changes in one area can have unintended consequences in others. Another significant limitation of isolated approaches is their inability to keep pace with rapid advancements in technology and evolving user needs, reducing their *long-term* applicability. Concentrating solely on reliability metrics like State-of-Health (SOH) or Remaining Useful Life (RUL) often overlooks crucial factors such as safety, environmental impact, and user experience. For example, a battery with a high SOH might still pose safety risks if not designed with comprehensive safety mechanisms. The lack of a holistic perspective, incorporating the reliability ecosystem and lifecycle framework, results in missed opportunities for systematic improvement and a comprehensive understanding of the battery's operational environment.

To overcome the above shortcomings on continuous enhancement of EV battery reliability and further propose a holistic approach, this study is structured to answer three research questions (RQs):

RQ1: Why is enhancing EV battery reliability a must from a comprehensive and holistic perspective?

How are EV battery reliability ecosystems defined at micro (individual), meso (industrial), and macro (society) levels?

Which factors interconnect and influence battery reliability at the micro, meso, and macro levels?

RQ2: What is the framework of the EV battery reliability lifecycle?

What is the difference between general reliability framework and lifecycle of EV batteries during various stages?

How to understand the difference between “Zero”-Life reliability and reliability?

How is the concept of Use and Reuse, Repurpose, and Recycle connected to the use reliability of EV batteries?

RQ3: What is holistic system cognition of EV battery reliability for reliability system optimization?

What is the composition of system cognation from point to System of Systems (SoS)?

How to understand the intrinsic nature of reliability system optimization?

To answer RQ1, Section 2 delves into the multifaceted necessity of high EV battery reliability, exploring its importance from micro, meso, and macro perspectives. It provides ecosystem analysis, illustrating how factors interconnect and influence battery reliability. The goal is to underscore the far-reaching impact of reliability on everything from individual consumer satisfaction and industrial competitiveness to broader environmental sustainability. To answer RQ2, Section 3 introduces an innovative approach to understanding the EV battery reliability lifecycle. It transitions from a general reliability framework to a specific focus on the lifecycle of EV batteries, including integrating focuses during the use stages (use, reuse, repurpose, recycle), and a novel concept of “Zero”-Life reliability is introduced—a stage that encompasses the period between battery manufacture to its initial operational use in a vehicle from its intended first lift within the lifecycle framework. To answer RQ3, Section 4 presents an integrated view of the reliability ecosystem and lifecycle frameworks of EV batteries, conceptualized through triangular geometries. It explores the concept of time as a pivotal factor that transforms the stationary status into a dynamic one, revealing the intrinsic nature of reliability system optimization. Following the above critical thinking, Section 5 engages in an extensive discussion on future directions, offering strategic insights into enhancing system reliability through continuous improvement of the reliability system. Through this work, the aim is to contribute novel insights and practical strategies to the ongoing discourse in sustainable transportation and EV technology, providing a pathway for enhancing EV battery reliability in alignment with global sustainability objectives.

2. The Crucial Quest for High Reliability in EV Batteries: Comprehensive Ecosystem Analysis Using Micro, Meso, and Macro Perspectives

This chapter begins by introducing the concept of the “Reliability Ecosystem” in the context of EV batteries, laying the foundation for subsequent analysis. It then systematically unpacks this ecosystem using micro, meso, and macro dimensions (Figure 1). Through this micro-to-macro approach, this chapter aims to provide insights into why improved EV battery reliability is necessary from comprehensive perspectives (RQ2) through a thorough understanding of “Reliability Ecosystems”, which is vital in the pursuit for high reliability in EV batteries (Table 1). This multi-perspective analysis not only highlights the complexities involved in achieving high reliability but also underscores the collaborative effort required between different stakeholders to drive the EV industry towards a more reliable, efficient, and sustainable future.

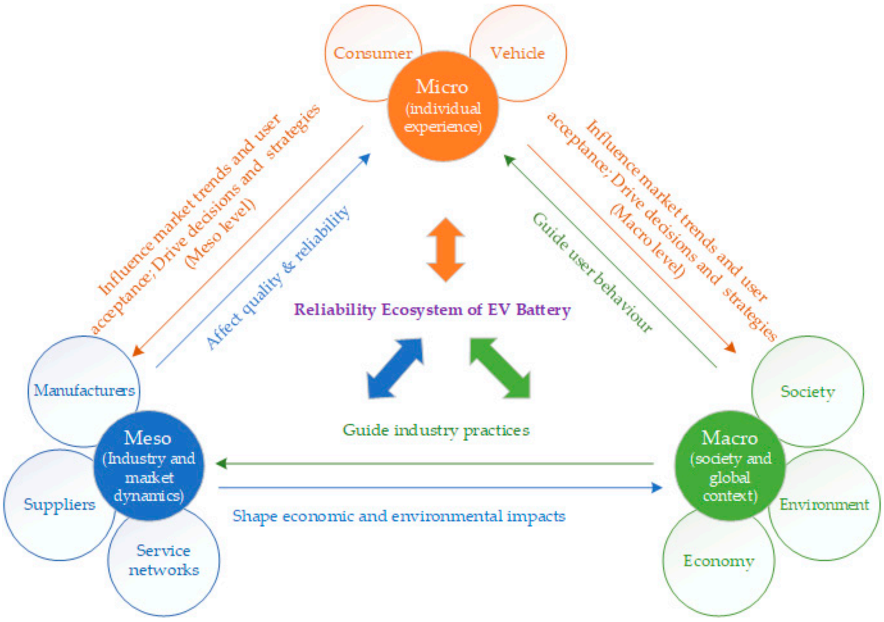

Figure 1. The reliability ecosystem of EV batteries.

Table 1. Crucial quest for high reliability in EV batteries.

Levels	Impacts	Sub Contents
Micro Level	Functionality and Performance	Consistent and Predictable Performance
		Long-Term Operational Efficiency
	Safety Assurance	Mitigation of Safety Hazards
		Trust in Technology
	Comfort and User Experience	Enhanced Driving Pleasure
		Peace of Mind
	Economic Considerations	Cost-Effectiveness
		Resale Value
	Sustainability Impact	Alignment with Environmental Values
		Contribution to Sustainable Mobility
Meso Level	Enhancing Brand Reputation and Competitive Advantage	Brand Image and Consumer Trust
		Competitive Differentiation
	Economic Implications	Reducing Warranty Claims
		Operational Efficiency
	Impact on the Supply Chain	Quality Standards for Suppliers
		Logistics and Distribution
	Influencing Industry Standards and Regulations	Setting Industry Benchmarks
		Regulatory Compliance
	The Ripple Effect to Micro and Macro Levels	Feedback to Consumer Level
		Shaping Market and Policy Trends
Meso Level	Conservation of Finite Resources	Importance of Longevity
		Impact on Resource Extraction
	Reducing Environmental Impacts	Mitigating Emissions
		Minimizing Waste
	Alleviating Pressure on Recycling Systems	Economic and Environmental Efficiency
		Facilitating Circular Economy
	Influencing Global Policies and Market Dynamics	Shaping Sustainable Policies
		Driving Market Trends

2.1. Reliability Ecosystem of EV Batteries

The reliability ecosystem of EV batteries is a multifaceted network of factors, stakeholders, processes, and interactions that collectively influence battery performance and longevity throughout their lifecycle (Figure 1). This ecosystem operates across three interconnected levels—micro, meso, and macro—each contributing unique insights and challenges to the reliability framework.

Micro Level: This perspective emphasizes individual consumer experiences, focusing on the direct impact of battery reliability on users. Feedback from real-world performance informs manufacturers about usage patterns and reliability needs, shaping targeted improvements.

Meso Level: At this level, industry stakeholders, including manufacturers, suppliers, and service networks, play a critical role. Their decisions and innovations directly influence battery design, quality, and operational reliability, while also setting industry standards and responding to regulatory requirements.

Macro Level: Broader societal, environmental, and economic factors define this perspective. Policies, market trends, and global environmental objectives shape the industry's direction, fostering innovations that align battery reliability with sustainability goals and societal well-being.

These perspectives form a dynamic feedback loop. Consumer experiences (micro) drive industry actions (meso), which are further shaped by macro-level policies and trends. Conversely, macro-level strategies guide industry practices and influence individual behaviors, creating a holistic ecosystem for continuous improvement in EV battery reliability.

By examining these interdependencies, this framework provides a comprehensive understanding of how EV battery reliability evolves and is optimized across scales, ensuring alignment with both immediate user needs and broader sustainability objectives.

2.2. Maximizing Consumer Benefits: The Micro-Level Impact of Enhanced EV Battery Reliability

In the rapidly evolving domain of EV technology, the importance of battery reliability from a micro-level perspective on individual consumers and their interaction with EVs is paramount. A more granular viewpoint sheds light on how reliability profoundly influences various aspects of the EV experience, encompassing functionality, safety, comfort, cost-effectiveness, and sustainability.

Functionality and Performance: High reliability in EV batteries is essential for ensuring consistent and predictable vehicle performance. This reliability is fundamental to providing consumers with a dependable range per charge, which is crucial for the effective planning and execution of journeys without the worry of unexpected power issues. Additionally, the sustained operational efficiency of reliable batteries means that the vehicle's performance remains robust over time, enhancing the overall driving experience.

Safety Assurance: Safety is intrinsically linked to the reliability of EV batteries. High reliability drastically reduces risks such as on-road power failures or battery-related fires, not only safeguarding the vehicle occupants but also ensuring overall road safety. As EVs continue to increase in number, the reliability of their batteries becomes a cornerstone in building and maintaining public trust in this emerging technology.

Comfort and User Experience: Reliable batteries significantly enhance driving pleasure by mitigating range anxiety and ensuring the consistent performance of vehicle features, thereby elevating overall user satisfaction. This reliability also provides consumers with peace of mind, knowing that their vehicle is dependable and will perform as expected, a crucial factor in the widespread adoption of EVs.

Economic Considerations: From an economic standpoint, the battery system, often being the costliest component of an EV, plays a significant role in determining the total cost of ownership. High reliability translates into fewer needs for battery replacements and lower maintenance costs throughout the vehicle's lifespan, offering substantial economic benefits. Furthermore, EVs known for their reliable batteries tend to maintain higher resale values, thereby providing an additional economic advantage to consumers.

Sustainability Impact: Reliability in EV batteries aligns with growing consumer awareness and the demand for environmental sustainability. By reducing the frequency of battery replacements, reliable batteries diminish the environmental burden associated with their production and disposal. Additionally, these batteries contribute to sustainable mobility by enhancing the longevity and performance of EVs, in line with global efforts to reduce carbon emissions and foster sustainable transportation.

This chapter underscores the finding that the reliability of EV batteries at the micro level transcends being merely a technical attribute; it is a pivotal factor that significantly impacts consumer experience, vehicle safety, economic value, and environmental sustainability. The advancements in battery reliability manifest in tangible benefits for consumers, promoting the increased adoption of EVs and contributing to a more sustainable and user-centric future in mobility.

2.3. Industry Evolution: The Meso-Level Influence of Advancing EV Battery Reliability

The meso-level landscape within the EV battery reliability ecosystem is characterized by the integral roles and responsibilities of industry stakeholders, including manufacturers, suppliers, and service networks. This section of the chapter delves into the profound significance of high reliability in EV batteries from a meso-level viewpoint, highlighting its substantial impact on industry dynamics, supply chain management, and the broader market.

Enhancing Brand Reputation and Competitive Advantage: At the heart of industry evolution lies the enhancement of brand reputation and competitive advantage. For manufacturers, the reliability of their EV batteries is deeply entwined with their brand reputation. High reliability is equated with quality and plays a crucial role in fostering consumer trust, a fundamental aspect of building brand loyalty and establishing a strong market presence. Additionally, in the rapidly evolving EV market, the reliability of batteries emerges as a critical factor for competitive differentiation. Manufacturers committed to consistently delivering highly reliable batteries position themselves at a competitive advantage, attracting a larger customer base and securing a more dominant market position.

Economic Implications—Warranty Costs and Efficiency: The economic implications of high battery reliability are significant, especially in terms of warranty costs and operational efficiency. Enhanced reliability directly leads to a decrease in warranty claims, as lower rates of battery failures and recalls translate into reduced after-sales service expenses. This reliability further influences operational efficiency, where reliable production processes and products minimize the need for frequent quality checks and rework, thereby streamlining operations and yielding cost savings.

Impact on the Supply Chain: The impact of high battery reliability on the supply chain is also profound. It necessitates stringent quality standards across the entire supply chain, encompassing rigorous testing of components and materials to ensure that every element of the battery adheres to high reliability criteria. This focus on reliability extends to logistics and distribution strategies, where efficient handling and transportation methods are crucial to maintain the integrity of batteries from production to consumer use.

Influencing Industry Standards and Regulations: Advancements in battery reliability at the meso level play a vital role in influencing both industry standards and regulations. Manufacturers leading in reliability often establish benchmarks that gradually evolve into industry standards, guiding practices, and product development across the sector. High reliability also aligns with, and frequently surpasses, regulatory standards. As regulations around EV batteries become more stringent, manufacturers prioritizing reliability find themselves well positioned in terms of compliance, thus avoiding potential legal and financial repercussions.

The Ripple Effect to Micro and Macro Levels: This meso-level commitment to reliability also has a ripple effect that extends to both micro and macro levels. At the micro level, advancements in battery reliability enhance consumer experiences, influencing individual preferences and behaviors. At the macro level, the industry's approach to reliability contributes to shaping broader economic and environmental trends, influencing market dynamics, guiding policy decisions, and shaping the regulatory landscape. This ultimately affects the global transition towards sustainable transportation.

This chapter emphasizes the critical importance of the meso level in advancing EV battery reliability. It highlights how industry players' dedication to reliability not only influences their immediate operational environment but also has far-reaching implications across the broader market and regulatory frameworks.

2.4. Strategic Sustainability: The Macro-Level Advantages of Boosting EV Battery Reliability

In the expansive macro-level landscape of the EV battery reliability ecosystem, this chapter explores the overarching significance of reliability within the context of sustainability. It delves into the intersection of enhanced EV battery reliability with macro-level sustainability objectives, economic strategies, and commitments to environmental stewardship.

Conservation of Finite Resources: The conservation of finite resources is a critical aspect at the macro level. The finite nature of essential raw materials like lithium and cobalt necessitates the extension of battery life. High reliability in EV batteries plays a pivotal role in prolonging their usable lifespan, thus conserving scarce resources and reducing the environmental footprint associated with extraction and processing.

Reduce Environmental Impacts: Addressing environmental impacts forms another key facet of this analysis. Reliable batteries are instrumental in reducing the carbon footprint of electric vehicles by ensuring longer lifecycles and reducing the frequency of manufacturing, thereby curtailing emissions related to production. Moreover, by extending the operational lifespan of EV batteries, the frequency of battery disposal is significantly lowered, reducing the generation of e-waste and mitigating its environmental impact.

Reduce Pressure on Recycling Systems: The role of high reliability in alleviating pressure on recycling systems is also examined. Enhanced reliability diminishes the strain on recycling infrastructures by lowering the rate of battery turnover. This not only promotes economic efficiency through reduced manufacturing and end-of-life handling costs but also contributes to environmental conservation. Furthermore, the potential for repurposing batteries for applications such as energy storage post-vehicle use exemplifies the principles of the circular economy, maximizing the utility of these materials and reducing waste.

Influencing Global Policies and Market Dynamics: The influence of battery reliability on global policies and market dynamics is profound. The pursuit of reliable EV batteries aligns with international sustainability and clean energy initiatives, shaping policy decisions and guiding regulations towards more sustainable practices. This push for reliability also drives market trends, steering the automotive industry toward environmentally responsible solutions.

This chapter broadens the scope of impact to consider the implications beyond individual benefits. High reliability in EV batteries emerges as a strategic imperative for global environmental sustainability, transcending the benefits realized at the micro and meso levels. The discussion in this chapter emphasizes the integral role of EV battery reliability within the broader context of sustainable development and environmental conservation, highlighting how advancements in this area are crucial not only for immediate stakeholders but for the overarching goals of sustainable progress.

3. Unveiling Operational Reliability: Transitioning Lifecycle Frameworks from General Assets to EV Batteries

After introducing the general asset lifecycle framework, this chapter provides a detailed exploration of the EV battery reliability lifecycle (RQ2), which enriches our understanding of both inherent reliability and use reliability for EV batteries.

This chapter also introduces and elaborates on the concept of “Zero”-Life Reliability, focusing on the use stages (use, reuse, repurpose, and recycle), and integrates this into an innovative lifecycle framework. This pioneering approach not only enhances the reliability of EV batteries from the outset but also contributes significantly to the broader ecosystem, influencing future innovations, operational strategies, and sustainability efforts in the realm of electric mobility.

3.1. Operational Reliability: Understanding the General Asset Lifecycle Framework

The operational reliability of a system (or component) during its operational phase, also known as overall reliability, is determined by a combination of factors from both its design and manufacturing stage (inherent reliability) and its actual usage conditions (use reliability). Operational reliability is the combination of inherent reliability and use reliability, capturing the complete spectrum of a product’s performance.

Achieving high operational reliability not only demands a focus on outstanding design and manufacturing for inherent reliability but also comprehensive understanding and adaptation to real-world usage to ensure long-term use reliability. As such, operational reliability provides a more accurate measure of a product’s overall reliability, considering the multitude of variables and conditions that influence performance outside of controlled environments.

The general reliability for a system or component, often described as a “birth to death” framework, follows a product from its initial conception through to its eventual failure and disposal (Figure 2). This framework is commonly used in various industries to manage and understand the reliability of physical assets. A breakdown of the key stages is shown in Table 2. In the general lifecycle framework, reliability is a concern at every stage, from ensuring a robust design that can withstand operational demands to maintaining the asset effectively during its use phase. The goal is to maximize the asset’s useful life while minimizing downtime and failures.

It should be noticed, having prepared the best possible engineering design, we can still be limited by inherent reliability if we ignore the necessity of stringent quality control during manufacture. Quality in its simplest interpretation is reliability during the manufacturing phase and ensures that only proper materials, processes, and quality control techniques are used.

Table 2. Breakdown of the key stages of general asset reliability lifecycle framework.

Stage		**Name**	**Contents**
Overall/Operational Reliability	Inherent Reliability	Concept and Definition (Birth)	- Defines the asset's purpose, specifications, and design. - Decisions made at this stage significantly impact the asset's long-term reliability.
		Design and Development	- Engineers and designers work to meet specified requirements, including reliability targets. - Involves material selection, architectural design, and consideration of manufacturing processes.
		Manufacture and Production	- Manufacturing Process: The asset is produced with a focus on quality control and assurance to meet design specifications and reliability standards. - Testing and Validation: Rigorous testing identifies defects or reliability issues before release.
		Distribution	- The asset is transported to its final location or delivered to consumers.
		Installation and Commissioning	- Proper installation ensures the asset functions as intended. - Commissioning verifies that all systems operate correctly and meet performance standards.
	Use Reliability	Operation and Maintenance	- Active Use: The asset enters its operational phase, which can last years or decades depending on its type. - Maintenance and Repairs: Regular maintenance preserves reliability, while unplanned repairs address unforeseen failures.
/	/	End of Life and Disposal (Death)	- Decommissioning: The asset is removed from service due to obsolescence, failure, or economic considerations. - Disposal/Recycling: The asset is dismantled, with materials either disposed of or recycled, prioritizing environmental and safety considerations.

3.2. The EV Battery Reliability Lifecycle Framework: Novel Insights on Operational Reliability

The lifecycle of an electric vehicle battery presents a distinctive framework for understanding the nuances of overall reliability, a perspective that differs considerably from the general asset lifecycle framework. As illustrated in Figures 3–5, the EV battery lifecycle offers unique insights into both inherent reliability and use reliability.

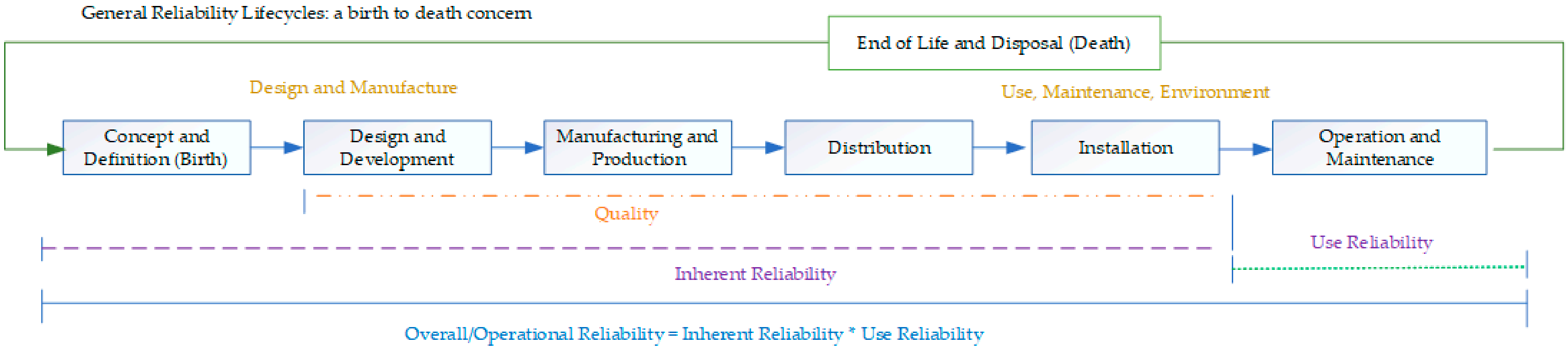

Figure 2. General asset reliability lifecycle framework.

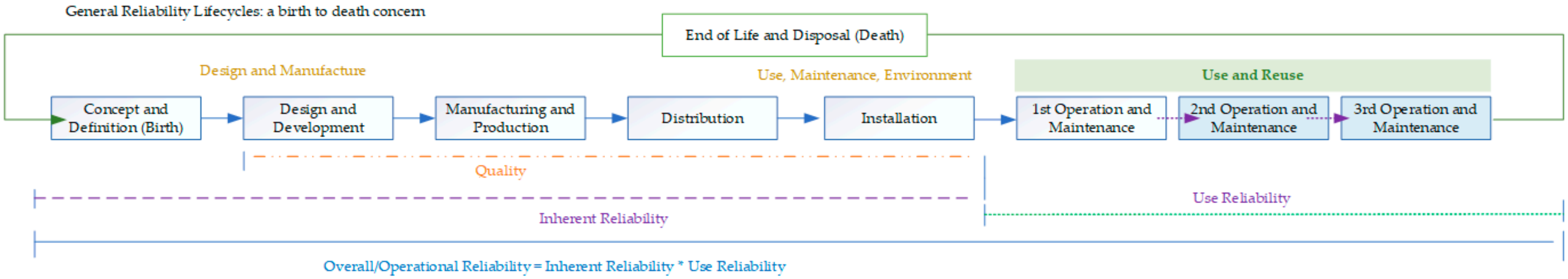

Figure 3. EV battery reliability lifecycle framework with 1st, 2nd, and 3rd life added.

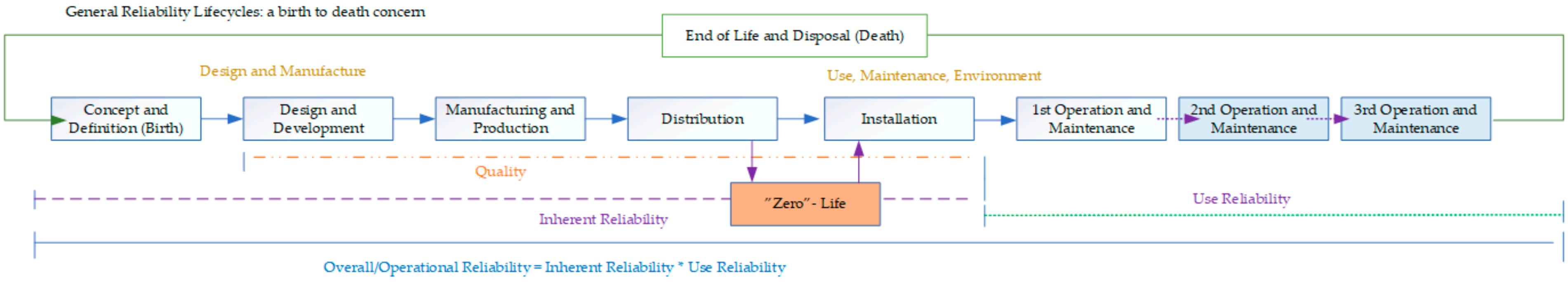

Figure 4. EV battery reliability lifecycle framework with zeroth, 1st, 2nd, and 3rd life added.

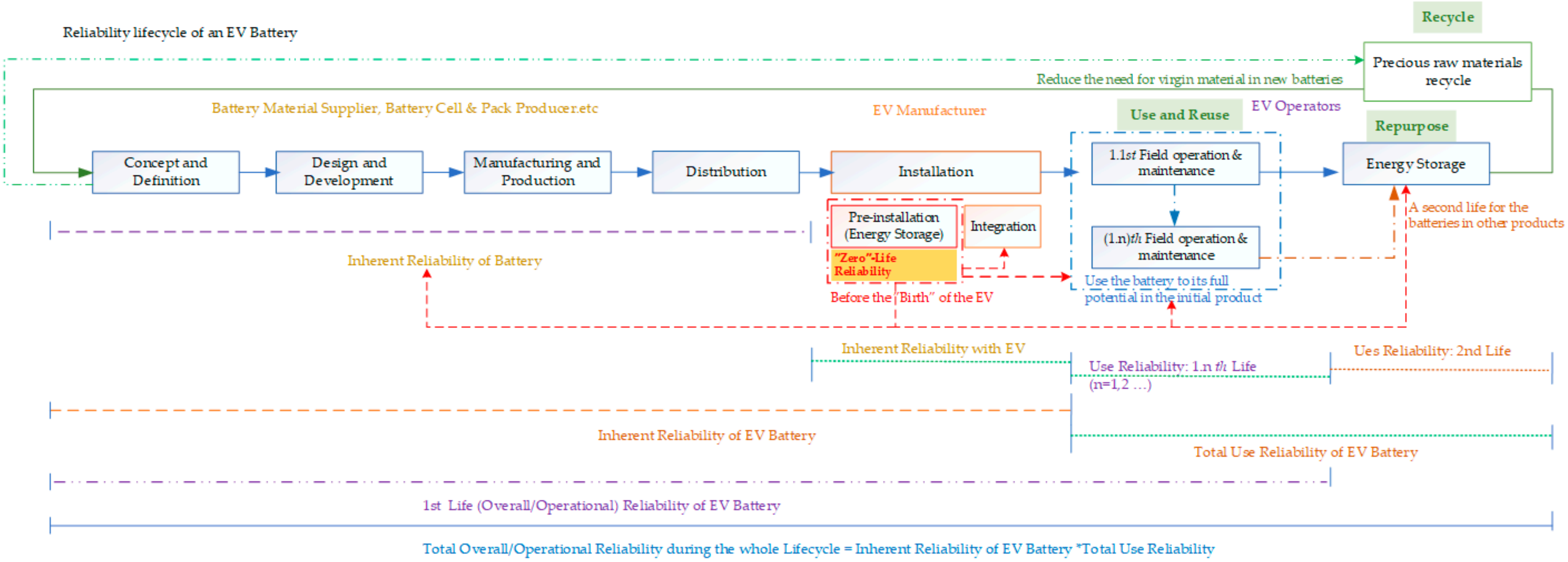

Figure 5. EV battery reliability lifecycle framework including more details of a "Zero"-Life stage.

From inherent reliability perspectives, the concept of inherent reliability in the context of EV batteries encompasses two key components. Firstly, there is the inherent reliability of the battery itself, which includes cells, modules, climatization, the control system, and the battery pack. This aspect focuses on the reliability engineered into the battery during its design and manufacturing stages. Secondly, inherent reliability is also linked to the integration of the battery within the EV by the manufacturer, highlighting the interdependence between the battery and the vehicle's overall design and functionality.

"Zero"-Life

The concept of "Zero"-Life reliability in EV batteries, introduced in Figure 4, represents a groundbreaking and essential stage in the assessment of battery inherent reliability. This concept refers to the period from the battery's manufacture up to the point where it is installed and begins operation in an electric vehicle. This study proposes a novel and cost-effective approach for vehicle manufacturers to begin utilizing EV batteries for energy storage purposes during the critical pre-installation stage, rather than simply storing them as inventory. This practice would not only serve as an efficient utilization of resources but would also start the operational lifecycle of the battery earlier, offering cost savings in terms of reduced tests for manufacturers. This innovative stage plays a pivotal role in establishing the foundational reliability of EV batteries. Detailed exploration of this novel concept is provided in Section 3.3, where its significance and impact on the overall reliability of EV batteries are thoroughly examined.

From use reliability perspectives, the lifecycle of an EV battery encompasses several stages, each contributing uniquely to its use reliability. Notably, there is the "use and reuse" stage (Figures 3–5), which sees the battery achieving multiple lifecycles within its initial product application. For instance, in Figure 5, a battery may have multiple lifetimes when installed in different EVs or other consequents fewer demanding applications. Since they continue to be utilized in vehicles, these various lifetimes are referred to as 1. n ($n \geq 1$) use life. Additionally, there is the "repurpose" stage, commonly seen in the form of energy storage applications, effectively constituting a second life for these batteries in different products. Consequently, use reliability can be conceptualized as comprising the 1. n (where $n = 1, 2, \ldots$) use reliabilities (encompassing multiple lifecycles within EVs).

While the disposal stage often receives limited attention in general reliability lifecycles, it holds a critical role in the EV battery reliability lifecycle. The "Recycle" stage, where raw materials from spent batteries are reclaimed for new batteries, provides pivotal reliability information, particularly under the lens of the sustainability development goals (SDGs). This stage underscores the growing importance of sustainable practices in the lifecycle of EV batteries.

The interconnections among inherent reliability, total use reliability, and recycling in the context of EV batteries form a continuous loop that reflects the entire lifecycle of the battery, from production to end-of-life (Figure 6). Here is how they are interconnected.

Inherent Reliability as the Foundation: Inherent reliability is established during the design and manufacturing stages of the EV battery. It sets the baseline for how the battery will perform under both normal and challenging conditions. This initial reliability is crucial as it determines the robustness, efficiency, and durability of the battery right from the start. High inherent reliability can lead to longer battery life, fewer early-life failures, and potentially more effective recycling outcomes.

Total Use Reliability as the Operational Extension: Total use reliability encompasses the battery's performance during its entire number of operational lives, including initial use in an EV and any subsequent reuse or repurposing, such as energy storage. The inherent reliability of the battery influences its total use reliability; a battery with high inherent reliability is more likely to maintain good performance over its lifecycle. This stage is where the battery experiences real-world conditions, and its performance can be affected by various factors like usage patterns, maintenance, environmental conditions, and aging.

Recycling as the End-of-Life Process: The end-of-life stage of the battery, particularly recycling, is influenced by both the inherent reliability and the total use reliability. A battery with high inherent reliability may retain more of its original capacity and quality, making it a more valuable resource for recycling. The condition of the battery at the end of its total use reliability stage (after primary and secondary uses) will determine the ease and efficiency of material recovery during recycling.

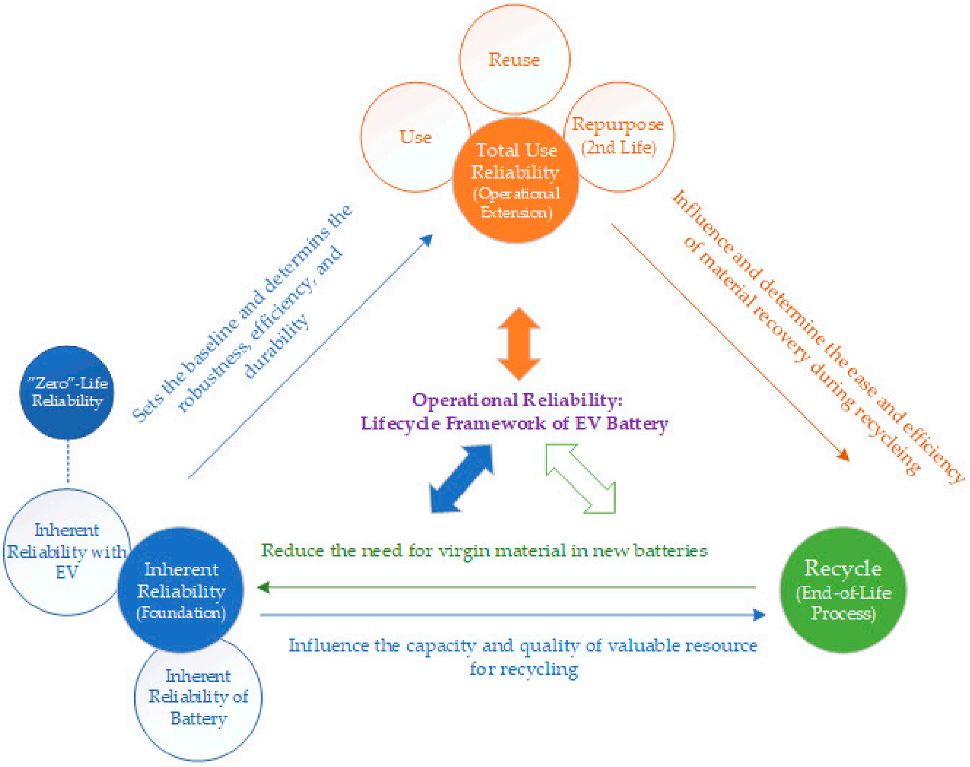

Figure 6. Operational reliability: lifecycle framework of EV batteries.

In summary, inherent reliability impacts total use reliability, which in turn influences the efficacy and value of recycling. This interconnection underscores the importance of considering the entire lifecycle when designing and manufacturing EV batteries, aiming not only for immediate performance but also for long-term sustainability and recyclability. Each stage is interdependent, with early decisions impacting the later stages, thereby creating a cycle that is crucial for sustainable battery management and environmental stewardship in the EV industry.

Implementing lifecycle stages such as reuse, repurposing, and recycling at scale involves several challenges, including accurately assessing battery degradation, ensuring compatibility with new applications, and overcoming logistical hurdles like collection and sorting. This study proposes solutions such as integrating advanced diagnostics and predictive analytics into battery management systems (BMSs) for real-time monitoring, standardizing battery designs to facilitate reuse, and leveraging AI-driven technologies for efficient sorting and classification. To address recycling challenges, innovative techniques like direct recycling are emphasized for higher material recovery efficiency, supported by regional recycling hubs and public–private partnerships to expand infrastructure. Additionally, harmonized international standards, a "battery passport" system, and economic incentives like extended producer responsibility (EPR) are proposed to overcome regulatory and financial barriers, enabling a scalable and sustainable approach to lifecycle management.

A comprehensive breakdown of key studies conducted during these various stages is presented in Tables 3–9. These Tables offer an in-depth look into how each stage of the EV battery lifecycle contributes to our understanding of operational reliability, highlighting the unique challenges and opportunities that arise at each phase. For clarity, it should be noted that Tables 3–9 do not specifically represent the micro, meso, or macro perspectives.

Table 3. Breakdown of the key studies of EV battery reliability lifecycle framework: concept and definition.

Character	Inherent Reliability	Stage	Concept and Definition
Highlights	This stage encapsulates the initial ideation, design choices, and planning that set the trajectory for the battery's development.		
Contents	Current research examples		
Initial Ideation and Purpose Definition	- Analyze market trends, consumer demands, and forecasted needs of the EV industry to determine the purpose and specifications for new battery designs. - Assess the feasibility of various battery chemistries and configurations, focusing on energy density, power output, safety, and cost.		
Design Parameters and Specifications	- Optimize battery design for performance by maximizing energy density, minimizing weight, and ensuring safety. - Use computational modeling and simulation to predict how design choices affect reliability. - Investigate material properties (e.g., cathode, anode, electrolyte) to improve performance, longevity, and cost-effectiveness. - Incorporate sustainability into design by selecting materials with low environmental impact during extraction and processing.		
Reliability Targeting	- Integrate reliability engineering principles, such as Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and reliability prediction models, into the design process. - Ensure compliance with existing and emerging standards and regulations for safety, performance, and reliability.		
Technological Innovation	- Explore new technologies, such as solid-state electrolytes and advanced battery management systems, to enhance performance and reliability. - Conduct early-stage development, including prototype creation and proof-of-concept testing, to validate design and specifications.		
Cross-Disciplinary Collaboration	- Facilitate collaboration among chemists, materials scientists, electrical engineers, and environmental scientists to address the complexity of EV battery design and ensure a comprehensive approach.		

Table 4. Breakdown of the key studies of EV battery reliability lifecycle framework: design and development.

Character	Inherent Reliability	Stage	Design and Development
Highlights	This stage requires a multidisciplinary approach, combining insights from chemistry, materials science, mechanical engineering, electrical engineering, environmental science, and regulatory expertise.		
Contents	Current research examples		
Performance Optimization	- Focus on maximizing battery performance within cost, size, weight, and usage constraints. - Includes efforts to increase energy density, improve charge rates, and enhance thermal management systems to prevent overheating.		
Advanced Materials Research	- Investigate new materials or innovative combinations to improve battery performance. - Includes research on high-lithium-content cathodes, silicon or graphene anodes, and stable or highly conductive electrolytes.		

Table 4. *Cont.*

Character	Inherent Reliability	Stage	Design and Development
Safety and Durability Studies	- Prioritize safety features to prevent or mitigate battery failure. - Conduct durability studies to ensure the battery maintains performance over numerous charge cycles and under diverse environmental conditions.		
Modeling and Simulation	- Use computer models and simulations to predict battery performance and identify potential design issues before physical prototyping. - Analyze areas prone to excessive heat or mechanical stress for improved reliability.		
Prototype Testing	- Produce and test prototype batteries, including both bench testing under controlled conditions and field testing in real-world EV applications. - Evaluate performance and reliability in actual operational scenarios.		
Design for Manufacturability	- Ensure the battery design is cost-effective and scalable for mass production. - Research focuses on assembly processes, automation, and quality control to improve manufacturing efficiency.		
Environmental Impact Assessments	- Evaluate the environmental impact of the battery across its full lifecycle, from raw material extraction to end-of-life disposal or recycling. - Guide design decisions to favor sustainable materials and processes with lower environmental footprints.		
Regulatory Compliance and Standards	- Ensure compliance with industry standards and government regulations across regions. - Guarantee that the battery can legally and safely be sold and used in its target markets.		
Iterative Design Improvements	- Refine and enhance the battery design through iterative testing and development cycles. - Continuously incorporate test results and evolving performance targets to achieve optimal design improvements.		

Table 5. Breakdown of the key studies of EV battery reliability lifecycle framework: manufacture and production.

Character	Inherent Reliability	Stage	Manufacture and Production
Highlights	This stage requires a careful balance between efficiency, cost, and quality, with research playing a vital role in navigating these sometimes-competing priorities.		
Contents	Current research examples		
Manufacturing Process Optimization	- Focuses on enhancing manufacturing efficiency and minimizing defects through automation of battery cell assembly lines. - Aims to improve consistency and reduce human error.		
Quality Control and Assurance	- Ensures batteries meet reliability standards through advanced quality assurance techniques. - Uses real-time monitoring and predictive analytics to identify and address defects proactively.		
Testing and Validation	- Conducts rigorous testing to confirm performance and safety standards. - Develops accelerated life testing methods to simulate long-term usage and identify potential failure modes early.		
Material Sourcing and Supply Chain Management	- Focuses on securing a stable supply of high-quality materials and managing the supply chain effectively. - Develops strategies for mitigating risks related to supply disruptions.		
Environmental and Safety Standard Compliance	- Researches cleaner production techniques to meet stringent environmental and safety regulations. - Evaluates and minimizes the ecological impact of manufacturing processes.		

Table 5. *Cont.*

Character	Inherent Reliability	Stage	Manufacture and Production
Scalability and Expansion Studies	- Addresses challenges of scaling up production capacity while maintaining quality. - Explores methods to expand manufacturing efficiently as EV adoption rates increase.		
Cost Reduction Strategies	- Investigates cost-effective manufacturing processes to reduce battery costs without compromising reliability.		
Innovations in Manufacturing Technology	- Adopts new technologies, such as integrating solid-state electrolytes into production, to enhance performance.		
Workforce Training and Development	- Emphasizes the importance of skilled workers for high-quality manufacturing. - Implements training programs to equip the workforce with necessary skills for producing reliable batteries.		

Table 6. Breakdown of the key studies of EV battery reliability lifecycle framework: distribution, installation, and commissioning.

Character	Inherent Reliability	Stage	Distribution, Installation, and Commissioning
Highlights	These studies are integral to the overall success of the EV battery's operational lifecycle, helping to guarantee that the battery's inherent reliability is preserved up to the point of use.		
Contents	Current research examples		
Distribution Logistics	- Develops optimized logistics strategies to ensure safe and efficient transportation of batteries from manufacturing plants to installation sites. - Explores packaging methods to protect batteries from temperature extremes and physical shocks during transit.		
Installation Procedures	- Focuses on creating standardized installation procedures to maintain battery integrity and performance. - Includes training for technicians and the use of specialized tools and equipment to ensure proper installation.		
Quality Assurance Post-Distribution	- Extends quality assurance measures to transit and installation stages. - Investigates tracking systems to monitor battery condition during distribution and post-installation testing protocols to ensure reliability.		
Impact of Storage Conditions	- Examines how various storage conditions affect battery reliability, including charge state, health, and performance. - Researches long-term storage impacts and develops best practices for storage management.		
Integration with Vehicle Systems	- Ensures seamless integration of batteries with vehicle systems, focusing on compatibility and performance. - Includes research on software updates for battery management systems and final quality checks before the vehicle is road-ready.		
Customer Education	- Develops effective customer education programs to guide proper battery use and maintenance. - Includes resources such as user manuals, instructional videos, and interactive apps for end-users.		
Feedback Loops for Continuous Improvement	- Establishes feedback mechanisms to gather insights from distribution and installation stages. - Utilizes data to identify areas for enhancement in battery design, manufacturing, and overall performance.		

Table 7. Breakdown of the key studies of the EV battery reliability lifecycle framework: operation and maintenance—1.n th lifetime (Some content may also be included in the "Repurpose" stage).

Character	**Use Reliability**	**Stage**	**Operation and Maintenance—1.n th Lifetime**
Highlights	Study in this phase is essential to ensure that EV batteries can reliably meet the expectations of consumers and the demands of daily operation.		
Contents	Current research examples		
Integration of Inherent and Use Reliability	- Examines the interaction between inherent reliability (from design and manufacturing) and use reliability (observed during operation) to determine overall battery reliability. - Assesses how design choices and real-world conditions impact degradation and failure rates.		
Long-Term Performance Monitoring	- Focuses on the continuous tracking of battery performance over its lifecycle, including capacity, power output, efficiency, and other key metrics under varying operational conditions.		
Predictive Analytics for Reliability	- Utilizes advanced data analytics and machine learning to predict reliability based on historical performance data. - Supports proactive maintenance and includes studies on parameters like SOC (State-of-Charge) and SOH (State-of-Health).		
Real-World Performance Metrics	- Measures battery performance in diverse driving conditions, such as urban traffic, highways, and varying climates. - Tracks metrics like range per charge, power output, and state of health over time.		
User Behavior andUsage Patterns	- Investigates how user behavior, such as charging habits, depth of discharge, and reliance on fast charging, affects battery life and reliability.		
Battery Management Systems (BMSs)	- Focuses on improving BMS algorithms to optimize charging/discharging, thermal management, and energy efficiency. - Enhances battery health and extends its useful life.		
Maintenance Practices	- Studies the impact of maintenance routines, including regular health checks, software updates, and condition-based maintenance, on battery reliability and lifespan.		
Degradation Analysis	- Explores the physical and chemical processes driving battery degradation over time. - Develops strategies to mitigate capacity and power loss, extending battery life.		
Failure Mode Analysis	- Identifies and analyzes potential failure modes through stress testing and post-mortem analysis. - Informs improvements in battery design and manufacturing to enhance reliability.		
Data Analytics and Predictive Maintenance	- Leverages big data and machine learning to forecast battery life and recommend proactive maintenance. - Predicts failures and optimizes service schedules.		
Impact of External Factors	- Studies the effects of external factors like temperature extremes, humidity, and mechanical vibrations on battery reliability. - Develops more resilient batteries for diverse operating environments.		
Sustainability and Second-Life Applications	- Explores second-life applications for degraded batteries, such as stationary energy storage. - Assesses reliability and feasibility in these new roles, supporting sustainability initiatives.		
User Feedback and Warranty Claims	- Analyzes customer feedback and warranty claims to identify recurring issues and improvement opportunities. - Establishes a feedback loop to refine battery design and manufacturing processes.		
End-of-Life Management	- Investigates efficient recycling processes and evaluates the potential for second-life applications. - Focuses on minimizing environmental impact and maximizing material recovery.		

Table 8. Breakdown of the key studies of EV battery reliability lifecycle framework: operation and maintenance—2nd lifetime (repurpose).

Character	**Use Reliability**	**Stage**	**Operation and Maintenance—2nd Lifetime (Repurpose)**
Highlights	This field addresses the potential for extending the useful life of EV batteries beyond their initial automotive application, delving into various aspects of their performance, adaptability, and overall viability in new roles.		
Contents	Current research examples		
Assessment of Battery Health for Repurposing	- Evaluates the remaining capacity and performance of used EV batteries. - Determines suitability for less demanding applications based on retained capacity and power metrics.		
Optimization for Second-Life Applications	- Focuses on adapting repurposed batteries for specific applications like stationary energy storage for homes, businesses, or utility projects. - Includes modifying battery management systems and optimizing charging/discharging patterns.		
Safety and Reliability in New Roles	- Investigates the safety and reliability of repurposed batteries in new operational contexts. - Analyzes failure risks in second-life environments and implements appropriate safety measures.		
Economic and Environmental Analysis	- Assesses the cost-effectiveness of repurposing compared to manufacturing new energy storage systems. - Evaluates environmental benefits, such as reduced waste and the demand for raw materials.		
Integration with Renewable Energy Systems	- Explores the potential for repurposed batteries to support renewable energy sources like solar and wind. - Studies how these batteries complement intermittent renewable energy production.		
Standardization and Regulatory Compliance	- Examines the need for standardized processes to ensure compatibility with existing energy systems. - Ensures compliance with electrical and safety standards for second-life applications.		
Development of Second-Life Market	- Explores business models and market opportunities for repurposed batteries. - Includes logistics for collection, testing, refurbishment, and the distribution of second-life batteries.		
Lifecycle Assessment	- Conducts lifecycle assessments to understand the full environmental impact of repurposing, from collection and transportation to disposal after their second life.		

Table 9. Breakdown of the key studies of EV battery reliability lifecycle framework: recycle.

Character	**Use Reliability**	**Stage**	**Recycle**
Highlights	The recycle stage studies encompass a wide range of interdisciplinary research areas, all aiming to improve the sustainability, efficiency, and profitability of EV battery recycling, while ensuring environmental safety and compliance with evolving regulations.		
Contents	Current research examples		
Material Recovery and Recycling Processes	- Efficiency of Material Recovery: Research focuses on improving the recovery yield and purity of valuable materials like lithium, cobalt, nickel, and manganese from used EV batteries. - Advanced Recycling Technologies: Develops innovative methods such as hydrometallurgical, pyrometallurgical, and bio-hydrometallurgical techniques for efficient battery disassembly and material processing. - Design for Recycling: Explores battery designs optimized for easier and more complete recycling at the end of their lifecycle.		

Table 9. *Cont.*

Character	Use Reliability	Stage	Recycle
Environmental Impact of Recycling	- Life Cycle Assessment (LCA): Evaluates the environmental impacts of battery recycling, including energy use, greenhouse gas emissions, and potential toxic substance releases. - Regulatory Compliance: Studies compliance with international environmental standards and regulations related to battery disposal and recycling.		
Economic and Policy Considerations	- Cost–Benefit Analysis: Examines the economic viability of recycling processes compared to the market value of recovered materials. - Policy Incentives: Investigates the role of policy measures, such as extended producer responsibility (EPR), in fostering efficient recycling ecosystems.		
Second-Life Applications	- Feasibility Studies: Assesses the viability of repurposed batteries for applications like stationary energy storage systems, evaluating their reliability in these new roles. - Performance Metrics: Measures performance factors such as capacity retention, energy efficiency, and the reliability of repurposed batteries post-recycling.		
Innovation and Future Directions	- Cutting-edge Techniques: Focuses on innovative methods like direct recycling, which preserves the electrochemical properties of battery materials for reuse. - Scalability and Infrastructure: Explores strategies to scale up recycling infrastructure to meet the demands of increasing EV adoption and battery disposal volumes.		

3.3. "Zero"-Life Reliability of EV Batteries: A Unique Focus on Inherent Reliability

As mentioned before, innovative manufacturing strategies can lead to the utilization of EV batteries for energy storage during their critical pre-installation phase, a shift from traditional inventory storage practices. This strategy not only initiates the operational lifecycle of batteries earlier but also offers significant cost benefits. By engaging batteries in active use before installation in vehicles, manufacturers enhance resource efficiency in the production process. This innovative manufacturing strategy is in the early stages of planning and testing by industries, including Scania AB in Sweden.

During this period, which can last up to twelve months to include seasonal variations, the batteries undergo thousands of charge and discharge cycles, a process that serves triple purposes. Besides the above energy storage, this extensive usage allows for the collection of comprehensive data, crucial for quality assurance. These data ensure that each battery not only meets the highest standards of quality before being integrated into an EV; moreover, and perhaps more significantly, the data gathered from these cycles facilitate a transition from traditional statistical process control (SPC) methods to a more forward-looking statistical process prediction (SPP) approach. Last, but not least, this shift enables manufacturers to perform detailed reliability analyses, predicting the battery's performance and lifespan across various stages of its use, including the 1.n (multiple use cycles within the EV) and 2nd lifetimes (post-EV usage in other applications).

Correspondingly, in the evolving narrative of EV battery reliability, a novel and critical concept emerges (Figures 3–5): "Zero"-Life Reliability. This concept, first introduced in Section 3.2, represents a pivotal stage in the EV battery lifecycle that has not been studied before. It is akin to a missing piece of the puzzle in understanding battery reliability, spotlighting the period from battery manufacture to its initial deployment in the field.

The "Zero"-Life Reliability of an EV battery represents a paradigm shift in battery manufacturing and reliability assessment. By effectively utilizing the batteries prior to their installation in EVs, manufacturers are not only optimizing resource utilization but also enhancing their predictive capabilities regarding the battery's future performance and reliability. This approach aligns with the broader goals of sustainability and efficiency in the EV industry, setting a new standard for how battery lifecycles are managed and analyzed. Anticipated outcomes of "Zero"-Life Reliability analytics include (but are not limited to) the following:

Quality Assessment Before Installation: The primary goal is to ensure that EV batteries meet stringent performance and safety benchmarks even before they are installed. This proactive quality assessment aims to pre-emptively address any potential issues and therefore make it possible from SPC to SPP.

Prediction of Remaining Useful Lifetime (RUL): By analyzing data from "Zero"-Life stages, it becomes possible to accurately forecast the RUL of EV batteries, extending from their first lifecycle to subsequent ones. This prediction aids in planning for maintenance, replacements, and recycling.

Guidance for In-Field Operations and Maintenance: The insights gained from "Zero"-Life Reliability Analytics provide essential guidelines for optimizing the performance, reliability, and longevity of EVs once they are operational.

Feedback Loop for Continuous Improvement: Establishing a robust feedback mechanism between vehicle manufacturers and battery producers is critical for continuous enhancements in battery design, manufacturing, and quality control.

Enriching the Battery Ecosystem: The data and knowledge gathered during this stage play a vital role in fostering a transparent and enriched battery ecosystem, beneficial for manufacturers, consumers, and researchers.

3.4. Total Use Reliability of EV Batteries: Redefining Assessment, Prediction, and Improvement

As introduced in Figures 3–5, a significant evolution of EV batteries is observed in the concept of reliability, extending beyond the traditional one-use lifecycle. The total use reliability of EV batteries encompasses the stages of use and reuse, repurposing, and recycling, each contributing to a broader, more comprehensive understanding of reliability. This expanded perspective challenges and redefines the conventional methods of reliability assessment, prediction, and improvement.

Traditionally, battery reliability was assessed and predicted based on a single-use phase, typically focusing on the battery's performance from installation to its end-of-life in a vehicle. However, the concept of reuse broadens this assessment. Reuse involves utilizing the battery to its full potential in its initial application, ensuring that the battery's life is maximized in its primary role. This stage demands a reassessment of the battery's performance and reliability as it continues to serve in the same application but with reduced efficacy due to aging and wear.

Once the battery reaches the end of its viable life in a vehicle, it can still hold significant value [35,36]. The stage of repurposing involves giving the battery a "second life" in different applications, such as in Battery Energy Storage Systems (BESSs). These systems, akin to large-scale power banks, can provide services like frequency balancing for grid operators or boosting local electric grids. This phase of the battery's life adds a new dimension to reliability assessment, as the battery now functions in a different context, with varying demands and stressors compared to its initial use in a vehicle [37].

The importance of reliability assessment for the reuse and repurpose of batteries is crucial for ensuring safety, maximizing utility, maintaining value, and ensuring regulatory compliance in the reuse of batteries, thereby playing a vital role in the sustainable lifecycle management of battery technology.

Determines Usability and Lifespan: Reliability assessment helps determine the RUL of the battery. It is critical in ascertaining how long the battery can effectively be used in its new application without significant performance degradation.

Ensures Safety: Assessing the reliability of batteries prior to reuse can help to identify potential risks, such as the likelihood of overheating or fire, which are critical considerations for both new users and regulatory compliance.

Influences Residual Value: The reliability assessment provides an indication of the battery's current state and potential for future use. This directly impacts the residual value of the battery in the second-hand market.

Guides Appropriate Application Selection: By understanding the reliability and capacity of the battery, decision makers can better match the battery to suitable reuse and repurpose applications where it can perform effectively, such as in less demanding stationary storage roles.

Helps in Warranty and Insurance Decisions: Reliable data on the battery's health and expected lifespan can guide warranty decisions and insurance policies for reuse and repurpose batteries, impacting both seller and buyer confidence.

Facilitates Regulatory Compliance: Many regions have stringent regulations for battery reuse and repurpose. A thorough reliability assessment ensures that the repurposed batteries meet the necessary safety and performance standards set by regulatory bodies.

Supports Efficient Resource Utilization: Understanding the remaining reliability of batteries enables more efficient use of resources. It helps in avoiding premature recycling of batteries that still have significant usable life, thereby contributing to sustainability.

Boosts Consumer Confidence: For consumers, knowing that a battery has been reliably assessed and is still in good condition can be a key factor in their decision to choose products that incorporate reused batteries.

The final stage in the total use reliability framework is recycling. When a battery can no longer be effectively used or repurposed, recycling becomes crucial. This process involves extracting valuable materials like cobalt for use in new batteries, thereby reducing the need for virgin materials. Reliability in this context shifts focus to the efficiency and efficacy of the recycling process and the quality of the recovered materials.

The expansion of reliability assessment to include reuse, repurposing, and recycling stages necessitates new approaches and methodologies. It is no longer sufficient to predict a battery's performance based solely on its first life in a vehicle. Instead, a more holistic view is required, considering the various potential phases of a battery's life. This approach also demands improvements and innovations in battery technology that consider these extended stages of use, focusing on factors like longevity, the degradation rate, and adaptability to different uses.

The total use reliability of EV batteries demands a shift from a linear view of battery life to a cyclical one, where each stage of the battery's life is considered integral to its overall reliability. This comprehensive approach not only enhances the sustainability and efficiency of battery use but also aligns with the broader goals of the circular economy and environmental stewardship in the EV industry.

4. System Cognition of EV Battery Reliability: Integrating the Reliability Ecosystem and Lifecycle Framework

This chapter explores a novel approach to understanding the reliability system of EV batteries. Such "cognition" of the reliability system consists of the integration of the reliability ecosystem and lifecycle frameworks for (EV battery) system reliability. Therefore, it begins by delineating the distinct characteristics of a reliability system and system reliability. Then, it presents multidimensional system cognition of EV battery reliability that correlates the fundamental elements of point, line, surface, system, and System of Systems (SoS). A key focus of this chapter is the conceptualization of the EV battery system reliability lifecycle as a hyperplane projection of its reliability system, where time serves as a critical dimension. This viewpoint allows for a dynamic understanding of the reliability system, considering how it evolves and is influenced over the battery's lifespan. This comprehensive approach not only fosters better understanding about a holistic system cognition of EV battery reliability constructed but also guides strategic decision making in the realm of EV battery system optimization (RQ3).

4.1. Reliability System and System Reliability of EV Batteries

The concept of a "reliability system" in the context of EV batteries encompasses a comprehensive array of methods, processes, tools, and practices dedicated to ensuring and enhancing the reliability of these batteries. This system includes various elements such as reliability engineering techniques, maintenance strategies, quality control measures, testing procedures, and data analysis methodologies. The emphasis here lies in the systematic approach towards achieving, sustaining, and improving reliability. It involves creating an infrastructure and methodology focused on ensuring that EV batteries perform reliably over their intended lifespan. Essentially, a reliability system addresses the "how" of reliability—the implementation of specific practices and principles to attain reliable outcomes.

Conversely, "system reliability" in the realm of EV batteries pertains to the probability or likelihood of these batteries performing their required functions without failure over a specified period under predefined conditions. It is a metric or characteristic of the system, typically measured through indicators like Mean Time Between Failures (MTBF) or failure rates. System reliability zeroes in on the actual performance and dependability of the EV batteries, representing the tangible outcome or attribute experienced by users. This term focuses on the "what" of reliability—the actual performance and reliability of the battery system as observed in real-world applications.

In essence, while a "reliability system" in EV batteries is about the strategic framework and methodologies employed to ensure reliability, "system reliability" refers to the demonstrable reliability performance of the battery system. The former encompasses a proactive and strategic approach, utilizing a variety of tactics and techniques, whereas the latter signifies a quantifiable measure or characteristic that reflects the battery system's likelihood to operate reliably.

4.2. Integrating Reliability Ecosystem and Lifecycle Frameworks: Cognation from Point to System of Systems (SoS)

This chapter presents an integrated view of the reliability ecosystem and lifecycle frameworks of EV batteries, conceptualized through the geometry of a triangular prism, as depicted in Figure 7. This geometric representation serves as a simplified model for understanding the complex structure and dynamics of reliability within EV battery systems.

Assuming a stationary status, the triangular prism embodies the multidimensional structure of the reliability system. It encompasses points, lines, surfaces, and the body—each representing a different aspect of the reliability system and lifecycle.

Points—The Fundamentals of Reliability: Points are depicted as the basic building blocks of the reliability system. Within the context of EV batteries, these points represent entities across the micro, meso, and macro perspectives outlined in Section 2. They include individuals or components at the micro level, industrial entities at the meso level, and societal elements at the macro level. From the lifecycle framework discussed in Section 3, points also symbolize crucial attributes or processes such as inherent reliability, total use reliability, or the recycling processes at the end of a battery's life. These points are the foundation upon which the reliability system is built.

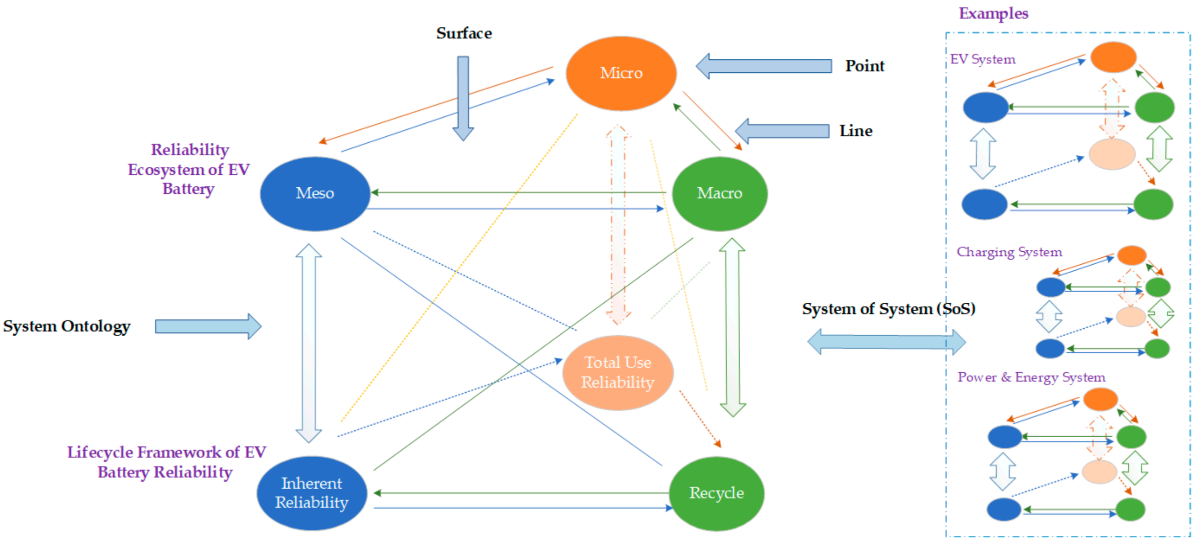

Figure 7. The reliability system of EV batteries: from point to System of Systems (SoS).

Lines—The Connections that Bind: Lines within the triangular prism model define the relationships among points. They represent the interactions between entities, attributes, and processes, or the constraints that govern the system's functioning and reliability. These lines are pivotal, as they form the connections that allow for the flow of energy, information, and materials between points, facilitating the system's integrated functioning.

Surfaces—Networks and Interactions: The prism consists of six surfaces, each symbolizing a network of points and lines—a subsystem within the greater reliability ecosystem. These surfaces can be seen as the interactions between various components and processes within the EV battery's lifecycle, including design, manufacturing, operation, and recycling. They also represent the interplay between different perspectives within the ecosystem, where micro-level interactions build up to meso and macro-level dynamics.

Body—The Reliability System Ontology: The body of the triangular prism is representative of the entire reliability system of EV batteries. It encompasses the aggregated knowledge and interactions encapsulated within the points, lines, and surfaces. The body is a holistic embodiment of the system's reliability, illustrating how components and processes coalesce to form a complete, functioning system.

System of Systems (SoS)—Beyond Individual Systems: When these systems interact with other systems—engaging in collaborative complexity—they form a System of Systems (SoS). As shown in Figure 7, some examples of other systems include the EV system, Smart Grid system, Charger Station system, etc. SoS cognition involves understanding how each system, with its unique goals and metrics, contributes to a larger, more complex goal when integrated with other systems. This is where emergent behaviors and functionalities arise, providing new capabilities that are not possible within individual systems.

From Components to Cognition: Each point within the system has its goals, leading to metrics for quantifiable measurement. Lines can evolve into platforms facilitating interactions, while surfaces may give rise to industry segments or research domains. This chapter elucidates how each component of the reliability system, from the micro-level points to the macro-level SoS, is integrated into a cohesive framework. It explores the implications of this integration for advancing the reliability, performance, and sustainability of EV batteries.

This chapter weaves together the reliability ecosystem and lifecycle frameworks into a comprehensive understanding of EV battery reliability. It lays out a structured model that captures the essence of a reliability system and demonstrates how it operates within the complex interrelations of a System of Systems.

The proposed holistic system optimization strategy is designed to be scalable across various EV applications, from individual consumer vehicles to fleet management and industrial-scale usage. For individual vehicles, the strategy emphasizes user-specific data integration and adaptive battery management systems (BMSs) to optimize reliability and performance. In fleet management, the approach leverages centralized data analytics, predictive maintenance models, and aggregated usage patterns to enhance operational efficiency and reduce downtime. For industrial-scale applications, the strategy incorporates advanced lifecycle frameworks, including the reuse and repurposing of batteries, along with robust diagnostic tools and scalable recycling infrastructures. Its modular design and reliance on data-driven insights ensure adaptability to diverse operational contexts, supporting scalability across different use cases.

4.3. Hyperplane Projection: Insights into the Intrinsic Reliability System Optimization of EV Batteries

Section 4.2 established a stationary framework for the reliability system of EV batteries, characterized by a structured interplay between points, lines, and surfaces. However, this depiction did not account for the critical dimension of time. This section explores the concept of time as a pivotal factor that transforms the stationary status into a dynamic one, revealing the intrinsic nature of reliability system optimization (Figure 8).

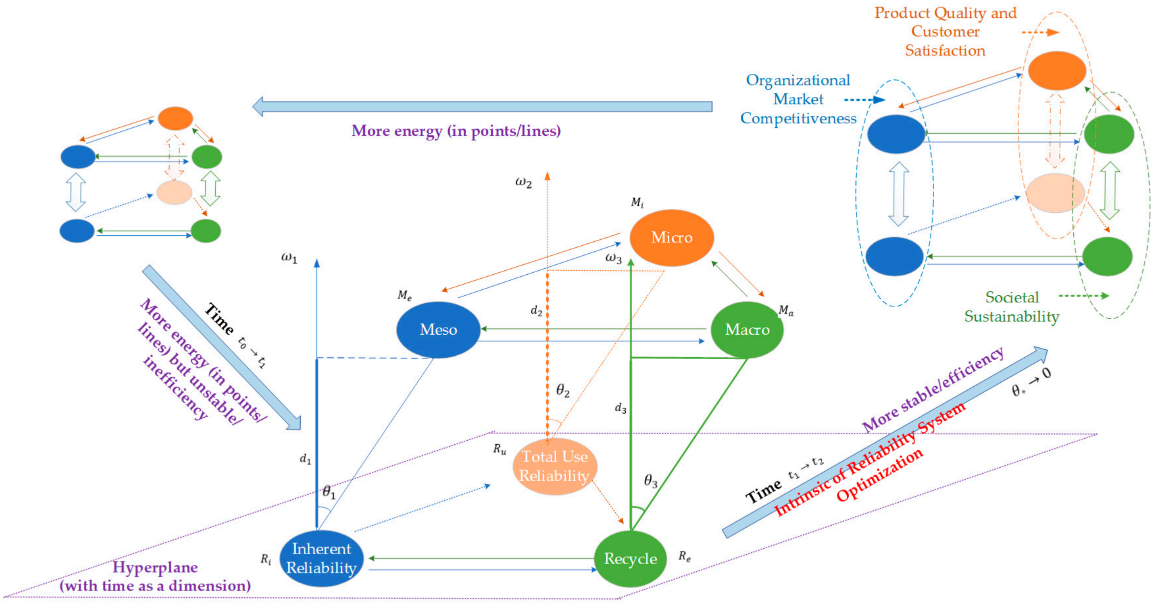

Figure 8. Hyperplane projection and intrinsic optimization.

Lifecycle Framework as a Hyperplane: The lifecycle framework can be conceptualized as a hyperplane—a multidimensional space that captures the complex interactions within the reliability system. On this hyperplane, key elements can be projected such as inherent reliability (R_i), total use reliability (R_u), and recycling (R_e). These projections represent the influences of the points of the micro (M_i), meso (M_e), and macro (M_a) levels within the reliability ecosystem. $\boldsymbol{\omega}$ represents the normal vector; θ_1, θ_2, θ_3 represent angles, and d_1, d_2, d_3 represent distance.

Stationary Status and Its Significance: When the vectors representing these projections align (i.e., the angle between them is zero), a stationary status can be achieved. This alignment signifies that the reliability system is optimally meeting the needs of all stakeholders in the ecosystem. In such a state, there is harmony between what is anticipated by the ecosystem (the stakeholders' needs) and what is delivered by the reliability system (the performance of the EV batteries).

Strategic Implications of Projections: The projection of the micro level influences critical aspects such as product quality and customer satisfaction. It underscores the direct impact on end-users, emphasizing the importance of reliability in the consumer experience. The projection of the meso level shapes organizational competitiveness. It encompasses the strategic maneuvers of businesses within the industry, reflecting how reliability affects operational excellence and market positioning. The projection of the macro level extends to societal sustainability. It captures the broader implications of EV battery reliability on environmental stewardship, resource management, and sustainable development.

Time as a Dynamic Element: Introducing time as a dimension allows us to observe the evolution of the reliability system from a static to a nonstationary status. For instance, in Figure 8, from $t_0 \rightarrow t_1$, this dynamic change is driven by the energy changes within points (such as new technological advancements or the wear and tear of components) or shifts along lines (like changes in market demands or regulatory updates); from $t_1 \rightarrow t_2$, the system is more stable and efficient after system optimization. It should be noticed that, when the system is stable, the angle equals 0. From this point, it indicates that the goal of reliability system optimization is to make $\theta_* \rightarrow 0$.

Energy Changes and System Optimization: Energy changes could be literal, in terms of the actual energy capacity and performance of the batteries over time, or metaphorical, representing shifts in industry trends, technological innovation, and policy reforms. These changes necessitate continuous optimization of the reliability system to adapt and respond to new conditions, ensuring that the system maintains its effectiveness and efficiency over time.

While this study introduces a dynamic system cognition perspective, several knowledge gaps remain within lifecycle innovation for EV battery reliability. Key areas for future research include improving predictive models for battery degradation under diverse real-world conditions, such as extreme climates and irregular charging patterns. Advanced materials and designs that enhance recyclability and second-life applications require further exploration to support a circular economy. Additionally, the integration of real-time data from smart grids and vehicle-to-grid (V2G) systems into lifecycle frameworks remains underdeveloped and critical for optimizing reliability. Investigating the socio-economic and policy challenges of implementing large-scale reuse, repurposing, and recycling systems can also offer valuable insights. Addressing these gaps will further refine lifecycle strategies, aligning them with evolving technological, environmental, and market demands.

In summary, this section provides a deep dive into the intrinsic characteristics of reliability system optimization for EV batteries (to make $\theta_* \rightarrow 0$), considering the dynamic nature of time (from $t_1 \rightarrow t_2$). It elucidates how projections on the hyperplane of the lifecycle framework can guide strategic decisions at various ecosystem levels and how the concept of time necessitates a flexible and adaptive approach to maintain optimal reliability. This section enhances our understanding of the evolving nature of EV battery reliability, offering insights that inform both current practices and future innovations.

5. Discussions

Following the above critical thinking from comprehensive ecosystem perspectives, lifecycle innovation, system cognation on EV battery reliability, Section 5 engages in examining the inconsistencies between theoretical and actual battery performance (Section 5.1); proposing the focus on enhancing battery reliability by emphasizing the importance of accurate sensor data through thorough assessment and calibration (Section 5.2); discussing the optimization of EV battery reliability system as a whole with global sustainability initiatives, including sustainable development goals (SDGs), environmental, social, and governance (ESG) criteria, and the "battery passport" (Section 5.3); and offering strategic insights into enhancing system reliability through continuous improvement of the reliability system by proposing a Social–Industrial Large Knowledge Model (S-ILKM) framework (Section 5.4). The aim is to provide a holistic perspective for advancing EV battery reliability, aligning with the larger goals of sustainable and efficient transportation.

5.1. Enhancing EV Battery Reliability Through Examining Inconsistencies: Dissecting the Gaps Between Theoretical vs. Actual Reliability

It is observed that there is a considerable gap between the expected (theoretical) and the observed (actual) reliability of EV batteries. For instance, while the inherent reliability of a battery product may predict a lifespan of 8–20 years (the lifetime of batteries is normally defined with times of charging and discharging cycles, but the end-users prefer "kilometers" and "years"), its actual performance in an EV often falls short, lasting only between 5 and 8 years. This inconsistency is not just a matter of statistical variance but a serious concern that necessitates deeper investigation. The significant inconsistency between the theoretical and actual reliability of electric vehicle (EV) batteries leads to a spectrum of negative consequences, as depicted in Figure 9. These implications range from immediate safety issues to long-term financial and environmental burdens.

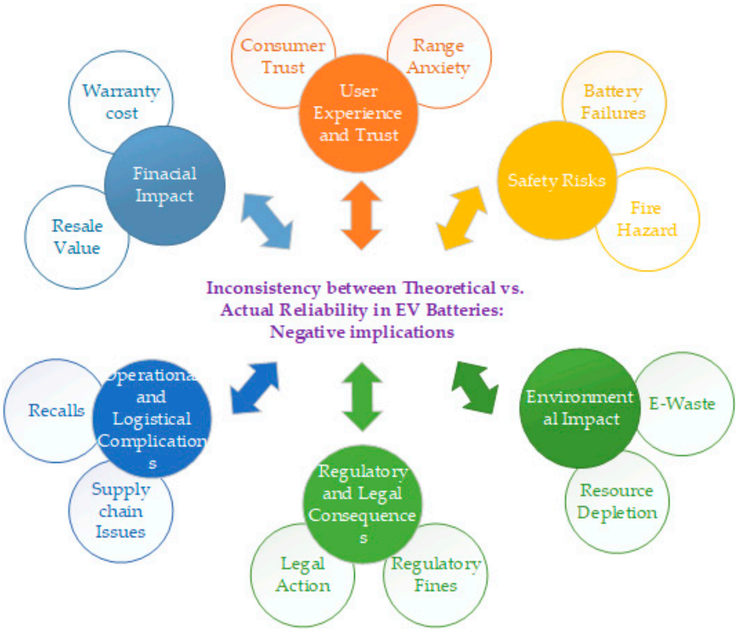

Figure 9. Impacts of reliability inconsistency in EV batteries.

Regarding safety risks, unexpected battery failures can leave drivers stranded, jeopardizing their safety. Additionally, a mismatch between the battery's actual reliability and theoretical safety models can increase the risk of overheating, potentially leading to fires. Financially, a high rate of battery failure escalates warranty claims, imposing financial strain on manufacturers. This issue also affects the resale value of EVs, as reduced reliability can diminish the market value, impacting both manufacturers and vehicle owners. From an environmental perspective, premature battery failure leads to increased electronic waste (e-waste), as recycling or repurposing becomes less feasible. Moreover, the need for frequent replacements of short-lived batteries accelerates the depletion of raw materials. Operationally, significant reliability discrepancies may trigger product recalls, incurring substantial costs and potentially damaging the brand's reputation. Additionally, unreliability issues can disrupt the supply chain, forcing a search for alternative suppliers or technologies. In terms of user experience and trust, frequent failures or performance issues can erode consumer trust in a brand, negatively affecting future sales and market share. One common concern among users is "range anxiety"—the fear that their vehicle will run out of power before reaching its destination, especially if the batteries do not last as long as expected. Finally, regulatory and legal consequences are also a concern. Failure to meet reliability standards can lead to regulatory actions, including fines or prohibitions on selling certain products. Moreover, manufacturers may face legal action if they were aware of the reliability gap but did not take steps to resolve it.

The inconsistency between the theoretical and actual reliability of EV batteries can be attributed to a range of factors throughout their reliability lifecycle. One of the primary reasons is inherent reliability issues that arise even before the battery is operated in vehicles. This includes challenges in battery component sourcing, where the quality and consistency of materials can vary significantly. Manufacturing variations, both in the production of the battery itself and the vehicle manufacture, also contribute to these discrepancies. For instance, two batches of batteries with slight differences in material composition or assembly can exhibit varied performance and longevity. Before installation, the way batteries are stored and the measurement capabilities of sensors used to monitor them play a crucial role. Batteries stored in conditions not conducive to their longevity or monitored with less accurate sensors might not retain their intended quality. Once the batteries are in use, their reliability is further challenged by the complexity of real-world scenarios compared to controlled lab conditions. Environmental factors like extreme temperatures or user behaviors such as frequent rapid charging and discharging can accelerate battery degradation, deviating from theoretical predictions. Bridging the gap between theoretical predictions and actual performance requires high-precision sensors with minimal drift, advanced calibration methods using machine learning, and multi-modal sensing to monitor thermal, electrochemical, and mechanical parameters. Real-time data processing through edge computing and robust communication protocols further enhances battery management, ensuring alignment between theoretical models and real-world performance. Moreover, the integration of the battery system within the vehicle, including its interaction with other systems and the battery management software, can introduce complexities not accounted for in theoretical models. As the battery ages, wear and tear, along with chemical degradation, further reduce its performance, often at a rate faster than anticipated. Economic and business factors, such as cost constraints and market pressures, can also influence the degree to which batteries are optimized for long-term reliability. One key insight for enhancing battery system reliability is the importance of integrating real-world usage data and feedback into the battery design and manufacturing process. For example, if data show that batteries degrade faster under certain environmental conditions, manufacturers can adjust the battery composition or protective measures to mitigate this effect. Similarly, understanding user behavior patterns can lead to designing batteries that are more resilient to specific usage patterns. This approach of continuous learning and adaptation, informed by actual usage data, can significantly close the gap between theoretical and actual reliability.

5.2. Optimizing EV Battery Reliability Through Evaluating and Calibrating the Measurement Capabilities of EV Battery Sensors

The measurement capabilities of sensors within electric vehicle (EV) battery systems are a critical, yet often overlooked, aspect of ensuring overall system reliability. These sensors play a vital role in monitoring various parameters such as temperature, voltage, current, and State-of-Charge (SOC), which are essential for accurate battery management. Over time, the precision and accuracy of these sensors can degrade due to factors like environmental conditions, aging, or mechanical stress. This degradation can lead to unreliable data being fed into the battery management system (BMS), resulting in inaccurate diagnoses and prognoses of the battery's health and performance.

The need for assessment and calibration of these sensors cannot be overstated. Proper calibration ensures that sensor readings remain accurate and consistent over time. This process involves adjusting the sensor output or the data interpretation methods to align with standard or reference measurements. Without such evaluation and calibration, there is a risk that the system might make decisions based on faulty data, which can lead to a range of issues—from inefficient battery utilization to safety hazards. For instance, if a temperature sensor starts to show readings that are higher or lower than the actual battery temperature, the BMS might unnecessarily trigger cooling systems or fail to prevent overheating, both of which can affect battery life and safety. Similarly, inaccurate SOC readings might lead to the undercharging or overcharging of the battery, reducing its lifespan and efficiency.

The consequences of not evaluating and calibrating sensors can be significant. Incorrect diagnostic and prognostic results can lead to premature battery failures, reduced operational efficiency, increased maintenance costs, and even safety risks. Therefore, it is crucial to integrate sensor evaluation and calibration into the operation and maintenance stage of EV battery systems during lifecycle management. This practice not only ensures the accuracy and reliability of sensor data but also contributes to the overall health and longevity of the battery system, ultimately enhancing the reliability and safety of electric vehicles.

5.3. Optimizing EV Battery Reliability System as a Whole: Aligning with the SDGs, ESG, and the "Battery Passport" Framework

The reliability of electric vehicle (EV) batteries holds a significant place in the broader context of the sustainable development goals (SDGs), environmental, social, and governance (ESG) criteria, and the emerging concept of the "battery passport". EV battery reliability is not an isolated technical feature; the integration of EV battery reliability within these frameworks demonstrates the multi-dimensional impact of technological advancements in achieving global sustainability goals.

When considering the novel EV battery reliability ecosystem, the framework of the EV battery reliability lifecycle, and the holistic system cognition for reliability system optimization in the context of SDGs, ESG criteria, and the "battery passport", it is imperative to acknowledge the unique nature of EV batteries as opposed to general assets. This is due to several reasons, listed as follows:

Complexity and Interconnectivity at Micro, Meso, and Macro Levels: The EV battery reliability ecosystem encompasses a wide range of stakeholders and factors at different levels, each playing a crucial role in the overall reliability and performance of the batteries. This includes individual consumers (micro level), manufacturers and industry players (meso level), and broader societal and environmental impacts (macro level). Addressing the SDGs, addressing ESG criteria, and implementing a "battery passport" system requires a deep understanding of these interconnections and the cumulative impact they have on the sustainability and ethical implications of EV batteries.

Lifecycle Framework Inclusivity: Traditional asset frameworks often overlook stages like "Zero"-Life reliability, reuse, repurpose, and recycle. However, these stages are vital in the context of EV batteries for achieving sustainability goals. The comprehensive lifecycle approach of EV batteries ensures that every stage, from production to end-of-life management, aligns with sustainability principles, thereby supporting various SDGs and ESG objectives. This includes reducing waste, promoting resource efficiency, and ensuring responsible production and consumption patterns.

Holistic System Cognition for Reliability System Optimization: The holistic approach to system cognition in EV battery reliability acknowledges the dynamic nature of these systems and their evolution over time. This approach is crucial for effective reliability system optimization, ensuring that solutions are adaptable, resilient, and sustainable in the long term. It aligns with the principles of the "battery passport", which seeks to track and optimize the battery's lifecycle for maximum efficiency and minimum environmental impact.

Alignment with Global Sustainability Goals: The novel ecosystem and lifecycle framework of EV batteries are directly aligned with several SDGs, including clean energy, sustainable cities, responsible consumption, and climate action. Enhancing reliability through this comprehensive approach ensures that EV batteries contribute effectively to these goals.

Compliance with ESG Criteria: ESG criteria emphasize responsible and sustainable business practices. A holistic approach to EV battery reliability, considering the entire ecosystem and lifecycle, ensures that these criteria are met not just in isolated instances but as an integral part of the business model. This includes ethical sourcing of materials, ensuring labor welfare, minimizing environmental impact, and demonstrating strong corporate governance.

Advancing Circular Economy Principles: The novel lifecycle approach, particularly in stages like reuse and recycling, is crucial for advancing circular economy principles. This approach is essential for reducing the ecological footprint of EV batteries, thereby aligning with the goals of sustainability and responsible resource management.

The study addresses challenges in standardizing global frameworks like the SDGs, ESG criteria, and the "battery passport" by advocating for harmonized international standards, collaboration among stakeholders, and public–private partnerships. It emphasizes developing a traceable "battery passport" system and aligning regional policies to build infrastructure and best practices, enabling scalable solutions that accommodate regional and industrial differences while aligning with global sustainability goals.

In summary, considering the novel EV battery reliability ecosystem, lifecycle framework, and holistic system cognition is crucial when addressing the SDGs, ESG, and "battery passport" due to the complex, interconnected nature of EV batteries and their significant impact on sustainability and ethical practices. This approach ensures that optimization in a battery reliability system is not just technical improvement but contributes to broader global goals of sustainability and responsible innovation.

5.4. Advancing to a Social–Industrial Large Knowledge Model (S-ILKM) Framework

The transition from traditional Industrial Large Knowledge Models (ILKMs) [38] to an expansive Social–Industrial Large Knowledge Model (S-ILKM) marks a significant evolution in the application of large language models (LLMs) within Industry 4.0 and smart manufacturing (Figure 10). ILKMs focus on integrating domain-specific knowledge into LLMs to address complex challenges in industrial settings, particularly in smart manufacturing. However, these models predominantly cater to industrial needs, with a concentration on meso-level inputs and outputs.

In the context of EV battery reliability and drawing insights from the reliability system cognition explored in Section 4, it becomes evident that ILKMs' focus could somewhat be extended to a broader scope. While they undoubtedly make manufacturing systems smarter and enhance inherent reliability at the meso level, there is a growing need for a more encompassing approach. This need is highlighted by the dynamic energy changes at the micro and macro levels that occur over time, indicating that a continuous improvement in the reliability system is essential (Figure 10).

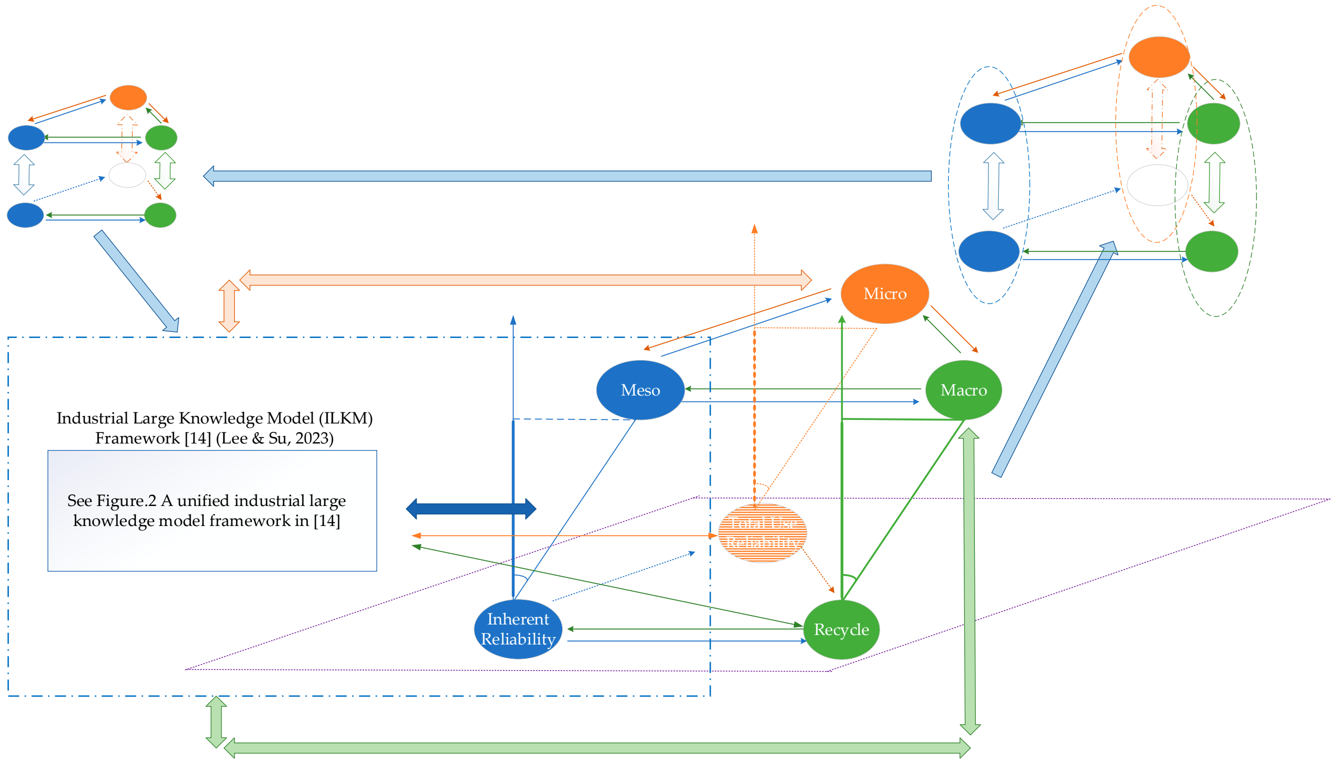

Figure 10. An expansive Social–Industrial Large Knowledge Model (S-ILKM) [14].

The S-ILKM extends beyond ILKMs' industrial focus, integrating insights from both micro and macro levels. This approach broadens the data scope to include both industry-specific, private data (like quality and reliability data) and diverse, public, open-source data (such as market trends, regulations, and user feedback). The purpose of the S-ILKM is to improve systems holistically, not just for industrial tasks or language-related challenges. This model fuses in-depth domain knowledge specific to EV battery industries with broader societal and global contexts.

Other key aspects of the S-ILKM include the following:

Data Diversity: Combining private, domain-specific data with public, diverse textual data, the S-ILKM offers a more comprehensive view for system improvement.

Expanded Purpose: The S-ILKM is designed for broader system improvements, transcending the specific industrial tasks of ILKMs and the language-centric focus of LLMs.

Knowledge Fusion: It integrates detailed domain knowledge pertinent to EV battery industries with broader individual experiences and societal insights.

Ecosystem Integration: Unlike ILKMs, the S-ILKM aligns with the entire ecosystem, encompassing micro, meso, and macro levels for a more holistic approach.

Real-Time Decision Making: The S-ILKM is equipped for immediate decision making within the battery reliability system, expanding its utility beyond just industrial applications.

In summary, the S-ILKM framework represents a leap forward in knowledge modeling, offering a comprehensive, integrated approach that considers the intricate interplay of individual, industrial, and societal factors in optimizing EV battery reliability. This advanced model is pivotal for addressing the dynamic complexities of modern EV battery systems and aligns well with the evolving landscape of sustainable transportation technology.

6. Conclusions

This study ventured beyond traditional approaches to battery reliability, advocating for a holistic, multi-faceted view that interweaves the reliability ecosystem, lifecycle innovation, and system cognition into a cohesive narrative. In Section 2, it explored the crucial quest for high reliability in EV batteries, dissecting the complex reliability ecosystem across micro, meso, and macro perspectives. This comprehensive analysis revealed the impact of battery reliability, extending from individual consumer satisfaction to broader industrial competitiveness and environmental sustainability. Section 3 delved into the operational reliability of EV batteries, transitioning from general asset frameworks to a more nuanced EV battery lifecycle. The introduction of the novel "Zero"-Life reliability stage and the emphasis on the use and reuse, repurpose, and recycle stages provided a fresh lens through which to view battery reliability, enriching our understanding and approach to lifecycle management. This study's innovative approach continued in Section 4, where it integrated the reliability ecosystem with the lifecycle framework to form a dynamic system cognition of EV battery reliability. This multidimensional perspective, visualized through the metaphor of a triangular prism, facilitated a deeper understanding of the intrinsic nature of reliability system optimization. In Section 5, its discussions synthesized these insights, addressing the inconsistencies between theoretical predictions and actual performance, emphasizing the critical role of evaluating and optimizing the measurement capabilities of the sensors involved, aligning EV battery reliability with global sustainability initiatives (including the SDGs, ESG criteria, and the "battery passport" framework), and proposing the transformative Social–Industrial Large Knowledge Model (S-ILKM) framework.

As this study concludes, it becomes evident that the enhancement of EV battery reliability requires a shift from isolated, component-focused approaches to a holistic system optimization strategy. This broader perspective not only addresses the immediate technical challenges but also aligns with global sustainability objectives. This study's insights and recommendations pave the way for future research and practical applications in sustainable transportation and EV technology, emphasizing the critical role of EV battery reliability in shaping a sustainable, efficient, and environmentally friendly future. In conclusion, this study contributes to the ongoing discourse in EV technology by offering a comprehensive, innovative framework for understanding and improving EV battery reliability. By embracing a holistic view that integrates ecosystem analysis, lifecycle innovation, and system cognition, this study sets a new benchmark in the pursuit of sustainable, high-performing, and durable EV batteries, crucial for the advancement of sustainable transportation worldwide.

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