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Battery Technologies and Intelligent Management Systems for Modern Power Systems: A Comprehensive Review

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ABSTRACT: Battery Energy Storage Systems (BESSs) have emerged as a critical enabler in modern power systems, facilitating large-scale integration of renewable energy sources, improving grid stability, and supporting the transition toward decentralized and low-carbon energy infrastructures. This paper presents a comprehensive review of battery energy storage technologies and their applications across utility-scale grids, industrial facilities, and residential energy systems. Recent advancements in battery chemistries, including lithium-ion, redox flow, sodium-based, and solid-state batteries, are examined with respect to energy density, efficiency, cost evolution, safety, and environmental impact. Furthermore, the paper explores emerging intelligent control strategies based on artificial intelligence, machine learning, and model-based approaches that enhance operational reliability, predictive maintenance, and battery lifetime in smart grids and microgrid environments. Key challenges hindering widespread deployment are discussed, including high capital costs, degradation and lifetime uncertainty, safety and thermal runaway risks, cybersecurity vulnerabilities in digitalized EMS/BMS platforms, and the lack of interoperability standards. Finally, the paper outlines future research directions such as second-life battery utilization, hybrid energy storage integration, decentralized and AI-driven energy management architectures, and regulatory frameworks to support large-scale adoption. This review aims to provide researchers, system designers, and policymakers with a structured perspective on the current state and future potential of battery energy storage technologies in evolving power systems.

KEYWORDS: Battery technologies Electrical power grid Energy transitions Cost Investment

I. INTRODUCTION

Battery technologies (BTs) constitute a salient feature within the energy domain, poised to assume a pivotal role in imparting stability and adaptability to electrical power systems amidst the escalating integration of variable renewable energy (RE) sources [1–4]. In this direction, the magnitude of BT deployment within the energy sector surpassed 2400 GWh in 2023, marking a quadrupling of usage since 2020. Over the past five years, in excess of 2000 GWh of lithium-ion BT capacity has been integrated, energizing more than 40 million EVs and numerous BT storage initiatives [10–12].

Grid-scale BTs are rapidly gaining ground in the energy storage sector. Although they currently represent a smaller capacity compared to pumped-storage hydropower, grid-scale BTs are expected to dominate future storage growth globally. These BTs are primarily utilized for sub-hourly, hourly, and daily energy balancing. As of the end of 2022, the total installed capacity of grid-scale BTs storage was approximately 28 GW, with the majority of this capacity having been added within the preceding six years [23–25]. The composition of grid-scale BTs in 2022 showed a continuity from 2021, with lithium-ion BTs storage maintaining its prominence as the predominant technology. This type continued to constitute the majority of all new capacity installed, underscoring its widespread adoption and reliability in the energy storage sector [26–30]. Table 1 highlights the yearly additions of grid scale BT storage from 2017 to 2022.

However, there remains a noticeable scarcity of detailed research that has thoroughly investigated the impact and potential of BTs in facilitating secure energy transitions.

In this study, researchers [35] examined the economic viability and operational performance of grid-connected Energy Storage System (ESS) technologies, focusing particularly on Proton Exchange Membrane-Reversible Fuel Cell (PEM-RFC) and Lithium-ion BT (LIBT), aimed at fulfilling load demands. Our findings indicate that the integration of ESS technologies does not present an optimal solution, primarily due to the high costs associated with their implementation. Recent study [36] was designed to harness the capabilities of machine learning models, particularly the Extreme Gradient Boosting (XGBoost) algorithm, to predict the Remaining Useful Life (RUL) of batteries, with an emphasis on the often-underrepresented temperature variable. By applying the XGBoost model and meticulously fine-tuning its hyperparameters, the approach demonstrated enhanced accuracy and efficiency in RUL estimation.

This article critically investigates the transformative role of BTs in fostering a secure and sustainable shift from fossil fuels to RE sources. Addressing the escalating energy demands and environmental challenges, it highlights the versatility and efficiency of batteries in storing and managing RE, thus ensuring a reliable power supply. The article explores the essential roles that batteries play in enhancing grid stability and facilitating the integration of RE into power systems. It also analyzes the regional deployment of BTs considering how geopolitical and economic factors influence their adoption and utilization. Additionally, the article delves into the financial dynamics of BTs, discussing the impact of investments on technological innovations, manufacturing capacities, and market growth. Ultimately, it assesses how batteries contribute to reducing carbon emissions and enhancing energy security, concluding with a synthesis of their strategic importance in global energy policies and economic strategies

Table 1
The yearly additions of grid-scale BT storage from 2017 to 2022

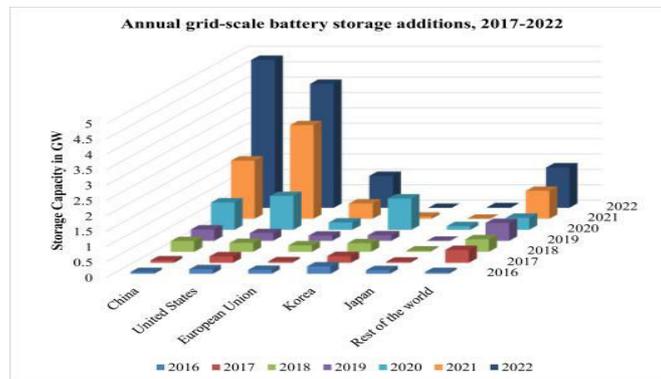


Table 1.1 Grid-scale BT storage from 2017 to 2022

However, there remains a noticeable scarcity of comprehensive studies that thoroughly investigate the impact and potential of battery technologies (BTs) in facilitating secure and sustainable energy transitions. According to Han et al. [32], lithium-ion BTs are extensively employed in electric vehicles (EVs). Battery degradation represents a major scientific challenge in battery research, as it limits the ability of batteries to store energy and deliver power, thereby directly affecting EV performance, cost, and service life. Consequently, a detailed examination of the fundamental mechanisms and challenges associated with BT degradation over the entire lifecycle is essential.

Overall, this study critically examines the transformative role of BTs in enabling a secure and sustainable transition from fossil fuel-based systems to renewable energy sources. It highlights the importance of batteries in managing renewable energy variability, improving grid stability, and ensuring reliable power supply. The paper also analyzes regional deployment trends, considering the influence of geopolitical and

economic factors, and explores the financial dynamics shaping technological innovation and market growth. Finally, the article synthesizes the strategic importance of BTs in reducing carbon emissions and strengthening energy security, and outlines the structure of the manuscript, as illustrated in Fig. 1.



Fig. 1.1 Structure of the manuscript

II. THE ROLE OF BATTERIES IN ELECTRICAL POWER SYSTEMS

Both utility-scale and behind-the-meter battery technology (BT) storage systems are capable of delivering a wide range of services to electrical power grids, as illustrated in Fig. 1. Utility-scale BT storage plays a vital role in balancing electricity supply and demand through energy shifting, while also contributing significantly to grid stability and supply reliability. These systems provide essential ancillary services, including inertia support, voltage regulation, frequency control, grid-forming capability, and fast-start reserve provision. In addition, utility-scale batteries enhance system adequacy and support congestion management in transmission and distribution networks.

Furthermore, when aggregated into virtual power plants (VPPs), distributed battery systems can collectively deliver services comparable to those of large utility-scale installations, enhancing grid flexibility and operational coordination

Table 2

Battery Type	Energy Density (Wh/kg)	Power Density	Round-Trip Efficiency (%)	Cycle Life (cycles)	Response Time	Cost Trend	Key Advantages	Key Limitations	Typical Applications
Lithium-ion (Li-ion)	150–250	High	90–95	3,000–10,000	Milliseconds	Rapidly decreasing	High efficiency, fast response, mature technology	Degradation, thermal runaway risk, recycling challenges	EVs, grid-scale storage, frequency regulation
Redox Flow Batteries (RFBs)	20–50	Medium	65–85	>10,000	Seconds	Moderate	Long cycle life, independent power and energy	Low energy density, higher upfront cost	Large-scale grid storage, renewable integration

Battery Type	Energy Density (Wh/kg)	Power Density	Round-Trip Efficiency (%)	Cycle Life (cycles)	Response Time	Cost Trend	Key Advantages	Key Limitations	Typical Applications
							scaling, high safety		
Sodium-ion (Na-ion)	90–160	Medium	80–90	2,000–6,000	Milliseconds	Decreasing	Abundant materials, lower cost, safer than Lithium	Lower energy density, early commercialization	Grid storage, stationary energy systems
Solid-State Batteries (SSBs)	250–400 (projected)	High	>90 (projected)	>5,000 (expected)	Milliseconds	High (currently)	Improved safety, higher energy density, longer lifespan	Manufacturing complexity, cost, scalability issues	Future EVs, advanced grid storage
Lithium-Sulfur (Li-S)	300–500	Medium	70–85	<1,000	Milliseconds	Experimental	Very high theoretical energy density, lightweight	Short cycle life, polysulfide shuttle effect	Aerospace, next-generation EVs
Lead-Acid	30–50	Low	70–85	500–2,000	Seconds	Low	Low cost, mature, recyclable	Low energy density, short lifespan	Backup power, UPS systems
Nickel-based (NiMH, NiCd)	60–120	Medium	70–85	1,000–3,000	Seconds	Stable	Robust, reliable	Memory effect, environmental concerns	Hybrid vehicles, niche applications

The state of energy (SoE) can be expressed as the ratio of the stored energy $E(t)$, which can potentially be released from the battery starting at time t , to the maximum stored energy E_{max} . As the battery ages over its lifespan, the amount of charge it can retain gradually decreases, resulting in a shift in the open-circuit voltage (OCV) curve. Consequently, the maximum amount of energy that can be stored by the battery also declines. The stored SoE can be interpreted in a manner similar to Ref. [44], as defined by Eq. (1).

$$SoE(t) = E(t) / E_{max}$$

In this context, both $E(t)$ and E_{max} are intrinsically linked to the OCV. The stored energy represents the voltage trajectory from the current charge level to the point at which no further energy or charge can be extracted, as the state of charge (SoC) and SoE asymptotically approach 0%. It should be noted that E_{max} does not account for operational losses. Similar to the relationship between SoC and OCV, a corresponding relationship between SoE and OCV can be established.

For practical implementation, it is advantageous to discretize the continuous expressions for the SoC, as shown in Eq. (2), and for the SoE, as presented in Eq. (3):

$$SoC_k = SoC_{k-1} + \frac{i_{Lk} \cdot \Delta t}{Q_{max}} \tag{2}$$

$$SoE_{stored,k} = SoE_{stored,k-1} + \frac{i_{Lk} \cdot U_{OCV,k} \cdot \Delta t}{E_{max,stored}} \tag{3}$$

Here, the subscript k denotes the current time step, while k-1 represents the previous state. The current at time step k is denoted by i_{Lk} , Q_{max} represents the maximum charge capacity, and Δt denotes the discrete time interval.

Equation (4) describes the current state of the unstable energy:

$$SoE_{u,k} = E_{u,k} / E_{max}$$

In Eq. (4), $SoE_{u,k}$ represents the current unstable state of energy, while $E_{u,k}$ denotes the corresponding energy value.

Table 3 provides a comprehensive overview of recent studies on battery technologies in electrical power systems.

Study / Reference	Focus / Topic	Key Contributions / Findings	Application / Relevance
Battery Energy Storage Systems: Energy Market Review (2024)	Market trends, ancillary services, capacity projections	Reviews frequency control, load following, voltage regulation services; shows rapid capacity growth (~150 GW/363 GWh) and projected needs. (MDPI)	Grid stability, system services, market analysis
Battery Energy Storage Systems: Modeling & Diagnostics (Carrasco Ortega et al. 2023)	State diagnostics & management	Reviews modeling, state of health (SoH), state of charge (SoC) diagnostics, and viability in modern electricity markets. (MDPI)	Diagnostics, health estimation, energy management
Scalable Optimal Power Management for BESS (Farakhor et al. 2023)	Power management optimization	Proposes clustering-based control to reduce computational overhead while balancing SoC and temperature in large-scale BESS. (arXiv)	Large BESS control, optimization
Economic Optimal Power Management of SL-BESS (Farakhor et al. 2024)	Second-life EV battery systems	Develops economic power management for second-life battery storage considering degradation and heterogeneity. (arXiv)	Cost-effective grid storage using retired EV batteries
Cyber Threats to Battery Storage Systems (Öhrström et al. 2025)	Cybersecurity risks	Analyzes vulnerabilities in remote cloud-controlled BESS, demonstrating impacts of cyberattacks on grid stability. (arXiv)	Security, resilience, control systems

Table 2.1 Summary of the latest research on BT in electrical power systems

2.1 Battery Technologies in Smart Microgrids and Building-Integrated Systems

Battery technologies (BTs) play an increasingly pivotal role in smart microgrids and building-integrated energy systems, where decentralized renewable generation and intelligent control mechanisms converge to optimize system performance. One major area of advancement is the integration of BTs with multi-layer Energy Management Systems (EMSs). Recent studies have proposed multi-stage EMS architectures combining anticipative optimization using Multi-Objective Particle Swarm Optimization (MOPSO) with real-time corrective control based on Extremum-Seeking (ES) techniques.

Overall, the integration of BTs within smart microgrids and building energy systems supports both real-time optimization of active and reactive power and long-term improvements in operational efficiency and energy autonomy. The combination of AI-driven EMSs, predictive forecasting models, and modular digital

infrastructures enables BTs to evolve beyond conventional storage roles into key enablers of resilience, sustainability, and cost-effectiveness in decentralized power systems. Insights from recent experimental studies, optimization-based frameworks, and digital twin implementations provide a clear roadmap for deploying BTs in next-generation urban energy infrastructures

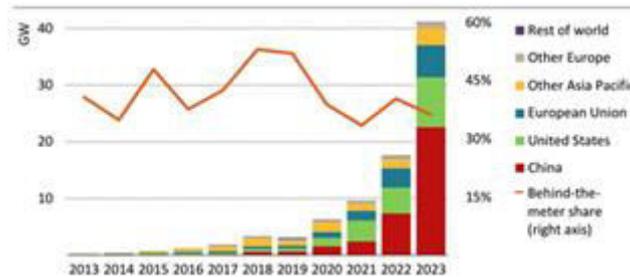


Fig. 2.1 World wide Battery storage capacity from 2013 to 2023

III. DEPLOYMENT OF BATTERY TECHNOLOGY BY REGION

3.1 Comparative Overview of Battery Technologies in Smart Microgrids

Ref.	Citation	System Type	Technologies / Components	Optimization / Modeling Approach	Key Findings
[65]	Gheouany et al. (2023)	Multi-stage EMS	PV, ESS	MOPSO, Extremum-Seeking	Real-time experimental validation; 6% reduction in energy cost and PAR compared to offline optimization
[66]	Gheouany et al. (2024)	Active/Reactive EMS	PV, ESS	Lexicographic PSO	58.9% reduction in active energy bills, 83.2% in reactive bills, and 49.3% CO ₂ reduction
[67]	Alami Merrouni et al.	Hybrid Optimization with DRPs	RES, ESS	IBT, DRP, Two-stage robust optimization	23.2% energy cost reduction and 7.7% emission reduction
[76]	Fully Renewable B2G Model	Smart Building + Microgrid	—	Stochastic tri-level optimization	38% cost reduction using B2G with comfort index evaluation
[77]	Energy IoT Resilience	Multi-layer Resilience	Smart Microgrids	IoT-based performance modeling	Hazard-resilient methodology across four system layers
[78]	Federated RL EMS	Privacy-preserving EMS	Residential Microgrids	PPO, Federated RL	Decentralized training with improved cost efficiency
[79]	RL-based DSM	Retail Demand Management	PV, Wind, ESS	RL, Q-table, AVO	Reduced power costs and improved NPV and LCOE
[80]	Coalition MG Model	Peer-to-peer Trading	MGs, Water Storage	Stochastic coalition optimization	ENS reduction of 301.63 kWh and 146.89 kWh
[81]	Smart	CHP Microgrid	CHP +	GA	Reduced losses, improved

Ref.	Citation	System Type	Technologies / Components	Optimization / Modeling Approach	Key Findings
	Transformer Control	Management	Microgrid		voltage profile, and environmental benefits
[82]	Two-stage EMS	DR & ESS with V/F Control	Smart City Microgrids	IPWPNFIA (Probabilistic Fuzzy)	Real-time prototyping with reduced computational burden
[83]	Stochastic Day-ahead Optimization	Multi-microgrid EMS	HRSS, EVPL	Stochastic-robust optimization	Effective day-ahead scheduling in multi-energy microgrids

Table3.1 Comparative Overview of Battery Technologies

3.2 Deployment Trends and Market Expansion

The Inflation Reduction Act has played a crucial role in facilitating the integration of utility-scale BT systems into ancillary service markets, particularly in the United States. These systems are increasingly deployed to provide balancing services and secure capacity, especially in regions with high penetration of variable renewable energy (RE) sources. This strategic deployment highlights the growing importance of advanced BT storage solutions in enhancing grid stability and resilience.

Within the European Union, installed BT storage capacity increased by approximately 70%, with annual additions reaching nearly 6 GW in 2023. Around 90% of this growth originated from behind-the-meter installations, predominantly in Germany and Italy. These markets have benefited from high retail electricity prices and favorable incentives, including tax credits and low-interest financing schemes. Notably, nearly 80% of rooftop PV installations in these countries during 2023 were paired with battery storage systems. On the utility-scale front, capacity auctions have emerged as a key driver, with Italy awarding 1.6 GW of BT storage contracts in 2022 for delivery by 2024, several of which became operational in 2023. These initiatives reflect a proactive approach to strengthening energy security and managing demand volatility.

IV. BATTERY TECHNOLOGY COSTS

The past decade has been transformative for battery technologies, largely driven by the dominance of lithium-ion batteries. Compared to legacy technologies such as lead-acid and nickel-cadmium batteries, lithium-ion batteries offer significantly higher energy density and longer cycle life. While lead-acid batteries typically exhibit specific energies of 35–40 Wh/kg, modern lithium-ion batteries achieve values ranging from approximately 90 to 300 Wh/kg at the cell level. This substantial improvement enables the development of lighter, more compact, and higher-performance battery packs across multiple applications. A lithium-ion cell comprises four core components: the cathode, anode, electrolyte, and separator. The cathode and anode serve as lithium-ion storage media, while the separator prevents short circuits and ensures operational safety.

4.1 Cost Evolution and Market Dynamics

Lithium-ion battery costs have declined dramatically over the past decade, falling from approximately USD 800/kWh to below USD 140/kWh by 2023. This reduction has been driven by sustained R&D, economies of scale, and advancements in manufacturing processes. As production costs decrease, raw material prices—particularly lithium, cobalt, and nickel—now constitute a larger share of total battery costs, increasing sensitivity to commodity price volatility and geopolitical

In 2022, price spikes in critical minerals temporarily reversed the downward cost trend. However, prices declined again in 2023 due to expanded mineral supply, increased manufacturing capacity, and lower-than-expected demand in certain markets, notably China. As a result, lithium-ion battery prices fell below 2021 levels, indicating a potential stabilization of market economics

Lithium iron phosphate (LFP) chemistry has emerged as a cost-effective alternative, offering robust performance and improved safety. Throughout 2023 and early 2024, LFP batteries maintained the lowest weighted-average prices globally, with costs dropping below USD 100/kWh by March 2024. Although prices remain lowest in China, regional disparities have narrowed significantly, suggesting increasing global price convergence driven by scaling production and market integration

V. BATTERY TECHNOLOGY INVESTMENT

Investment in EV batteries and BT storage has expanded rapidly, with EV battery investments increasing eightfold and grid-scale storage investments rising fivefold since 2018. In 2023, global investment reached approximately USD 150 billion, including USD 115 billion for EV batteries and USD 40 billion for BT storage [7]. China, Europe, and the United States dominate investment flows, while developing and emerging economies accounted for only about 2% of total investment

These trends have created new revenue opportunities for energy storage systems, reinforcing their strategic role in future low-carbon power systems.

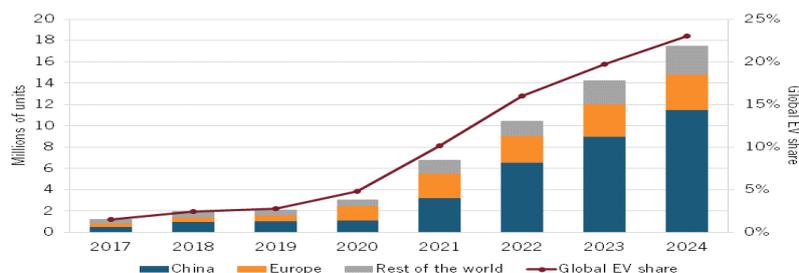


Fig. 5.1 The global level of investment in EVBT from 2018 to 2023.

VI. CONTRIBUTION OF BATTERY TECHNOLOGIES IN SECURE ENERGY TRANSITIONS

In the rapidly evolving landscape of global energy systems, battery technologies (BTs) have emerged as a cornerstone for enabling secure energy transitions. Their increasing deployment supports the transformation of conventional power systems toward more sustainable, reliable, and flexible architectures. This section examines how recent advancements in BTs contribute to energy security by enhancing grid resilience, facilitating large-scale integration of renewable energy (RE) sources, and reducing dependence on fossil fuels.

BTs play a critical role in mitigating the intermittency and variability associated with RE generation by providing fast-response energy storage, load balancing, and ancillary services. Moreover, their integration with advanced energy management systems (EMSs) and intelligent control strategies enables real-time optimization, predictive maintenance, and improved system reliability under dynamic operating conditions. As a result, batteries enhance both operational security and long-term sustainability of power systems.

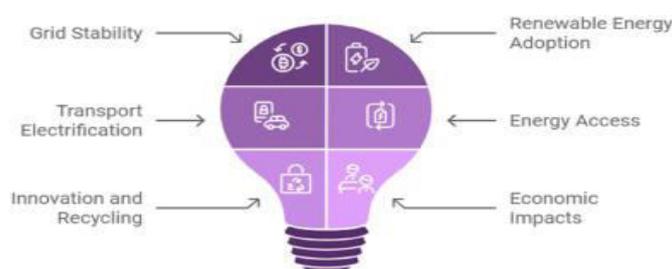


Fig.6.1 Battery technologies to secure energy transitions.

Furthermore, BTs support decentralized energy architectures, including microgrids and behind-the-meter systems, which strengthen energy access, resilience against grid disturbances, and cyber-physical security. These capabilities are particularly valuable in regions with high RE penetration or weak grid infrastructure. Cyber-physical security is another emerging dimension of secure energy transitions supported by BTs. As batteries are increasingly integrated with digital EMS and cloud-based control platforms, they can be equipped with advanced monitoring, encryption, and fault-detection mechanisms. When properly designed, BT-enabled systems improve situational awareness and reduce vulnerability to cyberattacks by enabling decentralized control and rapid isolation of compromised components.

In addition, the sustainability of energy transitions is reinforced through advances in battery lifecycle management, including second-life applications and recycling. Repurposing retired electric vehicle batteries for stationary storage extends asset value while reducing material demand and waste. Concurrently, improvements in recycling technologies and circular economy frameworks mitigate supply-chain risks associated with critical minerals, thereby enhancing long-term energy security.

VII. INNOVATIONS IN BATTERY MANAGEMENT SYSTEMS (BMS) AND LIFECYCLE OPTIMIZATION

Modern Battery Management Systems (BMSs) have evolved into a critical enabler for the safe, efficient, and long-term operation of battery technologies (BTs) in smart grids, microgrids, and building-integrated energy systems. Contemporary BMS architectures extend beyond basic voltage and current regulation to incorporate comprehensive lifecycle optimization strategies that jointly address electrochemical degradation, thermal stability, operational safety, and predictive fault prevention.

Recent advancements emphasize accurate state-of-health (SoH) estimation using data-driven and physics-informed diagnostics to track degradation mechanisms and predict remaining useful life. Adaptive charge–discharge control strategies—enabled by model predictive control (MPC), reinforcement learning (RL), and hybrid optimization techniques—dynamically regulate current profiles in real time, balancing performance requirements against battery aging constraints. Thermal management has similarly progressed through temperature-aware control schemes that coordinate active and passive cooling systems, mitigating thermal stress and reducing the risk of thermal runaway.

A transformative trend in BMS development is the integration of predictive maintenance through artificial intelligence (AI) and machine learning (ML). By exploiting historical operational data and real-time measurements, AI-enabled BMSs can detect anomalies, forecast incipient failures, and proactively adjust control setpoints. However, these capabilities introduce trade-offs related to increased system complexity, sensing requirements, computational overhead, and tighter coupling with higher-level Energy Management Systems (EMSs). Consequently, an optimal balance must be achieved between BMS sophistication and the tangible lifecycle benefits obtained.

VIII. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Despite the rapid progress of battery technologies, several challenges continue to limit their widespread and long-term deployment. From a technical perspective, the absence of highly accurate, adaptive battery degradation models constrains effective lifecycle optimization and reduces control reliability. Additionally, integrating heterogeneous battery chemistries within unified EMS frameworks remains complex, particularly when coordinating active and reactive power flows in real time.

Economic barriers persist due to high upfront investment costs and maintenance expenses associated with both advanced batteries and sophisticated BMS/EMS infrastructures, especially in developing regions. Environmental concerns related to raw material extraction, resource scarcity, and end-of-life disposal raise questions about the sustainability and circularity of current battery supply chains. Moreover, the increasing digitalization of BMS and EMS platforms introduces cybersecurity vulnerabilities, while regulatory

fragmentation and lack of standardized interoperability protocols impede seamless system integration across regions and markets.

Future research should focus on developing adaptive, AI-driven aging and degradation models suitable for real-time control applications. Greater attention is needed for decentralized and community-scale EMS architectures, second-life battery utilization, and hybrid storage configurations that improve economic viability. In parallel, robust cybersecurity frameworks, standardized communication interfaces, and harmonized regulatory policies are essential to ensure secure, scalable, and interoperable deployment of BT-based systems. Table 7 outlines these limitations and highlights key research opportunities necessary for accelerating sustainable battery integration.

IX. CONCLUSION

Batteries have become an indispensable component of modern energy systems, underpinning the transition toward renewable, low-carbon electricity in both transportation and power sectors. Their widespread adoption—from personal electronics to electric vehicles (EVs) and grid-scale storage—reflects their critical role as a flexible and emission-free energy carrier at the point of use.

In recent years, global battery deployment has expanded rapidly, surpassing 2400 GWh in 2023, representing a fourfold increase since 2020. This growth has been driven primarily by the proliferation of electric vehicles, with over 40 million EVs supported by lithium-ion battery capacity exceeding 2000 GWh. Concurrently, stationary battery storage in the power sector has accelerated, with more than 40 GW added in 2023 alone to support energy shifting, ancillary services, congestion mitigation, and electricity access. These trends have been reinforced by strong policy support and record investments totaling approximately USD 150 billion in 2023.

This article highlights the pivotal contributions of battery technologies to secure, cost-effective, and resilient energy transitions. Advances in battery management systems, lifecycle-aware optimization, and AI-enabled predictive maintenance have significantly enhanced operational efficiency, safety, and sustainability. Nevertheless, limitations remain due to data availability constraints, modeling uncertainties, and regulatory diversity. Future work should prioritize longitudinal performance studies, next-generation battery technologies such as solid-state and flow batteries, and the development of sustainable recycling and circular economy frameworks.

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