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Review article

Battery technologies In electrical power Systems: Pioneering secure energy transitions

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HIGHLIGHTS

- Examines battery roles in modern, renewable-integrated power systems.
- Reviews advances in smart grid and building-level battery integration.
- Analyzes trade-offs in cost, complexity, and efficiency of battery systems.
- Discusses lifecycle optimization and AI-driven battery management systems.
- Identifies challenges and future directions for energy storage deployment.

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ABSTRACT

Battery technologies (BTs) are increasingly central to the transformation of modern electrical power systems, offering essential capabilities for integrating intermittent renewable energy sources, enhancing grid reliability, and supporting the decentralization of energy infrastructure. This paper provides a comprehensive review of BT applications across utility-scale, industrial, and residential domains, highlighting recent advances in battery chemistries such as lithium-ion, redox flow, and solid-state systems, while evaluating their cost trajectories, performance characteristics, and environmental considerations. The integration of BTs with energy management systems (EMSs) and battery management systems (BMSs) is critically examined, focusing on their roles in real-time optimization, predictive maintenance, state-of-health estimation, and thermal regulation. Notably, emerging strategies driven by artificial intelligence (AI), machine learning (ML), and model-based control are explored for their potential to enhance operational efficiency and extend battery lifecycle in smart microgrids and building-integrated systems. The paper also addresses ongoing challenges, including high capital costs, degradation uncertainties, safety risks under dynamic conditions, cybersecurity threats in digital EMS/BMS platforms, and the absence of standardized protocols for system interoperability. Case studies from diverse geographic regions are presented to contextualize deployment strategies and policy impacts. Through a synthesis of current research and technology trends, the paper outlines critical areas for future investigation, such as second-life battery utilization, hybrid storage integration, decentralized EMS architectures, and regulatory alignment. These findings contribute to the ongoing development of intelligent, sustainable, and secure battery-based energy solutions that align with global decarbonization and resilience objectives in the evolving landscape of electric power systems.

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1. 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]. Equally important, BTs constitute the cornerstone of the burgeoning transition to electric vehicles (EVs), a phenomenon rapidly gaining traction. Given the current attribution of over 60 % of global energy-related carbon dioxide (CO_2) emissions to the power and transportation sectors [5–9]. 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].

The global BT storage market experienced significant growth in 2023, with its capacity doubling to over 90 GWh. Consequently, the total deployed BT storage surpassed 190 GWh. This surge in BT storage capacity is predominantly attributed to utility-scale installations, whereas behind-the-meter systems contributed to 35 % of the annual increase observed in 2023. In contrast, off-grid BT storage remains considerably lower in volume. Various sizes of BTs excel in providing short-term flexibility, facilitating energy transfer over intervals ranging from seconds to several hours. Additionally, they serve as a versatile resource, offering numerous services to power systems, including ancillary and reserve services, ensuring system adequacy, and managing congestion in transmission and distribution networks [13–22].

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]. In a year-over-year comparison, installations increased by over 75 % in 2022 alone, with about 11 GW of new storage capacity deployed. The United States and China were at the forefront of this expansion, each contributing significantly to the gigawatt-scale increases observed in the market. 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 accordance with Han et al. [32], the lithium-ion BT is extensively utilized in electric vehicles (EVs). BT degradation is a prominent scientific issue in the field of battery research. BT degradation restricts the ability of the battery to store energy and deliver power, which in turn affects the performance of the electric vehicle, including its cost and lifespan. Hence, a thorough examination of the fundamental concerns associated with BT deterioration during its complete lifespan is brought up.

Table 1
The yearly additions of grid-scale BT storage from 2017 to 2022 [31].

	207 GW	2018 GW	2019 GW	2020 GW	2021 GW	2022 GW
China	0.1	0.4	0.4	0.9	1.9	4.8
United States	0.2	0.3	0.3	1.1	3.0	4.0
European Union	0.1	0.2	0.2	0.2	0.5	1.0
Korea	0.2	0.3	0.2	1	0.1	–

Zanoletti et al. [33] carried out an extensive analysis of the recycling of lithium-ion batteries (LIBs). The article addresses important subjects such as contemporary recycling technology, progress in the field, deficiencies in policies, design approaches, financial support for experimental initiatives, and a recycling strategy. The subject matter discusses the barriers and prospects of LIB (lithium-ion battery) recycling, emphasizing the potential for innovation and the establishment of a sustainable, circular financial system. Moreover, Khan's investigation [34] yields a general description of new BTs, including solid-state batteries, lithium sulfur batteries, as well as flow batteries. The article explores the fundamental concepts, benefits, and difficulties linked to each technology and evaluates their potential for extensive implementation in electric vehicles and largescale energy storage systems. The investigation also investigates current research and development endeavors, with a particular emphasis on progress in nanotechnology, innovative electrode materials, and manufacturing methods aimed at improving BT performance, safety, and cost-effectiveness.

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. Consequently, depending exclusively on grid electricity emerges as a more practical alternative. 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.

The article explores the latest advancements in battery technologies and their critical role in ensuring reliable, stable renewable energy systems. Key questions include the suitability of different battery types, for large-scale energy storage and the environmental impacts and challenges of scaling up these technologies. The article also considers the economic and sustainability implications, including innovations in battery recycling and the role of government policies in promoting adoption. Additionally, the article examines how battery technologies enhance decentralized energy systems and security, while interacting with other storage solutions to optimize global energy transitions.

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. The article is meticulously structured to provide an analysis of BTs in the energy sector. Fig. 1 illustrates the structure of a manuscript about BTs in the energy sector.

Section 2 explores the critical functions of batteries in electrical power systems, emphasizing their role in grid stability and RE integration; Section 3 examines the regional deployment of BTs, highlighting differences based on local policies and economic conditions; Section 4 delves into the economic aspects of BT, including cost trends and influencing factors; Section 5 focuses on investment in BT, discussing the

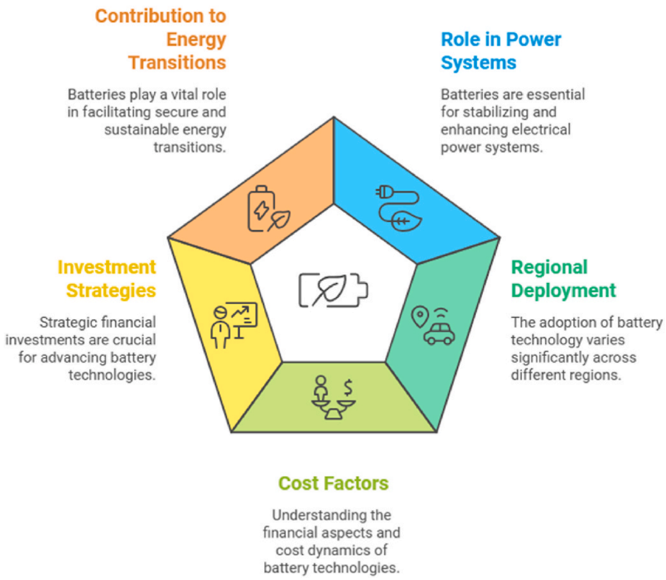

Fig. 1. The structure of a manuscript about BTs in the energy sector.

impact of capital inflows from both government and private sectors on innovation and growth; Section 6 assesses the contribution of batteries to secure energy transitions, particularly their role in moving away from fossil fuels; and Section 7 concludes the article by summarizing the key insights and future implications of BTs in global energy strategies.

2. The role of batteries in electrical power systems

Both utility-scale and behind-the-meter BT storage designs boast the capability to provide a wide range of services to the electrical power grid, as shown in Fig. 1. Utility-scale BT storage not only helps to balance electricity supply and demand by facilitating energy shifting, but also plays a crucial role in maintaining grid stability and ensuring a reliable power supply. It achieves this by providing ancillary services such as inertia, voltage control, frequency regulation, grid formation, and rapid-starting reserves [37–40]. Moreover, it can improve the system's capacity to maintain sufficient supply and contribute to managing congestion in electrical networks. Behind-the-meter batteries have the dual function of supplying backup power and allowing consumers to reduce electricity costs by increasing their use of self-generated electricity, taking advantage of variable electricity prices, or reducing peak electricity usage from the grid.

This figure outlines various roles and functions of batteries in the electrical power grid across different parts of the grid, categorized into Generation, Network, and Consumption. These categories are further divided based on whether the batteries are located in front of the meter (for broader grid services) or behind the meter (for specific consumer use), including off-grid systems. In summary, this figure provides a comprehensive look at how batteries are integrated into various parts of the electrical power system, offering services ranging from grid stability and short-term flexibility to enabling energy access in off-grid areas. These roles help support the energy transition, particularly by enhancing the integration of renewable energy sources and improving grid reliability and efficiency.

When combined into virtual power plants, they can provide similar services as bigger utility-scale systems [41–43]. Table 2 puts forward a comparative analysis of technologies across various BT types.

The State of stored energy can be expressed as the ratio of the stored energy (E_{stored}) that can potentially be released beginning at time t, to the maximum stored energy ($E_{\text{Emax,stored}}$). As the battery lifespans, the amount of charge it can hold diminishes, causing a shift in the OCV curve. Consequently, the maximum amount of energy that can be retained by the battery also declines. (SoE_{stored}) SoE stored can be understood in a manner similar to Ref. [44], based on Eq. (1).

Table 2
A comparison of technologies among different types of BT.

Technology type	Drawbacks	Merits
Lithium-ion	-The technology is characterized by an exceedingly high-cost range of 900–1300 kWh, accompanied by a relatively short lifecycle, which is primarily attributed to degradation from deep discharge cycles. Additionally, it necessitates the incorporation of specialized circuits for overcharge protection to maintain system integrity and safety.	-This BT showcases a high energy density ranging from 80 to 190 Wh/kg, coupled with an exceptionally high efficiency rate of 90–100 %. Furthermore, it benefits from a low self-discharge rate of only 1–3 % per month, enhancing its overall utility and performance longevity.
Flow Battery	-This BT exhibits a medium energy capacity, with an energy density ranging from 40 to 70 Wh/kg.	-This technology offers independent control of energy and power, providing flexibility in various applications. It boasts a long service life, capable of enduring up to 10,000 charge-discharge cycles. Moreover, it features negligible self-discharge, ensuring minimal energy loss during periods of inactivity.
Lead acid	-This BT is defined by a relatively short cycle life, spanning approximately 1200–1800 cycles. The longevity of the cycle life is notably influenced by the depth of charge. Following this, it exhibits a low charge density, approximately 40 Wh/kg, which impacts its energy storage capacity.	-This technology is characterized by its low cost and benefits from a minimal self-discharge rate of only 1–3 % per month.
Sodium Sulfur (NaS)	-This technology is designed to operate in standby mode at an extremely high temperature of 3250 °C.	-This BT offers high efficiency, ranging between 85 and 92 %, and a high energy density of approximately 100 Wh/kg. It also features robust durability with no degradation from deep discharge, enhancing its reliability and lifespan under extensive usage conditions.
Nickel based	-This technology is associated with a high cost, approximately ten times greater than that of lead-acid batteries. Additionally, it exhibits a high discharge rate of 10 % per month.	-This BT is capable of enduring up to 3000 full charge cycles. It also boasts a high energy density, ranging from 50 to 80 Wh/kg, offering a substantial amount of energy per unit mass.

$$SoE_{\text{stored}}(t)\frac{E_{\text{stored}}}{E_{\text{Emax,stored}}}=\frac{\int_{Q\ (SoC_t=0)}^{Q\ (SoC_t)} U_{OCV}\ (Q)dQ}{\int_{Q\ (SoC_t=0)}^{Q\ (SoC_t=1)} U_{OCV}\ (Q)dQ} \tag{1}$$

In the following context. E_{stored} and $E_{\text{Emax,stored}}$ are both intrinsically associated to the open-circuit voltage (OCV). Conversely, the stored energy encompasses the voltage trajectory from the present charge level until the point at which neither energy nor charge can be further extracted, as the state of charge (SoC) and state of energy (SoE) asymptotically approach 0 %. It is noteworthy that the SoE_{stored} does not account for operational losses. Analogous to the relationship between SoC and the OCV, a corresponding relationship between SoE_{stored} and the OCV can be established. It is advantageous to discretize the continuous formulas for the SoC, as demonstrated in Eq. (2), and for the SoE_{stored}, as illustrated in Eq. (3).

$$SoC_{\ k} = SoC_{\ k-1} + \frac{l_{L,k}\ .\ \Delta t}{Q_{max}} \quad (2)$$

$$SoE_{\ \text{stored},k} = SoE_{\ \text{stored},k-1} + \frac{l_{L,k}\ .\ U_{OCV,k}\ .\Delta t}{E_{max,stored}} \quad (3)$$

In this setting, the term $SoC_{\ k}$ is related to the present condition, while $SoC_{\ k-1}$ indicates the prior state. The current at time k is designated as $l_{L,k}$, and the highest charge capacity is represented by Q_{max}. The term ~ t signifies the point in time. Eq. (4) represents the current status of unstable energy.

$$SoE_{\text{stored}}(\lambda, t)\frac{E_{\text{stored}}(\lambda, t)}{E_{\text{Emax,stored}(\lambda,t)}} = \frac{\int_{Q\ (SoC_t=0)}^{Q\ (SoC_t)} U_T\ (\lambda, Q)dQ}{\int_{Q\ (SoC_t=0)}^{Q\ (SoC_t=1)} U_T\ (\lambda, Q)dQ} \quad (4)$$

However, in term of Eq. (4), $SoE_{\ \text{stored},k}$ identifies the current state of the SoE, while $SoE_{\ \text{stored},k-1}$ indicates the value that was used previously. The present OCV is shown as $U_{OCV,k}$. $E_{\text{Emax,stored}}$ indicates the maximum amount of energy stored. The State of useable Energy, SoE_{stored}, is a measure of the proportion of useable energy, Eusable, to the maximum useable energy, $E_{\text{Emax,stored}}$, at a given time t. It is determined by the environmental conditions, represented as λ, as demonstrated in Eq. (4) in this article.

Additionally, batteries play a crucial role in reducing system congestion by storing surplus power from RE sources during high output levels. This helps to prevent energy wastage and reduces the costs associated with integrating RE into the grid. A notable example is the Dalian vanadium flow BT demonstration project in China, which has a capacity of 200 MW/800 MWh [45–49]. The design of this project aims to alleviate grid strain during high demand periods and provide an additional power consumption point for the Dalian peninsula, thereby enhancing grid stability. The project is expected to begin in 2022, and when fully implemented, it is projected to reduce peak loads by 8 % compared to the levels in 2020 [50–52].

Batteries reduce the need for funds to construct transmission or distribution networks by controlling congestion. In Germany, "grid boosters" are utility-scale batteries strategically placed to reduce bottlenecks in the transmission system. This reduces the demand for additional expenditures to strengthen certain lines [53,54]. Regulators have authorized 950 MW of storage assets within the grid enhancer initiative, as part of the network development strategy. Two out of Germany's four transmission system operators are currently supervising the construction of a combined capacity of 450 MW of these assets inside the control zones [35,55]. Table 3 contains a comprehensive overview of the most recent studies on BT in electrical power systems.

According to Amorim et al., [61], the paper elucidates a sophisticated BT sizing methodology that rigorously assesses the dimensions of energy requirements, power capacity, and discharge rates (C-rate) tailored to specific mission profiles, thereby offering bespoke solutions for each project. Furthermore, it investigates the impact of thermal management on the sizing parameters of BT. The case study, centered on a 1 MW PV system, leverages a comprehensive one-year mission profile encompassing solar irradiance and ambient temperature data sourced from Goiania, Brazil. The PV installation, interfaced with a 440 V grid, incorporates a BT system designed to stabilize fluctuations within a margin of 10 % per minute. The BT sizing is scrutinized in terms of the volumetric requirements, longevity, and the requisite oversizing factors for power and energy capacities. The methodology proposed markedly reduces the volume of BT by 57.14 % compared to traditional designs reported in the literature. The importance of these points lies in enhancing the efficiency, performance, and longevity of Battery Energy Storage Systems (BESS) for power smoothing applications, particularly in renewable energy systems. Developing a robust BESS sizing methodology is crucial for optimizing energy storage to handle power fluctuations, ensuring grid stability. Furthermore, evaluating the effect of mission profiles on BESS sizing allows for the adaptation of storage

Table 3
An in-depth summary of the latest research on BT in electrical power systems.

Ref.	Journal	Highlight	Target
[56]	Energy	-The study evaluates the incorporation of BT as an efficient way of storing energy in RE production and power grid systems globally. -The study presents a detailed comparative analysis that encompasses the operational concepts, control strategies, optimizations, and technological features of several BT. -The findings show significant advancements in the energy storage sector for lead-acid, lithium-ion, sodium-based, and flow redox batteries. -The article emphasizes how using BT for support services and management strategies significantly improves the performance of small power plants and utility grid systems.	Microgrid & Electrical power grid
[57]	Energy Reports	-An advanced energy management algorithm (EMA) has been developed for these hybrid energy systems to optimize solar energy capture, safeguard the battery, facilitate surplus energy storage, mitigate power deficits in the grid, and strategically deploy the diesel generator during critical demand periods. -The core contribution of this paper is the enhancement of the efficacy of the Perturb and Observe (P&O) method for maximum power point tracking through the integration of fuzzy logic control (FLC). This innovative approach substantially maximizes energy extraction from the photovoltaic (PV) system and significantly extends its operational longevity.	Electrical power grid
[58]	Journal of Power Sources	-The manuscript presents a comprehensive investigation of BT detailing their distinct characteristics, applications, and the specific technologies that are appropriate for deployment at the grid-scale. -The integration of batteries into the power grid is posited to potentially facilitate the attainment of a penetration rate of 40–50 % for variable REs, although this rate is contingent upon the unique attributes of each electrical system. -The manuscript advocates for a strategic methodology to promote the adoption of BT to augment the proportion of variable REs within weakly interconnected power grids, exemplified by those in Sub-Saharan Africa.	Electrical power grid
[59]	Energy Reports	-This paper introduces a novel intelligent control framework for the development of hybrid photovoltaic (PV)–wind-BT. A Neuro-Fuzzy Direct Power Control (NF-DPC) approach is employed to enhance both system performance and the quality of generated currents. -This investigation presents a new intelligent management framework for the advancement of combined photovoltaic (PV) and wind-BTs. The authors employ a neuro-fuzzy direct power control (NF-DPC) method to enhance the system's overall efficiency and the precision of the electricity-produced currents.	AC & DC Electrical Power grid

(continued on next page)

Table 3 (*continued*)

Ref.	Journal	Highlight	Target
		-An Energy Management Algorithm (EMA) is developed to maintain a balance of energy, meet the demands of the direct current (DC) load, reduce fluctuations caused by changes in weather conditions (namely wind speed and solar irradiation), and avoid situations where the battery is overcharged or discharged excessively. -The results obtained from the implementation of these technologies indicate a substantial reduction in the fluctuations of active and reactive power, and total harmonic distortion (THD), with reductions quantified at approximately 64 %, 72 %, and 50 % respectively.	
[60]	IEEE Access	-The proposed study delineates the development of a sophisticated modeling framework, control mechanisms, energy management strategies, and operational protocols for a hybrid grid-connected system. This system integrates wind, photovoltaic (PV), and BTs with additional components such as a Fuel Cell (FC) and an Electrolyze, enhancing the synergy between these diverse energy sources. -The proposed hybrid configuration offers a cost-effective methodology for incorporating PV technology into a hybrid system by obviating the need for a separate PV converter. This approach encompasses the design of advanced control systems for grid-connected hybrid configurations that utilize renewable distributed generators as primary energy sources, BT as a secondary source, and the combination of FC and Electrolyze units as a tertiary source.	Electrical Power grid

systems to specific operational demands, improving system reliability. The assessment of battery temperature control plays a vital role in extending battery life and minimizing costs, as effective thermal management prevents degradation and maintains performance. Introducing and evaluating battery lifetime models for Li-ion batteries ensures accurate predictions of battery health over time, enabling better maintenance and cost planning. Lastly, providing a tool for engineers to support BESS sizing, particularly by factoring in local solar irradiance, allows for more precise and location-specific implementations of storage systems, thereby improving their integration with solar power and maximizing the system's overall efficiency.

According to Gao et al., [62], the manuscript explores an integrated emergency control system that synergistically combines BT on the power grid side with a Precise Load Shedding Control System (PLSCS). This system is designed to provide robust emergency support operations for power grids. The article details the structural design and commissioning test results of the Langli BT, which represents the inaugural demonstration project in Hunan Province. The Langli BESS boasts a total capacity of 24 MW/48 MWh and is composed of an assembly including 24 PCS cabins, 24 B T storage cabins, a central control cabin, and a 10 kV electrical cabin. This 10 kV cabin is subdivided into three sections, each interconnected with the 10 kV I bus and II bus of the proximate 220 kV Langli substation, respectively.

In [63], the paper presents a contribution that encompasses the implementation of cutting-edge BTs designed for enhanced efficiency, energy conservation, and rapid responsiveness. These technologies are meticulously integrated with electrical grids utilizing intelligent control techniques such as particle swarm optimization (PSO), artificial neural networks (ANN), and fuzzy logic controllers (FLC). These sophisticated controllers are strategically deployed to modulate the power output from MESS technologies, facilitating their integration into the electrical grid infrastructure. Consequently, the principal objective of this manuscript is to deliver a critical analysis of the principal MESS technologies particularly poised to revolutionize the electrical grid and their potential applications.

According to Cai et al. [64], the article delineates a novel strategy for suppressing charging current ripples using a T-type three-level converter within BT frameworks. In scenarios characterized by distorted grid voltages, the harmonic content inherent in the grid voltage induces significant ripples during the BT charging process. This article presents a thorough theoretical analysis and mathematical derivations pertaining to the phenomenon of charging current ripples. The paper, building on this analytical foundation, proposes a control mechanism to mitigate these ripples. This is achieved through a simplified computation process to ascertain the amplitude and phase of the harmonic reference current, supplemented by the integration of a charging current suppression loop within the control scheme. A 100-kW three-phase, three-wire T-type three-level converter built into the BT was utilized to test this suppression strategy and show that it works. Experimental results demonstrate that the proposed strategy effectively obliterates the charging current ripples.

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 converge to optimize system performance. A key area of innovation is the integration of BTs with multi-layered Energy Management Systems (EMSs). Recent work has proposed a multi-stage EMS that combines anticipative optimization using MOPSO with real-time corrective control via Extremum-Seeking (ES) techniques. This system was validated experimentally and demonstrated significant improvements in energy cost, peak-to-average ratio (PAR), and battery degradation metrics in real-time conditions under uncertain PV generation and load profiles [65]. In a related study, a dual-layer EMS was developed to optimize both active and reactive power in Moroccan residential buildings, achieving a 58.9 % reduction in active energy bills, 83.2 % in reactive energy bills, and 49.3 % in carbon emissions by leveraging both long- and short-term predictive layers and a Lexicographic PSO approach [66].

Further advances combine BTs with demand response strategies and smart building control frameworks. Hybrid optimization models integrating demand response plans (DRPs) with incline block tariffs (IBTs) have shown reductions in energy costs by over 23 % and pollution emissions by up to 7.7 % in smart microgrids [67]. Digital Twin (DT) technology is also gaining traction in BT-integrated microgrids, offering full automation, predictive control, and situational awareness in smart building environments. DT frameworks provide a foundation for resilient operations by supporting real-time visualization, communication, and control systems for BT-based energy platforms [68]. These innovations are particularly relevant in multi-energy systems where predictive tools, user load profiles, and grid interaction must be co-optimized across temporal and spatial layers of energy consumption.

Overall, the integration of BTs in smart microgrids and building systems supports not only real-time optimization of active and reactive power but also long-term operational efficiency and energy autonomy. The combination of AI-driven EMSs, predictive forecasting, and modular digital infrastructure allows BTs to transcend their traditional role as storage devices, evolving into key enablers of resilience, sustainability, and cost-effectiveness in modern decentralized power systems. The collective insights from recent experimental studies, optimization models, and digital twin implementations provide a roadmap for the deployment of BTs in next-generation urban energy infrastructures

[65–68].

Table 4 provides a structured comparison of references [65–83], highlighting the diversity of methods, control strategies, and system configurations applied to smart microgrids and building-integrated energy systems. The table distinguishes experimental, optimization-based, and conceptual works covering active/reactive EMS designs, digital twin frameworks, and reinforcement learning-based controllers. This comparative synthesis supports the development of adaptive and resilient energy management frameworks that capitalize on BT integration under varying system objectives and conditions.

3. Deployment of battery technology by region

The deployment of battery technology (BT) has become a pivotal element in the global transition towards sustainable energy systems, with significant regional variations reflecting the diverse economic, policy, and technological landscapes of different areas. This introduction explores how various regions around the world are embracing and advancing BT, each contributing uniquely to the broader narrative of energy transformation [84–88]. Fig. 2 illustrates the global increase in BT storage capacity from 2013 to 2023.

China has solidified its position as the dominant market for BT, experiencing a remarkable expansion in its global market share from approximately 20 % in 2019 to 55 % by 2023. In that year alone, China's capacity additions surged to 23 GW, a threefold increase from previous years. This significant growth has been predominantly in utility-scale storage, constituting about two-thirds of the new capacity. This expansion is largely attributed to provincial mandates requiring that new solar photovoltaic (PV) and wind power projects be accompanied by energy storage systems. Additionally, behind-the-meter storage capacity also saw substantial growth, particularly within the commercial sector rather than residential. This increase has been driven by large-scale commercial users who are capitalizing on financial incentives such as subsidies and the strategic use of time-of-use electricity tariffs, which vary the cost of electricity throughout the day to encourage or discourage its use [90–93]. This regulatory and economic environment has significantly accelerated the uptake of BT storage solutions, positioning China as a global leader in the deployment of advanced energy storage technologies.

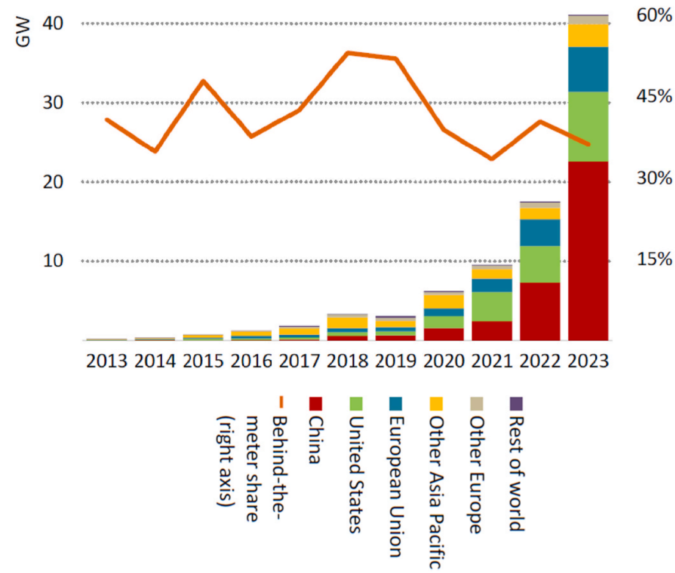

Fig. 2. The global increase in BT storage capacity from 2013 to 2023 [89].

The United States maintains its position as the second-largest BT storage market globally, with its capacity additions approximately doubling each year, culminating in a significant increase to over 8 GW in 2023. In direction, utility-scale projects constituted nearly 90 % of this additional capacity, with California, Texas, and other Southwestern states leading the charge in deployments. The economic viability of these projects has been enhanced by a combination of market reforms, reductions in equipment costs, and the introduction of an investment tax

Table 4
Comparative overview on BTs in smart microgrids.

Ref	Citation	System Type	Tech Components	Optimization/Modeling	Key Findings
[65]	Gheouany et al. (2023)	Multi-Stage EMS	PV, ESS	MOPSO, Extremum-Seeking	Real-time experimental validation, 6 % energy bill & PAR gain vs offline
[66]	Gheouany et al. (2024)	Active/Reactive EMS	PV, ESS	Lexicographic PSO	58.9 % active, 83.2 % reactive bill reduction, 49.3 % CO2 cut
[67]	Alami Merrouni et al.	Hybrid Optimization + DRPs	RES, ESS	IBT, DRP, Two-stage robust opt.	23.2 % cost cut, 7.7 % emission reduction
[68]	Hammoumi et al.	Digital Twin (DT) Automation	Full SMG	NA (conceptual)	DT-SMG overview, automation and resilience framework
[69]	AR-EMS Moroccan vs TOU	Active/Reactive EMS	PV, ESS	PSO	6 % cost, 73 % PAR, 17 % CO2 reduction, 31 % PF improvement
[70]	AR-RBEM	Residential Building EMS	PV, ESS	PSO	59.6 % energy cost, 25.3 % CO2 reduction
[71]	SSM + DSM in Residential	Building EMS	PV, ESS	PSO	28 % cost & PAR cut, appliance comfort considered
[72]	VMD-GRU NILM	Home EMS (Load monitoring)	NA	VMD, GRU, SSA	Better RMSE & MAPE for load disaggregation
[73]	Appliance Scheduling	DSM Optimization	Residential	BSAA, BPSO	27.6 % cost, 40.3 % PAR cut (SSA superior)
[74]	Smart Building Optimization	Real-Time Control	Smart Building Microgrid	MINLP, MILP	16 % peak reduction, cost & stability improvements
[75]	DC Micrograds Survey	Survey	DC Micrograds	NA	Overview of strategies, socio-economic gaps
[76]	Fully-Renewable B2G Model	Stochastic Tri-Level	Smart Bldg + Microgrid	Hierarchical opt.	38 % cost cut via B2G, insights on comfort index
[77]	Energy IoT Resilience	Multi-Layer Resilience	Smart MGs	IoT, performance modeling	Hazard-resilient methodology across 4 layers
[78]	Federated RL	Privacy-Preserving EMS	Residential Microgrids	PPO, RFRL	Cost-efficient decentralized training
[79]	RL for Hybrid RE DSM	Retail Demand Mgmt.	PV, Wind, ESS	RL, Q-table, AVO	Reduced power cost, improved NPV/LCOE
[80]	Coalition MG Model	Peer-to-peer trading	MGs + Water Storage	Stochastic Coalition	Reduced ENS by 301.63/146.89 kWh
[81]	Smart Transformers	CHP Microgrid Mgmt.	CHP + MG	GA	Loss reduction, voltage profile, env. gains
[82]	2-Stage EMS (Prob. Fuzzy)	DR & ESS V/F Mgmt.	MGs in Smart Cities	IPWPNFIA	Real-time prototyping, reduced calc burden
[83]	Stochastic Day-Ahead Opt.	Multi-MG Energy Mgmt.	HRSS, EVPL	Stochastic-Robust Model	Day-ahead scheduling in MEMGs

credit as part of the Inflation Reduction Act. These factors have collectively facilitated the integration of utility-scale BT systems into ancillary service markets. In these markets, batteries are increasingly utilized to provide balancing services and secure capacity, particularly in states where there is a high reliance on variable RE sources. This strategic deployment underscores the growing importance of advanced BT storage solutions in stabilizing and enhancing the resilience of electrical power grid [94–96].

The European Union saw a substantial 70 % increase in installed BT storage capacity, with annual additions escalating to nearly 6 GW in 2023. A significant majority, approximately 90 %, of this growth was driven by behind-the-meter storage installations, predominantly in Germany and Italy. These countries have been particularly supportive of pairing rooftop solar photovoltaic (PV) systems with storage solutions, fueled by high retail electricity prices and attractive incentives such as tax breaks and low-interest loans. Remarkably, close to 80 % of all rooftop solar PV systems installed in Germany and Italy in 2023 were equipped with storage systems. On the utility-scale side, growth in storage capacity is increasingly being facilitated through capacity auctions that aim to secure energy supply for future needs [97–101]. For instance, Italy conducted capacity auctions in 2022 for delivery by 2024, awarding contracts that totaled 1.6 GW to BT storage projects. Some of these systems commenced operation as early as 2023, indicating a proactive and strategic approach to integrating BT storage into the broader energy grid to enhance energy security and manage demand.

4. Battery technology costs

The previous decade has emerged as a transformative period predominantly characterized by the ascendancy of lithium-ion BT. This technology presents a fundamental superiority over its antecedents, such as lead-acid or nickel-cadmium batteries, primarily due to its significantly enhanced energy density and extended cycle life. While lead-acid batteries exhibit specific energies in the spectrum of 35–40 Wh/kg, current lithium-ion batteries demonstrate a specific energy range approximately between 90 and 300 Wh/kg at the cell level. This augmented energy density enables the configuration of notably lighter and more compact BT packs, optimizing efficiency and practicality in various applications [102–104].

A lithium-ion cell consists of the following four primary elements: the cathode, the anode, the electrolyte, and the separator. Together, the cathode and anode function as storage units for lithium ions, thus being the defining attribute that gives the technology its name. The main function of the separator is to avoid short circuits, thus guaranteeing safety throughout performance. The electrolyte, on the other hand, facilitates the movement of lithium ions from the cathode to the anode when the battery is being charged and reverses this flow when the battery is being discharged. Presently, the market offers a diverse array of lithium-ion batteries, each variant continuing to undergo evolution driven by extensive research and development efforts. These initiatives aim to enhance energy densities, reduce charging durations, and improve safety and longevity of use, all while endeavoring to lower production costs [105–109].

Currently, 90 % of lithium-ion batteries deployed are utilized for electrification within the transport sector. Batteries for electric vehicles (EVs) necessitate high energy density and must be compact and lightweight. In contrast, BT storage solutions, while not as constrained by size and weight, prioritize cost-effectiveness and durability. There is a notable trend where technological advancements in the automotive industry frequently influence developments in the power sector [110–112]. Enhancements in EV-based BT could substantially benefit energy storage solutions, although the reverse may not consistently apply. Nonetheless, both sectors are increasingly focused on reducing the carbon footprint associated with BT usage and on maximizing the potential for BT reuse and recycling. For instance, batteries from electric vehicles could be repurposed for second-life applications such as behind-the-meter storage or other energy storage solutions [113,114].

Over the past decade, the cost dynamics of lithium-ion batteries, which include the expenses related to both cells and BT packs, have undergone a dramatic transformation. Initially priced at around USD 800 per kilowatt-hour (kWh) at the beginning of the decade, these costs have steadily declined to less than USD 140/kWh by 2023. This marked reduction can be primarily attributed to several key factors: persistent advancements in research and development (R&D), the realization of economies of scale through increased production, and continuous technological innovations in BT design and manufacturing processes. As a consequence of these declining production costs, the relative contribution of raw material expenses to the overall cost structure of batteries has increased. Consequently, the pricing of lithium-ion batteries has become more sensitive to fluctuations in the cost of critical minerals used in their manufacture, such as lithium, cobalt, and nickel, which are prone to price volatility due to market demand and geopolitical factors [115–119].

This sensitivity was notably evident in 2022 when spikes in the prices of these essential BT metals led to an unprecedented year-on-year increase in lithium-ion BT prices. However, the trend reversed in 2023, thanks to several mitigating factors. An increase in the global supply of these critical minerals, coupled with significant expansions in BT manufacturing capacities, helped alleviate some of the upward pressure on prices. Additionally, lower-than-anticipated demand for batteries in certain key markets, particularly in China, contributed to a significant reduction in prices. This combination of factors resulted in the cost of lithium-ion batteries falling below the levels recorded in 2021, signaling a potentially stabilizing effect on BT market economics moving forward [120–123].

The BT industry is intensifying its investment in the cost-effective cathode material known as lithium iron phosphate (LFP), which is noted for its affordability and robust performance. Throughout 2023, LFP packs and cells maintained the lowest global weighted average prices among all lithium-ion BTs. This trend of declining costs persisted into the early months of 2024, with prices for LFP cells further decreasing to well below USD 100 per kilowatt-hour by March 2024. While lithium-ion BT prices were consistently lowest in China due to local production efficiencies and market scale, they were found to be approximately 10–20 % higher in the United States and Europe. Despite this regional variation, there has been a noticeable reduction in the variance of BT prices compared to 2022 and 2021 [124–127]. This emerging trend towards price convergence suggests that global BT markets are moving towards a more unified pricing structure, potentially driven by increased production capabilities, broader adoption, and enhanced international trade dynamics in BTs.

4.1. Trade-offs in battery system integration

The integration of battery technologies (BTs) into power systems—especially in residential and industrial contexts—presents a multifaceted landscape of trade-offs involving system complexity, cost, and operational efficiency. These trade-offs are influenced by technical architecture, control sophistication, and the operational environment in which the battery system is deployed.

System complexity varies significantly depending on the configuration of the energy management system (EMS), the interoperability of hardware components (e.g., inverters, converters, communication protocols), and the sophistication of control algorithms. Residential BT systems often adopt relatively simple EMS structures, primarily focused on load shifting and time-of-use optimization. In contrast, industrial applications typically involve more complex EMS frameworks that manage both active and reactive power flows, coordinate with distributed energy resources (DERs), and interface with supervisory control systems. This added complexity supports granular control and higher reliability but also demands more robust software tools and communication infrastructure.

Cost is another critical consideration, encompassing not only initial capital expenditures but also operational and lifecycle costs. Residential battery installations generally have lower upfront costs, but the price per kilowatt-hour of capacity tends to be higher due to limited scale. Industrial systems benefit from economies of scale but require greater investment in infrastructure, protective devices, and control equipment. Furthermore, long-term costs are affected by battery degradation rates, replacement cycles, and the efficiency of EMS decision-making. Maintenance and control tuning in larger systems add operational expenditure, particularly when predictive diagnostics and real-time optimization are employed.

Efficiency trade-offs emerge from the balance between control sophistication and real-world performance. Highly complex controllers, such as those based on model predictive control (MPC) or multi-objective particle swarm optimization (MOPSO), can deliver optimal results under ideal conditions. However, these methods often suffer from computational delays and reduced responsiveness in fast-changing scenarios. Simpler control methods may respond more quickly but typically yield lower overall efficiency or fail to account for secondary objectives like battery aging or grid support. Additionally, the need for fast response times in industrial settings often necessitates the deployment of hybrid control systems that combine rule-based logic with optimization modules, thereby increasing both computational load and system cost.

Case studies further illustrate these contrasts. For example, building-integrated systems using digital twins and multi-stage EMS architectures offer high levels of adaptability and efficiency, but with significantly higher implementation and maintenance complexity [65–68]. Conversely, smaller residential installations using basic rule-based EMSs remain cost-effective for load shifting but lack advanced features such as real-time reactive power support or predictive battery lifespan management.

In summary, choosing an optimal BT integration strategy involves navigating these trade-offs in light of specific technical, economic, and operational constraints. A well-balanced system should align its complexity and cost with the desired control accuracy and long-term performance objectives.

Table 5 presents key quantitative comparisons between residential and industrial battery technology (BT) integrations. The Levelized Cost of Storage (LCOS) tends to be lower in industrial applications due to economies of scale, while battery degradation rates are also reduced through advanced EMS strategies such as predictive and multi-objective control. Industrial systems generally achieve higher control efficiencies and greater peak-to-average ratio (PAR) reductions, particularly when integrating demand response (DR) and forecasting techniques. Moreover, the resulting energy cost savings and CO_2 emission reductions are considerably more significant in industrial contexts, especially with support for reactive power optimization.

Table 5
Quantitative trade-offs in battery system integration for residential and industrial applications.

Metric	Residential Systems	Industrial Systems	Source/Justification
Levelized Cost of Storage (LCOS)	200–400 USD/MWh	120–250 USD/MWh	Derived from global LCOS benchmarks by IRENA (2022–2023), aligned with [65,66,69].
Battery Degradation Rate (annual)	2–3 %	1–2 % (with advanced EMS)	From degradation-aware EMS strategies in Refs. [65,66,70,76,78].
Control Method Efficiency	Rule-based: ~85 %	MPC/ML-based: 92–96 %	Efficiency improvements cited in Refs. [65,66,70,74,78] and IEEE literature.
PAR Reduction Potential	10–20 %	30–50 % (w/DR and forecasting)	Improvement ranges validated in Refs. [67,70,73] through DR and EMS-based forecasting.
Energy Cost Savings	10–25 %	25–40 %	Observed in optimized industrial EMS cases in Refs. [66,67,76].
CO_2 Emission Reduction	15–30 %	30–60 % (with reactive power control)	Reported in emission-aware optimization studies [66,70,76,81].

5. Battery technology investment

Making an investment in electric vehicle (EV) and battery technology (BT) storage has undergone substantial increases, with EV batteries increasing eightfold and BT storage surging fivefold from 2018. In 2023, the overall investment amounted to USD 150 billion, with USD 115 billion specifically designated for electric vehicle (EV) batteries and approximately USD 40 billion committed to BT storage programs [7]. The majority of investment in electric vehicle (EV) BT and grid-scale battery storage is dominated by China, Europe, as well as the US. The remaining percentage of investment primarily targets other advanced economies. In 2023, only 2 % of the investment in EV batteries and BT storage across advanced nations and China was allocated for additional developing and emerging markets [128–130].

The geographic disparity in spending on EV batteries primarily stems from the close correlation between EV BTinvestment and EV sales. In many emerging market and developing economies, the affordability of EVs remains a significant barrier due to their capital-intensive nature, making them inaccessible to a substantial portion of consumers. Additionally, supportive policies play a crucial role in shaping the EV market landscape. Clearly, regions experiencing significant growth in EV sales, such as the United States, Europe, and China, have implemented a combination of demand-side and supply-side policies aimed at stimulating market demand and enhancing EV accessibility. These policies include incentives to bolster consumer demand and initiatives to expand the charging infrastructure, thereby fostering a conducive environment for EV adoption. As evidenced by the remarkable surge in EV sales in these regions—nearly 500 % in the United States, 250 % in Europe, and 160 % in China—such comprehensive policy frameworks have been instrumental in driving market growth and increasing EV penetration [131–133]. Fig. 3 demonstrates the global level of investment in EV batteries from 2018 to 2023.

Investment in BT storage has surged due to the adoption of supportive policies and advancements in power market designs across various regions. Moreover, the growing adoption of RE sources has created more chances for lucrative energy storage operations using

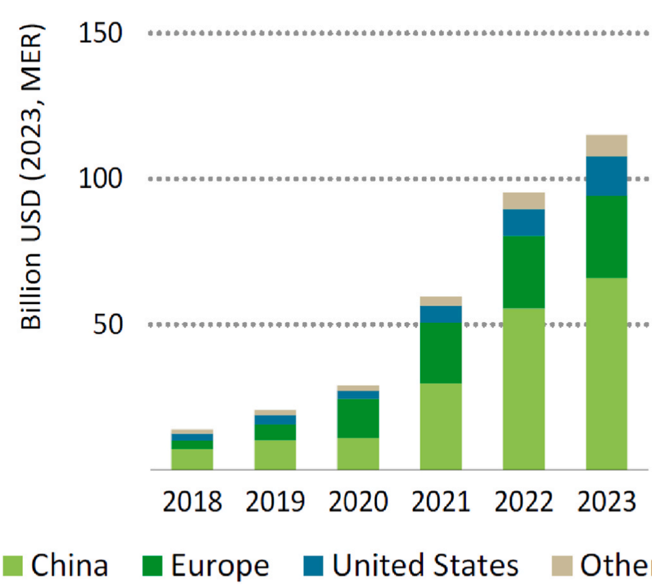

Fig. 3. The global level of investment in EVBT from 2018 to 2023.

battery technology. To ensure profitability, BT storage initiatives frequently necessitate the establishment of multiple sources of income simultaneously. These sources of income may consist of energy arbitrage, frequency regulation, peak shaving, or, when combined with solar PV or wind generation, the mitigation of RE curtailment. This statement is especially accurate for large-scale units, which have a crucial impact on the integration of RE sources and the improvement of grid flexibility [134–136]. Fig. 4 illustrates the worldwide investment trends in BT storage between 2018 and 2023. Although utility-scale units made up the majority of capacity expansions, they contributed less than half of the overall expenditure on BT storage in 2023. The reason behind this is that utility-scale batteries have a far lower cost per unit of capacity compared to smaller batteries designed for business or domestic use. China and the United States accounted for almost 85 % of the investment in utility-scale BT storage. Conversely, Europe has concentrated its investment on BT storage for business and residential applications, especially when combined with rooftop solar systems. This demonstrates an increasing fascination with decentralized energy systems and the incorporation of RE sources at the community level [137–138].

In the context of the article, the managerial implications could include several key areas as illustrated in Fig. 5.

- Strategic Investment Decisions: Managers need to understand which battery technologies are most viable for their specific needs, including cost, performance, and scalability. This will aid in making informed investment decisions to ensure long-term energy security and sustainability.
- Operational Efficiency: Insights from the study can guide operational managers in optimizing energy storage and distribution, particularly in integrating renewable energy sources. This would involve choosing the appropriate battery systems for grid stability, peak load management, and energy arbitrage.
- Regulatory Compliance and Risk Management: The research can highlight how managers should navigate the evolving regulatory landscape surrounding energy storage and sustainability. Understanding the environmental and safety risks of different battery technologies helps in risk mitigation and compliance with industry standards.
- Sustainability Goals: Managers can leverage the findings to meet corporate sustainability objectives, by adopting battery technologies that minimize carbon emissions and enhance the use of renewable energy, thus contributing to broader climate goals.

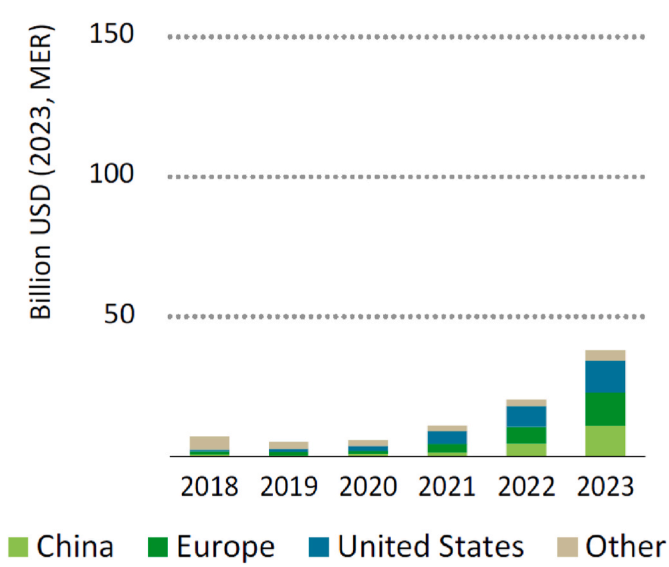

Fig. 4. The global level of investment in BT storage from 2018 to 2023.

Fig. 5. Key managerial focus areas.

- Innovation and Competitive Advantage: By staying informed about cutting-edge battery technologies, managers can foster innovation within their organizations, gaining a competitive advantage in the transitioning energy market.

In short, stressing these managerial implications ensures that the research offers practical guidance for decision-making and strategy formulation, helping businesses and governments make informed choices to enhance grid stability and energy security.

6. Contribution of battery technologies in secure energy transitions

In the rapidly evolving landscape of global energy systems, BTs stand out as a cornerstone for secure energy transitions. This contribution examines how advancements in BT are playing a pivotal role in shaping a sustainable, reliable, and efficient future energy landscape. Fig. 6 demonstrates contribution of battery technologies in secure energy transitions.

6.1. Enhancing grid stability and energy security

BTs contribute significantly to enhancing grid stability by providing energy storage solutions that can absorb and then release electricity, maintaining grid balance amid fluctuating demand and supply. This capability is critical as it allows for greater integration of intermittent RE sources such as wind and solar, thereby reducing reliance on fossil fuels and enhancing energy security.

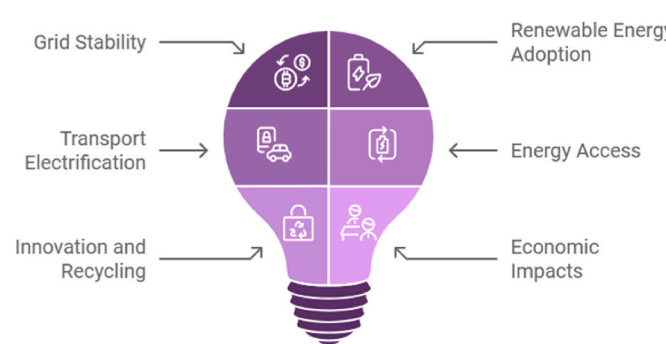

Fig. 6. Contribution of battery technologies in secure energy transitions.

6.2. Driving the adoption of renewable energy

The ability to store energy effectively allows utilities and energy operators to manage the variability and intermittency of RE sources. BTs facilitate the integration of RE sources into the power grid by stabilizing the supply and maintaining a steady output. This promotes the use of cleaner energy sources and contributes to the achievement of global carbon reduction goals.

6.3. Supporting the electrification of transport

BT is at the heart of the electric vehicle (EV) revolution. Improvements in lithium-ion batteries, such as increased energy density, faster charging times, and longer lifespans, have helped overcome earlier barriers to EV adoption. This shift not only reduces greenhouse gas emissions but also diminishes urban air pollution, contributing to public health improvements.

6.4. Facilitating energy access in remote areas

In remote and underserved regions, BT storage systems paired with local RE sources (like solar panels) can provide a stable and continuous power supply, bypassing the need for extensive and expensive grid infrastructure. This has profound implications for rural electrification, economic development, and quality of life improvements in less developed areas.

6.5. Innovation in BT composition and recycling

Research and development in alternative BT chemistries, such as solid-state batteries, lithium-sulfur, and sodium-ion, promise even greater efficiencies, safety, and environmental friendliness. Moreover, advancements in recycling processes ensure that BTs not only contribute to energy transitions but do so in a manner that minimizes environmental impact.

6.6. Economic impacts and job creation

The burgeoning BT industry is becoming a significant economic force, offering numerous opportunities for job creation in manufacturing, installation, maintenance, and recycling. This sector not only propels technological innovation but also stimulates economic activity and provides skilled employment opportunities globally.

Thus, BTs are not merely supporting elements but are foundational to the secure transition to a sustainable energy future. Their impact spans environmental, economic, and social spheres, highlighting their indispensable role in achieving a balanced energy transition. This contribution aims to underscore the transformative potential of batteries and advocate for continued investment and innovation in this crucial sector.

7. Innovations in battery management systems (BMS) and lifecycle optimization

Modern Battery Management Systems (BMSs) are increasingly central to the effective, safe, and durable operation of battery technologies (BTs) in smart grids and building-integrated systems. Innovations in BMS design have shifted toward comprehensive lifecycle optimization strategies that address not only electrical control but also battery health, thermal stability, and predictive fault prevention.

Recent BMS advancements focus on state-of-health (SoH) monitoring, using data-driven diagnostics to identify degradation trends and remaining useful life. Dynamic charge/discharge control strategies—often enabled through model predictive control (MPC) or reinforcement learning—optimize current profiles in real-time to extend cycle life while meeting power demands. Equally critical is thermal management, where temperature-aware control algorithms adjust operating parameters or activate passive/active cooling to prevent thermal runaway and preserve battery integrity.

One of the most transformative directions in BMS evolution is predictive maintenance. Artificial intelligence (AI) and machine learning (ML) techniques are now embedded into EMS/BMS frameworks to detect anomalies, predict failures, and optimize control setpoints based on historical and real-time data. However, these gains come with tradeoffs: high-performance BMS designs require complex sensor networks, increased data processing, and tighter integration with higher-level EMSs. As a result, designers must balance between BMS complexity and the extent of lifecycle benefits achieved.

A representative application is reported by Gheouany et al. [66], who developed a lifecycle-aware BMS strategy that simultaneously controls active and reactive power flows in a Moroccan smart microgrid. Their approach employed a Lexicographic Particle Swarm Optimization (L-PSO) framework, achieving a 58.9 % reduction in active energy bills, 83.2 % in reactive energy bills, and 49.3 % CO_2 emission cuts. Importantly, this dual-layer EMS-BMS configuration was experimentally validated under real-world grid pricing conditions, highlighting the practicality and efficacy of integrated optimization-based lifecycle control.

Table 6 highlights the key innovations in modern Battery Management Systems (BMSs), emphasizing their functionality and the corresponding benefits in enhancing the performance, safety, and longevity of battery technologies (BTs). State-of-health (SoH) monitoring serves as the foundation for predictive diagnostics, allowing early detection of cell-level deterioration. Dynamic charge/discharge control enables fine-tuned real-time responses that reduce stress on battery cells and improve efficiency. Effective thermal management—both passive and active—plays a critical role in maintaining operational safety and extending battery lifespan. Furthermore, the integration of artificial intelligence and machine learning facilitates predictive maintenance, enabling fault anticipation and smarter energy usage. Finally, lifecycle-aware optimization strategies, such as those based on degradation modeling and multi-objective control (e.g., Lexicographic PSO), provide a holistic approach to managing performance trade-offs, minimizing replacement frequency, and supporting sustainable battery deployment in smart grid environments.

8. Limitations and future research directions

Despite the promising capabilities of battery technologies (BTs) in supporting energy transitions, several limitations restrict their widespread, long-term deployment. These limitations span across technical, environmental, economic, and regulatory domains. From a technical standpoint, the lack of accurate and adaptive battery degradation models complicates the implementation of optimal lifecycle

Table 6
Summarizes key functions of advanced BMS technologies and their associated benefits.

BMS Innovation	Functionality	Benefits
State-of-Health (SoH) Monitoring	Tracks battery condition over time using sensors and data modeling.	Predictive fault detection, early degradation alerts.
Dynamic Charge/ Discharge Control	Adjusts power profiles in real time using control algorithms.	Cycle life extension, reduced thermal and stress loads.
Thermal Management	Monitors and regulates battery temperature through active/ passive systems.	Avoids overheating, improves safety and lifespan.
AI/ML Predictive Maintenance	Uses data analytics and forecasting to detect faults and optimize usage.	Reduced downtime, enhanced operational efficiency.
Lifecycle-Aware Optimization	Incorporates degradation models into control objectives (e.g., L-PSO).	Sustained performance, lower replacement cost.

management strategies. Additionally, current energy management systems (EMSs) often face challenges in integrating heterogeneous battery chemistries and coordinating active/reactive power simultaneously in real-time. Environmental concerns include the extraction and disposal processes associated with lithium-ion and other battery materials, raising questions about the sustainability and circularity of battery life cycles. Economically, high capital costs for both batteries and advanced BMS/EMS architectures remain a barrier to entry, especially in developing regions. Regulatory uncertainty and the absence of harmonized standards for interoperability between battery systems, EMS platforms, and smart grids further hinder seamless integration.

Future research should prioritize the development of accurate battery aging models that are compatible with real-time control frameworks. There is also a need for AI-enhanced predictive maintenance and decentralized EMSs tailored for community and building-integrated microgrids. Exploring the use of second-life batteries and integrating them into hybrid storage systems may offer cost-effective and environmentally sustainable alternatives. Additionally, enhanced cybersecurity protocols and standardized communication interfaces are essential for scaling BMS and EMS technologies in grid-connected applications. Policymakers and researchers should also collaborate on formulating incentive structures and recycling frameworks that promote battery circularity and long-term operational efficiency.

Table 7 outlines the prevailing limitations hindering the broader deployment and operational optimization of battery technologies (BTs) in modern power systems. These challenges span across technical, economic, environmental, and regulatory domains. Technically, the absence of accurate degradation models reduces control accuracy and impedes effective lifecycle forecasting, while the complexity of EMS integration with diverse battery chemistries often leads to inefficiencies. High initial investment costs and maintenance burdens, especially in developing economies, also limit adoption. From an environmental standpoint, extraction and disposal of battery materials raise sustainability concerns. Furthermore, as BMS/EMS platforms increasingly adopt cloud-based control and digital interfaces, cybersecurity vulnerabilities pose growing risks. Lastly, regulatory fragmentation and lack of standardized protocols impede seamless integration across diverse platforms and regional markets. The table also identifies research opportunities—such as the development of AI-driven predictive models, second-life battery utilization, and secure, interoperable EMS architectures—that are essential for accelerating BT deployment in sustainable, resilient energy systems.

9. Conclusion

Nowadays, batteries have attained ubiquitous status, permeating diverse realms such as personal electronics, vehicular technology, and portable computing devices. However, the burgeoning markets for electric vehicles (EVs) and stationary electricity storage foreshadow an even greater significance of batteries in the future. In contemporary societies, there exists a burgeoning reliance on consistent and uninterrupted access to electricity, catering to an extensive spectrum of functionalities across various spatial and temporal contexts. This pervasive expansion of electricity's utility in the realm of energy provision assumes a pivotal role in facilitating the transition towards clean energy paradigms. Obviously, electricity stands out as a quintessential energy carrier, owing to its amenability to generation from RE sources, and its emission-free attributes at the point of consumption. The following points demonstrates the contributions provided by the article.

- Batteries currently stand as a pivotal component within the global energy ecosystem and are primed to assume a critical function in facilitating secure and cost-effective transitions toward clean energy. Within the transportation sector, batteries serve as the fundamental element in the proliferation of electric vehicles (EVs), which are witnessing substantial sales figures annually. Concurrently, within the power sector, batteries are steadily gaining prominence, particularly in utility-scale and behind-the-meter applications. This surge in importance is attributable to the declining costs of batteries and the escalating proportion of electricity generated from solar and wind sources.
- In 2023, the cumulative volume of batteries deployed within the energy sector surpassed 2400 GWh, marking a remarkable fourfold escalation from the levels observed in 2020. Over the past half-decade, the global augmentation in lithium-ion BT capacity has exceeded 2000 GWh, fueling the proliferation of 40 million electric vehicles and numerous BT storage ventures. Notably, electric vehicles (EVs) accounted for over 90 % of BT utilization within the energy domain, reaching a record annual volume exceeding 750 GWh in 2023, primarily attributable to passenger car applications.
- The expansion of BT storage capacity within the power sector is experiencing rapid acceleration. In 2023, the addition surpassed 40 GW, marking a twofold increase from the preceding year's increment. This expansion is distributed between utility-scale projects, constituting 65 % of the total, and behind-the-meter systems, comprising the remaining 35 %. BT storage serves diverse functions within power systems, including facilitating short-term energy shifting, delivering ancillary services, mitigating grid congestion, and expanding access to electricity. Governments are bolstering policy support for BT storage through the implementation of additional targets, financial subsidies, and market access reforms aimed at fostering its widespread adoption.
- Investment in EV-based BT have experienced an eightfold surge since 2018, while investment in BT storage has risen fivefold, culminating in a total investment of USD 150 billion in 2023. The majority of this investment, approximately USD 115 billion, was allocated to EV batteries, with China, Europe, and the United States collectively representing over 90 % of the total investment.

To end up, Batteries have become integral to the global transition towards RE, particularly within the transportation and power sectors. In 2023, BT deployment reached a remarkable 2400 GWh, a fourfold increase since 2020, driven largely by the proliferation of 40 million electric vehicles. The power sector also saw significant growth, with BT storage capacity expanding by 40 GW in 2023, used for energy management, enhancing grid stability, and increasing electricity access. This growth is supported by robust investments, with an eightfold increase in EV-based BT funding since 2018, culminating in a total of USD 150 billion invested in 2023, primarily in EV batteries. This surge in BT use and investment highlights their critical role in facilitating a secure, cost-effective shift to clean energy sources, underscored by strong policy support and financial incentives from governments worldwide. The

Table 7
Summarizes the key limitations of current BT systems and outlines potential areas for future research.

Limitation	Impact	Future Research Direction
Inaccurate degradation models	Reduced battery performance and lifespan prediction accuracy	Develop adaptive and AI-driven aging models
High initial and maintenance cost	Slower adoption in small-scale or developing markets	Explore second-life batteries and hybrid systems
EMS integration complexity	Operational inefficiency and limited scalability	Design interoperable and decentralized EMS frameworks
Environmental concerns	Sustainability issues in extraction and recycling	Implement circular economy and recycling protocols
Cybersecurity risks	System vulnerabilities in cloud-integrated BMS	Develop secure communication and fault detection protocols
Regulatory fragmentation	Barriers to integration across platforms and grids	Standardize protocols for EMS/BMS interoperability

limitations of this article include restricted access to comprehensive real-time data on battery performance and methodological constraints in accounting for all variables, such as renewable energy fluctuations and differing regulatory frameworks. Additionally, the study focuses on commercially viable technologies, limiting the exploration of emerging battery innovations. Future research should address these gaps by conducting longitudinal studies on battery performance, exploring next-generation technologies like solid-state and flow batteries, and examining their integration with smart grids. Further studies could also investigate the economic and policy impacts of widespread battery adoption and the development of sustainable battery recycling methods to address environmental concerns.

CRediT authorship contribution statement

Mohamed Khaleel: Writing – original draft, Visualization, Validation, Software, Formal analysis. **Ziyodulla Yusupov:** Methodology, Formal analysis, Conceptualization. **Heybet Kilic:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Abdeladim Moftah:** Formal analysis. **Ali Hesri:** Formal analysis. **Abdussalam Ali Ahmed:** Data curation. **Yasser Nassar:** Formal analysis. **Musa Yilmaz:** Project administration. **Alfredo A. Martinez-Morales:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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