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Editorial Note

Evolution of energy storage: from passive backup to intelligent energy assets

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ABSTRACT

Energy storage is undergoing a fundamental transformation from passive backup devices into intelligent energy assets that actively support modern power systems. This evolution is driven by advances in electrochemical storage technologies, power electronics, artificial intelligence, digital communication, and distributed energy management, enabling storage systems to operate as adaptive and value-generating components of future energy infrastructures. This editorial presents a conceptual framework describing four stages of energy storage evolution: passive backup, monitored storage, smart storage, and intelligent energy assets. Building upon this progression, it discusses the enabling technologies, system architecture, and emerging applications that support increasingly autonomous and data-driven energy management. The integration of battery technologies with intelligent energy management systems, advanced analytics, and interoperable communication networks enables energy storage to provide services beyond energy balancing, including renewable integration, grid flexibility, market participation, and resilience enhancement. The editorial further argues that future energy storage systems should be evaluated not only by energy capacity and efficiency but also by their intelligence, adaptability, interoperability, sustainability, and system value. This perspective positions intelligent energy storage as a strategic foundation for flexible, resilient, and carbon-neutral electrical energy systems.

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1. INTRODUCTION

The global transition toward low-carbon and digitally connected energy systems is fundamentally transforming the role of energy storage in modern electrical infrastructures. Traditionally, energy storage technologies have been deployed primarily as passive backup resources designed to provide short-term power continuity during supply interruptions. Today, rapid advances in electrochemical storage technologies, power electronics, artificial intelligence, digital communication, and distributed energy management are redefining energy storage as intelligent and actively managed assets that contribute directly to power system flexibility, resilience, and sustainability.

This transformation is driven by the increasing complexity of electrical networks characterized by high penetrations of renewable energy resources, bidirectional power flows, distributed energy resources, and dynamic electricity markets. Under these conditions, conventional storage systems with fixed operational strategies are no longer sufficient to satisfy emerging requirements for real-time coordination, autonomous operation, and system-wide optimization. Intelligent energy storage therefore represents a fundamental shift from storing energy to intelligently managing energy within increasingly interconnected power systems.

Figure 1 summarizes this conceptual evolution by illustrating the progression of energy storage through four developmental stages—from passive backup and monitored storage to smart storage and ultimately intelligent energy assets. Beyond this technological progression, the framework integrates the enabling technologies, intelligent system architecture, application domains, and value drivers that collectively transform energy storage into an active component of future electrical infrastructures. As such, Figure 1 serves as the conceptual framework for this editorial, linking technological evolution with system integration and value creation across the entire intelligent energy storage ecosystem.

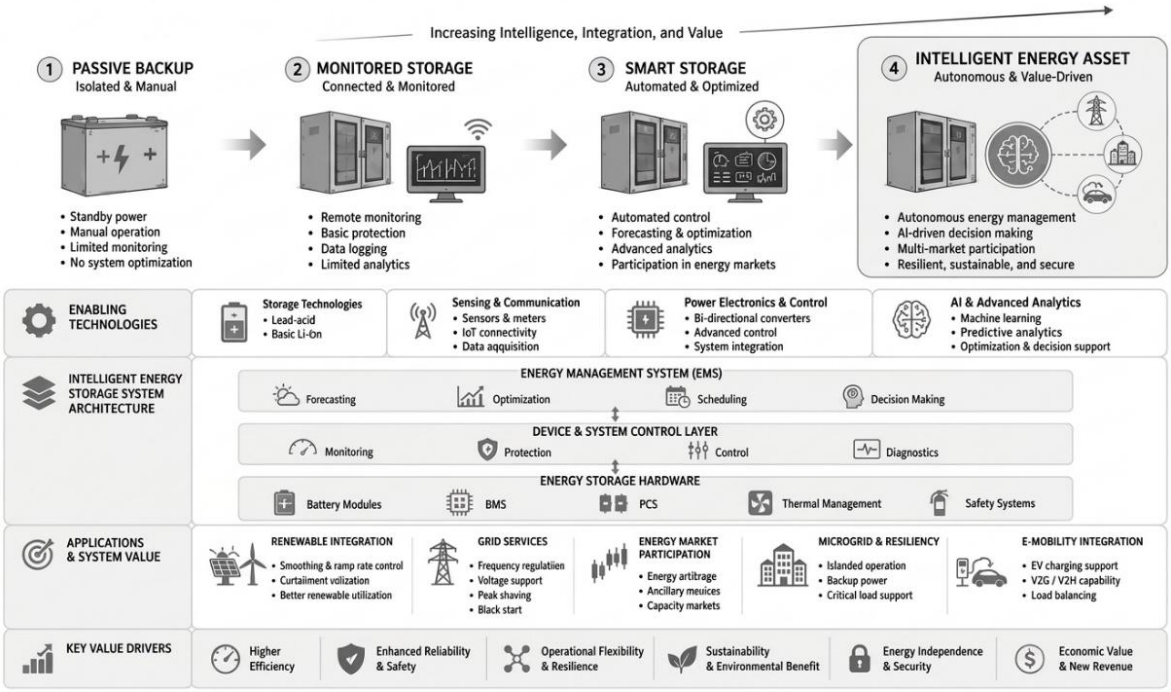


Figure 1. Conceptual evolution of energy storage from passive backup to intelligent energy assets

Building upon this conceptual framework, this editorial examines the evolution of intelligent energy storage, the technologies enabling this transformation, the architecture of intelligent energy storage systems, and the expanding applications that position storage as a strategic asset for flexible, resilient, and carbon-neutral electrical energy systems.

2. EVOLUTION OF ENERGY STORAGE

Energy storage has evolved from a passive supporting technology into an intelligent and strategically managed component of modern electrical infrastructures. Historically, storage systems were deployed primarily to provide emergency backup power during supply interruptions, operating independently with minimal monitoring and limited interaction with surrounding electrical networks. Under this conventional paradigm, storage performance was evaluated mainly through energy capacity, discharge duration, reliability, and operational availability.

The rapid expansion of renewable energy generation, distributed energy resources, and digital power systems has fundamentally redefined these expectations. Modern electrical networks require storage systems capable of responding dynamically to fluctuating generation, variable electricity demand, and increasingly decentralized grid architectures. Consequently, energy storage has progressed beyond passive energy

reservation toward active participation in system monitoring, operational coordination, and intelligent decision support.

As illustrated in Figure 1, this evolution can be understood through four progressive stages. The passive backup stage represents isolated storage systems designed primarily for standby operation with minimal monitoring or optimization. The monitored storage stage introduces digital sensing, remote supervision, data logging, and basic operational analytics, enabling improved visibility into storage performance while maintaining largely centralized control.

The subsequent smart storage stage incorporates advanced power electronics, forecasting algorithms, automated control, and optimization techniques that enable storage systems to respond autonomously to changing operating conditions. Rather than functioning solely as energy reserves, storage systems become active participants in renewable energy integration, peak demand management, and grid support services. Intelligence increasingly shifts from human operators toward data-driven operational decision-making supported by artificial intelligence and real-time system analytics.

The final stage, intelligent energy assets, represents a fundamental transformation in which storage systems operate as autonomous, interconnected, and value-generating components of future energy ecosystems. At this stage, energy storage continuously coordinates with energy management systems, distributed energy resources, electricity markets, and digital communication networks to optimize technical performance while simultaneously supporting economic efficiency, system resilience, and environmental sustainability. Energy storage therefore evolves from a passive hardware resource into an intelligent cyber-physical asset capable of delivering multiple services across increasingly integrated electrical infrastructures.

This conceptual evolution demonstrates that advances in energy storage are no longer defined solely by improvements in battery chemistry or storage capacity. Instead, future progress increasingly depends on the integration of intelligent control, digital connectivity, predictive analytics, and autonomous energy management that collectively transform storage into an essential platform for flexible, resilient, and carbon-neutral energy systems. This evolution naturally raises the question of which technological innovations enable these capabilities, forming the basis for the next section.

3. ENABLING TECHNOLOGIES FOR INTELLIGENT ENERGY STORAGE

The transformation of energy storage from passive backup devices to intelligent energy assets has been enabled by the convergence of multiple technological innovations rather than by advances in battery technologies alone. Modern energy storage systems increasingly integrate electrochemical storage, intelligent power conversion, artificial intelligence, digital communication, and advanced control technologies into unified cyber-physical platforms capable of autonomous operation. This technological convergence enables storage systems to move beyond energy reservation toward intelligent coordination with broader electrical energy infrastructures.

Advances in electrochemical energy storage provide the physical foundation for this transformation. Continuous improvements in lithium-ion, lithium iron phosphate, solid-state, flow battery, and hybrid storage technologies have enhanced energy density, operational safety, cycle life, and scalability across diverse applications. At the same time, innovations in battery management systems enable continuous monitoring of cell conditions, state-of-charge estimation, thermal regulation, and health diagnostics, thereby improving system reliability and operational longevity.

Power electronics constitute the second enabling pillar by providing the interface between energy storage and electrical networks. High-efficiency bidirectional converters, wide-bandgap semiconductor devices, and advanced converter topologies enable rapid energy exchange, precise power regulation, and seamless integration with renewable generation, microgrids, and distributed energy resources. These capabilities allow storage systems to support multiple operational objectives while maintaining high efficiency and stable system performance.

Artificial intelligence and advanced data analytics further expand the operational capabilities of intelligent energy storage. Machine learning algorithms, predictive analytics, and optimization techniques enable forecasting of renewable generation, electricity demand, battery degradation, and market conditions, allowing storage systems to make adaptive operational decisions under changing conditions. Rather than responding reactively, intelligent storage increasingly operates proactively by anticipating future system states and optimizing energy management accordingly.

Equally important, digital communication technologies provide the connectivity required for coordinated system operation. Internet of Things platforms, edge computing, secure communication protocols, and interoperable information standards enable continuous information exchange among storage systems, energy management systems, renewable energy resources, and grid operators. This digital connectivity transforms individual storage units into interoperable components capable of participating in coordinated, data-driven, and distributed energy management.

Collectively, these enabling technologies establish the technological foundation for intelligent energy storage. However, realizing their full potential requires an integrated system architecture that coordinates sensing, optimization, control, and decision-making across multiple operational layers. This architectural perspective forms the focus of the following section.

4. INTELLIGENT ENERGY STORAGE SYSTEM ARCHITECTURE

The transition toward intelligent energy assets requires more than the integration of advanced technologies; it depends on a system architecture capable of coordinating sensing, analysis, decision-making, and control across multiple operational layers. Rather than functioning as isolated hardware, intelligent energy storage systems operate as cyber-physical platforms in which physical storage devices, digital intelligence, and communication infrastructures interact continuously. This layered architecture enables storage systems to respond autonomously while maintaining reliable, secure, and coordinated operation within modern electrical networks.

The upper layer is represented by the energy management system (EMS), which performs supervisory functions including forecasting, optimization, scheduling, and operational decision-making. By integrating information from energy markets, renewable generation, electricity demand, and storage availability, the EMS determines optimal charging, discharging, and energy allocation strategies under changing operating conditions. Consequently, energy management evolves from predefined scheduling toward predictive and adaptive system optimization supported by real-time data analytics.

Beneath the EMS, the device and system control layer translates high-level operational objectives into coordinated control actions. This layer integrates continuous monitoring, system protection, converter control, diagnostics, and communication among storage devices and external power system components. Through closed-loop control and real-time feedback, it maintains operational stability while ensuring that system responses remain consistent with technical constraints and overall operational objectives.

The physical foundation of the architecture consists of the energy storage hardware layer, including battery modules, battery management systems, bidirectional power conversion systems, thermal management, and safety mechanisms. These components provide the electrochemical storage and power conversion capabilities upon which intelligent operation depends. Continuous monitoring of battery condition, temperature, charging status, and system health enables higher operational reliability, improved safety, and longer service life.

The effectiveness of this architecture depends on continuous information exchange across all operational layers. Measurements collected from hardware components are transmitted to higher-level control functions, while optimization decisions generated by the EMS are translated into coordinated control actions throughout the system. This bidirectional flow of information enables intelligent energy storage systems to adapt dynamically to changing operating conditions while maintaining secure, efficient, and reliable operation.

This integrated architecture transforms energy storage from an isolated electrical device into an intelligent infrastructure capable of supporting multiple energy services simultaneously. By combining physical storage, intelligent control, and digital communication within a unified platform, intelligent energy storage becomes a strategic asset for renewable integration, grid flexibility, market participation, and resilient energy management. These expanding capabilities are reflected in the diverse application domains discussed in the following section.

5. APPLICATIONS AND SYSTEM VALUE

The evolution of energy storage into intelligent energy assets significantly expands its role across modern electrical energy systems. Rather than serving as isolated backup resources, intelligent storage systems increasingly function as active participants in power system operation, supporting renewable integration, grid stability, market coordination, and distributed energy management. Their ability to monitor operating conditions, exchange information, and make adaptive decisions enables energy storage to deliver multiple services simultaneously while improving the overall flexibility and resilience of electrical infrastructures.

One of the most significant application domains is the integration of renewable energy resources. The increasing penetration of solar and wind generation introduces variability and uncertainty that challenge conventional power system operation. Intelligent energy storage addresses these challenges through predictive charging and discharging strategies, renewable energy smoothing, peak demand management, and real-time balancing between electricity generation and consumption. These capabilities improve renewable energy utilization while reducing curtailment and enhancing overall grid flexibility.

Beyond renewable integration, intelligent energy storage has become an essential resource for modern grid services. Advanced storage systems support frequency regulation, voltage control, spinning reserve, black-start capability, and congestion management through rapid and coordinated responses to changing network conditions. By continuously interacting with energy management systems and grid operators, intelligent storage enhances operational reliability while reducing dependence on conventional reserve generation.

Digital connectivity also enables intelligent energy storage to participate actively in electricity markets. Through forecasting, optimization, and real-time communication, storage systems can perform energy arbitrage, provide ancillary services, and participate in emerging flexibility and capacity markets. This evolution transforms storage from a cost-intensive infrastructure component into a value-generating asset capable of creating both operational and economic benefits for utilities, industries, and prosumers.

Intelligent energy storage further strengthens the resilience of microgrids and distributed energy systems. During grid disturbances or extreme events, storage systems support islanded operation, maintain critical loads, and coordinate distributed energy resources to sustain reliable electricity supply. Similar capabilities are increasingly applied to electric mobility, where storage enables fast charging, vehicle-to-grid integration, and intelligent load management that improve both transportation electrification and power system flexibility.

Collectively, these applications demonstrate that the value of intelligent energy storage extends far beyond energy capacity alone. Intelligent storage simultaneously enhances operational efficiency, reliability, flexibility, sustainability, energy independence, and economic performance, creating value across the entire energy ecosystem. This multidimensional contribution positions intelligent energy storage as a strategic infrastructure for future carbon-neutral electrical energy systems. At the same time, realizing these benefits requires addressing important technical, economic, and regulatory challenges, which are discussed in the following section.

6. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite remarkable technological progress, the transition from conventional energy storage to intelligent energy assets remains accompanied by significant technical, operational, and institutional challenges. While advances in battery technologies, artificial intelligence, and digital communication have expanded storage capabilities, the integration of these technologies into reliable, secure, and scalable energy infrastructures remains an ongoing engineering challenge. Future research must therefore focus not only on improving individual technologies but also on strengthening their interoperability within increasingly complex electrical energy systems.

One of the foremost technical challenges lies in enhancing battery intelligence and lifecycle management. Although modern battery management systems provide continuous monitoring and diagnostics, accurately predicting battery degradation, remaining useful life, and failure mechanisms under diverse operating conditions remains difficult. Future research should integrate physics-informed models, machine learning techniques, and real-time sensing to develop adaptive battery management systems capable of improving reliability, operational safety, and long-term asset utilization.

Another important challenge concerns the increasing complexity of distributed energy coordination. As energy storage becomes interconnected with renewable generation, electric vehicles, microgrids, and active distribution networks, future energy management systems must coordinate thousands of distributed energy assets operating simultaneously. Scalable optimization algorithms, distributed control strategies, multi-agent systems, and edge intelligence will therefore become increasingly important for maintaining system stability while supporting decentralized decision-making.

Cybersecurity and data governance represent equally critical research priorities. Intelligent energy storage systems rely heavily on continuous communication, cloud-based services, and data-driven operational decisions, making them increasingly vulnerable to cyberattacks, data manipulation, and communication failures. Future engineering solutions must integrate cybersecurity, privacy protection, secure communication protocols, and resilient system architectures as fundamental design requirements rather than supplementary protective measures.

The emergence of digital twins offers particularly promising opportunities for next-generation intelligent energy storage. By combining real-time operational data with predictive simulation models, digital twins enable continuous monitoring, performance optimization, predictive maintenance, and scenario analysis throughout the storage lifecycle. Coupled with artificial intelligence, these virtual representations can support autonomous operational planning, improve system resilience, and accelerate decision-making across interconnected energy infrastructures.

Beyond technological innovation, future research should also address the broader dimensions of sustainability and lifecycle assessment. The environmental impacts of battery manufacturing, critical material

availability, recycling strategies, circular economy principles, and carbon footprint assessment will increasingly influence the long-term sustainability of intelligent energy storage. Integrating these considerations into energy management and operational optimization will enable storage systems to create value not only through technical performance but also through responsible resource utilization.

Ultimately, future research should view intelligent energy storage not simply as an energy technology but as an intelligent cyber-physical infrastructure that integrates electrochemical storage, artificial intelligence, digital communication, and autonomous energy management within a unified engineering ecosystem. Advancing this vision will require close collaboration among electrical engineers, computer scientists, materials researchers, energy economists, and policymakers to develop storage systems that are intelligent, resilient, interoperable, and sustainable. Such multidisciplinary efforts will accelerate the realization of intelligent energy assets as a cornerstone of future carbon-neutral electrical energy systems.

7. CONCLUSION

This editorial has presented the evolution of energy storage from passive backup systems to intelligent energy assets capable of supporting modern electrical infrastructures. While conventional storage technologies were primarily evaluated by energy capacity and operational reliability, intelligent energy storage extends this role through the integration of advanced storage technologies, power electronics, artificial intelligence, digital communication, and adaptive energy management. This transformation represents not only technological advancement but also a fundamental shift in how energy storage contributes to the operation and optimization of future electrical energy systems.

The convergence of enabling technologies, intelligent system architecture, and expanding application domains positions energy storage as a strategic infrastructure for renewable integration, grid flexibility, distributed energy management, and carbon-neutral energy transition. Consequently, the value of future energy storage systems will increasingly be determined not only by their ability to store energy but also by their capacity to perceive operating conditions, support intelligent decision-making, coordinate with interconnected energy resources, and create technical, economic, and environmental value across the entire energy ecosystem.

Ultimately, intelligent energy storage represents a new engineering paradigm in which storage systems evolve from passive electrical components into active, adaptive, and value-generating energy assets. This evolution establishes energy storage as a cornerstone of future flexible, resilient, and sustainable electrical energy systems while providing a strategic direction for continued innovation in electrical and computer engineering. As energy systems become increasingly digital, decentralized, and intelligent, the evolution of energy storage will remain central to achieving secure, efficient, and carbon-neutral energy infrastructures.