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APEC Urban Energy Report

Storage to Enable Energy Transition

APEC Energy Working Group

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Produced by
APEC Sustainable Energy Center (APSEC)
Tianjin University
216 Yifu Building, 92 Weijin Road, Nankai District, Tianjin 300072 China
Tel: + (86) 022-2740 0847
Email: apsec2014@126.com

For
Asia-Pacific Economic Cooperation Secretariat
35 Heng Mui Keng Terrace
Singapore 119616
Tel: (65) 68919 600
Fax: (65) 68919 690
Email: info@apec.org
Website: www.apec.org

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APEC PROJECT

Research on Energy Storage to Enable Energy Transition in APEC cities
(EWG 03 2024S)

PROJECT OVERSEER

Jinlong MA

IMPLEMENTING ORGANIZATION

APEC Sustainable Energy Center, Tianjin University, China

PROJECT TEAM AND REPORT AUTHORS

Jinlong MA
Li ZHU
Yong SUN
Zhexing YAN
Pengfei XIE
Yujiao HUO
Steivan DEFILLA

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Executive Summary

Urban areas are the principal centers of economic activity and the essential provision of daily life necessities, making them the focal points where energy consumption is significantly concentrated. The dense population coupled with the high level of industrial and commercial activities within cities contributes to this phenomenon. Consequently, cities are uniquely positioned to influence global energy transitions, as their concentrated energy usage underscores the need for advanced systems to meet these demands efficiently while addressing environmental concerns. Urban areas now house over 55% of the global population and are responsible for consuming more than two-thirds of the world's energy. Additionally, these densely populated regions contribute approximately 50–60% of the total global carbon emissions, emphasizing their critical role in addressing environment and energy related challenges. This significant concentration of energy usage and emissions positions cities as pivotal arenas in the global effort to combat climate change and achieve carbon neutrality.

Urban centers are uniquely positioned to act as critical focal points in the pursuit of increasing the integration of renewable energy resources, implementing cutting-edge energy technologies, enhancing energy system resilience, stability and overall energy efficiency. These necessitates the formulation of multifaceted approaches to energy management that incorporate advancements in technology, rigorous governance and regulatory frameworks, comprehensive policy initiatives, and robust regulatory mechanisms. Furthermore, achieving energy transitions in urban areas involves fostering conducive business environments and market conditions that support the adoption of innovative energy solutions.

The continued research and development in the domain of urban energy systems within the APEC region hold profound importance for guiding the transition toward low-carbon energy practices and addressing the growing demand for sustainable solutions. Such efforts are instrumental in fostering a holistic approach that merges economic growth, energy efficiency, and environmental sustainability. By exploring innovative strategies and technologies, the region can effectively navigate the complexities of urban energy challenges, ensuring that cities remain resilient and adaptable in the face of shifting energy demands. Furthermore, this work contributes to the broader goals of achieving carbon neutrality and advancing green energy transitions, positioning the APEC region as a leader in global efforts to harmonize urban development with energy and environmental objectives.

Urban energy systems are facing a range of challenges such as large-scale and high-proportion development and utilization of renewable energy, secure and stable energy supply, energy system resilience, improvement of energy efficiency. There is broad consensus that the deployment of energy storage technologies can play a vital role in addressing these challenges. With diverse functionalities, energy storage can provide a wide range of services to energy systems, as a key pillar for the green and low-carbon transition of energy systems. Energy storage can effectively complement with variable renewable energy sources such as wind and solar, facilitating the large-scale development and consumption of renewable energies. As a representative fast and flexible resource, energy storage can enhance security, resilience, flexibility, and reliability, and technical and economic efficiency of energy systems, deploying energy storage can enable injecting new momentum into and enable urban green energy transition. The major international organizations, such as IEA and IRENA, all view energy storage as a key technology to secure the global energy transition and achieve the carbon natural goals. In the past decade, electrochemical energy storage, represented by lithium-ion batteries, has made remarkable progress in terms of technological maturity, operational stability and safety, and cost effectiveness, offering favorable conditions for the commercialization and large-scale deployment of new energy storage technologies. IEA suggested that that 1,500GW of storage capacity will be needed to facilitate energy transition and enable global renewable energy targets by 2030. The 29th United Nations Climate Change Conference (COP29) in November 2024 paid particular attention on the development and integration of storage into the grid and the reinforcement of the grid supporting green energy transition and achieving net-zero emissions by 2050. At COP29, the world leaders signed a pledge to collectively increase global energy storage capacity to the target set by IEA.

The APEC region is the most important market in the world for research, manufacturing, supply, and application of new energy storage technologies, represented by electrochemical energy storage, also a dominant region for mining and processing of key mineral materials that is a key segment of energy storage industry and supply chains. As of the end of 2022, six out of the top ten economies globally in terms of cumulative installed capacity of new energy storage projects having been put into operation were APEC economies, namely, China; the United States; Korea; Australia; Japan; and the Philippines, with a total installed capacity accounting approximately 70% of the global total; In 2022, five out of the top ten economies globally in terms of installed capacity of energy storage projects newly put into operation were from APEC economies, namely China; the United States; Australia; Japan; and the Philippines, whose newly added capacity in 2022 collectively accounting 69% of the global total; About 70% of both the world's total cumulative installed capacity and new installed capacity are attributed to the APEC region. The APEC region also contributes 91.5% of global lithium extraction, 77.8% of nickel, 66.1% of copper, and 64.6% of natural graphite, all critical raw materials for battery energy storage; China holds a dominant position in the processing of these critical mineral materials for battery energy storage manufacturing.

New energy storage represents a critical technology and foundational infrastructure for the future renewable energy-dominated energy systems. It stands as a core technology in the energy revolution and a strategic high ground that economies must compete for. Many APEC economies have introduced various favorable policies to accelerate the development of the energy storage industry, propelling the deployment of energy storage onto a fast track. Energy storage has now risen to the level of economy development strategy in economies such as Australia; China; Japan; Korea and the United States, and significant progresses have been made regarding the deployment of energy storge economy-wide and in urban areas.

This study focuses on the application and promotion of energy storage in urban energy systems. It investigates and analyzes the current status and development trends of major energy storage technologies, systematically summarizes their application values across different segments—generation, transmission, and demand—of the power system, and explores specific application conditions of energy storage within urban energy systems. The study reviews a multi-dimensional assessment framework covering technical and economic aspects, tabulates key techno-economic indicators of typical energy storage technologies and their suitability for various urban applications. Furthermore, it analyzes energy storage technical standards and specifications, with particular attention on safety issues, standards and relevant regulations regarding battery energy storage system. The study analyzes the related development strategies, policies, and plans of the APEC economies for development of energy storage industry and deployment of energy storage. At the same time, the research analyzes the main driving forces and potential barriers to the application and promotion of energy storage technologies in the economies and cities. These are achieved from multiple perspectives, including the development of energy storage projects, integration and operation of energy storage facilities to power systems and provision of system service, participation of energy storage in electricity markets, building resilient and secure industry and supply chains for green manufacturing and supply, and fostering a market-oriented, rule-based business environment for energy storage deployment. A number of energy storage demonstration projects with different technology and application in China are presented. The study examines the practices and applications of energy storage systems within selected economies in the APEC region, including Australia; China; Korea; and the United States,. It delves into various aspects such as the development of energy storage projects, integration into existing power systems, and participation in electricity markets. By exploring the strategies adopted by these economies, the analysis highlights key approaches to enhancing the deployment and operational efficiency of energy storage technologies. These practices serve as valuable examples for fostering innovation and advancing the adoption of energy systems that align with broader sustainability goals, thereby contributing to the progression of renewable energy initiatives and green transitions.

Building upon the comprehensive research and analysis outlined, it is imperative to formulate detailed policy recommendations that facilitate the widespread adoption and integration of energy storage systems within urban environments across the APEC region. These recommendations should focus on creating a robust framework that supports the deployment of advanced energy storage technologies, addresses the unique challenges posed by urban energy systems, and aligns with the overarching goals of renewable energy development and green energy transitions. In particular, policies must prioritize the establishment of conducive regulatory environments, the development of economic incentives, and the promotion of innovative applications to ensure the seamless integration of energy storage systems into urban infrastructure.

Such measures would not only enhance the resilience and efficiency of urban energy systems but also contribute significantly to achieving regional and global energy sustainability objectives.

(1) Refining and enhancing regulatory frameworks and policy guidelines is of utmost importance to provide comprehensive direction for the progress, widespread adoption, and seamless integration of energy storage systems into modern energy infrastructures, ensuring their effective operation and contribution to energy transition goals.

Achieving the goals for energy storage development requires improvement of operating practices or regulatory frameworks for the deployment of the technologies and project development. Policymakers should implement and consistently update clear, streamlined permit processes that account for the unique characteristics of BESS, avoiding outdated regulations designed for traditional generation or loads. Market mechanisms and financial incentives are crucial, which include establishing clear valuation and allowing for the multiple services that BESS provides and offering direct subsidies, tax credits, or performance-based incentives to de-risk investments and improve project economics. In addition, robust and adaptable safety codes and technical standards must be uniformly adopted and rigorously enforced, coupled with ongoing training for first responders and public awareness campaigns to ensure community acceptance for the battery storage projects. With rapid advancement of battery technologies, policymakers and regulators can encourage familiarization with storage through the development of more pilot projects. These projects allow stakeholders to experiment with various technical, operational, and regulatory options to incorporate energy storage in urban energy systems. Such pilot projects could be significantly important when determining how to use distribution-level storage facilities to meet the needs of both distribution and the transmission systems. The pilots will also help regulators determine the better ownership models to provide the most benefits to the grid at least cost, and can help utilities familiarize themselves with providing electricity services with the storage facility that they own or procure from the third parties. The pilot projects are also pivotal in disseminating best practices and identifying optimal strategies for technology deployment, enabling stakeholders to refine operational models and updating relevant technical standards.

(2) It is essential to enhance innovation in the development of new energy storage technologies while facilitating the transformation of research outcomes into practical applications. Additionally, efforts should focus on expanding use cases and establishing diverse business models to maximize the potential of energy storage solutions.

Innovation is the key driver of technological and industrial advancement. As a multidisciplinary field, new energy storage technologies are currently advancing toward large capacity, high density, long cycle life, enhanced safety, and intelligent operation, which requires collaborative efforts among governments, enterprises, research institutions, and other stakeholders to actively pursue breakthroughs in new materials, technologies, and equipment for energy storage. For battery technologies, these include significant and sustained government investment in fundamental and applied R&D to explore novel battery chemistries (e.g., solid-state, sodium-ion, flow batteries) and long duration energy storage. Alongside R&D, policies should implement targeted manufacturing incentives, such as production tax credits, investment tax credits, and grants for domestic gigafactories and supply chain development, to scale up efficient and cost-effective production of advanced battery cells and components.

Effective collaboration among the stakeholders is critical to promote information sharing and technical exchange, thereby driving coordinated development across the entire energy storage industry chain; Strengthen close cooperation with universities and energy storage enterprises, combine academic knowledge with industry demands, and accelerate the incubation and transformation of new technologies. Concurrently, the energy storage industry should leverage demonstration projects as innovation drivers to accelerate technology commercialization and spearhead sector-wide advancement; Efforts should be made to explore the new application cases such as grid integration, integrated services of solar PV-energy storage-EV charging, and virtual power plants, demonstrating the actual benefits and potential of advanced energy storage technologies in actual applications across various sectors—such as industrial, transportation, residential and commercial buildings.

(3) It is essential to enhance technical regulations and establish comprehensive standard systems that encompass the entire lifecycle of energy storage solutions, thereby providing a solid foundation for their efficient deployment.

The standardization supports the commercial and large-scale application of energy storage technologies, ultimately accelerating the global transition toward low-carbon energy systems. To promote the deployment of new energy storage, priority should be given to enhance technical regulations and standard norms, covering the entire life cycle of the BESS. Technical guidance and standards for energy storage play a core role in promoting the safe and efficient operation of energy storage systems and their compatibility with existing and future energy systems.

Integrating energy storage into the power system and accessing its full value require technical regulations that ensure reliable, predictable behavior from the asset during both normal operations and in response to contingency events. Such regulations could cover myriad topics from communication capabilities, level of observability over the storage system for system operators, and various operational characteristics such as minimum response times to signals from a system operator. Although existing technical codes standards may adequately cover most of the technical requirements, energy storage systems that provide power to both the distribution and transmission system may need additional review and capabilities. To support the safe and effective integration of BESS into the power grid, focused areas include: i) Technical rules should ensure BESS are installed and operated safely, addressing risks like fires or chemical leaks. Standards should also require batteries to communicate smoothly with the grid, helping to stabilize voltage and frequency during outages or sudden changes in energy supply; ii) From a grid operator’s perspective, regulations and standards for BESS should prioritize reliability, simplicity, and fairness.

Connection rules shall ensure batteries can respond quickly and safely to grid needs. Standards must address safety risks like fires or overheating by mandating proven designs, emergency shutdown features, and regular inspections. Grid operators need straightforward protocols for how batteries connect to the grid, reducing delays and technical conflicts; iii) Policies should be prepared helping batteries compete fairly in energy markets while supporting grid stability. Remove outdated rules that penalize batteries for charging from the grid or limit how they can earn revenue. Grid operators need flexibility to use batteries for multiple purposes, like easing congestion on overloaded power lines or delaying costly grid upgrades.

(4) To ensure the safety and reliability of energy storage systems, it is essential to enhance quality control across the supply chain, optimize operation and management practices, and address public concerns effectively.

Improving safety of energy storage systems requires great efforts from multiple aspects including design, operation, and management. During the design phase, modular structures and thermal management systems can be used to control battery temperature and prevent thermal runaway risks; During operation, enhanced maintenance and real-time monitoring systems should be implemented to detect and address potential issues promptly; At the same time, AI-based safety maintenance and system optimization management are among effective methods. Safety education and emergency training are essential for ensuring operational safety; virtual training and case analysis can enhance emergency response capabilities. With increased attentions and greater efforts from the authorities and technology advancement, safety records of energy storage systems have improved greatly in recent years. Improved safety directly impacts market confidence of energy storage products. Implementing high safety standards significantly reduces investment risks, increases consumer acceptance of energy storage technologies, and thus drives research, development, and commercialization of energy storage system. These not only ensure the deployment of energy storage systems but also provide safe and reliable supports for energy system stability and large-scale applications of renewable energy.

The safe operation of energy storage systems has become a critical challenge, requiring strengthened quality control across the supply chain. Firstly, cities and local governments should incorporate sufficient fire safety distances and spatial arrangements for energy storage facilities into controlled detailed planning and specialized planning for land use; Secondly, drawing on international experience, establishing quality standards and safety technical specifications that cover all stages—including manufacturing, construction, installation, operation monitoring, and recycling—and applying them throughout the industry chain; Thirdly, improving the early warning mechanisms before thermal runaway events in electrochemical energy storage battery systems along with protective measures during incidents and anti-diffusion strategies after accidents; Finally, encouraging enterprises research efforts, through technological innovation to improve the quality and safety of energy storage products and services. In addition, grid operator and power dispatching agencies should develop detailed grid connection rules and guidelines, clearly defining grid connection procedures, relevant technical standards, and requirements for grid-related testing, laying a solid foundation for the safe and efficient operation of energy storage systems.

(5) To enhance the strategic planning and operational efficiency of power networks, it is imperative to establish a systematic approach to the development of energy storage solutions, ensuring the effective utilization of the diverse services provided by storage systems, thereby contributing to the overall optimization and reliability of the power infrastructure.

Long-term energy storage targets and integrated resource planning can provide critical policy certainty, signaling a stable market for developers and investors while accelerating the integration of BESS into urban energy system. Alongside renewables development, utilities need to fully include energy storage in long-term grid planning of urban energy system, ensuring integrated considerations of batteries for various power system services. Such requirements can help make sure more novel approaches to power system needs are considered on an even playing ground with more traditional investments.

The ability of batteries to provide both network services and market services means that both networks and other parties can lead the roll-out of energy storage infrastructure. Distribution network service providers in cities could effectively support scaling up BESS deployment by: i) fully embedding BESS into the planning and design of networks, for example, due to network operator's intimate knowledge of evolving electricity demand and future infrastructure augmentation requirement, as well as related replacement and operational needs of the network; ii) taking the advantage to use existing land assets of the urban network operators, such as land adjacent to zone substations, to host batteries, lowering the cost of delivery. This also avoids the social license cost of procuring new land within communities and effectively navigating change of its use; iii) partnering with market facing third parties, including BESS developers and integrators, which can reduce the barriers for those parties to manage wholesale electricity market risks and sustain the BESS project development; iv) leveraging existing processes and workforce for the operation and maintenance of energy storage assets to maximize the values and benefits of BESS.

(6) Initiatives should center on streamlining procedures, ensuring the seamless integration of energy storage systems with the power grid, and facilitating the advancement of energy storage projects.

To accelerate the grid integration of BESS project, policy recommendations should prioritize streamlining and standardizing interconnection procedures. This involves developing clear, efficient, and transparent processes for connecting BESS to both transmission and distribution networks, which are often characterized by significant delays and uncertainties. Key policy actions include establishing firm deadlines for grid operators to complete interconnection studies and approvals, implementing "cluster study" approaches instead of serial processing to manage backlogs, and requiring higher readiness requirements for projects entering the queue to ensure only mature proposals proceed. Furthermore, policies should promote the provision of granular and accessible grid data, such as hosting capacity maps and circuit strength information, enabling developers to identify optimal interconnection points and design more effective projects, thereby reducing speculative applications and subsequent withdrawals.

Additionally, policies should address the technical and financial aspects of interconnection to facilitate BESS deployment. This includes updating technical standards to specifically accommodate the unique operational characteristics of BESS, such as their fast response times and ability to provide grid-forming services, rather than treating them solely as traditional generators. Policies should also clarify cost allocation mechanisms for necessary grid upgrades associated with BESS interconnections, ensuring that these costs are allocated fairly and do not disproportionately burden BESS developers. Finally, encouraging innovative connection models, such as co-location with existing renewable generation or shared connection points, can further optimize grid infrastructure utilization and reduce the need for extensive new transmission or distribution investments, thereby accelerating project timelines and reducing overall costs for BESS integration.

(7) Effectively advocate for distributed storage systems to deliver cost-effective and reliable energy services to consumers.

Supporting the widespread adoption of distributed BESS, including community battery programs, industrial and commercial storage, and virtual energy storage, requires a multi-faceted approach. Governments and regulators should prioritize targeted financial incentives such as grants, low-interest loans, and performance-based payments that specifically encourage the deployment of these systems at various scales. Concurrently, regulatory frameworks need to be updated to fairly value the diverse grid services offered by distributed BESS, including peak shaving, demand response, and frequency regulation, ensuring they can fully participate and monetize their benefits in electricity markets. Cities can streamline local planning and permitting processes for these installations, reducing administrative burdens and accelerating deployment. Clear guidelines for community engagement and benefit-sharing, such as discounted electricity rates for participants, will also foster public acceptance and drive widespread adoption. Clear and streamlined interconnection rules are also essential to reduce project development times and costs, facilitating faster deployment.

In cities in developing economies, where industrialization and energy demand are soaring, policies can encourage industrial and commercial BESS through demand charge reduction incentives, preferential grid access for BESS-integrated renewable energy, and support for microgrids in industrial parks. These in industrialized economies cities should continue to leverage existing tax credits and relevant mandates for storage projects. Fostering the growth of virtual energy storage and I&C BESS necessitates regulatory innovation. This involves developing sophisticated market mechanisms that allow aggregated smaller storage units to participate in wholesale energy markets and provide ancillary services, effectively creating VPPs. These VPPs can optimize distributed BESS assets across a city, enhancing grid stability and efficiency, allowing them to provide demand response and grid services to the local network. For industrial and commercial users, policies should incentivize the integration of BESS with on-site renewable generation through tax credits or specific tariffs that reward self-consumption and grid support. continued investment in research and development, alongside public education on technology advancement and safety of distributed BESS.

(8) In order to ensure the successful development and implementation of energy storage projects, it is essential to devise effective fiscal and tax policies while simultaneously establishing a robust mechanism that allows comprehensive participation of energy storage systems in electricity markets.

Effective fiscal and tax support policies play a significant role in accelerating the early-stage development of energy storage and facilitating its transition from commercialization to large-scale deployment. Governments should study and develop appropriate subsidy policies for energy storage, while actively exploring financial models that support the development of new energy storage technologies. For the standalone energy storage model, on one hand, governments can reduce upfront investment costs through industrial policies, enabling more energy storage companies to participate in spot market competition and thus help reduce peak-to-valley load differences; On the other hand, governments can also increase the charging and discharging revenue of standalone energy storage systems to reduce operators' incentives to withhold capacity from the market. For the renewable energy-integrated storage model, governments may promote shared energy storage business models to realize society-wide allocation of storage resources, thereby maximizing the ability of energy storage to flatten peak and valley loads. For the user-side storage model, on one hand, governments can provide subsidies for the installation costs of energy storage systems to enhance users' self-regulation capabilities; On the other hand, governments can also implement time-of-use (TOU) pricing policies to widen the price gap between peak and off-peak hours, thus strengthening users' willingness to adopt energy storage solutions. Governments should streamline cost transmission mechanisms for energy storage and establish a comprehensive mechanism for energy storage participation in the electricity market. Governments should relax the access conditions for energy storage participating in the electricity market, and continue to refine the rules governing participation in spot trading, improve the auxiliary service market mechanisms and trading products, establish and improve cost recovery mechanisms for energy storage capacity, so as to eliminate barriers preventing new types of energy storage from participating in the electricity market. Furthermore, governments should encourage enterprises to explore innovative profit channels and business models that better align with market development through policy measures and legal frameworks—such as shared leasing, arbitrage in the spot market, virtual power plant models, and community energy storage models, and recognize and protect the legality of enterprise revenues.

(9) The establishment of a supportive and strategically structured business environment is of paramount importance to fostering the growth and driving the innovation required for the advancement of sophisticated energy storage solutions. This approach ensures that entry barriers are minimized while simultaneously maximizing opportunities for sustainable development and expansion within the energy storage sector.

To accelerate investment in BESS, policy recommendations should focus on creating stable revenue streams, reducing upfront costs, streamlining regulatory processes, and fostering market transparency. For the deployment of BESS in urban areas, cities should focus on targeted incentives for distributed energy resources, including rebates or low-interest loans for behind-the-meter batteries for households, small businesses, and apartment complexes. Policies should facilitate the deployment of community batteries in residential and commercial area, leveraging underutilized urban spaces and integrating with local renewable generation like rooftop solar. Streamlining local planning and permitting processes is crucial, specifically recognizing BESS as a permissible and valued urban infrastructure. Cities can also lead by example through municipal BESS initiatives and also foster VPP programs that aggregate urban distributed storage capacity, providing grid services and offering financial benefits to participants. Related recommendations include: i) Actively explore various flexible and efficient market-oriented profit channels and business models. The government should introduce policies and legal regulations to encourage and safeguard enterprises in generating legitimate revenues through proper profit channels and business models. ii) Improve market condition: granting non-discriminatory access to electricity markets and provision of services, and defining permissible use cases to facilitate planning by investors and operators and to make it easier to assess likely revenues. Where feasible, it would also mean reforming power markets to establish wholesale markets that help deliver cost-effective short- and medium-term flexibility, and can be a significant revenue driver for battery storage projects, especially with increased variable renewables in energy mix; iii) Mitigate off-taker risk: Lowering the risk of delayed payments or failure to pay for services provided to transmission networks would help to provide a more secure investment environment, which could be done by expanding off-taker guarantee and credit enhancement mechanisms; and iv) Lower the cost of capital: reducing perceived risks and enhancing investor confidence through stable and predictable revenue streams from diverse grid services, potentially facilitated by clear regulatory frameworks and long-term contracts. Government incentives, including tax credits, grants, and subsidies, directly lower the upfront capital required and improve project returns, making them more attractive to investors. Furthermore, the increasing availability of green financing options, such as green bonds, can offer favorable interest rates and attract environmentally conscious investors, lowering the cost of capital.

(10) To ensure a comprehensive approach to enhancing the energy storage industry, it is essential to strengthen coordination across various dimensions of battery manufacturing processes. This includes implementing robust Environmental, Social, and Governance (ESG) management practices that aim to foster diversification and promote environmentally sustainable practices throughout the energy storage industry's supply chain. Such measures are vital for ensuring the long-term viability and growth of the sector while aligning with global sustainability trends.

From a government perspective, the planning and design of the energy storage equipment supply chain should be synchronized and coordinated with the industrial chain, capital chain, innovation chain, and value chain. Comprehensive considerations should be given to logistics, industrial layout, investment and financing, scientific research and innovation, as well as value enhancement. Governments should optimize and upgrade the upstream, midstream, and downstream segments of each chain—strengthening weak links, filling gaps, and reinforcing capabilities—to stimulate market vitality and innovation; deeply integrate upstream and downstream resources to improve supply-demand transparency and guide investments into new production capacities, thereby ensuring a healthier and more stable supply chain operation. A resilient and secure supply chain should be both regionalized and diversified. City governments, along with key domestic and foreign enterprises across the energy storage supply chain—including manufacturers, suppliers, and developers—should establish strategic partnerships by reaching public-private collaboration, establishing joint ventures and sharing resources to improve operational efficiency and streamline supply chain processes, while also enhancing the bargaining power. Enterprises should seek for long-term cooperation, co-financing, acquisition, and distribution arrangements with various raw material and equipment suppliers to ensure adequate supply. While enterprises with sufficient capabilities may expand internationally through cross-border operations, tapping into global markets and coordinating upstream and downstream supply chain entities within and across economies to bypass trade barriers, integrate R&D and technological innovation strength, and reduce costs and risks. Moreover, ESG (Environmental, Social, and Governance) compliance in the supply chain is an inevitable global trend. Stakeholders along the supply chain should enhance ESG management from a full life-cycle perspective of energy storage equipment, aiming to build a green supply chain.

(11) To foster the development of Battery Energy Storage Systems, it is essential to establish robust mechanisms for information and knowledge sharing that allow stakeholders across various domains to exchange data, practical insights, and lessons learned. Additionally, sharing experiences derived from demonstration projects and pilot initiatives implemented across different economies can provide valuable guidance for the design and execution of similar endeavors on a broader scale.

Effective policy for BESS development hinges on robust information and knowledge sharing mechanisms. This includes establishing international platforms and forums where diverse stakeholders – including governments, regulators, industry players, researchers, and fire services – can regularly exchange data, best practices, and lessons learned from BESS deployment. Key areas for sharing encompass safety protocols, technical standards (e.g., harmonizing UL, IEC, domestic and international standards), operational guidelines, and insights into new battery chemistries and their associated risks and benefits. Furthermore, transparent reporting of BESS incidents, including near-misses and root cause analyses, is crucial to identifying systemic vulnerabilities and refining safety measures. Policies should incentivize the development of open-access databases and analytical tools that synthesize this information, enabling a proactive and data-driven approach to BESS regulation and innovation.

To accelerate BESS adoption and ensure its safe integration into energy systems, it is vital to share experiences from demonstration and pilot projects across different economies. This involves documenting and disseminating detailed case studies that highlight successful project implementations, innovative financing models, regulatory frameworks that foster investment, and the performance of BESS in various grid applications (e.g., frequency regulation, peak shaving, renewable energy integration, off-grid solutions). Particular attention should be paid to lessons learned regarding project complexity, integration challenges, and the evolution of operational and maintenance procedures. By analyzing these real-world examples, policymakers can identify effective strategies for de-risking BESS investments, tailoring policies to local contexts, and fostering public-private partnerships that are essential for scaling up BESS deployment globally.

(12) Facilitating and advancing international collaboration in the field of innovative energy storage technologies is of great importance for addressing the multifaceted challenges inherent in transitioning towards energy systems that incorporate a significantly higher proportion of renewable energy resources while ensuring stability and sustainability.

As a core technology in the energy revolution and a strategically critical area of competition, energy storage has been elevated to economy-wide strategies in APEC economies including Australia; China; Japan; Korea; and the United States. It is recommended that the APEC region, guided by the principles of complementary strengths and mutual benefit, draw on the experience of mature markets regarding energy storage development. To foster and promote international cooperation in the APEC region for energy storage development, policies should prioritize the harmonization of standards and regulatory frameworks. Given the diverse economic and energy landscapes within APEC economies, a "one-size-fits-all" approach is impractical. Instead, policies should encourage the development of common technical standards, safety codes (such as those for BESS), and interoperability guidelines. This would facilitate cross-border trade of energy storage technologies, components, and expertise, while reducing market fragmentation and investment risks. Furthermore, policies should support joint research and development initiatives, potentially through APEC's existing expert groups, to accelerate technological advancements in areas like long-duration storage, grid integration, and sustainable supply chains for critical minerals. This includes fostering public-private partnerships to co-fund innovative projects and facilitate technology transfer.

Beyond technical cooperation, policies should focus on building robust capacity and promoting inclusive policy dialogues across APEC member economies. This involves creating platforms for policymakers, regulators, and industry leaders to share best practices on market design, financial incentives, and regulatory mechanisms that successfully attract investment in energy storage. Targeted capacity-building programs, workshops, and peer reviews, particularly for developing economies within APEC, can help bridge knowledge gaps and accelerate the adoption of effective energy storage policies. Ultimately, a strong emphasis on consistent, transparent policy signals and a commitment to collaborative learning will be critical for unlocking the full potential of energy storage in supporting APEC's ambitious goals of enhancing energy security, integrating renewables, and achieving carbon neutrality.

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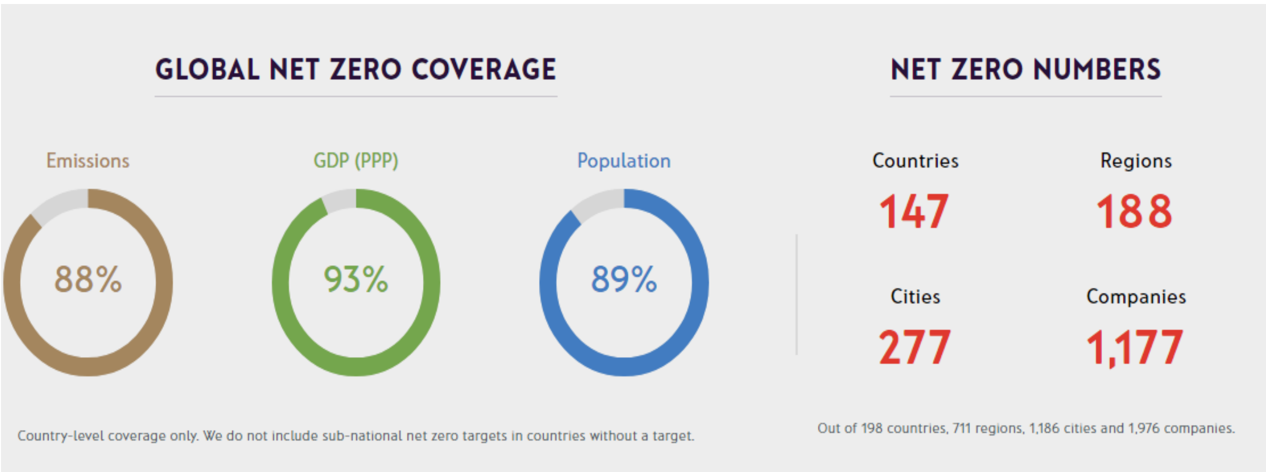
Chapter I Introduction

1.1 Climate change and APEC cities

1.1.1 Climate change and energy transition

Since the 1980s, people have become increasingly aware of and focused on the challenges and consequences of climate change. Climate change has emerged not only as a key obstacle to achieving sustainable development but also as a major focal point in global social, environmental, economic, and political discussions. On 20 March 2023, the Intergovernmental Panel on Climate Change (IPCC) released the *AR6 Synthesis Report: Climate Change 2023*, which pointed out that: during the period from 2011 to 2020, the global surface temperature was approximately 1.1°C higher compared to the average temperature recorded between 1850 and 1900.

It is unequivocal that human activities have led to the warming of the atmosphere, oceans, and land, resulting in broad and rapid changes in the atmosphere, ocean, cryosphere, and biosphere. Climate change has caused a significant increase of extreme events such as droughts, floods, heatwaves and wildfires across the global, posing long-term and significant threats to global food security, water resources, ecosystems, energy infrastructure, and the safety of people's lives and properties. To effectively address climate change, economies have established an international climate governance system based on foundational agreements including the *United Nations Framework Convention on Climate Change (UNFCCC)*, the *Kyoto Protocol*, and the *Paris Agreement* and others.

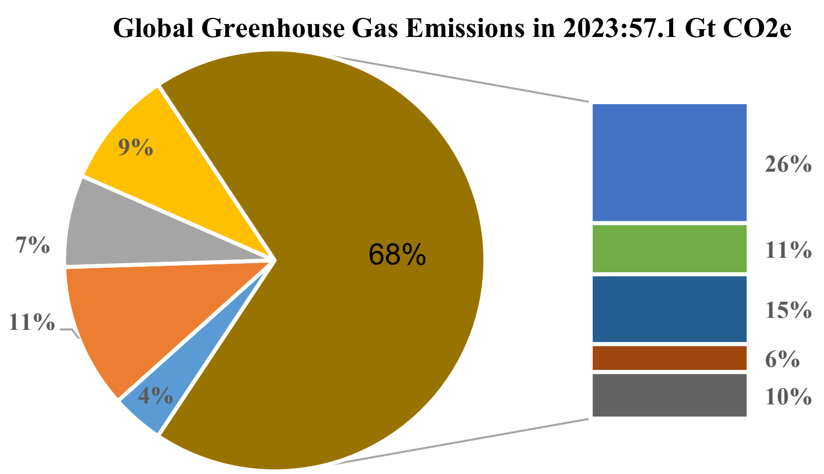


Source: Net Zero Tracker

Figure 1-1 Global Carbon Neutrality/Net Zero Emissions Goals

The 2015 *Paris Agreement* has set the goal of achieving net-zero emissions in the second half of this century. More governments have been translating the goal into their economy-wide strategies and formulating the visions for a carbon-free future. According to statistics from the Net Zero Tracker[1], as of September 2024, a total of 147 economies globally has set carbon neutrality or net-zero emission targets, which cover more than 88% of global carbon emissions, 93% of global GDP, and 89% of the world's population. Tackling climate change has become the common denomination of global community, and achieving carbon neutrality has emerged as the central focus for fostering cooperation among economies globally.

Energy is the key battlefield, and electricity is the main focus to achieve the goal of carbon neutrality. The latest *Emissions Gap Report 2024*[2] released by the United Nations Environment Programme (UNEP) reveal that global greenhouse gas emissions set a record of 57.1 Gt CO_2e in 2023, a 1.3% increase from the 2022 level. It shows that greenhouse gas emissions from the energy sector account for 68% of current global emissions, with electricity production remaining the largest source of emissions globally, contributing 26% of total global greenhouse gas emissions, reaching 15.1 Gt CO_2e. At the 28th United Nations Climate Change Conference (COP28) held in December 2023, the President of the European Commission, together with total 118 economies, launched the "Global Renewables and Energy Efficiency Pledge" initiative. The initiative calls for that, by 2030, the global renewable energy capacity shall be tripled and energy efficiency doubled; and fossil fuels shall be phased out from the energy system in a just and orderly manner, achieving net zero emissions by 2050 and aiming at keeping the global warming to 1.5°C.



Source: UNEP, Emissions Gap Report 2024

Figure 1-2 Global Greenhouse Gas Emissions and Composition in 2023

[1] Net Zero Tracker. https://zerotracker.net/

[2] UNEP. 2024. Emissions Gap Report 2024, UNEP, 2024/10/24. https://www.unep.org/resources/emissions-gap-report-2024 .

1.1.2 Energy systems and transition of APEC cities

The APEC region is the largest consumer of energy globally with the highest growth rate. The 21 APEC member economies account for approximately 60% of global energy and electricity demand. Accelerating the transition to clean energy and achieving inclusive, green and sustainable development have become a shared mission among all APEC economies.

The APEC region includes four of the world's top five energy users: China; the United States; Russia; and Japan, the significant players in global energy supply and consumption. In 2021, the primary energy supply and energy consumption in the APEC region reached 362,051PJ and 204,910PJ, respectively, accounting for 58.9% and 49.3% of the global totals. The region generated and consumed 18,604.0TWh and 15,884.4TWh of electricity, which account for 65.0% and 59.9% of the global totals[3,4]. From the perspective of end-use energy consumption structure, in 2021, the APEC region consumed 23,032PJ of coal, 68,664PJ of oil, 29,022PJ of natural gas, and 57,184PJ of electricity, taking a share of 11.24%, 33.51%, 14.16%, and 27.91% respectively. The combined share of the three major fossil fuels (coal, oil, and natural gas) in end-use energy consumption reached 58.9%. The proportion of electricity in end-use energy consumption increased from 17.1% to 27.9% over the period, indicating a continuous rise in the level of electrification at the final energy use level.

The 2011 APEC Leaders' Declaration proposed an APEC energy intensity target to reduce the total energy intensity of the APEC economies by 45% by 2035 compared to the 2005 level. At the 11th APEC Energy Ministers' Meeting in 2014, the APEC renewable energy development goal was officially announced: to double the share of renewables in the region's primary energy mix by 2030 compared to 2010. It is anticipated that APEC will achieve the energy intensity target six years ahead of schedule, by 2029, and meet the renewable energy development goal four years early, by 2026. The 2023 APEC Leaders' San Francisco Declaration further reiterated that "APEC economies need to accelerate clean, sustainable, just, affordable, and inclusive energy transitions through various pathways to achieve global net-zero greenhouse gas emissions/carbon neutrality around mid-century; ensure regional energy security, resilience, and accessibility; and strive to contribute to triple global renewable energy capacity by 2030". The APEC region has become one of the most important forces driving the global transition to green and low-carbon energy and achieving carbon neutrality. As of November 2024, except for Brunei Darussalam and the Philippines, all other 19 APEC economies have explicitly committed to carbon neutrality through legislation, regulation, policy or declaration, covering 99.3% of total carbon emissions, 99.3% of GDP, and 96.1% of population of the APEC region.

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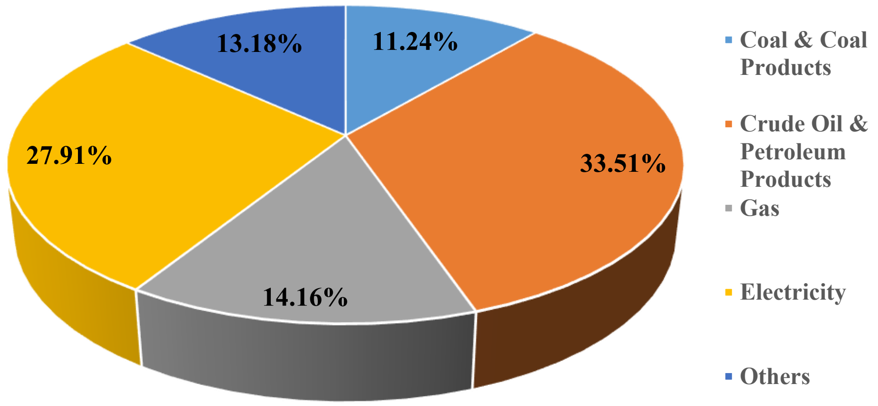
[3] APEC Energy Working Group EGEDA (2024) APEC Energy Database. https://www.egeda.ewg.apec.org

[4] IEA (2024) Energy Statistics Data Browser. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser



Source: APEC Energy Statistics 2021

Figure 1-3 Structure of End-Use Energy Consumption in APEC Region, 2021

Cities, as centers of human socioeconomic activities, consume the majority of global resources including energy resources. According to the data from UN-Habitat, as of 2022, over 55% of the global population live in urban areas, consuming more than two-thirds of the world's energy. Carbon emissions in urban areas account for approximately 50 to 60% of total global emissions. By 2040, cities are expected to account for approximately 80% of global energy consumption. Cities are therefore the main battlefield and a key focal point for achieving carbon neutrality. Rapid urbanization has raised concerns about balancing urban development with energy transition in pursuit of carbon neutral goal.

(1) Urban energy consumption is characterized by high density, elevated carbon emissions, the coexistence of centralized and decentralized energy systems, and diverse usage patterns.

In urban energy systems, energy is primarily consumed in industries, transportation, and buildings for economic activities and residential living. The constantly changing situations and requirements on both power supply and consumption sides pose increasing challenges for energy suppliers and distribution network operators in cities. In response to climate change, many cities have established carbon neutrality goals with specific deadlines and defined responsibilities. These targets will present challenges to urban development strategies, economic systems, industrial frameworks, residential lifestyles, urban management capabilities, and supporting infrastructures. These involve the absence of complete carbon-neutral city standards and systems, challenges in aligning stakeholder interests, extensive use of renewable energy in urban areas, and enhancement of urban energy efficiency. The urban energy transition is an essential process for achieving low-carbon development and meeting carbon neutrality objectives.

(2) There is an evident trend towards the extensive utilization of renewable energy in urban areas, resulting in the restructuring of city energy systems.

Cities play a crucial role in energy transitions. Governments globally are actively implementing measures to expedite the integration of renewable energy within urban environments. This includes installing renewable energy generation facilities, purchasing or contracting for renewable electricity to meet urban energy needs, and using various policy instruments to incentivize distributed renewable energy generation and utilization. As the composition of electricity supply changes, especially with the widespread installation of distributed solar PV and distributed energy storage systems in cities, the flexibility of the power system has become a key focus of the energy transition in the power sector. This involves decarbonizing electricity supply and further electrifying end-use sectors. Electrification at the terminal end is currently the most cost-effective and mature technological pathway for achieving carbon neutrality.

(3) Facilitating investments to advance urban energy transition and achieve carbon neutrality.

The importance of emission reduction in addressing climate change has gained global consensus. Urban investment in carbon neutrality is showing a significant upward trend worldwide. More and more cities are setting goals and launching action plans. In terms of funding demand, on one hand, it is necessary to establish a sound institutional framework for carbon-neutrality-related investments and financing, and improve related incentive mechanisms. On the other hand, efforts must be made to actively encourage private capital investment by addressing issues such as maturity mismatch, information asymmetry, and the lack of appropriate financial products and analytical tools in current investment and financing practices. Additionally, some key energy technologies and enabling technologies are not yet fully mature or remain costly when deployed at scale, and urban energy infrastructure requires upgrading and modernization. Fiscal and tax policies, monetary policies, and macro prudential financial regulations need enhancement to more effectively facilitate investments in low-carbon initiatives. At the same time, public participation and supports are essential for achieving urban carbon neutrality goals.

1.2 Urban energy systems challenges

(1) Reliability of energy supply needs to improve

The reliability of energy supply directly affects economic activities and residents' quality of life in cities. The swift increase in installed capacity and the proportion of renewable energy within the generation mix have introduced considerable challenges to the stability of energy systems due to their volatility and intermittency. Wind power and solar photovoltaic systems are significantly influenced by weather conditions, which can present challenges in meeting the increasing demand for electricity during winter cold spells or summer heatwaves. The daily generation patterns of solar PV electricity do not align with the load profiles observed in urban areas. The mismatch between fluctuating renewable energy generation and load demand over time poses operational difficulties. Furthermore, extreme weather events induced by climate change, including typhoons, elevated temperatures, and severe cold spells, are becoming increasingly frequent. This escalation exerts significant pressure on urban energy infrastructure. Energy storage technologies can play an important role in addressing these issues. By deploying electrochemical energy storage, pumped hydro storage, and other storage technologies, peak-to-valley imbalances in power systems can be effectively managed, improving both the stability of energy generation and the reliability of electricity supply to customer. For example, developing integrated wind-solar-storage projects in areas with abundant resources can effectively mitigate the spatial and temporal discrepancies between energy supply and demand.

(2) Urban energy security necessitates further enhancement.

Energy security primarily centers on urban areas. As the core carriers of socioeconomic development, cities face growing energy demands driven by population growth and economic expansion. However, cities—especially large and megacities—often lack sufficient local energy resources and rely heavily on external inputs. This imbalance makes urban areas highly sensitive to fluctuations in global energy markets. In recent years, geopolitical uncertainties and climate-induced supply disruptions have increasingly affected energy security in some regions. For example, the Russia-Ukraine conflict led to natural gas shortages across Europe, with far-reaching consequences for global energy markets. In this context, energy security has become not only a technical issue but also a complex matter involving politics, economics, and environmental considerations. To balance urban energy security with sustainable development goals, regional energy cooperation needs to be strengthened, along with sharing of resources and technological capabilities and know-how.

(3) The utilization of renewable energy requires significant expansion.

Scaling up urban renewable energy deployment brings a series of challenges across city planning, power systems, gas distribution, heating networks, and transportation infrastructure. According to the *World Energy Outlook 2023* by the International Energy Agency (IEA), the share of renewables in global electricity consumption increased from 26.3% in 2019 to 28.2% in 2020—the largest single-year increase since tracking of Sustainable Development Goals began in 2015. The report also notes that the 2021–2022 energy crisis continues to drive renewable deployment and improvements in energy efficiency, with many governments announcing increased investment plans. Data show that among international public funds supporting clean energy development in 2021, only USD10.8 billion was directed toward developing economies, which was 35% lower than the average amount between 2010-2019. Moreover, this funding was concentrated in a small number of developing economies, with just 19 economies receiving as much as 80% of the total. In terms of investment in related technologies and practical demonstration projects, it concluded that insufficient funding prevents the replacement of outdated infrastructure in line with actual needs. The extensive deployment of renewable energy within urban areas encounters considerable challenges.

(4) Urban energy efficiency needs further improvement.

Improving end-use energy management and energy efficiency is not only one of the key measures for reducing carbon emissions, addressing climate change impacts, preventing local environmental pollution, and achieving carbon neutrality, it is also a core requirement and a major driving force for promoting economic prosperity, building sustainable development models, and realizing a low-carbon economic transition in cities. The APEC region accounts for approximately 50% of global final energy consumption and 63% of global electricity consumption, indicating vast potential and urgent demand for energy conservation and efficiency enhancement. Within APEC economies, the share of electricity in final energy consumption continues to rise, reflecting a clear trend toward electrification. Energy conservation and efficiency improvements represent the most cost-effective emission reduction strategy. Electricity, as a clean, efficient, and convenient secondary energy source, enables reduced fossil fuel consumption and promotes quality upgrades and efficiency gains across various industries through increased end-use electrification.

(5) Insufficient attention has been given to urban energy governance resilience

Currently, urban energy governance systems remain largely centralized and top-down in structure, lacking sufficient flexibility and resilience to meet today's complex and dynamic energy demands. Particularly when facing sudden energy crises, traditional centralized energy systems often demonstrate limited adaptability and high recovery costs. With the rapid development of emerging technologies such as artificial intelligence (AI), modern telecommunications technologies and blockchain, energy governance is gradually transitioning from a centralized model to a more networked and decentralized structure. Future development of urban energy governance will place greater emphasis on flexibility and system resilience. For example, optimizing power dispatching using AI and enabling multi-directional energy supply through distributed energy resources have become widely applied approach in energy transition. In addition, public participation in energy governance needs to be strengthened. By establishing energy-sharing platforms, residents can install rooftop solar PV systems and sell surplus electricity back to the grid, achieving both economic returns and energy benefits. The inclusive model of energy governance not only enhances the overall efficiency of the energy system but also strengthens community energy independence and resilience against external risks.

1.3 Energy storage and urban energy transition

(1) Energy storage serves multiple functions and offers diverse services to energy systems, acting as versatile regulatory resources for power grids.

Energy storage, especially new types of storage represented by electrochemical energy storage, is a disruptive technology that addresses pressing issue of energy and power supply and demand across dimensions such as time, space, form, and intensity. It is referred as one of the five pillars of the Third Industrial Revolution[5], serving as a critical support for the global green and low-carbon transition in energy and power systems. As mentioned, it also constitutes flexible regulation resources (flexible resources) for power systems. The IEA classifies different types of energy storage technologies according to their

[5] Jeremy Rifkin. 2011. The Third Industrial Revolution: How Lateral Power Is Transforming Energy, the Economy, and the World. Palgrave Macmillan.

importance in achieving energy net-zero emissions, categorizing some as "important" (e.g., pumped hydro storage, flow battery storage, sensible heat storage, high-temperature latent heat storage, ammonia storage), while identifying others, such as lithium-ion batteries, as "very important". Energy storage can provide a wide range of services to energy systems, including bulk energy supply, ancillary services, grid infrastructure support, and end-user energy management. It offers multiple functionalities such as energy output control, energy transfer, energy backup, energy management, inertia reserve, voltage control, reactive power compensation, output smoothing, and black-start capabilities.[6,7]

(2) Energy storage serves as the optimal complement to intermittent renewable energy sources such as wind and solar, facilitating the large-scale development and utilization of urban renewable resources.

Variable renewable energy (VRE), such as wind and solar power, exhibits characteristics of volatility, randomness, anti-peak behavior, windless periods during heatwaves, and diminished solar power output at night. These features make large-scale grid integration and consumption extremely challenging, often leading to curtailment of wind and solar power ("wind and solar curtailment"). In severe cases, this could trigger large-scale cascading disconnection incidents, posing serious threats to the safe and stable operation of power systems. By integrating VRE with energy storage in a complementary and synergistic manner, the intermittency, volatility, uncertainty, and unpredictability of VRE can be effectively addressed. This combination helps resolve frequency and voltage regulation challenges and enables rapid frequency response, transforming VRE into a grid-friendly, dispatchable power source. Co-locating, installing energy storage on the generation site, such as storing wind energy or regulating low-quality electricity from solar PV generation, can reduce curtailment while smoothing renewable power output. This balances the randomness and volatility of VRE, thereby effectively preventing power shortages caused by declining VRE output or raising electricity demand. Furthermore. Deploying energy storage on the power grid can effectively regulate voltage, frequency and phase variations caused by renewable electricity generation, ensuring dynamic equilibrium between generation and demand.

(3) As a flexible regulation resource, energy storage enhances the resilience, flexibility, reliability and economic efficiency of urban power systems.

From the perspective of power system operations, energy storage provides regulation capabilities that bridge mismatches between supply and demand, ensuring system flexibility and stability. Power systems are real-time systems integrating electricity generation, transmission, distribution, and consumption. The introduction of energy storage adds an additional component to traditional power systems, transforming them from rigid structures into "flexible" systems. Consequently, the power grid can gradually be transformed from the conventional "source–grid–load" operational mode to a coordinated "source–grid–load–storage"

[6] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023
[7] IEA. Technology Roadmap Energy storage [R]. 2014

mode, significantly enhancing the security, flexibility, and reliability of power systems. Particularly, in response to the intrinsic needs of large-scale renewable energy integration, with the development of smart grids and advanced control systems, energy storage plays a foundational and enabling role.

As the share of traditional fossil-fuel-based adjustable power sources, such as coal-fired plants, continues to decline, energy storage becomes essential as a new source of regulation capacity to enhance grid flexibility and stability. During the transitional period, integrating energy storage systems with thermal power units not only improves the flexibility and auxiliary service capability of thermal plants but also reduces the need for excessive flexibility requirements on conventional generators. This allows power plants to operate at optimal output and efficiency levels, reducing equipment wear and lowering the likelihood of higher emissions as the result of rapid load changes, thus minimizing environmental impacts of power generation.[8]

(4) Energy storage supports urban energy transition and is crucial for managing renewable energy and fluctuating loads.

According to projections by the International Energy Agency (IEA), under a net-zero emissions scenario, the share of renewables in global electricity generation will rise from 29% in 2020 to over 60% by 2030, reaching nearly 90% by 2050.[9] However, renewable power generation—primarily wind and solar—exhibits characteristics of volatility, intermittency, and randomness. Therefore, ensuring the safe and stable operation of power systems under high renewable energy penetration has become one of the most critical challenges facing urban energy systems. Energy storage is an indispensable key technology for addressing this challenge and represents one of the most crucial components of the future energy system dominated by new and renewable energy resources. Without energy storage—especially various types of new energy storage technologies represented by electrochemical energy storage,[10] the green and low-carbon transition of urban energy systems would be unimaginable. Therefore, international organizations such as the IEA and IRENA regard energy storage as a key enabling technology to ensure a smooth global energy transition and to meet the goals set out in the *Paris Agreement*—namely, to limit the global temperature rise to well below 2°C above pre-industrial levels, and to pursue efforts to limit it to 1.5°C.

The 29th United Nations Climate Change Conference (COP29), took place in Baku, Azerbaijan, in November 2024 paid particular attention on the development and integration of storage into power grid and the reinforcement of the grid supporting green energy transition and achieving net-zero emissions by 2050. At COP29, the world leaders signed a pledge to collectively increase global energy storage capacity to

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[8] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023.

[9] IEA. Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach 2023 Update[R]. 2023.

[10] In China, according to the *Notice on Promoting Grid Connection and Dispatching Application of New Energy Storage* issued by the National Energy Administration in April 2024 (Document No. 26 [2024] of NEA), "new energy storage" is defined as energy storage technologies that do not include pumped hydro storage, primarily output electricity, and provide services externally. It offers advantages such as short construction cycles, flexible deployment, and fast response times. It can perform multiple functions in power systems, including peak shaving, frequency regulation, voltage control, backup power, black start capability, and inertia response, which make it an important supporting technology for building a new type of power system.

1,500GW by 2030 to facilitate energy transition and enable global renewable energy targets.[11] Aiming at to increase global energy storage capacity six times above 2022 level, the pledge brought the United Nations in line with the commitments by G7 and G20.

1.4 About this report

As mentioned, an enabling technology and a critical component of modern power system, energy storage facilitates renewable energy integration, enhances grid stability, improves energy supply reliability and resilience of urban energy system. The APEC Sustainable Energy Center (APSEC) conducted comprehensive research in this domain in APEC economies. The research reviews storage technology advancements, collates assessment method for storage technologies, summarizes the performance of diverse storage technologies, analyzes policy and regulatory frameworks for the development of energy storage. With a focus on battery energy storage systems (BESS), the research examines their deployment and applications of across APEC economies, analyzes system integration issues, operational practices, and electricity market participation mechanisms, as well as provision of power system services. The issues related to energy storage development in urban areas are investigated. Selected application cases of emerging storage technologies in cities are examined in detail. The research identifies barriers and drivers for the technology adoption and proposes the mechanism and policy recommendations to support BESS deployment. The research focuses on electrochemical energy storage, particularly within urban contexts of the APEC economies, along the economy-wide applications.

This report, entitled "*APEC City Energy Report 2024 -- Energy Storage Supports Energy Transition*", resulted from the research outcomes, which is the second of APSEC annual flagship report series, "*APEC City Energy Report*". This report comprises the following sections:

- Overview of energy storage technologies: The status of development and applications of main energy storage technologies, innovation and trend of deployment and costs of storage technologies; (Chapter 2)
- Evaluation of storage technology: Review the indicators and evaluation framework of energy storage technologies, relevant technical standards and specifications, and management of energy storage safety; (Chapter 3)
- Energy storage development policies and plans: Overview main policies and development plans of energy storage in APEC economies, as well as related regulatory systems; (Chapter 4)
- Deployment of BESS: Review and analyze the deployment of battery energy storage systems in APEC economies, including trends, market environment, typical battery energy storage projects, and applications of energy storage in urban energy systems; (Chapter 5)

[11] COP29. 2024. Declarations and Pledges Letter. https://cop29.az/storage/1135/COP29-Declarations-and-Pledges-Letter.pdf.

- Grid connection and operation of BESS: Introduce the role of storage in the resilience of urban energy systems; outline the requirements of the power grid for grid integration of storage systems, relevant guidelines and standards, as well as the operation of battery energy storage systems; (Chapter 6)
- Market participation of energy storage systems: Analyze the conditions and practices of BESS participating in the electricity market and providing power system services in APEC economies; (Chapter 7)
- Business environment of BESS projects: Analyze the investment in battery energy storage and business conditions for project development and relevant strategies; (Chapter 8)
- Selected application cases of energy storage systems in China; (Chapter 9)
- Summary and policy recommendations. (Chapter 10)

This report aims to share insights on the advancement of new energy storage technologies, promote best practices to accelerate the deployment of energy storage systems in APEC economies, and provide a reference for the formulation and implementation of relevant policies. By doing so, it seeks to expedite the energy transition and scale up renewable energy development in the APEC region.

Chapter II Current Status and Development of Energy Storage Technologies

2.1 Overview of energy storage technologies

In a broad sense, energy storage refers to the process of storing energy through certain media or devices, in which energy is stored in the same or different form and then released at a later time as needed. Broad-spectrum energy storage includes the storage of various forms of energy, including primary energy resources (raw coal, crude oil, natural gas, nuclear energy, hydro etc.), secondary energy (electricity, hydrogen, town gas, gasoline, etc.), and thermal energy. In the narrow sense, energy storage refers to a series of technologies and measures that store energy through mechanical, electromagnetic, chemical, or other means, including the input and output of energy and materials, as well as energy conversion and storage equipment. The energy storage technologies discussed in this report refer to the narrow sense.

2.1.1 Classification of energy storage technologies

(1) Classification of energy storage by type of energy carrier

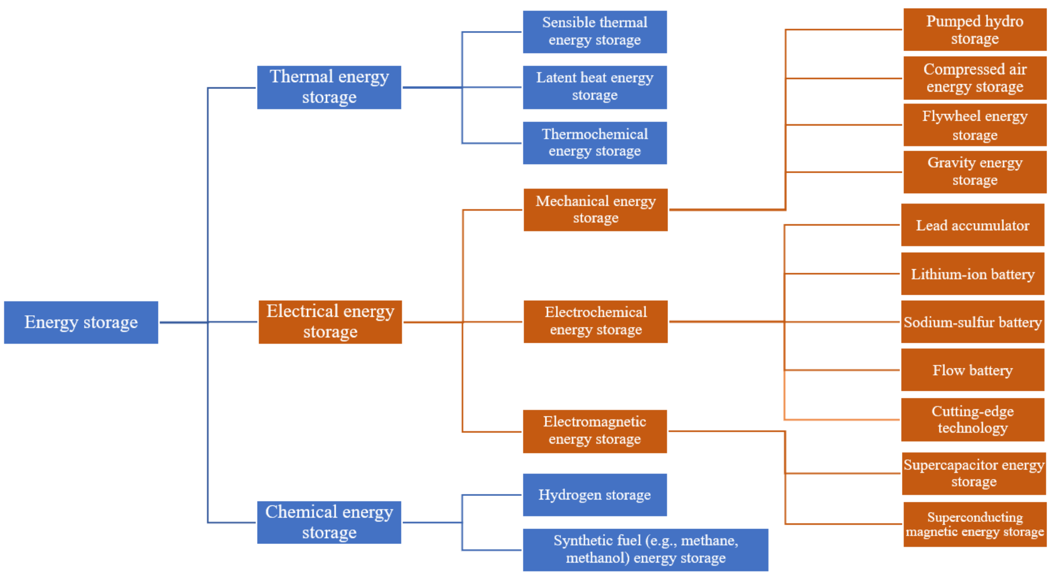


Figure 2-1 Classification of Energy Storage Technologies by Type of Energy Carrier

Energy storage technologies can be categorized in multiple ways. According to the type of energy carrier, energy storage technologies are primarily divided into three categories: thermal energy storage, chemical energy storage, and electrical energy storage (where both input and output are in the form of electrical energy). Among these, electrical energy storage is one of the most widely applied types of energy storage technology, which includes mechanical energy storage (also known as physical energy storage), electrochemical energy storage, and electromagnetic energy storage.[12,13,14]

i) Thermal energy storage: Depending on the principle of heat storage, thermal energy storage can mainly be classified into three forms: sensible heat storage, latent heat storage (also referred to as phase change material storage), and thermochemical heat storage. Sensible heat storage technology is the most mature, cost-effective, and widely used, particularly in power systems for the recovery and reuse of waste heat from thermal power plants and in solar thermal power generation. Currently, common sensible heat storage materials include water, thermal oil, and molten salts, with molten salts emerging as a research hotspot in high-temperature storage applications and finding significant utility in the field of solar thermal power generation.

ii) Chemical energy storage: This method uses electrical power to convert low-energy substances into high-energy substances for storage. Common chemical energy storage methods today primarily include hydrogen storage and synthetic fuel (methane, methanol, etc.) storage. Among these, hydrogen storage is relatively mature, relying on water electrolysis equipment and hydrogen fuel cells (or hydrogen gas turbines) to achieve the conversion between electrical and hydrogen energy. For storage, surplus electricity is used to produce hydrogen through water electrolysis and store it; for energy release, hydrogen fuel cells or hydrogen generators are used to generate electricity.

iii) Mechanical energy storage: Mechanical energy storage involves storing energy in the form of mechanical energy such as potential energy and kinetic energy. It is generally used for large-scale energy storage and mainly includes pumped hydro storage, compressed air energy storage, flywheel energy storage, and gravity energy storage. Pumped hydro storage is currently the most mature large-scale energy storage technology particularly for long-duration storage, with installed capacity far exceeding all other types of energy storage devices. Multiple sources indicate that pumped hydro storage accounts for over 90% of total global electricity storage capacity. Some even put it as high as 94-97% of the world's long-duration energy storage capacity.[15] It is mainly used for peak load adjustment, frequency regulation, emergency backup, black start, and providing standby capacity in power systems. Compressed air energy storage plants are primarily used for peak load adjustment, frequency regulation, and providing rotational reserves in power systems. Flywheel energy storage can output significant power over short period but has a limited discharge duration (on the order of minutes), making it a typical power-type energy storage technology suitable for improving power quality and frequency regulation applications. The main advantages of gravity energy storage include the use of relatively mature crane and braking energy recovery technologies, easy material

[12] IEA，Technology Roadmap - Energy Storage [R]. 2014

[13] Zhang Kai, Wang Huan, Energy Storage Science and Engineering [M]. Beijing: Science Press, 2023

[14] Global Energy Interconnection Cooperation Organization, Roadmap for Large-Scale Energy Storage Technology Development M]. China Electric Power Press, Beijing. 2020.

[15] ESMAP. (2022). Pumped Storage Hydropower. https://www.esmap.org/sites/default/files/ESP/WB_PSH_16Jun22.pdf.

storage for long-term retention, and abundant site resources.

iv) Electrochemical energy storage: Electrochemical energy storage technologies mainly utilize chemical elements as storage media, achieving charging and discharging processes through reversible redox reactions among these elements. As an important branch of electrical energy storage technologies, electrochemical energy storage offers advantages like flexible configuration, fast response, energy conversion unrestricted by Carnot cycle limitations, and suitability for mass production and large-scale applications. However, it also faces challenges such as limited cycle life, high costs, and safety concerns that need improvement. Electrochemical energy storage technologies are widely applied in power systems across generation, transmission, distribution, and end-use stages, with primary functions including peak load adjustment, frequency regulation, peak shaving and valley filling, and smoothing renewable electricity fluctuations.

Depending on temperature differences, electrochemical energy storage can be divided into room-temperature batteries and high-temperature batteries; among which, the room-temperature batteries mainly include lead-acid batteries, lithium-ion batteries, and flow batteries; high-temperature batteries are primarily sodium-sulfur batteries. In recent years, these types of electrochemical energy storage technologies have made significant breakthroughs in energy conversion efficiency, safety, and economics, showing great prospects for industrial application. Additionally, emerging electrochemical energy storage batteries under research and development include solid-state batteries, aqueous batteries, multi-electron secondary batteries (aluminum-ion batteries, magnesium-ion batteries), metal-air batteries, and liquid metal batteries.

v) Electromagnetic energy storage: Electromagnetic energy storage directly stores energy in the form of electricity within electric or magnetic fields, without undergoing any energy conversion process. This results in high efficiency. However, its continuous discharge duration is short and difficult to extend, making it a typical power-type energy storage technology. The two main forms of superconducting magnetic energy storage are supercapacitor energy storage and superconducting energy storage.

Supercapacitors are characterized by high power density and low energy capacity. They are currently mainly used in applications requiring high peak power but low overall capacity, such as power supplies for consumer electronics in electric vehicles and military equipment. In power systems, they are primarily employed to improve power quality and stabilize voltage and power fluctuations. Superconducting magnetic energy storage (SMES) features high power density, fast response speed, and high conversion efficiency (greater than 95%). However, its discharge duration typically lasts only a few seconds, and it requires strict environmental temperature control. It is mainly used to address power quality issues such as instantaneous power outages and voltage sags that affect electrical equipment.

(2) Classification of energy storage by duration of operation

Based on the duration of energy storage and release, energy storage technologies can be categorized into three types: sub-minute storage, minute-to-hour storage, and over-one-hour storage. Specific classification methods and application scenarios are detailed in Table 2-1.

Flywheel energy storage, superconducting magnetic energy storage, and supercapacitor energy storage are representative short-duration energy storage technologies. These systems can deliver large bursts of energy in a short time and are well-suited for applications requiring uninterrupted and high-quality power supply within brief intervals.[16]

The energy storage technology with a continuous discharge duration of at least four hours is generally known as long-duration energy storage (LDES). LDES can realize charge-discharge cycles across days, months, or even seasons. Currently, the main LDES technologies include pumped hydro storage, compressed air energy storage, solar thermal energy storage, hydrogen energy storage, and flow batteries.[17]

Table 2-1 Classification of Energy Storage Technologies by Response Time

Time Scale	Main types of energy storage	Operational characteristics	Main application scenarios
Sub-minute	Flywheel energy storage, superconducting magnetic energy storage (SMES), supercapacitor energy storage	Random operation cycles, millisecond-level response speed, high-power charge/discharge	Supporting primary frequency regulation, improving power quality
Minute to hour level	Electrochemical energy storage	Frequent charge/discharge switching, second-level response speed, considerable energy capacity	Secondary frequency regulation, tracking planned output, smoothing renewable energy generation, improving utilization of transmission and distribution infrastructure
Hourly and above	Pumped hydro storage, compressed air energy storage (CAES), thermal storage, hydrogen storage	Large-scale energy storage	Peak shaving and valley filling, load management

(3) Classification of energy storage technologies by functional requirements

Energy storage technologies are categorized into four types according to their functional requirements in different applications: capacity, energy, power, and standby.[18,19]

i) Capacity-type storage: This type typically requires an energy storage duration of no less than four hours and is applied in provision of capacity services such as peak shaving and valley filling, or off-grid

[16] Mei Shengwei et al., Energy Storage Technologies [M]. Beijing: China Machine Press, 2023

[17] Comparative Analysis and Development Pathways for Long-Duration Energy Storage Technologies [EB/OL]. https://mp.weixin.qq.com/s/Q7owHuR738LM90yArS3iRA, 30 October 2023.

[18] Zhang Kai, Wang Huan, Energy Storage Science and Engineering [M]. Beijing: Science Press, 2023

[19] Greenpeace and All-China Environment Federation, New Momentum for Decarbonizing the Power System-Report on Innovation Trends in Electrochemical Energy Storage Technology [R]. 2022

energy storage. The use of long-duration energy storage technology can reduce the load's peak-to-valley difference, improve the efficiency and equipment utilization rate of the power system, and decrease the need for the construction of new transmission lines and power plants. There are various types of energy storage technologies capable for such service, including advanced lithium-ion batteries, lead-carbon batteries, flow batteries, sodium-ion batteries, compressed air energy storage, thermal/cold storage, and hydrogen energy storage. Among them, lead-carbon batteries, thermal/cold storage technologies have already entered the commercialization phase; however, future efforts should focus on enhancing technological innovation for large-scale applications, reducing initial investment costs, extending service life, and developing green manufacturing and recycling processes.

Flow batteries and sodium-ion batteries have reached the demonstration stage, but they currently face common challenges such as high costs and the need for further breakthroughs in some key performance indicators. New types of lithium-ion batteries (e.g., lithium slurry batteries, aqueous lithium-ion batteries) are currently at the pilot production or critical technology breaking-through stage. Building upon the existing lithium-ion battery industry for electric vehicles, further development is needed to create high-safety, low-cost, and recyclable large-capacity battery technologies.

ii) Energy-type storage: This type falls between capacity and power-type energy storage. It is generally used in hybrid energy storage situations where the system must provide multiple functions such as peak shaving, frequency regulation, and emergency backup. The continuous storage duration is typically 1–2 hours, suitable for the applications like standalone energy storage stations or grid-connected storage. The main technology for such services is lithium iron phosphate (LFP) battery with a charge rate of 0.5C or 1C. These batteries have already entered the stage of commercial deployment and represent the primary type of lithium-ion battery currently used in energy storage in power systems. In the future, the applications may also evolve into a hybrid energy storage systems combining both power- and capacity-oriented storage technologies.

iii) Power-type storage: This type of energy storage system typically has a storage duration of 15 to 30 minutes and is used to provide services for assisting automatic generation control (AGC), frequency regulation, or smoothing power fluctuations from intermittent renewable energy resources. In this kind of applications, the energy storage system is required to absorb or release energy instantaneously, providing rapid power support. Short-term power-type energy storage technologies include superconducting magnetic energy storage (SMES), flywheel, supercapacitors, and various batteries. The main current challenges include high system costs, low reliability, and high maintenance requirements. It is expected that future efforts would continue to focus on innovation in key materials and high-capacity components of the systems.

iv) Standby storage: When the power grid experiences sudden outages or voltage drops, the energy storage system can act as an uninterruptible power supply (UPS), providing emergency power for a minimum duration e.g. 15 minutes. The applications of this type of standby storage applications include at data centers and communication base stations. The technologies for standby energy storage require low self-discharge rates, fast response times, stable performance, and high safety and reliability. Lead-acid batteries, second-life batteries, and flywheel energy storage systems can all meet these operational requirements.

Table 2-2 Classification of Energy Storage Technologies by Functional Requirements

Type	Functional requirements	Function	Applications	Applicable technology	Development stage
Capacity	Large-capacity, long-duration (≥4h)	Peak shaving and valley filling	Peak shaving and valley filling, off-grid energy storage	Lead-carbon batteries, flow batteries, sodium-ion batteries, compressed air, thermal/cold storage, hydrogen energy storage, pumped hydro storage, etc.	Lead-carbon batteries, thermal/cold storage, etc., have already entered the commercialization stage; Flow batteries and sodium-ion batteries have reached the demonstration application stage
Energy	Flexibility, safety, medium-to-short duration (1~2h)	Smoothing power fluctuations, frequency regulation	Standalone battery energy storage stations, grid-side energy storage	Mainly lithium iron phosphate (LFP) batteries	Commercial application stage
Power	Fast response, short-duration energy storage (≤30min)	Temporary peak output	Supporting AGC frequency regulation, smoothing power fluctuations from intermittent sources	Superconducting magnetic energy storage (SMES), flywheel energy storage, supercapacitors, and various types of power-oriented batteries	Superconducting magnetic energy storage, flywheel energy storage, and supercapacitors are still in the early research and development stage
Standby	Discharge duration ≥15 minutes	Off-grid black start	Backup power scenarios such as data centers and communication base stations	Lead-acid batteries, second-life batteries	Lead-acid batteries are already commercially applied; second-life battery applications are at the demonstration stage

(4) Classification by scale and capacity level

Energy storage technologies are often categorized into large-, medium-, and small-scale systems based on their capacity levels; however, currently there is no universally accepted definition for these categories. In China, the following definitions are commonly used:[20]

- **Large-scale:** Power rating from 10MW to hundreds of MW, with storage duration lasting several

[20] Hua Zhigang, Key Technologies of Energy Storage and Business Operation Models [M]. Beijing: China Electric Power Press, 2019.

hours, and the technologies include pumped hydro storage, large-scale underground compressed air energy storage, high-capacity electrochemical energy storage, hydrogen energy storage, and thermal energy storage;

- **Medium-scale:** Power rating at the MW level, with storage duration on an hourly basis, such as chemical energy storage and small-scale CAES;
- **Small-scale:** Power rating generally below MW level, including small-capacity electrochemical energy storage and supercapacitor energy storage.

In the United States, the Energy Information Administration (EIA), Department of Energy (DOE) collects and publishes data on two general categories of battery energy storage systems (BESS) based on the size of power generation capacity:[21]

- **Large-scale or utility-scale BESS:** the systems has at least 1MW of net generation capacity, and they are primarily owned by electric utilities or independent power producers and are designed to provide grid support services, such as balancing supply and demand, frequency regulation, peak shaving, and integrating renewable energy;
- **Small-scale systems:** they are these have less than 1MW of net generation capacity; these systems are typically connected to a distribution network and can include residential or commercial battery systems, or smaller community-scale storage; and many are owned by electricity end users that use solar PV systems to charge a battery.

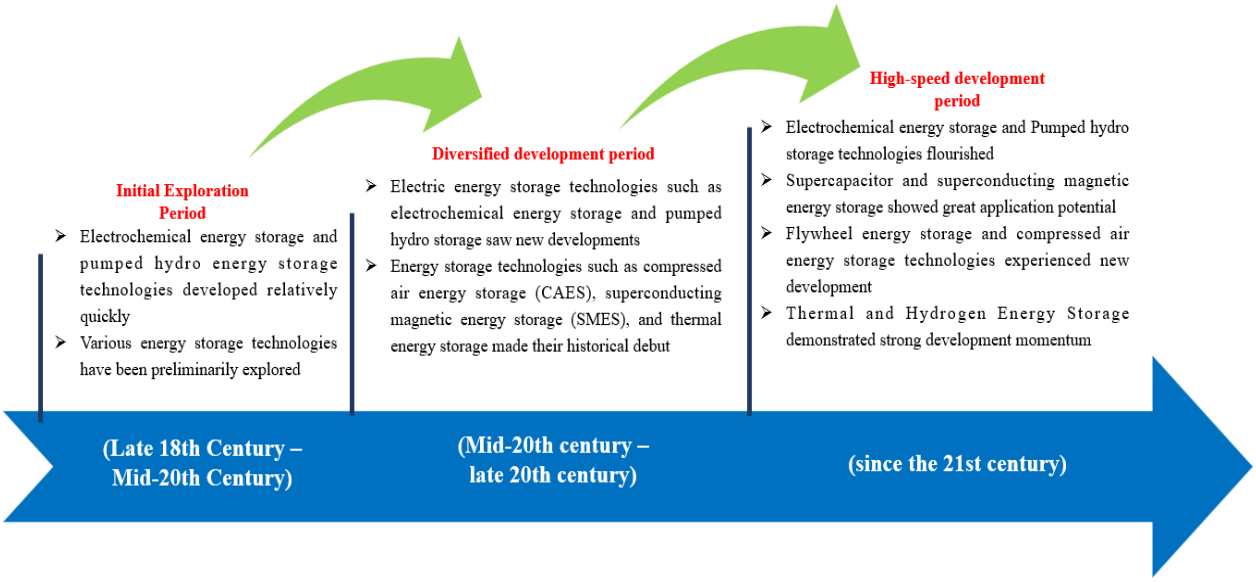
This distinction is important for the EIA's data collection and reporting, as it allows them to track trends and analyze the impact of different scales of battery storage on the US electricity grid. The reporting cut-offs for their surveys (like Form EIA-860 for electric generators and Form EIA-861 for the electric power industry) are based entirely on this power capacity threshold.

2.1.2 Development of energy storage technology

From the invention of the first voltaic pile in 1799 to the continuous emergence of modern energy storage technologies, energy storage has a development history of over 200 years. As illustrated in Figure 2-2, according to the characteristics of energy storage utilization in different historical stages, the development process can be divided into three periods: the preliminary exploration period (from late 18th century to the mid-20th century), the multi-faceted development period (from the mid-20th century to late 20th century), and the high-speed development period (since the 21st century).[22]

[21] EIA. 2024. Energy storage for electricity generation. https://www.eia.gov/energyexplained/electricity/energy-storage-for-electricity-generation.php.

[22] Mei Shengwei et al., Energy Storage Technologies [M].Beijing: China Machine Press, 2023



Source: Mei Shengwei et al. 2023

Figure 2-2 Stages of Energy Storage Technology Development

From the mid-20th century to the end of the 20th century, the multi-faceted development period saw electrochemical energy storage technologies entered a new developmental stage, particularly marked by the invention of lithium-ion batteries, which became a significant milestone in the advancement of battery-based energy storage systems. In addition, several new energy storage technologies, such as compressed air energy storage, superconducting magnetic energy storage, and thermal energy storage, also gradually came into the public views. Since the 21st century, scientific and technological advancements have greatly promoted the progress of energy storage technologies, ushering them into a high-speed development phase. Among these, electrochemical energy storage is currently the fastest developing and most promising type of energy storage technology.

At present, pumped hydro storage and lithium-ion battery energy storage dominate the energy storage installations in power systems. As shown in Figure 2-3, based on the technological maturity and industrial development status, pumped hydro storage and lithium-ion battery energy storage have well-established industrial and supply chains and are already in the commercial application stage; Compressed air energy storage and flow battery energy storage have developed early prototype products and are ready for demonstration and then commercial application; Flywheel energy storage is mainly used in power-oriented applications and already has relatively mature technologies and products; Gravity energy storage and sodium-ion batteries have established technical foundations and are actively preparing for demonstration projects; Metal-air batteries, aqueous batteries, and liquid air energy storage technologies are still in the R&D and breakthrough stages.[23]

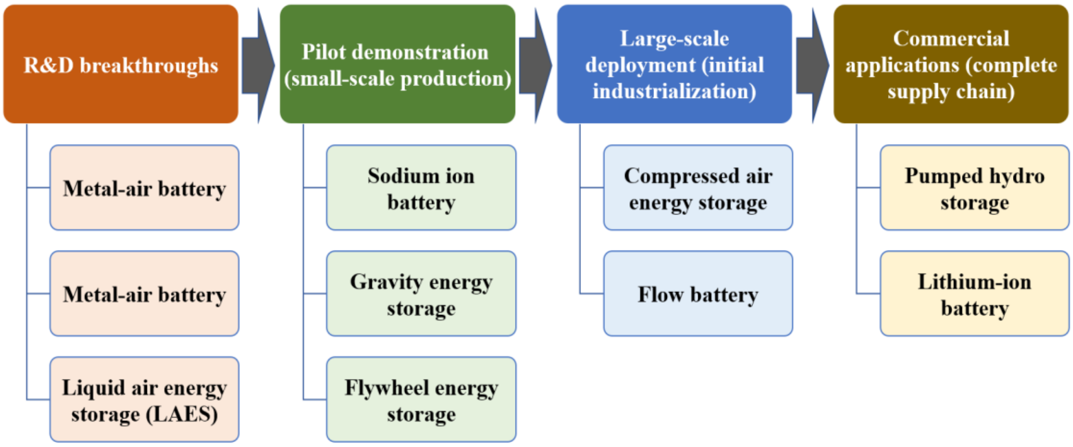


Figure 2-3 Maturity Levels of Selected Energy Storage Technologies

For energy storage technologies that have been put into large-scale commercial installations or demonstration applications, in general, the status of development and their main characteristics can be summarized as below:

- Pumped hydro storage is currently the mainstream technology for large-scale energy storage, offering advantages such as large energy capacity, high system efficiency, long operational life, and technological maturity;
- Lithium-ion batteries offer high energy density, high charge/discharge efficiency, fast response speed, and long cycle life, which have made them the fastest developing new energy storage technology;
- Compressed air energy storage (CAES) offers its advantages including large energy capacity, long storage duration, high system efficiency, long service life, and low unit investment cost. It is considered one of the most promising large-scale energy storage technologies;
- Flow battery energy storage provides high safety, long lifespan, and flexible configuration of power and capacity units, making it highly advantageous for large-scale, long-duration energy storage applications;
- Sodium-ion batteries share similar working principles and structural design with widely used lithium-ion batteries. Compared to lithium-ion batteries, which face resource constraints, sodium-ion batteries use abundant raw materials and offer excellent performance, holding broad application

[23] China Electric Power Planning and ngineering Institute, Development Report on New Energy Storage in China [M]. People's Daily Press. Beijing, 2023.

prospects in both electrical vehicles and power system energy storage applications;

- Gravity energy storage offers advantages such as flexible site selection, environmental friendliness, large energy storage capacity, long cycle life, high depth of discharge, fast response, and high efficiency. It is a type of energy storage technology capable of achieving large-scale and long-duration storage, with very broad application prospects;
- Flywheel energy storage is of high-frequency, high-efficiency, long-life, low-cycle-cost physical energy storage technology suitable for applications ranging from several hundred kW to tens of MW, lasting from seconds to minutes, with frequencies exceeding 100,000 cycles. It is an essential technology for voltage stabilization and frequency regulation.

Since the beginning of the 21st century, various electrochemical energy storage technologies have entered a period of rapid development.[24] As shown in Figure 2-4, the key points regarding developmental trends of storage technologies over this period are summarized as below.

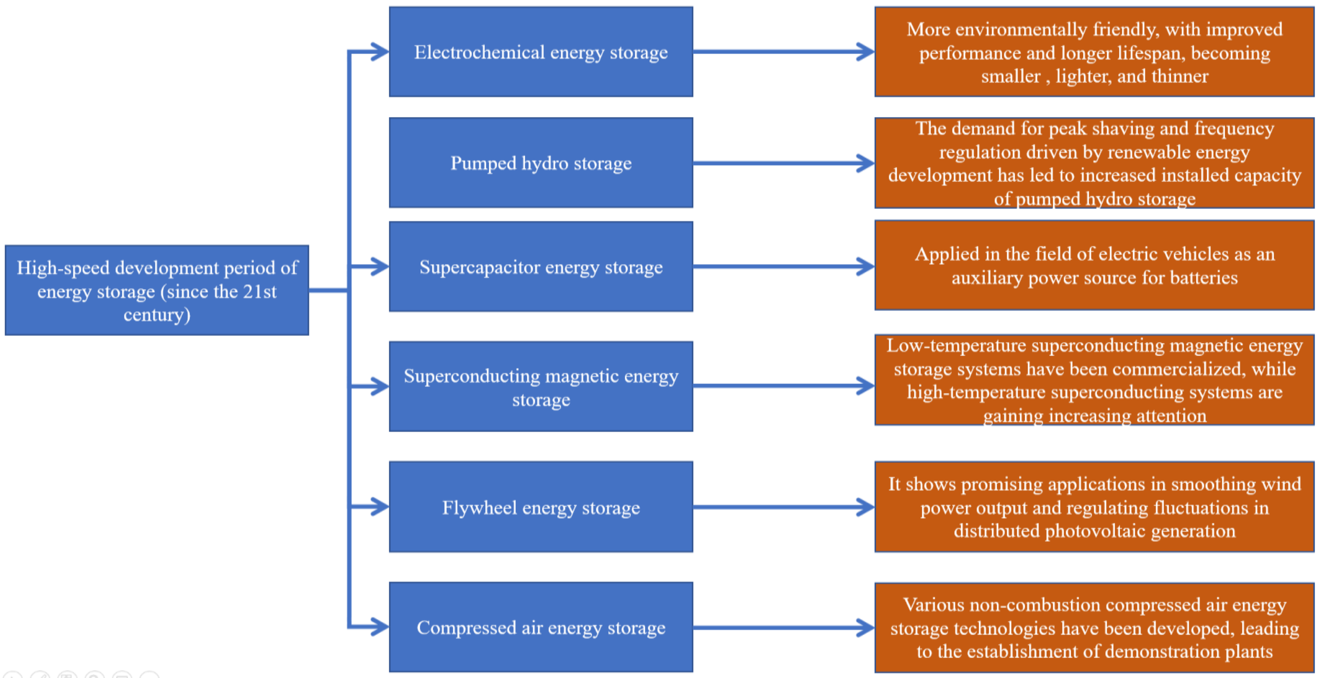


Figure 2-4 Development Trends of Selected Energy Storage Technologies

i) Development of electrochemical energy storage. Firstly, environmental protection has gained significant importance, resulting in rapid developments in sustainable battery technologies such as lithium-ion batteries and nickel-metal hydride batteries. Secondly, the shift from primary battery/cell (non-rechargeable, e.g., alkaline batteries) to Secondary battery (rechargeable, e.g., lithium-ion, lead-acid) has significantly improved battery performance and lifespan; Thirdly, there is a trend towards making batteries

[24] Mei Shengwei et al., Energy Storage Technologies [M]. Beijing: China Machine Press, 2023

smaller, lighter, and thinner. Currently, lead-acid batteries and lithium-ion batteries have achieved large-scale manufacturing and applications. Various new electrochemical energy storage technologies are continuously emerging, including redox flow batteries, metal-air batteries, lithium-sulfur batteries, solid-state lithium metal batteries, and liquid metal batteries. In general, the direction of development for electrochemical energy storage focuses on breakthroughs in high energy density, high thermal stability, long cycle life, enhanced safety, higher efficiency, lower costs, and recyclability.

ii) Increased renewable energy integration into the grid has driven new development in pumped hydro storage. With the rapid development of renewable energy, the pressure for peak shaving and frequency regulation in the system continues to increase. As a major regulating power source in the power system, pumped hydro storage is experiencing new opportunities for development. Currently, pumped hydro storage technology is evolving towards high-head, large-capacity systems, hybrid pumped hydro storage. Seawater pumped hydro storage and abandoned mining site pumped hydro storage are among other types tailored to specific local conditions; Hybrid pumped hydro storage stations offer advantages such as lower investment costs, shorter construction periods, and conservation of local site resources, making them a valuable complement to conventional pumped hydro storage facilities; It is noted that seawater pumped hydro storage and abandoned mining site pumped hydro storage also have promising development prospects subject to local conditions.

iii) Supercapacitor energy storage and superconducting magnetic energy storage (SMES) show significant potential for development. In recent years, with the advancement of electric vehicles, supercapacitors have been applied as auxiliary power sources in the electric vehicle sector. Supercapacitors can compensate for deficiencies in power characteristics of electric vehicles, improve the speed and performance of starting motors, and enable energy recovery during braking, thus possessing a substantial commercial market. In the realm of superconducting magnetic energy storage, small-scale cryogenic SMES systems have already been commercialized, while high-temperature superconducting materials-based SMES systems are receiving considerable attentions and becoming an important research focus.

iv) Flywheel energy storage technology and compressed air energy storage (CAES) technology are developing rapidly. Flywheel energy storage is a typical power-oriented energy storage technology with broad application prospects in smoothing power fluctuations from renewable energy resources. the United States, which leads in flywheel energy storage technology, has also researched aerospace flywheel energy storage and transferred relevant technologies to civilian uses, reaching commercial applications. From non-supplementary fired compressed air energy storage (CAES), multiple technological pathways have emerged, including advanced adiabatic CAES (AA-CAES), cryogenic liquefied air energy storage (LAES), isothermal CAES, and hybrid CAES systems. Currently, Germany and the United States have commercially operational traditional CAES plants, while advanced adiabatic CAES is in the demonstration phase, and cryogenic liquefaction and supercritical air storage remain in the experimental stage.

(5) Long-Duration Energy Storage (LDES) has emerged as a significant focus for research and development. Energy storage has the potential to accelerate decarbonization of the power system. LDES, which can address storage needs across days, weeks, or even seasons, is critical for green energy transition. Especially given the increasing frequency of extreme weather events and natural disasters globally, it is expected that LDES will play a crucial role in emergency situations. Current short-duration energy storage can support low levels of renewable energy penetration, but as more renewables are integrated into the power system, higher penetration levels will require longer-duration energy storage technologies to ensure adequacy, flexibility, and reliability of electricity supply. Prominent LDES technologies currently include flow batteries and compressed air energy storage, while emerging technologies like gravity energy storage and supercritical CO_2 energy storage are making significant breakthroughs.

2.1.1 Techno-economic performance of energy storage technology

(1) Technical performance characteristics

As discussed, there are various types of energy storage technologies, most of which are still in rapid development. Different power capacities, energy capacities, and technical characteristics determine their varied applications. Table 2-3 summarizes the key indicators of technical performance of currently used storage technologies.[25]

Figures 2-5 and 2-6 provide a comparative overview of the power and duration characteristics, as well as the energy density and power density characteristics of various energy storage technologies used in power systems.[26] As listed, the discharge time of different electrochemical energy storage technologies ranges from seconds to hours, with system rated powers or module scales ranging from kW to GW levels. Among these storage technologies, pumped hydro storage and compressed air energy storage systems have larger rated power modules (up to hundreds of MW), enabling economically viable discharges lasting tens of hours, typically used for large power management. In contrast, flywheel energy storage, high-power supercapacitors, and superconducting magnetic energy storage have much shorter discharge duration and are usually employed for uninterruptible power supply (UPS) applications or improving power quality and reliability. The relationship between energy and power density in energy storage may limit the use of certain technologies in specific applications. Given a certain amount of energy, high power and energy densities mean that smaller-sized storage systems are feasible. Conversely, lower energy or power densities imply that the storage system will require larger volumes and footprints, making them unsuitable for applications with space constraints.

This report primarily focuses on energy storage technologies applied in urban power systems, and unless otherwise specified, energy storage technologies refer to electrochemical energy storage technologies, and

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[25] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023

[26] IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 [R]. 2017

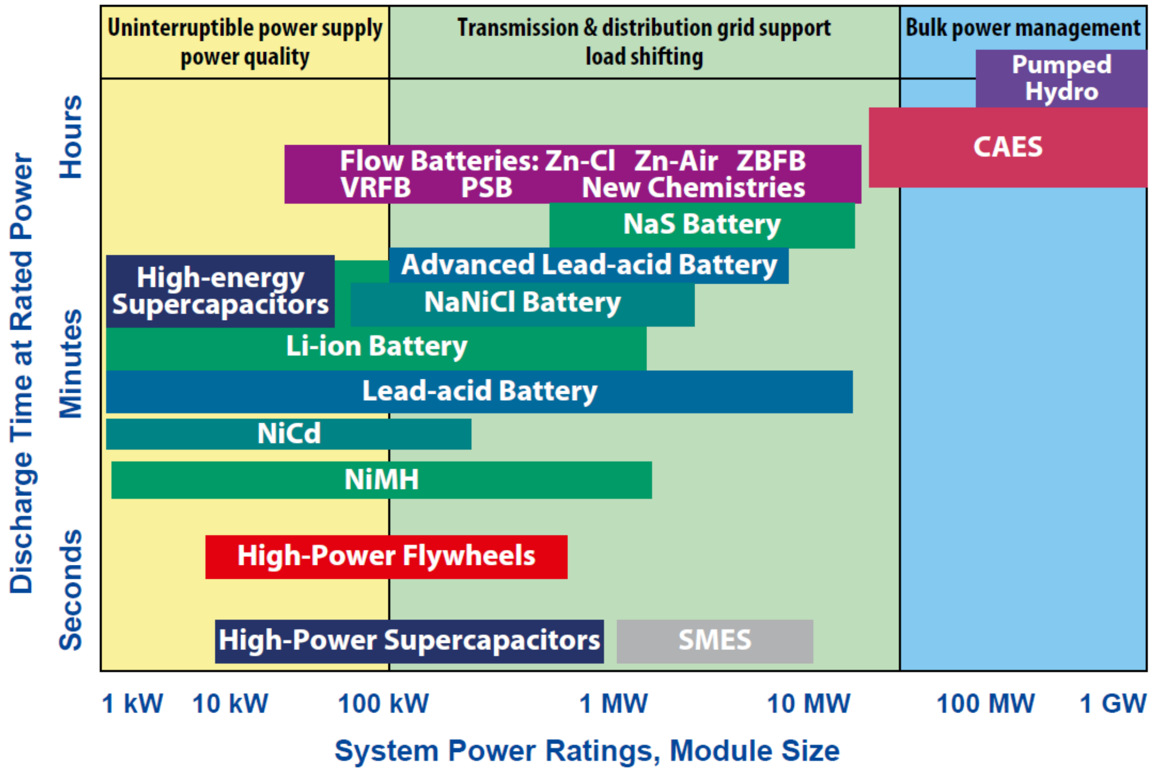
battery energy storage system (BESS) is the term used when discussing the application of energy storage technologies.

Table 2-3 Key Technical Performance of Energy Storage Technologies

Technology category		Energy density		Power density		Power capacity (MW)	Round-trip efficiency in working cycles (100%)	Duration of energy release	Response time	Daily self-discharge rate (%)	Environmental impact level	Service life (year)	Technology maturity
		Unit mass (Wh/kg)	Unit volume (kWh/m³)	Unit mass (W/kg)	Unit volume (kW/m³)								
Electrochemical energy storage	Lead acid battery	10~50	25~100	75~415	10~700	0~50	65~92	≤4h	5~10ms	0.033~0.6	High	3~15 (Number of cycles 250-4500)	Mature and fully commercialized
	Ni-CD battery (Ni-Cd)	30~80	30~150	50~00	100~450	0~45	60~90	Second level-hour level	20ms~1s	0.067~0.6	High	5~20 (Number of cycles 2000~2500)	Fully commercialized
	Nickel-metal hydride battery (Ni-MH)	30~120	83~320	177~600	7.8~588	0.01~3	50~80		Second level	0.3~0.83		3~15	Fully commercialized
	Lithium-ion battery	50~260	200~735	80~370	50~5000	0.005~300	77~86	Minute level-hour level	20ms~1s	0.036~0.33	Medium-low	5~20 (Number of cycles 500 to over 20,000)	Commercially verified
	Sodium-sulfur battery (NaS)	100~240	140~300	150~230	150~300	0.05~50	70~90	1~24h	Second level	0.05~20	High	5~25 (Number of cycles 1000-10000)	
	Sodium-nickel chloride Battery (ZEBRA)	100~120	150~280	150~200	150~300	0.3~3	85~92	Second level-hour level	Second level	11~15	Medium-low	8~22 (Number of cycles 1000-8000)	
	Vanadium flow battery (VRB)	10~50	10~70	80~166	0.5~34	0.05~200	60~85	Second level~10h	Millisecond level ~10min	0.2	Medium-low	5~24 (Number of cycles 12000~14000)	
	Sodium polysulfide - bromine flow battery (PSB)	10~29	10~60	1.31	1.35~4.16	0.1~15	60~83	Second level~10h			Medium	10~15	Test verification
	Zinc-bromine flow battery (ZBB)	20~85	20~70	90~110	2.58~6	0.1~15	65~85	Second level~10h		0.24	Medium	5~20 (Number of cycles 300~14000)	Demonstration
	Iron-chromium flow battery (Fe-Cr)		10~20			0.25~1	70					Number of cycles 10000 above	
Electromagnetic energy storage	Supercapacitor (SCES)	0.5~30	1~35	500~10000	1000~5000	0~10	65~99	Millisecond level-hour level	≤10ms	5~40	Extremely low	8~20 (Number of cycles 50000 above)	Mature or commercially verified
	Superconducting magnetic energy storage (SMES)	1~75	0.2~13.8	500~2000	300~4000	0.1~20	80~98	Millisecond level-hour level	≤10ms or ＜100ms	10~15	Low	20~30	Commercially verified

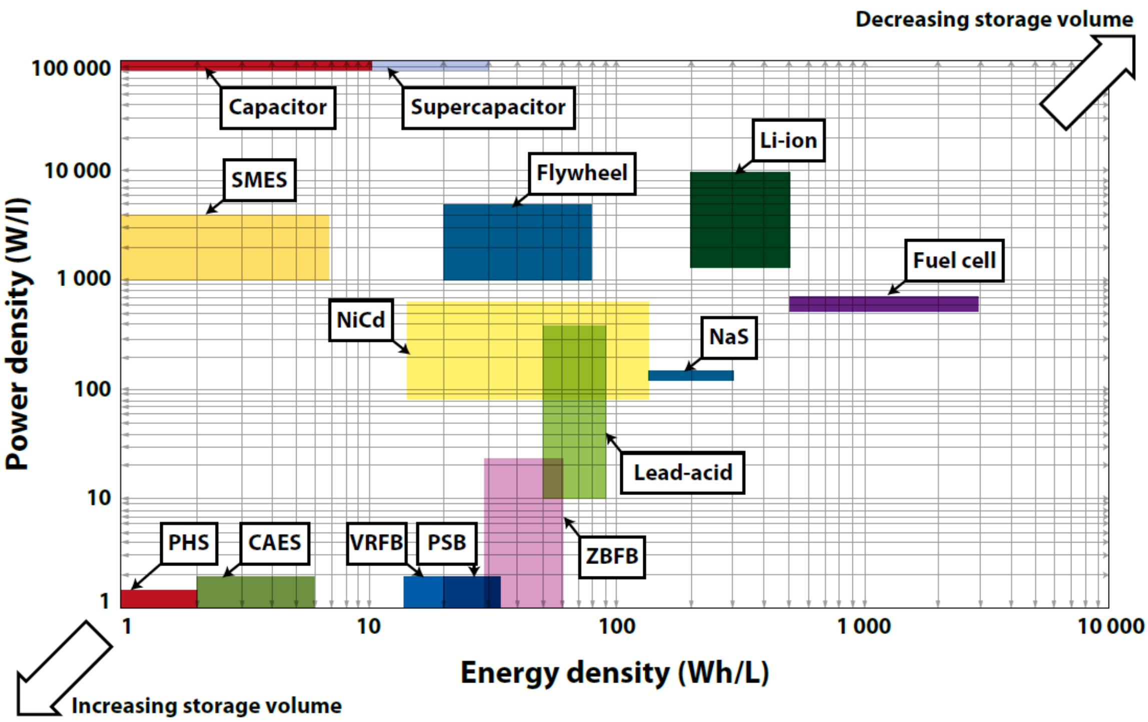
Technology category		Energy density		Power density		Power capacity (MW)	Round-trip efficiency in working cycles (100%)	Duration of energy release	Response time	Daily self-discharge rate (%)	Environmental impact level	Service life (year)	Technology maturity
		Unit mass (Wh/kg)	Unit volume (kWh/m³)	Unit mass (W/kg)	Unit volume (kW/m³)								
Thermal energy storage	Sensible thermal energy storage (STES)	10~250	80~120	10~30		0.001~10	30~90	≤10min		0.05~1	Extremely low	10~30	Mature or commercialized
	Latent heat energy storage (PCM)	80~250	80~500	10~30		0.001~1	40~90	Hour level-Days	≤10min	0.5~1	Low	20~40	Mature or commercially verified
	Thermochemical energy storage (TCS)	80~250	80~250	10~30		0.01~1	30~100	Hour level-Days	≤10min	0.05~1	Low	10~30	Demonstration
Mechanical energy storage	Compressed air energy storage (CAES)	30~60	2~6		0.5~10	5~300	40~60	1~24h+	3~15min	Low	Medium-low	20~100 (Number of cycles 10000~100000)	Commercially verified
	Pumped hydro storage (PHS)	0.05~2	0.05~2	0.5~1.5	0.5~1.5	10~5000	70~85	1~24h+	Second level~2min	Extremely low	High-medium	30~100 (Number of cycles 12000~100000)	Mature or commercialized
	Flywheel energy storage (FES)	10~30	20~200	400~1500	800~2000	0.1~20	80~90	Millisecond~1h	≤10ms or ＜4ms	100	Extremely low	15~25 (Number of cycles more than 100,000 to 1,000,000)	Mature or commercialized
Chemical energy storage	Hydrogen energy storage	33000	3(1bar)			0.3~60	20~66	Day-month	＜1s			5~30 (Number of cycles 10000~20000)	
	Methane	1389.9	9.96				30~38	Day-month	＜1s				

Source: Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023



Source: IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 [R]. 2017

Figure 2-5 Power and Duration Characteristics of Energy Storage Technologies



Source: IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 [R]. 2017

Figure 2-6 Capacity Intensity and Energy Intensity of Storage Technologies

(2) Techno-economic indicators

Table 2-4 lists the key technical and economic indicators of mechanical energy storage (including pumped hydro storage, compressed air energy storage, and flywheel energy storage), lead-acid batteries, lithium-ion batteries (including nickel-manganese-cobalt (NMC), nickel-cobalt-aluminum (NCA), lithium iron phosphate (LFP), and lithium titanium oxide (LTO) batteries), high-temperature sodium batteries (including sodium-sulfur (NaS) and sodium-nickel chloride (NaNiCl) batteries), and flow batteries (including zinc-bromine (ZnBr) and vanadium redox (VRB) batteries).

The technical indicators listed include efficiency, minimum C-rate, maximum C-rate, depth of discharge (DOD), maximum operating temperature, and safety (thermal stability). Economic indicators include average capital expenditure (CapEx), development and construction cycle, operational expenditure (OpEx), energy density, power density, full charge-discharge cycles, and technology maturity level.

The following provides a comparison of the key technical and economic indicators of the aforementioned typical energy storage technologies, along with a brief outline on their suitable applications in urban energy systems.

i) Mechanical energy storage

Pumped hydro storage is technically mature, offers high system efficiency, and has the lowest construction cost; however, it has the longest construction period to build. The requirement for mountainous terrain and large-scale civil engineering works restricts its development and utilization; Pumped hydro storage is suitable for large-scale deployment (with installed capacity reaching over 1GW) and, as discussed before, is applicable to grid peak shaving and power balancing over daily or weekly timeframes, but it has limited adaptability in urban applications.

Through decades of development, compressed air energy storage has generally reached a commercialization level; CAES is not constrained by geographical conditions and can be built at load centers so to reduce transmission losses, help to improve energy utilization efficiency, and address local energy consumption issues. As a relatively new type of large-scale electrical energy storage technology, CAES integrates a thermal energy storage subsystem, enabling it to play a role in heating and thermal supply applications. Relying on its high-performance energy storage and thermal accumulation technology, CAES systems can achieve various types of thermal supply, including heating for large buildings, urban communities, industrial parks, working with efficient coal-fired heating units, and large-scale renewable energy bases. In addition, CAES systems can be used for cooling purposes, which is currently a research hotspot. CAES can perform frequency regulation in power systems and has the dual capability of cooling and heating. It is expected to play an important role in the integrated multi-energy storage and supply fields in future urban energy systems.[27]

[27] Zhu Weijie, Dong Ti, Zhang Shuhong. Comparative Analysis of Domestic and International Safety Standards for Lithium-ion Batteries i n Energy Storage Systems [J]. Energy Storage Science and Technology, 2020, Vol.9(1): 279-286

Table 2-4 Key Techno-economic Indicators of Selected Energy Storage Technologies

Energy storage technology		Mechanical energy storage			Lead acid battery	Lithium battery				High-temperature sodium battery		Flow battery	
		Pumped hydro storage (PHS)	Compressed air energy storage (CAES)	Flywheel energy storage (FES)	Valve-regulated lead acid battery (VRLA)	Nickel manganese cobalt Ternary lithium battery (NMC)	Nickel cobalt aluminum Ternary lithium battery (NCA)	Lithium iron phosphate battery (LFP)	Lithium titanate battery (LTO)	Sodium-sulfur battery (NaS)	Sodium-nickel chloride battery (Zebra)	Zinc-bromine flow battery (ZBB)	Vanadium flow battery (VRB)
Technical indicator	Efficiency (%)	80%	64%	85%	81%	92%	92%	86%	96%	81%	85%	72%	72%
	Minimum C ratio	C/20	C/10	1C	C/10	C/4	C/4	C/4	C/4	C/8	C/8	C/8	C/8
	Maximum C ratio	C/6	C/4	4C	2C	2C	1C	2C	10C	C/6	C/6	C/4	C/4
	DOD (%)	90%	40%	85%	50%	90%	90%	90%	95%	100%	100%	100%	100%
	Maximum operating temperature (T2) (ºC)	/	/	/	50	55	55	65	65	/	/	50	50
	Safety (thermal stability)	/	/	/	High	Medium	Low	High	High	Medium	Medium	Medium	High
Economic Indicators	CapEx ($/kWh)	21	48	2656	226	339	284	466	880	436	323	696	268
	Development and construction cycle (year)	5	3	1	0.25	0.5	0.5	0.5	0.5	0.5	0.5	1	1
	OpEx ($/kWh)	2	1	80	3	8	8	8	6	8	8	15	11

Energy storage technology	Mechanical energy storage			Lead acid battery	Lithium battery				High-temperature sodium battery		Flow battery	
	Pumped hydro storage (PHS)	Compressed air energy storage (CAES)	Flywheel energy storage (FES)	Valve-regulated lead acid battery (VRLA)	Nickel manganese cobalt Ternary lithium battery (NMC)	Nickel cobalt aluminum Ternary lithium battery (NCA)	Lithium iron phosphate battery (LFP)	Lithium titanate battery (LTO)	Sodium-sulfur battery (NaS)	Sodium-nickel chloride battery (Zebra)	Zinc-bromine flow battery (ZBB)	Vanadium flow battery (VRB)
Energy density (Wh/L)	1	4	110	75	470	410	410	410	220	215	45	42.5
Power density (W/L)	/	/	7500	355	5050	5050	5050	5050	140	210	13	2
Complete charge and discharge cycle	20000	20000	＞10000	500	3500	1500	3500	10000	5000	3500	4000	10000
Technology maturity	Mature	Commercialized	Early commercialized	Mature	Commercialized	Commercialized	Commercialized	Early commercialized	Commercialized	Demonstration	Early commercialized	Early commercialized

Source: IRENA，Electricity Storage Valuation Framework: Assessing system value and ensuring project viability[R]. 2020-03

Flywheel energy storage technology is currently in the early commercialization stage and has been implemented in multiple application areas. In urban energy systems, it can play an important role in grid frequency regulation, urban rail transit, and electric EV charging stations. Flywheel energy storage offers high charge/discharge efficiency, fast response speed, and high safety, effectively compensating for shortcomings of traditional generation units in grid frequency regulation.

An example is the Beacon Power 20MW energy storage station in New York. Flywheel energy storage systems can achieve energy savings and stabilize grid voltage during urban rail traction processes, and in China, the technologies have already been deployed commercially in Beijing and Qingdao metro lines. Promoting electric vehicles is an inevitable trend for cities to move toward carbon neutrality, and the supporting charging infrastructure development will continue. Traditional charging stations often require grid expansion, which involves high investment costs for capacity upgrading and related infrastructure, especially in already networked areas such as old urban districts where expansion would encounter difficulty; Flywheel-based charging stations can meet the high-power requirements of fast EV charging without relying on grid expansion, while also enabling greater economic returns through peak-valley price arbitrage, making them particularly suitable for city centers and old urban areas constrained by grid capacity.[28]

ii) Lead acid battery

Lead-acid batteries are currently the most technically mature and longest-commercialized electrochemical energy storage technology, with the lowest construction and operational costs. However, due to their short lifespan (approximately 500 charge-discharge cycles, far below other electrochemical batteries) and low energy density (about 1/5 that of lithium-ion batteries), lead-acid batteries have faced increasing competition from lithium-ion batteries, limiting their use in large-scale energy storage systems. Nevertheless, lead-acid batteries offer advantages, particularly low cost, good safety performance, and easy recyclability. In recent years, based on traditional lead-acid batteries, upgraded versions such as lead-carbon batteries have been developed, which significantly enhance key performance like cycle life and energy density, offering promising application prospects.[29]

It is expected that in the future, more applications would likely be developed in line with the characteristics of lead-acid batteries, especially advanced lead-carbon batteries. These include distributed solar PV generation site paired with storage, customer-end peak shaving and valley filling, demand-side management, and power backup for important customers such as telecommunications, banking, hospitals, airports, as well as other user-end applications.

iii) Lithium battery

Lithium-ion batteries are currently the secondary battery with the highest energy density. As previously

[28] LeadLeo，2022 China Flywheel Energy Storage System (FESS) Industry Research: Application Scenario Analysis [R]. 2022-10.
[29] Hao W, Zheng L, Hai-Ying L I. Research progress for lead-carbon batteries[J]. Chinese Journal of Power Sources, 2018.

mentioned, they dominate the field of new energy storage, accounting for nearly 97% of the market. They offer advantages such as long cycle life, high efficiency, and large energy density. Due to supportive policies and technological innovation, manufacturing costs have steadily decreased, leading to explosive growth in their applications in the energy storage sector.

Lithium-ion batteries are suitable for most applications such as grid peak shaving and frequency regulation, integration of renewable energy, emergency backup power, and black start. However, they also have notable disadvantages with lower safety records in the past. During its operation, internal exothermic reactions may occur, potentially leading to thermal runaway under certain conditions, posing risks such as fire, combustion, and explosion. This limits their application in some high-safety-demand and densely populated areas. With safety being a major research focus in the lithium-ion battery field, improvement has been observed in recent years.

The characteristics and suitable applications of different types of lithium-ion batteries are summarized in the Table 2-5.

Table 2-5 Characteristics and Applications of Lithium Batteries

Battery type	Characteristics	Applications
Nickel-Manganese-Cobalt (NMC) Lithium Battery	The NMC cathode material offers high specific energy and specific power, as well as excellent low-temperature performance. It was once considered one of the most successful lithium-ion chemistries by the industry. However, its safety performance has not yet seen significant breakthroughs.	It is primarily used in power batteries, tool batteries, polymer batteries, cylindrical batteries, and aluminum-cased batteries.
Nickel-Cobalt-Aluminum (NCA) Lithium Battery	It offers high specific energy, relatively good specific power, and long cycle life, sharing similarities with NMC. However, its disadvantages include lower safety performance and higher cost.	It is mainly used in medical equipment, industrial applications, and electric vehicles.
Lithium iron phosphate battery (LFP)	The raw materials are low-cost, and the resources of phosphorus, lithium, and iron are abundant. It has a moderate operating voltage (3.2 V), high specific capacity (170 mAh/g), high discharge power, fast charging capability, and long cycle life. It also exhibits high thermal stability under high-temperature conditions, making it one of the lithium-ion battery chemistries that best meets the requirements for environmental friendliness, safety, and high performance from an industry perspective; Its disadvantages include low energy density and poor low-temperature performance.	It is primarily used in electric vehicles, power energy storage, 5G base stations, two-wheeled vehicles, heavy-duty trucks, and electric ships.
Lithium titanate battery (LTO)	The nominal battery voltage is 2.40 V, and it supports rapid charging. The LTO battery can achieve discharge rates exceeding 10C, offering more charge-discharge cycles than conventional lithium-ion batteries. It is also safer and performs well at low temperatures.	It is primarily used in uninterruptible power supplies (UPS), solar streetlights, and electric vehicles.

iv) High-temperature sodium battery

High-temperature sodium batteries use sodium ion-conducting ceramic electrolytes as separators and metallic sodium or its compounds as active materials. The typical systems include sodium-sulfur (NaS) batteries and sodium-nickel chloride (NaNiCl) batteries. The main advantage of high-temperature sodium batteries lies in their abundant raw material resources — sodium and sulfur that are relatively easy to obtain. However, their disadvantages are equally apparent, including poor safety performance and high operational temperature requirements. The operating temperatures of sodium-sulfur and sodium-nickel chloride batteries are 300–350°C and 250–300°C, respectively. This means they require continuous heating during their operation. Additionally, the electrode material — metallic sodium — is highly reactive and undergoes violent reactions upon contact with water. Therefore, when applying high-temperature sodium batteries to large-scale energy storage in power systems, potential safety risks need to be assessed and managed.

High-temperature sodium batteries offer advantages in efficiency and energy density, placing them at a medium-to-high level among electrochemical energy storage technologies. They exhibit no self-discharge effect (with DOD reaching 100%), and can operate under high-temperature conditions, making them competitive and a promising energy storage solutions. Their applications include peak shaving and valley filling, power quality improvement, emergency power supply, and smoothing power output from renewable electricity generation.

v) Liquid flow battery

Flow batteries, as a highly promising and valuable energy storage technology, have broad application prospects and market potentials in power systems. In flow batteries, active materials are stored in liquid form within two separate tanks. The electrolyte solution is pumped through an independent stack where the electrochemical reactions occur. Since the stack and the tanks are separated, the locations for energy storage and energy release are decoupled. This allows independent configuration of power and capacity, enabling easy scalability and flexible installation layouts. Compared to lithium-ion batteries, flow batteries offer advantages such as large capacity, high safety, long lifespan, and deep discharge capability. Compared to sodium-sulfur batteries, flow batteries offer advantages such as ambient temperature operation, instant startup, and enhanced safety. However, due to their relatively low energy density, flow batteries are better suited for stationary energy storage systems where energy density is not a critical requirement, as well as for applications demanding high safety and long service life.

There are various technical pathways for flow batteries, and they have strong applicability across generation, grid, and end-user sides of the power system, aligning well with current technological needs. Currently, vanadium redox flow batteries (VRB) and zinc-bromine flow batteries (ZnBr) show the most promising commercialization potentials, and both have achieved initial commercialization. The characteristics and suitable applications of vanadium redox flow batteries and zinc-bromine flow batteries are summarized in Table 2-6.

Table 2-6 Characteristics and Application of Liquid Flow Batteries

Battery type	Main characteristics	Applications
Zinc-bromine flow battery (ZBB)	• Advantages: The zinc-bromine flow battery (ZBB) is one of the flow battery systems with the highest energy density and small size; ZBB uses metallic zinc as the negative electrode active material, offering advantages such as widely available active materials, low cost, and ease of recycling; It is inherently safe and does not pose fire or explosion risks caused by thermal runaway. • Disadvantages: Self-discharge caused by leakage of active materials between electrodes, zinc dendrite formation, and corrosion/pollution issues arising from bromine's inherent properties — including corrosiveness, chemical oxidizing behavior, high volatility, and permeability; Additionally, since ZBB is a deposition-type flow battery, its capacity and power cannot be fully decoupled, leading to limitations imposed by the zinc electrode on overall capacity.	Its applications are relatively concentrated in user-side scenarios such as industrial and commercial users, remote areas, and military applications.
Vanadium flow battery (VRB)	• Advantages: Vanadium Redox Flow Batteries (VRB) represent the most commercially mature and technically advanced flow battery technology currently available. They offer high energy conversion efficiency, large energy capacity, flexible site selection, deep discharge capability, long service life (over 10,000 cycles), and excellent safety and environmental performance, making them one of the preferred technologies for large-scale, high-efficiency energy storage. • Disadvantages: However, VRBs face challenges such as relatively high upfront investment costs, sensitivity to vanadium price fluctuations, and low energy density.	Application scenarios include peak shaving and valley filling, demand response, deferring grid upgrades, power supply in remote areas, distributed generation, smart grids, and microgrids.

2.2 Applications of energy storage system

This section provides a summary of the applications of various energy storage technologies within power systems.

2.2.1 Power system and energy storage

Typically, power systems have two typical characteristics: one is the simultaneity of generation and consumption time, meaning that electricity must be generated and used simultaneously. The amount of electricity generated must always equal the amount consumed; otherwise, an imbalance in supply and demand can harm the stability and quality (voltage and frequency) of the power system; The second characteristic is the spatial separation between generation and consumption. That is, power plants are usually located far from load centers where resources are available, and the electricity they produce needs to be transmitted to the load centers via transmission lines, and then distribution network to the customers. When large-capacity power flows cause congestion in transmission lines or when grid failures occur, the power supply may be affected or even interrupted. Currently, traditional power systems are evolving into new power systems characterized by increased proportion of renewable energies such as wind and solar, more power electronics-based converters/inverters, and the likely integration of main grids with microgrids. As the penetration rate of variable renewable energies (VRE) like wind and solar continue to increases, the challenges posed by their volatility, intermittency, unpredictability, and uncertainty become more apparent for the security, reliability, flexibility, and resilience of the power systems.

Energy storage is a critical flexible resource for power systems, capable of alleviating time and space mismatches in power generation and load level, solving issues related to energy conversion, and enhancing density and flexibility of energy use. Electricity storage system can store surplus energy directly or indirectly and release it back into the power system as needed in the form of electricity. With its unique capabilities to absorb, store, and reinject electricity, large scale energy storage installations can transform the classic model of instantaneous balance between supply and demand, where generation, transmission, distribution, and consumption occur simultaneously, bringing revolutionary changes to the organizational structure of power sector, planning and design, topological forms, dispatch control, operational models and management of power systems. Energy storage can also effectively address the aforementioned challenges faced by power systems and is a key solution to technical challenges associated with integrating renewable energies. The large-scale application of energy storage enables reliable substitution of fossil fuels with renewable energies and decouples generation from consumption in terms of both time and space, playing a crucial role in the construction of new power systems.[30,31]

As shown in the following figure, with the increasing penetration of renewable energy in power systems, the functions and values provided by energy storage in three major application segments, namely generation, grid, and user side, supporting real-time power balancing (power value), improving system capacity factors (capacity value), and absorbing, releasing, and transferring energy (energy value).[32]

[30] The US Department of Energy Office of Fossil Energy，Electricity Storage Technology Review [R]. 2020-06-30.
[31] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023
[32] Comprehensive Guide to Energy Storage! Industry Chain Map and Future Market Assessment [EB/OL]. https://mp.weixin.qq.com/s/hE8LWEg0dFJPDAQkAdPB8A, 28, January 2023.

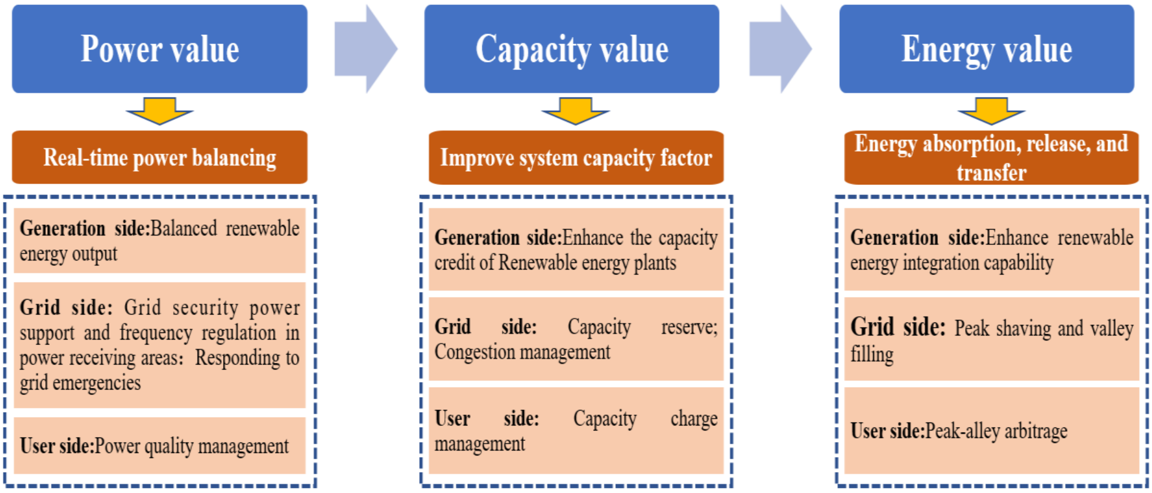
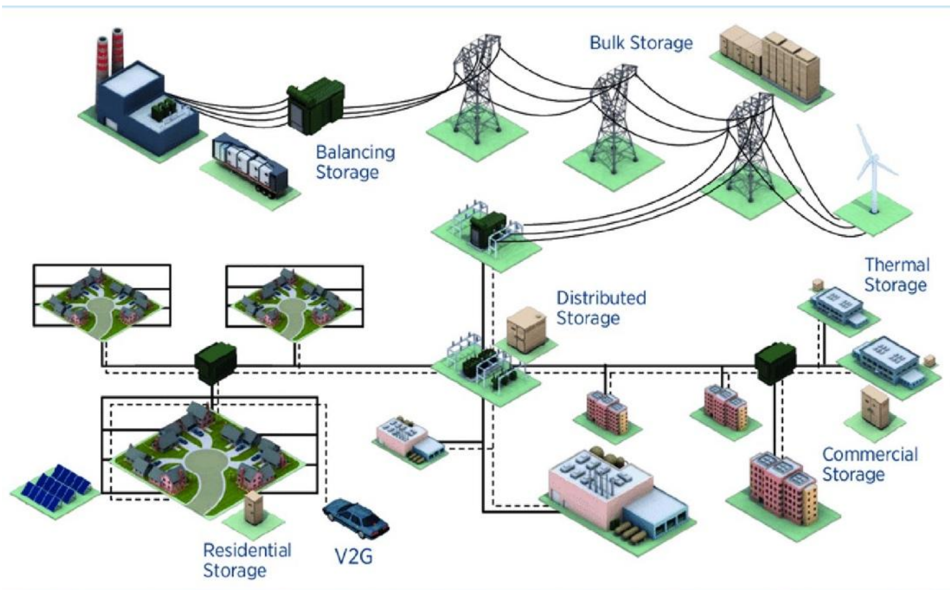


Figure 2-7 Application Value of Energy Storage in Power Systems

2.2.2 Applications of energy storage system

The potential locations and applications of energy storage in the power systems are as shown in the figure below.



Source: IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 [R]. 2017

Figure 2-8 Illustration of the Location and Lpplication of Energy Dtorage in Power System

Depending on the location within the power system or the type of service to be provided, energy storage systems installed can be categorized in different ways:

(1) According to the position relative to the metering point in power system: front-of-meter storage and

behind-the-meter storage.[33,34,35]

Front-the-meter-storage: Fronter the meter storage (FTMS), also known as "large-scale storage" or "utility-scale storage", refers to energy storage deployed before the metering point in the power system, where stored energy must pass through the meter to reach the customers for consumption. Both "generation-side storage" and "grid-side storage" fall under FTMS. The ownership of FTMS typically belongs to power system operators. Various energy storage technologies, including large-scale storage such as pumped hydro storage and compressed air energy storage, as well as modular battery systems such as lead-acid batteries and lithium-ion batteries, can be deployed as FTMS systems.

Behind-the-meter-storage: Behind-the-meter storage (BTMS) refers to energy storage installed after the metering point in the power system at customer end, where stored energy can be directly used by users without passing through the meter, hence also known as "customer-side storage" and also referred as distributed energy storage. BTMS includes residential and commercial energy storage, microgrid-side storage, and off-grid energy storage applications. Ownership of BTMS typically belongs to the customers, independent developers or energy service companies. Technologies commonly used in BTMS systems include various modular electrochemical energy storage technologies such as lead-acid batteries, lithium-ion batteries, and lithium-sulfur batteries.

(2) Based on the deployment location in power system: generation-side storage, grid-side storage, and user-side storage.[36,37,38]

Generation-side energy storage: Also known as source-side storage, refers to energy storage facilities constructed behind the connection points of power plants, including thermal plants, wind and solar PV station, or at the connection points of substations. Generation-side storage is primarily configured at the source end and can provide peak shaving and frequency regulation, ancillary services to the grid, delay the expansion or construction of new generating units for conventional power sources like thermal power plants, with improved overall efficiency and reduced greenhouse gas emissions, It is also widely used in applications such as peak shaving and valley filling for renewable energies like wind and solar, smoothing the output fluctuations of renewable power, enhancing the absorption of renewables, increasing the flexibility or dispatchability of renewables. Generation-side storage facilities include traditional storage methods such as pumped hydro storage and new forms such as electrochemical energy storage. As technology advances and costs decrease, the penetration rate of renewable energy generation in power systems continues to increase,

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[33] Infineon Technologies AG，Energy Storage Systems [EB/OL]. https://www.infineon.com/cms/en/applications/industrial/energy-storage-systems/，2024-04-16

[34] IEEE，Behind the Meter: Battery Energy Storage Concepts, Requirements, and Applications [EB/OL]. https://smartgrid.ieee.org/bulletins/september-2020/behind-the-meter-battery-energy-storage-concepts-requirements-and-applications，2020-09

[35] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023

[36] KPMG, China Electricity Council, New Energy Storage Facilitating Energy Transition [R]. March 2023. Available at: kpmg.com/cn

[37] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023

[38] Greenpeace and All-China Environment Federation, New Momentum for Decarbonizing the Power System-Report on Innovation Trends in Electrochemical Energy Storage Technology [R]. 2022

posing increasingly severe challenges to the safe and stable operation of power systems. To cope with the issues related to variable renewable generation, such as output forecasting, mismatching with real-time grid balancing requirements, insufficient reliable output during certain periods, "Renewable-paired storage" has gradually become an important application for generation-side storage in more recent years.[39]

Grid-side energy storage: Narrowly defined grid-side storage involves constructing energy storage systems within substations, or at dedicated sites, which are directly connected to power grid. These systems primarily serve functions such as providing backup for emergencies, optimizing grid structures, resolving grid congestion, enhancing grid regulation capabilities, deferring network investments, participating in system peak shaving and frequency regulation, and improving power quality. This definition primarily distinguishes considering the locations where storage facility connects to the power network. The grid-side storage in broad sense refers to energy storage resources within the power system that can be centrally dispatched by the dispatching centers, respond to grid flexibility needs, and play a holistic and systematic role in power system operation. Under this definition, the location of energy storage projects therefore is unrestricted, and the project developers can be diverse.

Grid-side storage can be further subdivided into "transmission-side storage" and "distribution-side storage. Transmission-side storage is deployed at critical nodes of the transmission grid, enhancing the flexible adjustment capabilities for large-scale, high-penetration renewable energy integration and large-capacity DC system connections. It provides auxiliary support for peak shaving and frequency regulation, reactive power support, relief of transmission congestion, and deferring the upgrade and expansion requirement of transmission network. Distribution-side storage is deployed at critical nodes of distribution networks, serving functions such as auxiliary support for peak shaving and frequency regulation, voltage support, relief of distribution network congestion, deferring the upgrade and expansion of distribution equipment, improving power supply quality and reliability, supporting the integration of distributed renewable energies.

More recently, the standalone energy storage model has been developed, which refer to these that operate as independent entities, are not restricted by connection locations, directly sign grid dispatch agreements with power dispatching centers, and participate in power market transactions. As a new market participant, standalone energy storage stations can obtain revenues by independently participating in various power market transactions such as spot energy markets, capacity markets, and ancillary service markets; Standalone energy storage stations transform the traditional 1-to-1 operating model into a 1-to-N or N-to-N model, achieving resource sharing and maximizing the value of energy storage through the sharing economy. Standalone energy storage stations offer advantages such as high flexibility, broad applicability, clear investment subjects and settlement interfaces, overcoming the disadvantages of high costs, single revenue

[39] Li Xiangjun, Ma Huimeng, Jiang Qian. "A Review on Energy Storage Configuration Technologies for Renewable Energy Applications [J]". China Electric Power, 2022, 55(1): 13-25.

channels, and poor economic viability associated with establishing energy storage stations on a single side (either the generation side or the grid side). They have become an important application and development trend for grid-side storage in recent years.[40,41]

Customer-side energy storage: Also referred as demand-side energy storage, it is installed within or near the user's internal site and connection to the user's internal power distribution system or load end, playing a role in energy time-shifting, peak shaving and valley filling, demand response, improving power supply quality, power reserve, and supporting the local utilization of distributed renewable energy such as solar PV. Additionally, multiple independent user-side energy storage units can be integrated to form aggregated storage, known as Virtual Power Plants (VPPs), contributing to energy management and participating in electricity market, including spot markets and ancillary service markets.

The user-side storage include residential energy storage ("household storage" or "home storage") for residential users, industrial and commercial energy storage for businesses, industries, or other specialized facilities. Microgrid-side storage, which combines the basic features of generation-side, grid-side, and user-side storage, but is generally much smaller in scale. User-side storage applications also include Vehicle-to-Grid (V2G), and recent innovative applications such as photovoltaic-energy-storage integrated charging stations.[42] In addition, off-grid storage installations support energy services in the remote areas without grid access.

Figure 2-9 illustrates and summarizes the services that could provide by energy storage facilities, from supporting renewable energy integration, energy services and ancillary services, to network support and user energy management.[43,44,45]

[40] Zhang M , Fan R , Zhu Z ,et al. Comprehensive Evaluation Method of Energy Storage System Considering Benefits of Auxiliary Services[C]//2020 12th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC). IEEE, 2020.

[41] Zeng Ming, Wang Yuqing, Zhang Min, et al. "Research on Business Models and Economic Benefits of Standalone Energy Storage under the Sharing Economy [J]". Price Theory and Practice, 2023(1): 179-183.

[42] Xinyu Chen, Zhonghua Gou, Xuechen Gui. A holistic assessment of the photovoltaic-energy storage-integrated charging station in residential areas: A case study in Wuhan [J]. Journal of Building Engineering, 2023(79): 1-20.

[43] Sandia National Laboratories，DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA [R] 2013-07. https://www.sandia.gov/ess/publications/doe-oe-resources/eshb/doe-epri-nreca

[44] China Energy Storage Alliance, Analysis of Energy Storage Industrial Policies and Typical Project Cases [M]. Beijing: Chemical industry Press, 2024

[45] Hua Zhigang, Key Technologies of Energy Storage and Business Operation Models [M]. Beijing: China Electric Power Press, 2019

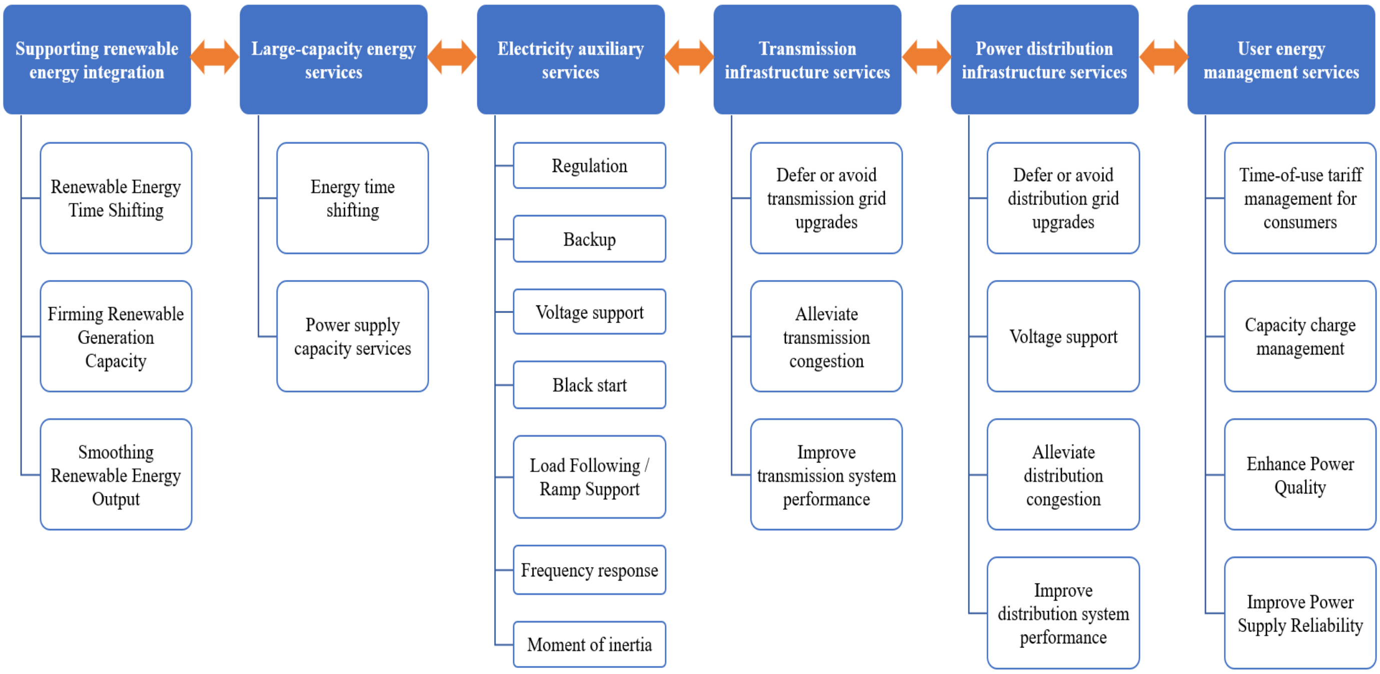


Figure 2-9 Services Provided by Energy Storage Facility in Power System

- **Supporting renewable energy integration:** By configuring energy storage in large photovoltaic power plants, wind farms or hybrid wind/solar power plants, based on predictions of plant output and scheduling of energy storage charge/discharge, intermittent renewable power outputs can be made usable, predictable, and adjustable. This enhances the stability of renewable energy power plants' grid-connected operations, increases the grid integration rate of renewables, reduces curtailment of wind and solar energy, promotes local consumption of renewable energy, and supports the large-scale evaluation of renewable energies;
- **Large-scale capacity and energy services:** Energy and capacity services primarily include energy time-shifting and capacity services;
- **Auxiliary services:** Energy storage can provide various ancillary services to the power system, including regulation, reserve, voltage support (reactive power balance services), black start, load following/ramp support, frequency response;
- **Transmission network support:** Energy storage can support transmission infrastructure by deferring or avoiding transmission grid expansion investment, alleviating transmission congestion, and improving transmission network performance;
- **Distribution network support:** Energy storage can support distribution infrastructure by deferring or avoiding the investment for distribution network expansion, voltage support, relieving distribution congestion;

- **User energy management:** User energy management mainly include time-of-use tariff management (peak-to-valley price arbitrage), capacity charge management, improvement of power quality, and enhancement of power supply reliability.

In theory, energy storage systems can be used for each of the aforementioned individual service, however, in practice, it is often difficult to ensure reasonable returns from a single service alone. Therefore, in real-world projects, the flexibility of energy storage systems is typically leveraged to deliver multiple or combined services, thereby generating benefits across different application areas, making energy storage more economically viable.

3) Based on grid operation characteristics: grid-following and grid-forming energy storage technology

Traditionally, grid-following energy storage systems operate based on a current source model. Their core principle lies in relying on existing grid voltage amplitude and frequency signals as a reference, using a highly precise Phase-Locked Loop (PLL) to track the phase information of the Point of Common Coupling (PCC) in real-time, thereby achieving strict synchronization with the main grid. This "passive following" mechanism makes the system entirely dependent on grid operations: when the grid experiences voltage collapse, frequency instability, or other faults, the grid-following systems, due to their inability to establish independent voltage and frequency references， trigger protective disconnection, rendering them unable to provide continuous power in islanded or weak grid conditions. The technical limitations primarily manifest in three areas: first, the inability to provide virtual inertia (VI), leading to decreased frequency disturbance resistance in grids with a high proportion of renewable energy; second, heightened sensitivity to the grid's Short-Circuit Ratio (SCR), often resulting in harmonic oscillations in weak grid scenarios; and third, limited dynamic response due to PLL bandwidth constraints, making it challenging to handle transient shocks caused by severe fluctuations in renewable energy output. The grid-following energy storage systems, currently commonly used, are mainly applied in strong grid environments for auxiliary services, such as smoothing minute-level power fluctuations of solar/wind power, participating in frequency regulation market bids, or providing second-level power support in load centers.

Grid-forming energy storage systems, which has been developed more recently, simulate the voltage source characteristics of synchronous generators, adopting autonomously set voltage amplitude and frequency as control references. Combining advanced algorithms like Droop Control, Virtual Synchronous Machine (VSM), or Power-Based Control, they actively establish voltage and frequency support points for the grid. Their core advantage lies in breaking the traditional "following" paradigm of grid-connected devices: during grid-connected mode, the system can dynamically adjust output voltage phases to align with the main grid while achieving flexible coupling with the grid through virtual impedance control; in islanded or standalone operation mode, it can independently maintain voltage/frequency stability for microgrids and provide black start capabilities for local loads. From a technical contribution perspective, grid-forming storage systems enhance the grid's inertia level by delaying the Rate of Change of Frequency (RoCoF) through virtual inertia control (mimicking the kinetic characteristics of synchronous generator rotors); their voltage source output characteristics can also boost the grid's short-circuit capacity, mitigating system strength weakening caused by the retirement of thermal power units. Additionally, in weak grid conditions, urban distribution grids, or the situations with 100% power electronics device integration, such systems utilize wide-band impedance reshaping techniques to suppress sub/super-synchronous oscillations, significantly increasing renewable energy penetration limits of the power system.

Grid-forming technology is an essential component for the construction of new power systems. The emerging technology has gradually been mature with increased grid demands, associated regulations, storage system standard configurations. As energy transitions accelerate, power systems are evolving from "synchronous generator-dominated" to "deep power electronics integration", bringing challenges like low inertia, weak damping, and wide-band oscillations—collectively termed "new power system syndrome". Against this backdrop, grid-forming energy storage technology, with its "active grid-forming" and "multi-modal operation" capabilities, is transitioning from an auxiliary technology to a key enabler for new power systems. The IEC (International Electrotechnical Commission) standard "Technical Requirements for Grid-Forming Inverters" (IEC TS 63102:2022) has already made it a mandatory configuration for grids with high penetration of renewable energy.

According to BloombergNEF, global grid-forming energy storage installations are expected to exceed 250GW by 2030, with renewable penetration rates surpassing 60%, driving technology reconstruction in industries like converters and energy management systems (EMS). On the policy front, China's "14th Five-Year Plan" for new energy storage implementation and the EU's *BATTERY 2030* initiative both list grid-forming capabilities as critical technical indicators, indicating the technology is nearing large-scale deployment. It can be foreseen that grid-forming energy storage will become the "digital neuron" for constructing zero-carbon power systems, playing a strategic role in the coordinated development of energy security, climate governance, and the digital economy.

2.2.3 Energy storage in urban energy systems

Table 2-7 presents the applications in urban energy systems. Generation-side energy storage includes "renewable energy-integrated energy storage" and "conventional power plant + energy storage". Grid-side storage covers "transmission and distribution network energy storage", "power auxiliary services", and "standalone energy storage stations". The "transmission and distribution network energy storage" and "power auxiliary services" have already been described previously. Customer-side storage is among the most common application in urban power systems, includes "industrial and commercial energy storage", "residential energy storage", "distributed energy and microgrid-side energy storage" which can be further categorized into "standalone energy storage" and "PV-integrated energy storage" based on whether distributed photovoltaic systems are installed.

"Distributed Energy and Microgrid-side Energy Storage" includes the applications such as "vehicle-to-grid (V2G)", " microgrid energy storage", "off-grid energy storage", and "integrated PV-storage-charging stations". Other typical user-side energy storage applications in cities include "urban rail transit energy storage", "photovoltaics-energy storage-direct current-flexibility buildings (PEDF)",[46] "5G base station energy storage", and "virtual power plants (VPP)".

Boxes 1, 2, and 3 demonstrate three types of promising applications for user-side energy storage in urban areas:

- **Box 1 Transportation + Energy Storage:** It is an innovative application of integrated photovoltaic-energy storage charging statin with battery testing service. With increasing electric vehicle penetration, this new type of charging station combining four functions — photovoltaic power generation, energy storage system, EV charging, and battery testing — will see growing applications in urban charging stations, highway service areas, and industrial parks;
- **Box 2 Building + Energy Storage:** Photovoltaics-Energy Storage-Direct Current-Flexibility (PEDF) technology transforms buildings from mere energy consumers into integrated entities capable of renewable energy production, consumption, and energy regulation — forming a "trinity" of functions. Developing PEDF buildings is an important technical approach to addressing the integration and utilization challenges of distributed PV, expected to serve as a key pathway toward zero-carbon transformation of building energy systems;
- **Box 3 Information Technology+Energy Technology:** As the share of renewable energy generation rapidly increases, power systems face challenges in absorbing surplus renewable energy during off-peak periods and ensuring stable power supply during peak load periods. Virtue power plant (VPP) aggregates various types of distributed adjustable resources on the demand side to support the power system in maintaining secure and stable electricity supply, which is an important technological mean to achieve smooth transition with broad development prospects.

[46] Schneider Electric, Application Innovation of New Power Systems under the Dual Carbon Background – Insights into " PEDF" Microgrids [R]. December 2023. www.se.com/cn

Table 2-7 Energy Storage in Urban Energy Systems

<table>
<tr><th>Category</th><th colspan="2">Application</th><th>Service and Objective</th></tr>
<tr><td rowspan="4">Generation side</td><td rowspan="3"></td><td>PV + stored energy</td><td rowspan="3">(1) Smoothing output fluctuations of renewable energy generation;
(2) Tracking planned generation output;
(3) Avoiding wind and solar curtailment;
(4) Reducing line congestion;
(5) Managing electricity tariffs;
(6) Providing power support to the grid during peak load periods;
(7) Reducing peak-shaving pressure on other power sources;
(8) Decreasing the required reserve power capacity.</td></tr>
<tr><td>Wind Power + Storage</td></tr>
<tr><td>Wind/Solar + Storage</td></tr>
<tr><td colspan="2">Conventional Power Plant + Storage</td><td>(1) Assisting dynamic operation: By leveraging the fast response capability of energy storage, dynamic operation of thermal power units can be improved, reducing carbon emissions; It also avoids damage to unit lifespan caused by frequent dynamic operations, thus lowering equipment maintenance and replacement costs.
(2) Replacing or delaying new units: Energy storage can reduce or delay the need for new power generation capacity;
(3) Enhancing Unit Flexibility: Energy storage enables "thermal-electric decoupling", improving the peak-shaving capability and overall system flexibility of conventional power units.</td></tr>
<tr><td rowspan="8">Grid side</td><td rowspan="4">Transmission and Distribution Network Energy Storage</td><td>Reactive Power Support</td><td>By measuring the actual voltage of the line through sensors, the reactive power output can be adjusted to regulate the entire line's voltage, enabling energy storage devices to perform dynamic compensation.</td></tr>
<tr><td>Alleviating Line Congestion</td><td>Energy storage systems are installed downstream of congested lines. The system charges during non-congestion periods and discharges during high-load periods, thereby reducing the demand for transmission capacity.</td></tr>
<tr><td>Delaying Transmission and Distribution Upgrades</td><td>In transmission and distribution systems where load approaches equipment capacity, energy storage can be installed downstream of the components that would otherwise require upgrading, helping to alleviate or avoid expansion needs.</td></tr>
<tr><td>Substation DC Power Supply</td><td>Energy storage systems within substations can serve as backup power for switching components, communication base stations, and control equipment, directly supplying power to DC loads.</td></tr>
<tr><td rowspan="4">Electricity auxiliary services</td><td>Regulation</td><td>Energy storage coordinates and reduces instantaneous deviations caused by fluctuations in generation and load (i.e., power supply-demand imbalances), helping to maintain grid frequency.</td></tr>
<tr><td>Backup</td><td>To ensure reliable power supply, grid-connected entities (e.g., coal-fired power, hydropower, wind power, photovoltaic power, pumped hydro, etc.) reserve regulation capacity and respond to dispatch instructions within specified timeframes as directed by the grid operator.</td></tr>
<tr><td>Voltage support</td><td>Power systems generally adjust voltage by controlling reactive power. Energy storage systems with fast response capabilities are deployed at the load end to release or absorb reactive power according to load demand, thereby regulating voltage levels.</td></tr>
<tr><td>Black start</td><td>(1) After a catastrophic grid failure, grid-side energy storage systems (e.g., pumped hydro storage, flywheel energy storage, etc.) can supply power to transmission and distribution lines, providing start-up power for power plants so they can resume grid connection and power generation;
(2) After a catastrophic grid failure, the power-side energy storage system (e.g., battery energy storage) can directly provide start-up power to large-scale power plants, enabling them to resume operation and restore power supply to the grid.</td></tr>
</table>

Category	Application		Service and Objective
		Load Following / Ramp Support	Energy storage responds to changes in power output demand with fast response speed (i.e., ramp rate), effectively achieving "load following up" when load increases and "load following down" when load decreases by discharging or charging.
		Frequency response	(1) Regulating frequency fluctuations by instantaneously balancing the difference between load and generation; (2) Adjusting frequency fluctuations by controlling the charging and discharging of grid-connected energy storage systems and their rates; (3) Reducing wear and tear on thermal power units.
		Moment of inertia	(1) Energy storage systems equipped with synchronous generators, such as pumped hydro and compressed air energy storage stations, naturally possess the capability to provide rotational inertia; (2) Flywheel, supercapacitor, and battery-based energy storage systems can rapidly respond to power system frequency control requirements, quickly suppressing sudden frequency variations — functioning equivalently to rotational inertia; (3) Short-response energy storage devices combined with inverters and converters, along with appropriate control mechanisms, form virtual synchronous generators that provide virtual inertia for variable renewable energy sources like PV and wind power.
	Standalone Energy Storage Stations		(1) Provide energy storage capacity leasing services to renewable energy operators; (2) Supply auxiliary services to the grid, including peak shaving, frequency regulation, phase control, black start, and emergency backup; (3) Participate in electricity markets to support grid peak shaving.
Consumer side	**Industrial and commercial energy storage**	Standalone Industrial and Commercial Energy Storage PV-integrated Industrial and Commercial Energy Storage	(1) Time-of-use tariff management: A tool for users to manage time-of-use tariffs — charging the energy storage system when electricity prices are low and discharging during high-price periods to realize peak-to-valley arbitrage; (2) Capacity charge management: Users charge the energy storage system during off-peak hours and discharge it during peak demand, thereby reducing their maximum load and lowering capacity charges; (3) Quality of electric energy: Improve the power supply quality and reliability for users; (4) Stand-by power supply: Serving as a backup power source to cope with unexpected power outages. (5) Distributed PV consumption: Optimizing the PV output curve, enhancing microgrid stability, and increasing self-consumption rates.
	Residential energy storage	Standalone Residential Energy Storage PV-integrated Residential Energy Storage	(1) Reduce user-side electricity costs; (2) Improve power quality; (3) Provide a reliable backup power source; (4) Address intermittency issues of residential PV systems and improve self-consumption rates.
	Distributed Energy and Microgrid-side Energy Storage	EV-Grid Interaction (V2G)	By flexibly adjusting EV charging and discharging power and timing, this approach helps achieve peak shaving and valley filling, congestion relief, and supports real-time power balance, contributing to secure, economical, and reliable grid operation.
		Campus Microgrid Energy Storage	(1) Address intermittency issues in renewable energy generation (e.g., rooftop PV within industrial parks); (2) Reduce user-side electricity costs; (3) Improve power quality; (4) Provide a reliable backup power source.
		Small-scale off-grid energy storage	(1) Provide stable voltage and frequency; (2) Stand-by power supply.

Category	Application	Service and Objective
	Photovoltaic-energy storage integrated charging stations	(1) Enhance self-consumption of photovoltaic power; (2) Help with peak shaving and valley filling, reducing the impact of EV charging stations on the grid; (3) Lower charging costs and increases revenue for charging stations; (4) In off-grid mode, enables emergency EV charging.
Other User-side Energy Storage Applications	Urban Rail Transit Energy Storage	(1) Recover regenerative braking energy from rail operations to achieve energy savings; (2) Supports traction network voltage and power, reducing land use, investment, and long-term maintenance costs associated with building new substations; (3) Provides backup emergency power.
	PEDF buildings	(1) Address intermittency issues of distributed PV generation in buildings; (2) Reduce conversion between AC and DC, thereby minimizing transmission losses and improving building energy efficiency; (3) Facilitate optimal distribution capacity planning and improves asset utilization efficiency; (4) Achieves peak shaving and valley filling, lowering operational costs and potentially generating revenue through electricity sales.
	5G Base Station Energy Storage	(1) Improve base station load characteristics, reduces peak load demand, enables peak-to-valley tariff arbitrage, and saves on electricity costs; (2) Acts as a backup power source to ensure communication reliability at base stations.
	Virtual Power Plant (VPP)	(1) Renewable generation forecasting and monitoring: Enhance forecasting and control of the power portfolio, helping utilities save on balancing costs caused by discrepancies between forecasts and actual demand; (2) Grid Resilience Aggregation: Generate revenue through capacity bidding and ancillary service provision; (3) Demand Response Aggregation: Earn income via ancillary service market bidding and reduces procurement costs; (4) Household virtual power plant: Aggregators earn profits by offering ancillary services to users, while utilities benefit from reduced grid upgrade expenses.

Box 1 "Transportation + Energy Storage": integrated solar PV-energy storage charging station with battery testing service

An advanced charging infrastructure that integrates four key functions: photovoltaic power generation, energy storage systems, electric vehicle charging, and battery testing.

Functionality

1) Solar PV power generation: Utilizes solar energy to generate electricity, supplying renewable power to the charging station;
2) Energy storage system: An intelligent energy storage system stores electricity generated by solar PV panels for use in EV charging or as emergency power when needed;
3) EV charging: Provides fast and convenient charging services for electric vehicles;
4) Battery testing: During the charging process, the battery of the EV undergoes comprehensive inspection and testing to ensure their safety, reliability, and extended battery life.

System operation

The energy storage system analyzes actual conditions and coordinates PV generation with EV charging demand, thereby alleviating pressure on the distribution grid. During peak load periods at charging stations, the energy storage system can discharge to supply power to EV and store excess electricity generated by photovoltaic systems. The energy storage system can also improve the characteristics of photovoltaic power generation and supply, reduce load fluctuations in the distribution network caused by EV charging, and achieve voltage stabilization, phase angle improvement, and active filtering effects.

Technical features

1) Environmental friendliness: Utilizing renewable energy sources such as solar power to provide charging services for EV effectively reduces carbon emissions;
2) Efficiency: Equipped with high-performance energy storage and charging equipment, fast charging can be achieved;
3) Economy: The construction and maintenance costs are lower than those of traditional gas stations, and the operating costs are also low;
4) Convenience: It provides 24/7 services, making it convenient for users to charge their vehicles at any time;
5) Flexibility: The site selection is flexible, without the need to upgrade the distribution grid, and is suitable for a range sites such as public parking lots and commercial buildings.

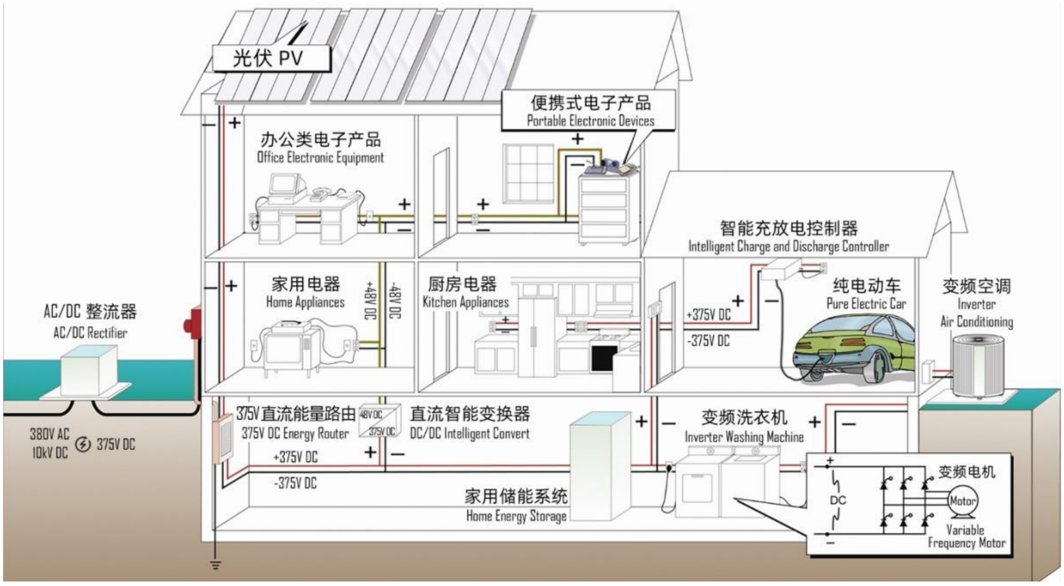
Photo Source: https://mp.weixin.qq.com/s/-a8cnEV-PTpFniGThoP0-g

Ningde Lithium Battery Town Intelligent Supercharging Station with PV, Storage, Charging, and Battery Testing

Box 2 "Building + Energy Storage": Innovative PEDF Plan

The concept of "Photovoltaics, Energy Storage, Direct Current, and Flexibility" (PEDF) was first proposed in 2020 by the research team of Tsinghua University, China. "PEDF" refers to a new type of building energy system (or building power distribution system) that integrates building-integrated photovoltaics and energy storage, adopts DC power distribution system, and features electrical appliances capable of active power response.

A typical PEDF building power distribution system is illustrated in the figure below. "Photovoltaics" refers to distributed solar PV; "Storage" refers to distributed energy storage (including electrochemical energy storage, cold/thermal storage, etc.) and utilizing EV battery resources from nearby parking areas; "Direct current" indicates that the building uses DC power internally; and "Flexibility" is the goal of PEDF, achieving flexible electricity consumption and acting as a flexible load or virtual flexible power source for the grid. In the PEDF building power distribution system, “photovoltaics” and “storage” are prerequisites, "direct current" is the approach, and "flexibility" is the ultimate goal.



Source: Shenzhen Institute of Building Research. Report on Building Electrification and Urban Energy Transition Path [R]. 16 November, 2020

Schematic Diagram of the New PEDF Building Power Distribution System

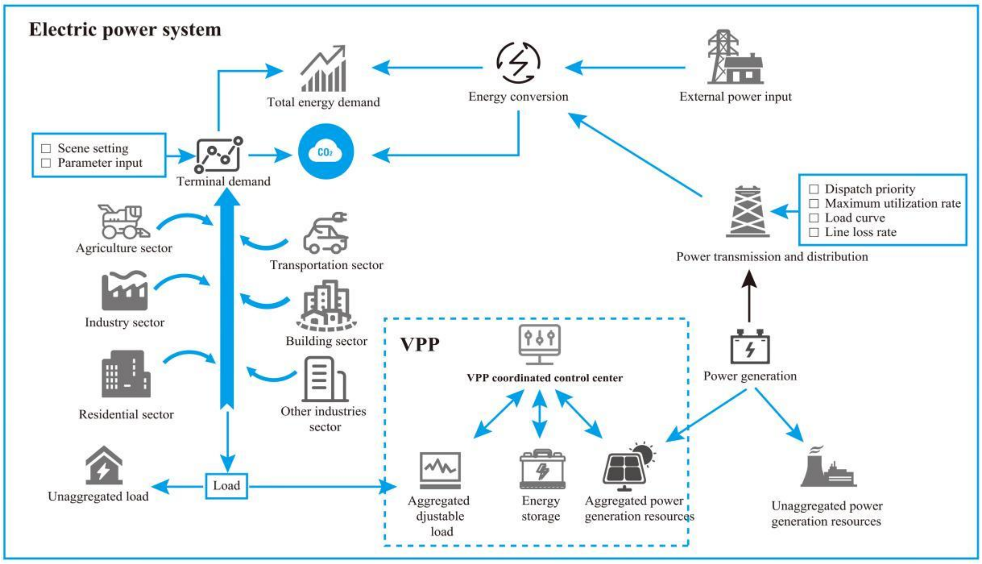
As a major energy consumer and possessing available surface area for installing distributed PV, buildings need to effectively fulfill tasks such as fully utilizing their own renewable energy resources and assisting low-carbon power systems in achieving effective regulation and storage. Conventional building power systems mainly focus on balancing electricity demand and the urban grid power supply, whereas the PEDF system emphasizes dynamic equilibrium among building PV, building energy storage, load demand, and the urban grid. Flexible electricity consumption is the goal of PEDF, which is among new directions for green and zero-emission buildings.

The PEDF technology integrates four key technologies — photovoltaic power generation, energy storage, DC power supply, and flexible electricity consumption — organically, transforming buildings from mere energy consumers into integrated entities with renewable energy production, consumption, and energy regulation capabilities. Developing PEDF buildings is an important technical approach to solving the integration and utilization challenges of distributed PV, a key driver for zero-carbon transformation of building power systems, and a crucial pathway toward achieving carbon neutrality.

Box 3 "Information Technology+Energy Technology": Virtual Power Plant

A Virtual Power Plant (VPP) is the result of deep integration between information and energy technologies. It aggregates and optimizes large numbers of distributed renewable energy sources, energy storage systems, and controllable loads (e.g., electric vehicles) using advanced telecommunication and monitoring and control technologies. The VPP acts as a coordinated power management system, functioning as a special power plant participating in grid operation and electricity markets, and appears externally as a controllable power source.

The VPP does not change how each distributed resource connects to the grid but instead aggregates various distributed resources through advanced control and telecommunication technologies, enabling their coordinated and optimized operation. Virtual power plants enhance grid balancing capabilities, promote high penetration of renewable energy, and ensure secure power supply. They are becoming a core component of the new power system construction.



Picture from: International Carbon Peaking and Carbon Neutrality Progress Report (2023) [M]. Beijing: Social Sciences Academic Press (China), 2023

Schematic Diagram of Regional Power System and Virtual Power Plant Model

Currently, VPP theory and practice are relatively mature in developed economies in Europe and America, while they remain nascent in many developing economies. European economies like Germany primarily aggregate distributed power sources; The United States focuses on controllable loads; Japan mainly aggregates user-side storage and distributed power sources; Australia focuses on aggregating user-side storage.

In China, VPPs are emerging as a new force in the new power system. On 26 August, 2022, the Shenzhen Virtual Power Plant Management Center was established, the first of its kind in China; Provinces such as Shanghai, Guangdong, and Shanxi have successively issued policy documents promoting VPP development, marking the beginning of a rapid growth phase for VPPs.

As the share of renewable energy generation rapidly increases, power systems face challenges in absorbing surplus renewable energy during off-peak periods and ensuring stable power supply during peak load periods. VPP aggregates various types of distributed resources on the demand side to support the power system in maintaining secure and stable electricity supply, which is an important technological mean to achieve smooth transition and has broad development prospects.

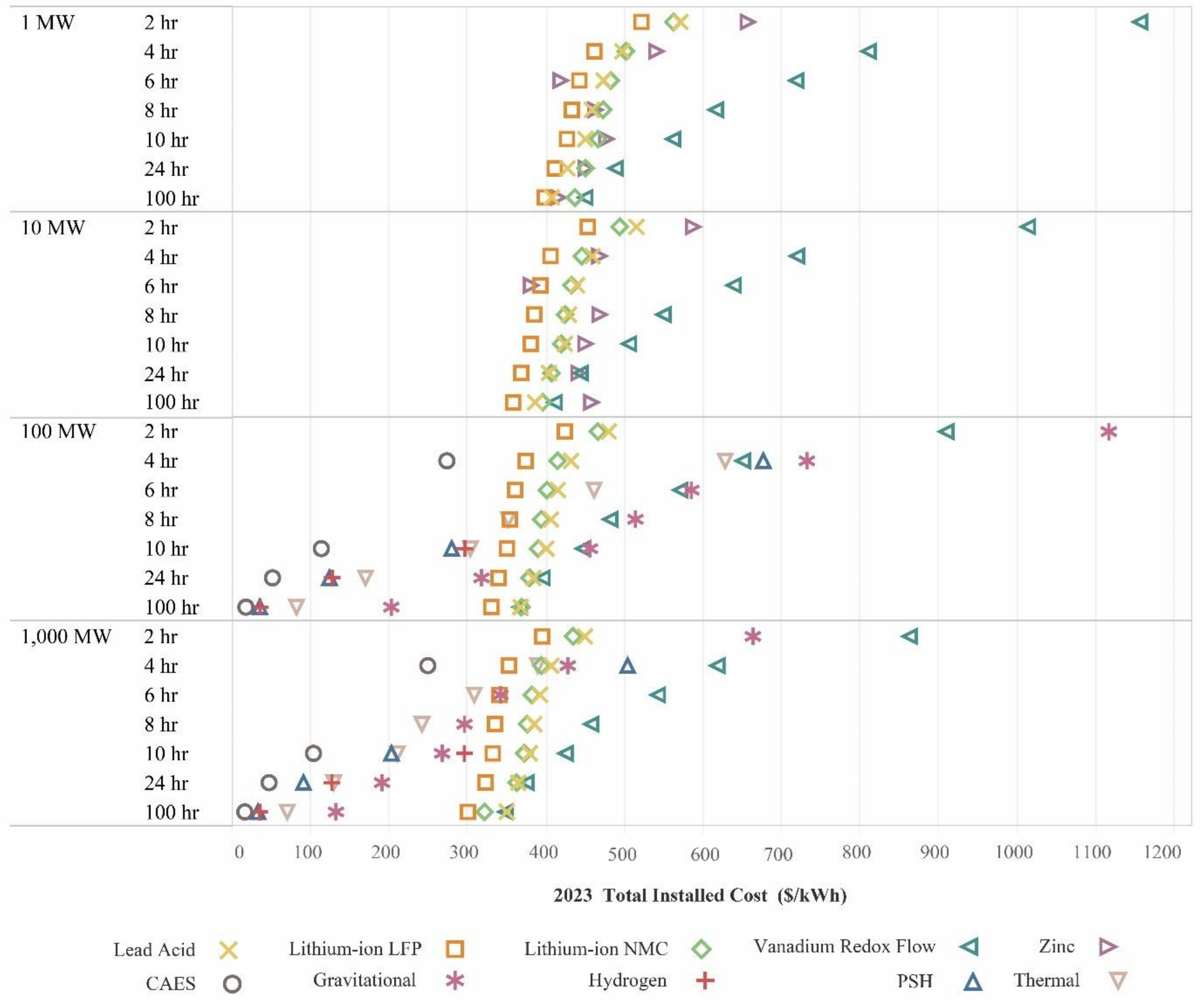
2.3 Costs of energy storage technologies

2.3.1 Construction costs

The Pacific Northwest National Laboratory (PNNL), under the US Department of Energy, has conducted analyses of the economic viability of various energy storage technologies, including mechanical storage (pumped hydro storage, gravity energy storage, compressed air energy storage), electrochemical energy storage (lead-acid batteries, LFP lithium-ion batteries, NMC lithium-ion batteries, all-vanadium flow batteries, zinc-based batteries), hydrogen storage, and thermal storage. Considering the commercially available systems, representative scales, and application cases for each energy storage technology. Electrochemical energy storage systems were analyzed at rated power levels of 1, 10, 100, and 1,000MW with discharge durations of 2, 4, 6, 8, 10, 24, and 100 hours respectively. The pumped hydro storage systems were analyzed at rated power of 100 and 1,000MW with discharge durations of 4, 10, 24, and 100 hours. Compressed air energy storage systems were evaluated at 100 and 1,000MW with durations of 4, 10, 24, and 100 hours. Gravity energy storage was assessed at 100 and 1,000MW with durations of 2, 4, 6, 8, 10, 24, and 100 hours. Thermal storage systems were studied at 100 and 1,000MW with durations of 4, 6, 8, 10, 24, and 100 hours. Hydrogen storage systems were analyzed at 100 and 1,000MW with durations of 10, 24, and 100 hours.[47]

Figure 2-10 illustrates a comparison of construction costs for various energy storage technologies in 2023, which include the costs of energy storage system, auxiliary systems, power equipment, instrumentation, control and communication systems, system integration, EPC (engineering, procurement, and construction), project development and grid connection costs.

[47] PNNL，Energy Storage Cost and Performance Database [EB/OL]. https://www.pnnl.gov/ESGC-cost-performance，2024-06-20.



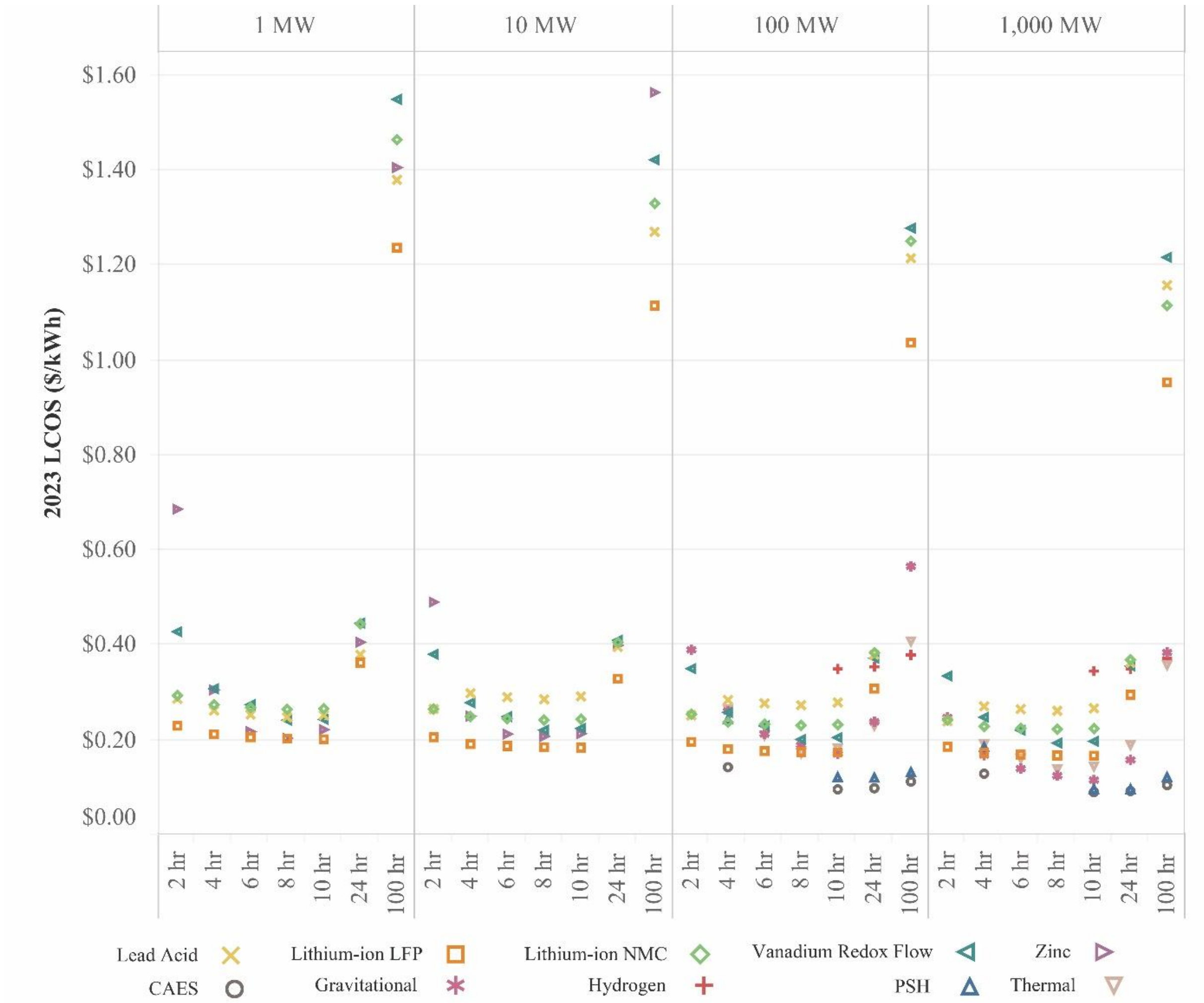
Source: PNNL，Energy Storage Cost and Performance Database [EB/OL]. https://www.pnnl.gov/ESGC-cost-performance，2024-06-20 .

Figure 2-10 Comparison of Energy Storage Technology Construction Costs in 2023

2.3.2 Levelized costs of storage

The Pacific Northwest National Laboratory also conducted economic analyses of the aforementioned energy storage technologies from the perspective of Levelized cost of storage (LCOS),[48] the comparison of which in 2023 is provided in Figure 2-11.

[48] PNNL，Energy Storage Cost and Performance Database [EB/OL]. https://www.pnnl.gov/ESGC-cost-performance，2024-06-20.



Source: PNNL，Energy Storage Cost and Performance Database [EB/OL]. https://www.pnnl.gov/lcos-estimates，2024-06-20 .)

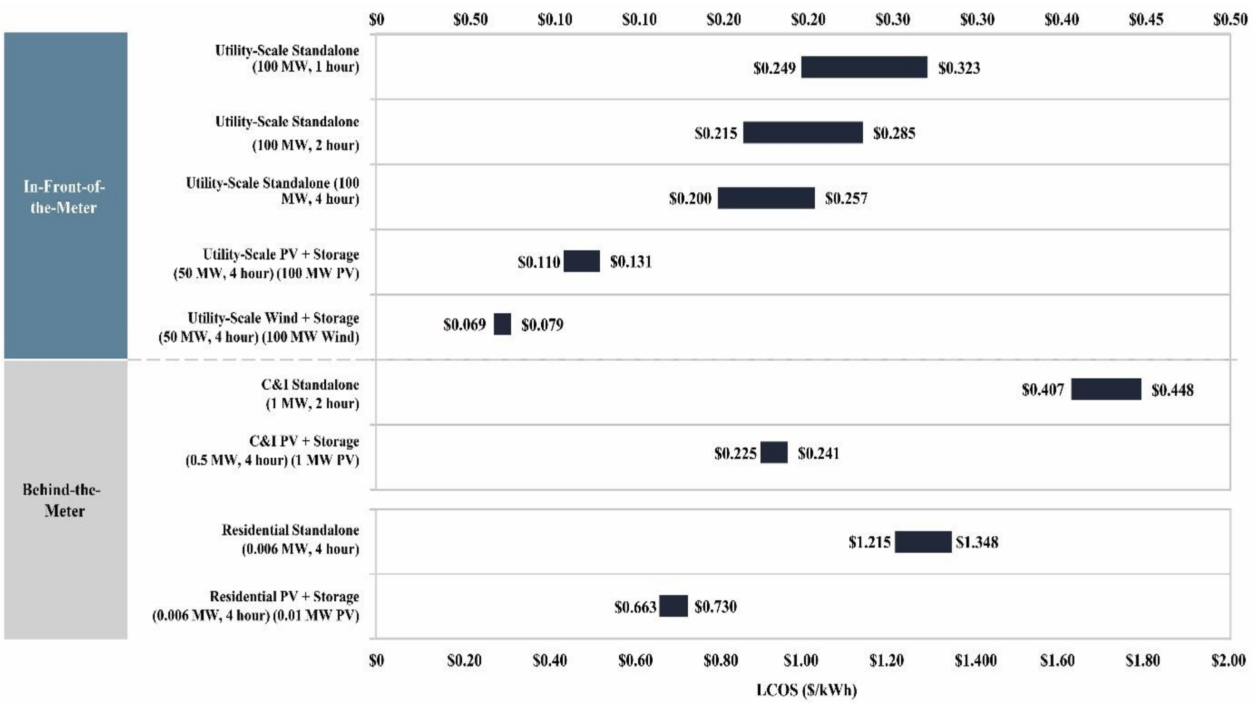
Figure 2-11 Levelized Cost of Storage for Energy Storage Systems in 2023

Lazard conducted an analysis of the LCOS for lithium-ion battery (LFP and NMC) based front-of-meter energy storage systems in typical utility-scale applications — including independent utility-scale storage, utility-scale PV + storage, and utility-scale wind + storage — as well as behind-the-meter storage systems in industrial and commercial, and residential applications, including the cases of standalone storage and PV + storage respectively.[49]

As shown in Figure 2-12, the LCOS of behind-the-meter storage is higher than that of front-of-meter storage, and the LCOS of residential storage is higher than that of industrial and commercial storage, as expected, which indicates that smaller-scale energy storage systems tend to have higher LCOS. The results

[49] LAZARD，2023 Levelized Cost Of Energy+ [R]. 2023-04. https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/

of analysis also suggests that regardless of whether it is behind-the-meter or front-of-meter storage, the LCOS of standalone energy storage systems is higher than that of renewable energy co-located systems (i.e., PV + storage or wind + storage). This shows that integration of energy storage systems with renewable generation benefits from lower-cost renewable electricity, making them economically more viable. The specific LCOS analysis for different energy storage scenarios is summarized as follows:



Source: LAZARD，2023 Levelized Cost Of Energy+ [R]. 2023-04.https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/)

Figure 2-12 LCOS of Front-of-Meter and Behind-the-Meter Energy Storage

- **Front-of-meter storage:** The LCOS for a 100MW/4-hour utility-scale standalone energy storage system ranges from USD0.200 to 0.257 per kWh; For a 50MW/4-hour utility-scale PV + storage system co-located with 100MW of solar PV, the LCOS is between USD0.110 and 0.131 per kWh; For a 50MW/4-hour wind + storage system paired with 100MW of wind power, the LCOS is between USD0.069 and 0.079 per kWh; These represent approximately 55% and 35%, respectively, of the LCOS of the 100MW/4-hour standalone utility-scale storage system.

- **Behind-the-meter-storage:** The LCOS for a 1MW/2-hour standalone industrial and commercial (I&C) energy storage system is USD0.407 to 0.448 per kWh; For a 1MW PV + 0.5MW/4-hour I&C hybrid energy storage system, the LCOS is USD0.225 to 0.241 per kWh, approximately 54% of that of the standalone 1MW/2-hour C&I energy storage system. For residential applications, the LCOS of a 6kW/4-hour standalone household energy storage system is USD1.215 to 1.348 per kWh; When integrated with a 10 kW PV system, the LCOS of the 6 kW/4-hour residential PV + storage system drops to USD0.663 to 0.730 per kWh, also about 54% of that of the standalone 6 kW/4-hour residential energy storage system.

2.3.3 China's energy storage system costs

According to survey organized by the China Energy Storage Alliance (CNESA), which collected inputs from technical experts and enterprises representing various industrial segments, the key technical indicators of mainstream domestic energy storage technologies, as well as the current and projected energy storage system costs in 20230, are shown in Table 2-8.

Table 2-8 Technical and Economic Indicators of Energy Storage Technologies in China, 2024

Technology		Scale of application	Response time	Number of cycles	Annual attenuation rate	Calendar life	Charging and discharging efficiency	Current storage system cost	Storage system cost in 2030
Mechanical energy storage	**Pumped hydro**	1,000,000 kilowatts level	Minute level	/	No attenuation	40-60 years	75%-80% (Comprehensive efficiency of the unit)	CNY750-1000/kWh	CNY875-1125/kWh
	Flywheel	10,000 kilowatts level	Millisecond level	>millions	No attenuation	>20 years	85%-91%	CNY4000-6000/kW	CNY1500-3000/kW
	Compressed air	100,000 kilowatts level	Minute level	>20000	No attenuation	>30 years	60%-75%	CNY800-1500/kWh	CNY500-1000/kWh
	Gravity energy storage	10,000 kilowatts level	Second level	/	No attenuation	Over 50 years	80%-85% (tower type)	CNY3000-5000/kWh	CNY2000-3000/kWh
Electrochemical energy storage	**Lead carbon battery**	10,000 kilowatts level	Millisecond level	3000	2%/years	10 years	80%	CNY1000/kWh	CNY850/kWh
	Lithium iron phosphate	100,000 kilowatts level	Millisecond level	8000-12000	2%	10-15 years	80%-85%	CNY800-1200/kWh	CNY500/kWh
	Semi-solid lithium battery	1,000 Kilowatt-level	Millisecond level	≥6000	2%	10-15 years	80%-85%	CNY1000-1500/kWh	CNY800/kWh
	Lithium titanate battery	1,000 Kilowatt-level	Millisecond level	>30000	2%	20 years	85%-90%	CNY3000-4000/kWh	CNY1800-3500/kWh

Technology		Scale of application	Response time	Number of cycles	Annual attenuation rate	Calendar life	Charging and discharging efficiency	Current storage system cost	Storage system cost in 2030
	Sodium ion battery	10,000 kilowatts level	Millisecond level	3000-6000	2%	10 years	80%-85%	CNY1200-1600/kWh	CNY800/kWh
	Vanadium flow battery	100,000 kilowatts level	Millisecond level	>20000	＜1%	>20 years	60%-75%	CNY2000-3000/kWh	CNY1500-1800/kWh
	Zinc-bromine flow battery	1,000 Kilowatt-level	Millisecond level	>6000	＜1%	>10 years	60%-75%	CNY2000-2300/kWh	CNY1500/kWh
	Iron-chromium flow battery	1,000 Kilowatt-level	Millisecond level	>20000	＜1%	>20 years	65%	CNY2000-3000/kWh	CNY1000-1400/kWh
Electromagnetic energy storage	**Hybrid supercapacitor**	10,000 kilowatts level	Millisecond level	Tens of thousands of times	1.20%	15 years	90%	CNY3000～4000/kW(5C)	CNY1000～2000/kW

Data source: China Energy Storage Alliance

The cost of energy storage systems in China is notably competitive on the international stage. According to research by BloombergNEF (BNFEA), the average price of a four-hour turnkey energy storage system worldwide in 2023 was USD263/kWh, marking a significant decrease from 2022. In China, the average price for a 4-hour turnkey energy storage system based on available capacity is approximately USD324/kWh. Compared to other international markets, China's energy storage system costs are on average 40% lower than those in the United States and 26% lower than in Europe. This positions China with a substantial cost advantage in the global energy storage market.[50]

2.4 Energy storage market

2.4.1 Scale of energy storage market

According to CNESA statistics, DataLink Global Energy Storage Database[51], as of the end of 2023, the global cumulative installed capacity of operational energy storage projects in power system reached 289.22GW, representing an annual growth rate of 21.9%. In 2023, the newly commissioned installed capacity of energy storage projects reached 52.0GW — with an annual increase of 69.5%. Electrochemical energy storage accounted for 87% of new energy storage[52], and the newly commissioned capacity reached a record high of 45.6 GW.

(1) Installed capacity

Pumped hydro storage: Pumped hydro storage is currently the most mature large-scale energy storage technology, which offers the best overall performance and provides critical services in many economies worldwide to ensure the safe and stable operation of power systems, dominating energy storage in power system with the largest share. However, in recent years, as new energy storage projects have developed rapidly, its share of total installed capacity has been declining annually. In 2023, which fell below 70% for the first time — a decrease of 12.3% compared to that in 2022. Due to high investment costs and geographical constraints, pumped hydro storage is not suitable for construction in water-scarce, flat terrain or areas with limited application space. (Figure 2-13)

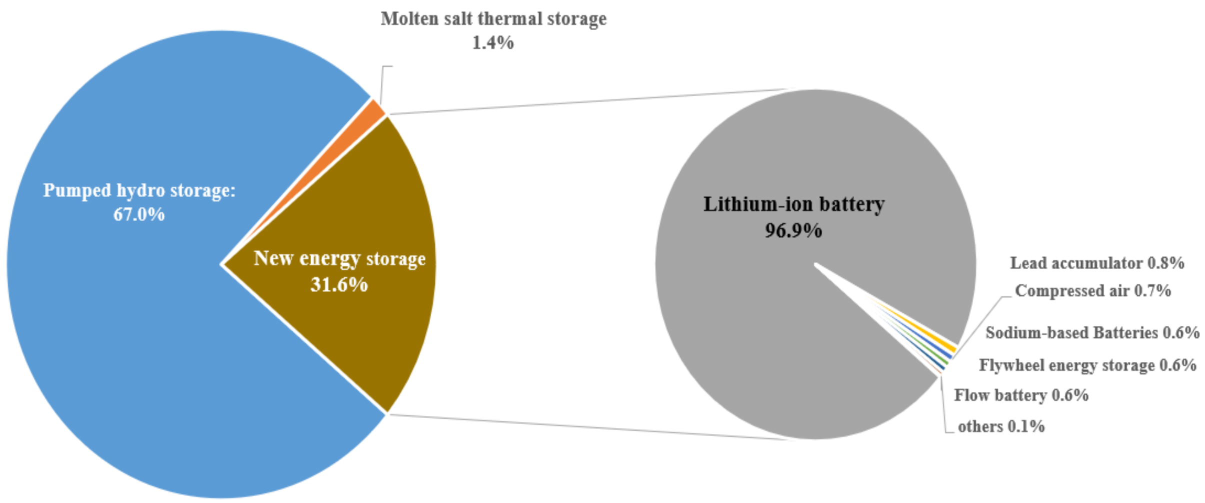
New energy storage: New energy storage technologies, especially electrochemical energy storage, have experienced rapid development in recent decade. The global cumulative installed capacity of new energy storage increased from 2.9GW in 2017 to 91.3GW in 2023 — with an average annual growth rate of 80% over the past seven years. As of the end of 2022, new energy storage technologies accounted for 31.6% of

[50] BNEF. Cost Research on Energy Storage Systems in 2023: [EB/OL]. https://mp.weixin.qq.com/s/gTSrOmwVgA_nBTE9RAOrXg，2024-01-04.

[51] China Energy Research Society Energy Storage Commission, China Energy Storage Alliance, White Paper on Energy Storage Industry Research 2024 [R]. 2024

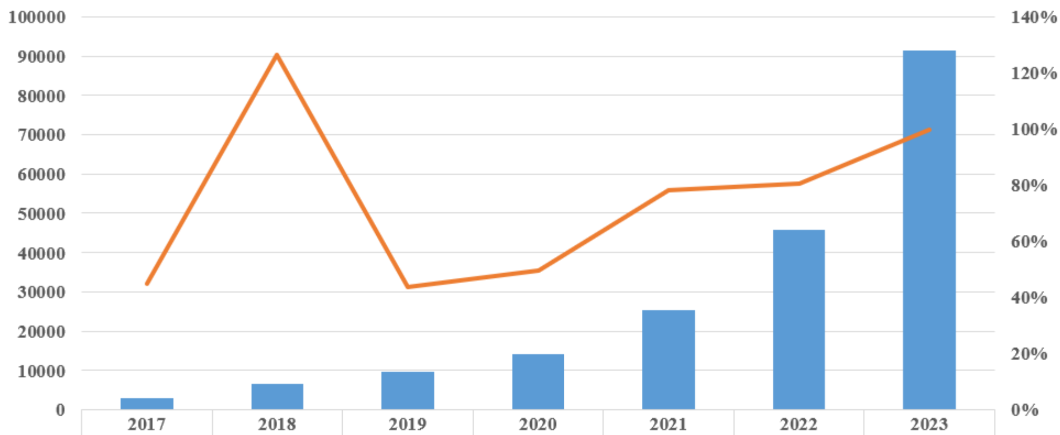
[52] In this report, "new energy storage" refers to energy storage technologies that output electricity as the primary form, excluding pumped hydro storage.

the total installed capacity of power system energy storage world-wide; Among them, lithium-ion batteries hold an absolute dominant position, accounting for nearly 97%. (Figure 2-14)



Source: CNESA

Figure 2-10 Installed Capacity of Power System Energy Storage by Technology, 2020-23



	2017	2018	2019	2020	2021	2022	2023
Installed capacity (MW)	2926.6	6625.4	9520.5	14247.3	25366.1	45749.1	91325.8
Annual growth rate	45.0%	126.4%	43.7%	49.6%	78.0%	80.4%	99.6%

Source: CNESA

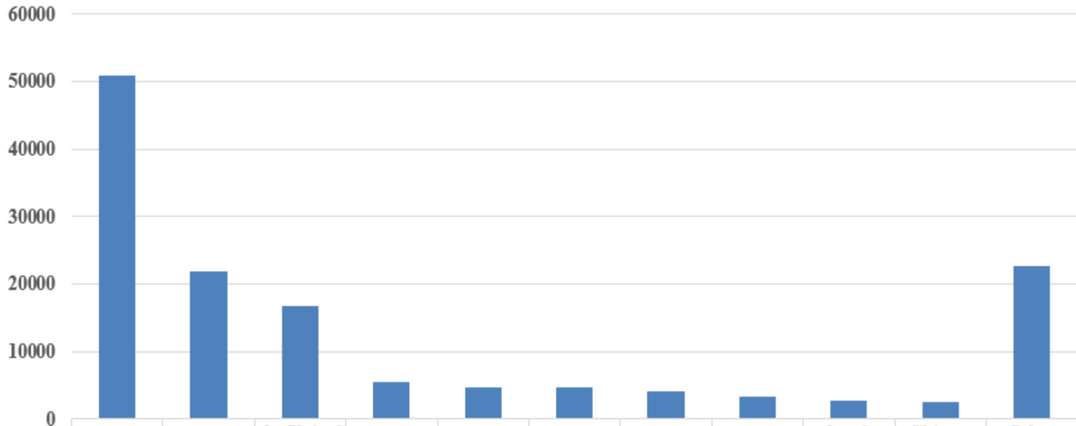
Figure 2-11 Global Cumulative Installed Capacity of New Energy Storage

(2) Geographical distribution

Pumped hydro storage: According to IRENA, as of the end of 2023, the global cumulative installed capacity of pumped hydro storage plants reached 139.8GW. In 2023, the newly added installed capacity was 5,467MW, mainly contributed by China (5,150MW) and the United States (123MW).[53] The top 10

[53] IRENA, Renewable Capacity Statistics 2024 [R]. 2024

economies in terms of cumulative installed capacity of pumped hydro storage are shown in the figure below. Five of them are APEC economies, namely China; Japan; the United States; Korea; and Chinese Taipei, which together account for 69.2% of global pumped hydro storage capacity. China; Japan; and the United States rank in the top three, with global shares of 36.4%, 15.6%, and 12.0%, respectively.



	China	Japan	the United States	Germany	India	Korea	Italy	Spain	South Africa	Chinese Taipei	Other economies
Installed capacity (MW)	50940	21817	16744	5423	4785.6	4700	4039	3331.4	2732	2602	22737
Global proportion (%)	36.4	15.6	12.0	3.9	3.4	3.4	2.9	2.4	2.0	1.9	16.3

Source: IRENA

Figure 2-12 Top 10 Economies by Installed Capacity of Pumped Hydro Storage, 2023

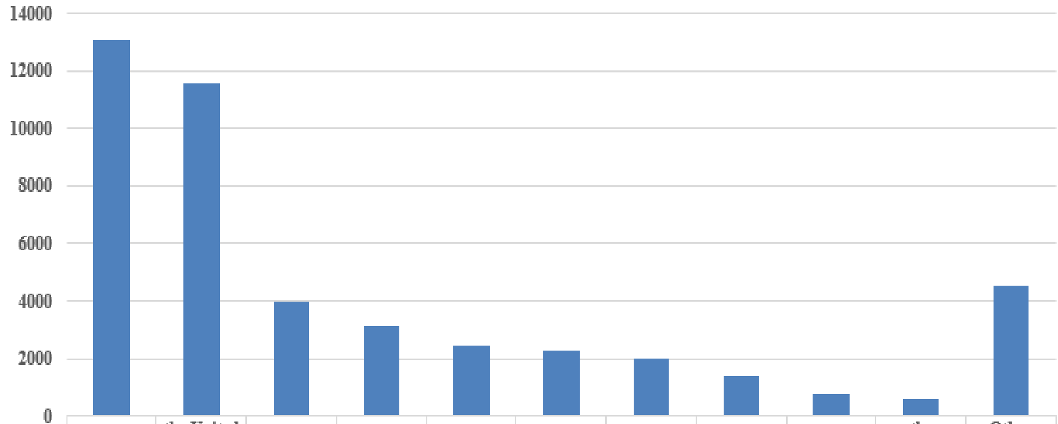
Currently, global pumped hydro storage projects under construction are mainly concentrated in Asia, especially in China. In August 2021, the National Energy Administration of China issued the *Medium- and Long-Term Development Plan for Pumped Hydro Storage (2021–2035)*. According to the plan, the total installed capacity will reach more than 62GW by end of 2025, and approximately 120GW by 2030.[54] Meanwhile, the development of pumped hydro storage in developed economies such as Europe and North America has gradually slowed down. Factors including stricter environmental regulations, increasing risks associated with electricity market reforms, rising construction costs, and rapid technological updates have made it increasingly difficult to build new stations. As a result, the focus has shifted from building new facilities to upgrading and expanding existing ones.[55]

New energy storage: As of the end of 2022, six out of the top 10 economies globally in terms of cumulative installed capacity of new energy storage projects (as shown in Figure 2-16) were APEC economies, namely China; the United States; Korea; Australia; Japan; and the Philippines, with a total installed capacity accounting approximately 70% of the global total. China and the United States rank in the

[54] National Energy Administration, Printing and Implementation of the *Medium- to Long-Term Development Plan for Pumped Hydro Stora ge (2021-2035)* [EB/OL]. http://www.nea.gov.cn/2021-09/09/c_1310177087.htm ，2021-09-09.

[55] China Energy Research Society Energy Storage Commission, China Energy Storage Alliance, White Paper on Energy Storage Industry Research 2023 [R]. 2023

top two positions, both with cumulative installed capacities exceeding 10GW, significantly outpacing other economies.



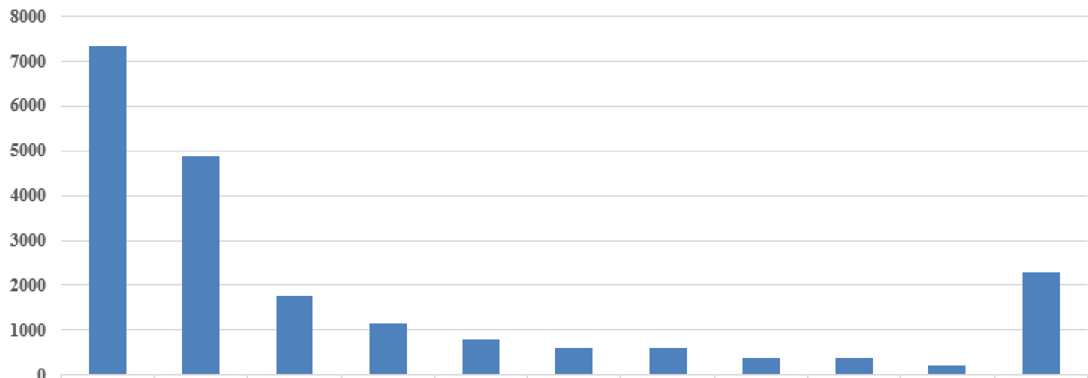
	China	the United States	Germany	The UK	Korea	Australia	Japan	Italy	Ireland	the Philippines	Other economies
Installed capacity (MW)	13076.9	11539.1	3963.6	3147.9	2474.9	2267.1	1992.5	1397.3	763.6	605.2	4521
Global proportion (%)	28.6	25.2	8.7	6.9	5.4	5.0	4.4	3.1	1.7	1.3	9.9

Source: IRENA

Figure 2-13 Top 10 Economies by Installed Capacity of New Energy Storage, 2022

In 2022, five out of the top 10 economies globally in terms of installed capacity of energy storage projects newly put into operation (as shown in Figure 2-17) were from APEC economies, who namely China; the United States; Australia; Japan; and the Philippines, whose newly added capacity collectively accounting 69% of the global total; China and the United States rank in the top two positions, with shares of 36.0% and 23.9%, respectively.

It is evident that the APEC region contributes to approximately 70% of the global total, whether considering cumulative installed capacity or newly added capacity. The APEC region has therefore emerged as the most significant market worldwide for new energy storage applications.



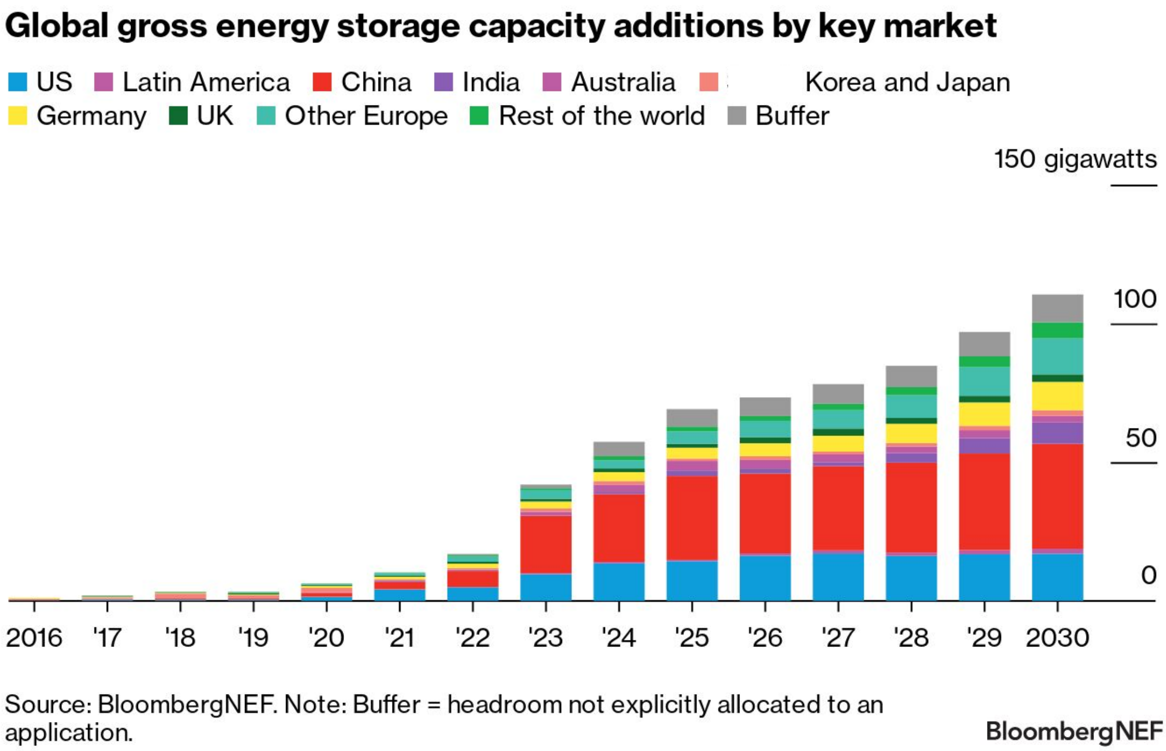
	China	the United States	Germany	Italy	Australia	The UK	Japan	the Philippines	Ireland	Austria	Other economies
Installed capacity (MW)	7347.1	4875.3	1772	1159.5	793	611.5	607.2	364	362	219	2289.4
Global proportion (%)	36.0	23.9	8.7	5.7	3.9	3.0	3.0	1.8	1.8	1.1	11.2

Source: IRENA

Figure 2-14 Top 10 Economies by Newly Installed Capacity of New Energy Storage in 2022

2.4.2 Outlook of the energy storage market

As shown in Figure 2-18, according to BloombergNEF forecast, global energy storage capacity will grow at a compound annual growth rate of 27% from 2023 to 2030. It is projected that by 2030, the global cumulative installed energy storage capacity will reach 650GW/1,877GWh, with annual new installations reaching 110GW/372GWh; Among which, the Asia-Pacific remains the leader in installed energy storage capacity, expected to account for nearly half (47%) of new installations by 2030; The Europe, Middle East, and Africa (EMEA) region will account for 24% of annual energy storage deployments (in GW); The Americas will account for 18% of annual energy storage deployments by 2030.[56]



Source: BNEF

Figure 2-15 Annual New Installed Energy Storage Capacity in Main Storage Markets

[56] BNEF, 2H 2023 Energy Storage Market Outlook [EB/OL]. https://about.bnef.com/blog/2h-2023-energy-storage-market-outlook/ , 2023-10-09.

Chapter III Evaluation and Specification of Energy Storage System

3.1 Methods for assessing energy storage technologies

3.1.1 Key metrics for evaluating energy storage systems

This chapter summarizes the key technical indicators proposed in literature for evaluating energy storage technologies from three dimensions: energy storage capability, performance, and costs. It should be noted that there is no unified definition for these evaluations. Different stakeholders — such as research institutions, manufacturers, integrators, engineering contractors, and EPC providers — may tailor the evaluation indicators by adding or removing certain metrics based on specific requirements to meet their assessment objectives.

(1) Criteria for assessing technical performance

The technical capability of energy storage mainly evaluates the grid-friendly performance of the energy storage system beyond its basic power control functions. As shown in Figure 3-1, the evaluation indicators for energy storage technical capabilities mainly include seven second-level indicators, namely, moment of inertia, reactive power control, black start, grid adaptability, overload capacity, low voltage ride-through capability, and high voltage ride-through capability.[57]

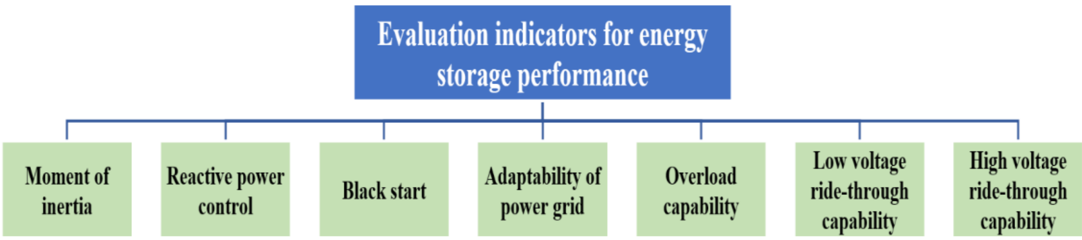


Figure 3-1 Indicators for Evaluating Technical Performance of Energy Storage

(2) Performance assessment for energy storage projects

Energy storage project performance mainly refers to the technical characteristics and functional

[57] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023

measurement indicators closely related to the capacity, charging energy, discharging energy, safety, environment, application, and usage aspects of the energy storage system project. The evaluation indicators mainly include six second-level indicators, namely power/energy, basic energy charging/discharging indicators, lifespan, application, safety, environment, and site conditions. As shown in Figure 3-2, each second-level indicator further includes several third-level indicators.

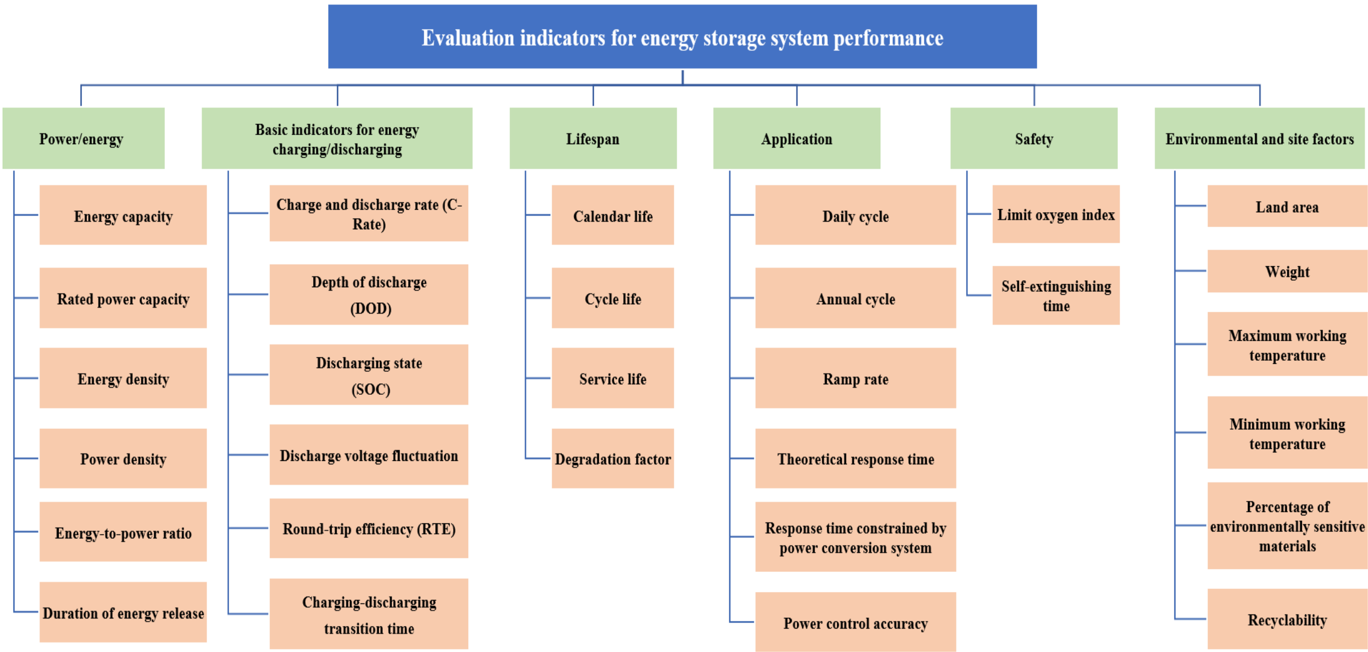


Figure 3-2 Performance Assessment for Energy Storage Project

(3) Indicators for evaluating energy storage project costs

The full life cycle costs of an energy storage system project mainly includes three major components: capital expenditure (CapEx), operational expenditure (OpEx), and decommissioning costs. Correspondingly, the evaluation indicators for energy storage project costs can be categorized into three second-level indicators: construction, operation, and decommissioning costs of the energy storage system. Among which, two types of construction costs are particularly important: the unit capacity construction cost, i.e., the cost per kW — capacity cost; the unit investment cost per kWh of stored energy — energy cost. These two are key economic parameters of an energy storage project.[58]

As mentioned before, the levelized costs based on full life cycle modeling has become a widely accepted indicator for evaluating the economics of energy projects. The levelized cost evaluation indicators for energy storage projects include Levelized Cost of Energy (LCOE) and Levelized Cost of Storage (LCOS). Both LCOE and LCOS reveal the average price required to sell a unit of energy output, considering all project

[58] Du Zhongming et al., New energy storage technologies for power systems [M]. Beijing: China Electric Power Press, 2023

costs of the energy storage station (including taxes, financing, operations, maintenance, and other expenses); However, compared to LCOE, LCOS explicitly incorporates components and concepts specific to energy storage, including clearly defined costs such as the costs of charging the energy storage system, and the costs associated with adding or replacing the energy storage equipment. Its terminology definition is more comprehensive, accurate, and standardized. Therefore, current international energy storage projects tend to adopt the LCOS indicator.[59,60]

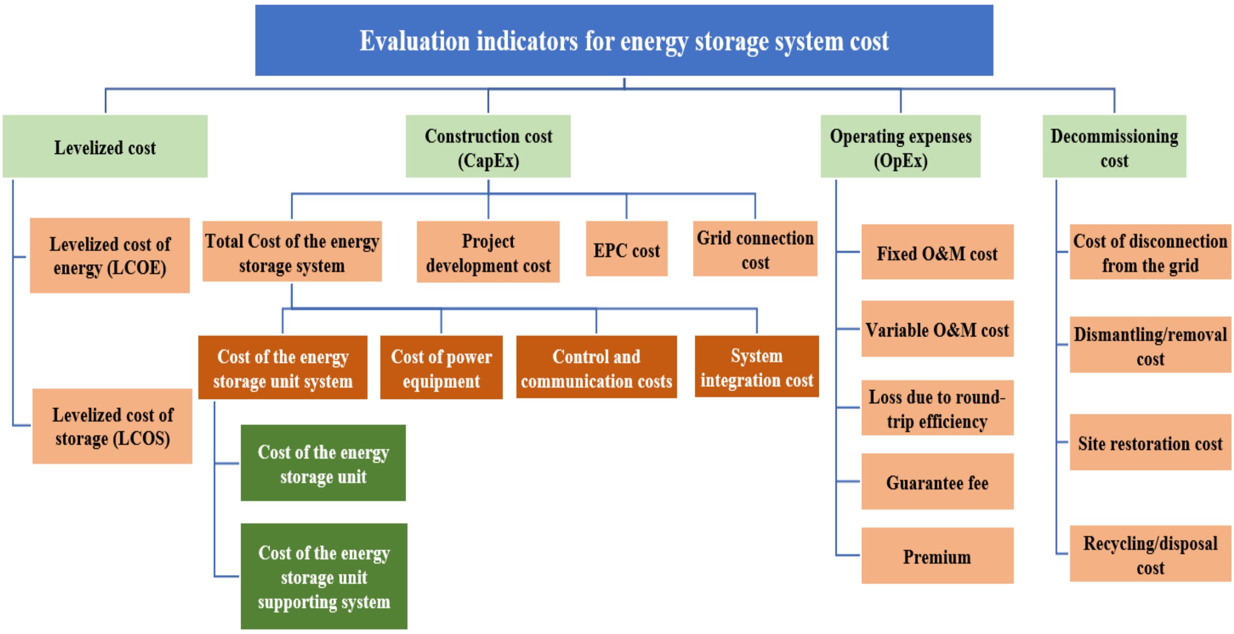


Figure 3-3 Indicators for Evaluating Energy Storage Project Costs

3.1.2 Methods for evaluating energy storage technologies

There are many types of energy storage technologies, each with its own advantages and disadvantages in terms of cost, efficiency, scale, safety, and performance. The development and utilization of energy storage technologies are presently in a diversified stage of advancement, characterized by notable differences in their techno-economic benefits and applications across various technologies. Due to the fact that some energy storage technology is not mature, many characteristic parameters are represented by a hybrid mean, involving mixed qualitative and quantitative indicators and numerous fuzzy factors, making it suitable for evaluation using fuzzy comprehensive evaluation methods. This method is based on fuzzy mathematics that applies the principle of fuzzy relation synthesis to quantify some unclear boundary and difficult-to-quantify factors, thereby conducting a comprehensive evaluation of the membership grade status of the evaluated object from

[59] DOE，2022 Grid Energy Storage Technology Cost and Performance Assessment[R]. 2022-08. https://www.energy.gov/eere/analysis/2022-grid-energy-storage-technology-cost-and-performance-assessment

[60] LAZARD，Lazard's Levelized Cost of Energy+ 2024[R]. 2024-06. https://www.lazard.com/research-insights/levelized-cost-of-energyplus/

multiple factors.[61,62]

The processes of evaluation for energy storage technologies based on the fuzzy comprehensive evaluation method include several main steps, as shown in Figure 3-4. The steps of the evaluation include: i) Define the energy storage application scenario and identify the candidate energy storage technology types; ii) Mapping application condition and energy storage technologies based on key technical indicators such as power rating, charge/discharge duration, charge/discharge rate, and response time of the energy storage technology, for preliminary screening of suitable technologies for specific application; iii) According to the specific evaluation object and purpose, establish an energy storage technology selection evaluation indicator system that includes indicators such as technical capability, performance and cost; iv) Select a specific application conditions; v) Set weights for each indicator by application; vi) Fuzzy comprehensive evaluation: The process of fuzzy comprehensive evaluation is illustrated in Figure 3-5. In this context, the factor set refers to the established evaluation index system, while the judgment set (evaluation set) consists of various overall evaluation results that evaluators may make regarding the evaluated object; vii) Calculate the scores of each indicator for different technologies; and viii) Analysis of evaluation results.

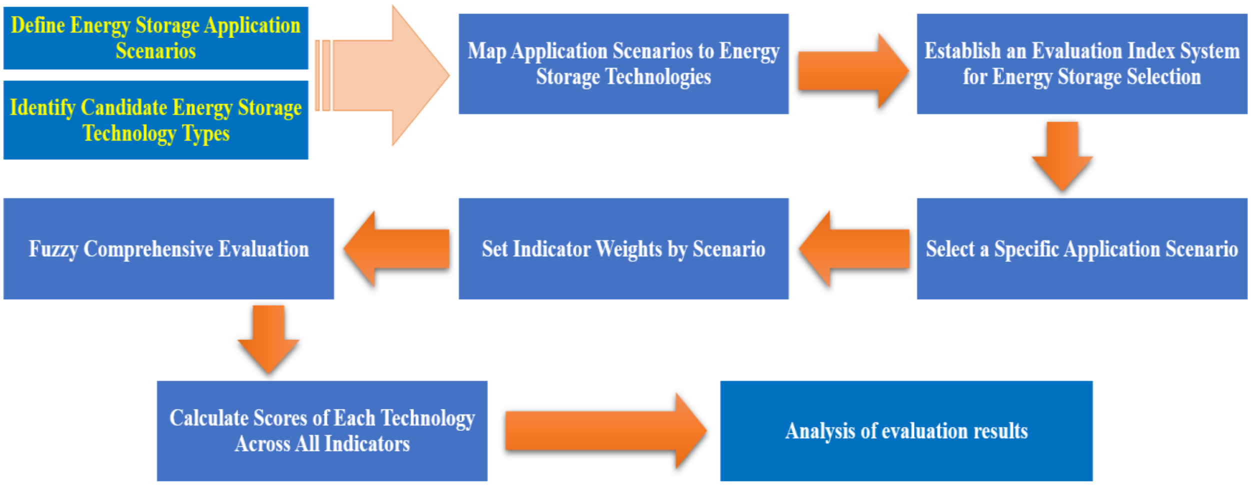


Figure 3-4 Processes of Evaluation for Energy Storage Technologies

[61] China Energy Storage Alliance, Natural Resources Defense Council, Comprehensive Value Assessment and Policy Research of Power-generation-side Energy Storage under the Background of China's Dual-carbon Goals [R]. 2023-08.

[62] China Electric Power Press, Development Roadmap for Large-scale Energy Storage technology [M]. Beijing: China Electric Power Press, 2020

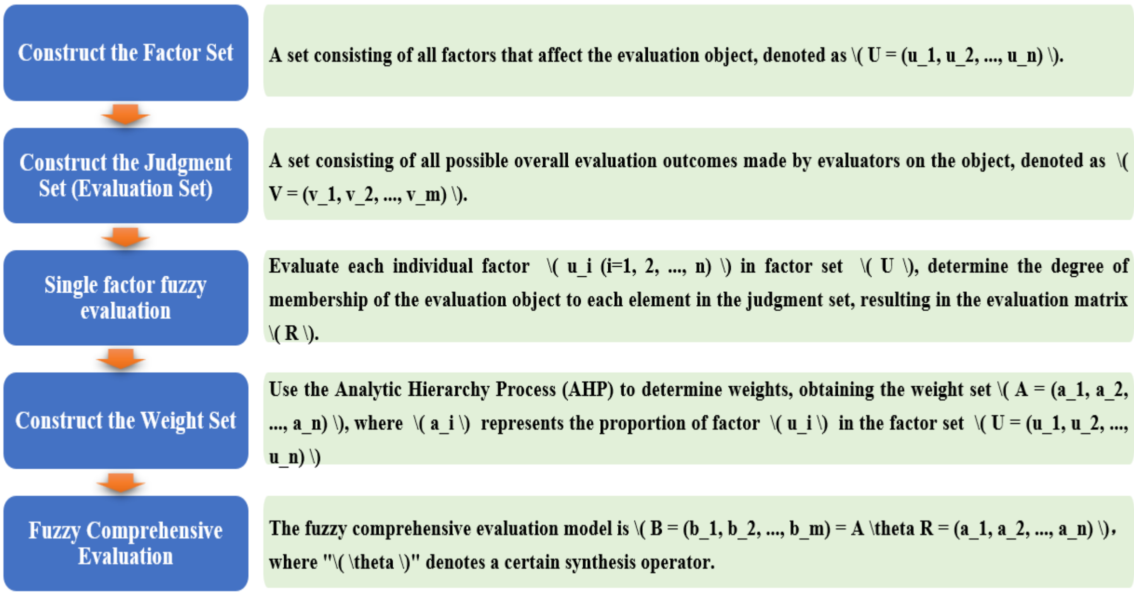
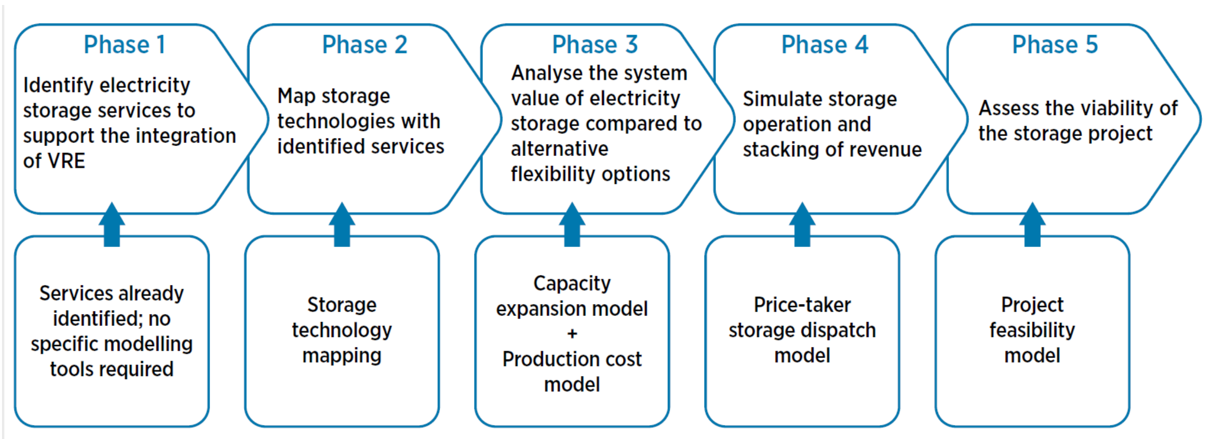


Figure 3-5 Process of Fuzzy Comprehensive Evaluation

3.1.3 Feasibility assessment of energy storage projects

In March 2020, the International Renewable Energy Agency (IRENA) released the report titled "*Electricity Storage Valuation Framework: Assessing System Value and Ensuring Project Viability*".[63] Within this report, IRENA designed and proposed an Electricity Storage Valuation Framework (ESVF) for evaluating energy storage systems. The ESVF framework and its corresponding modeling methods introduce how to assess the value that electricity storage brings to the power grid and the feasibility of energy storage projects. The ESVF framework includes five stages as shown in Figure 3-6.



Source: IRENA，Electricity Storage Valuation Framework: Assessing system value and ensuring project viability[R]. 2020-03

Figure 3-6 Stages of the ESVF Framework and the Models Used in Each Stage

[63] IRENA，Electricity Storage Valuation Framework: Assessing system value and ensuring project viability[R]. 2020-03. https://www.irena.org/publications/2020/Mar/Electricity-Storage-Valuation-Framework-2020

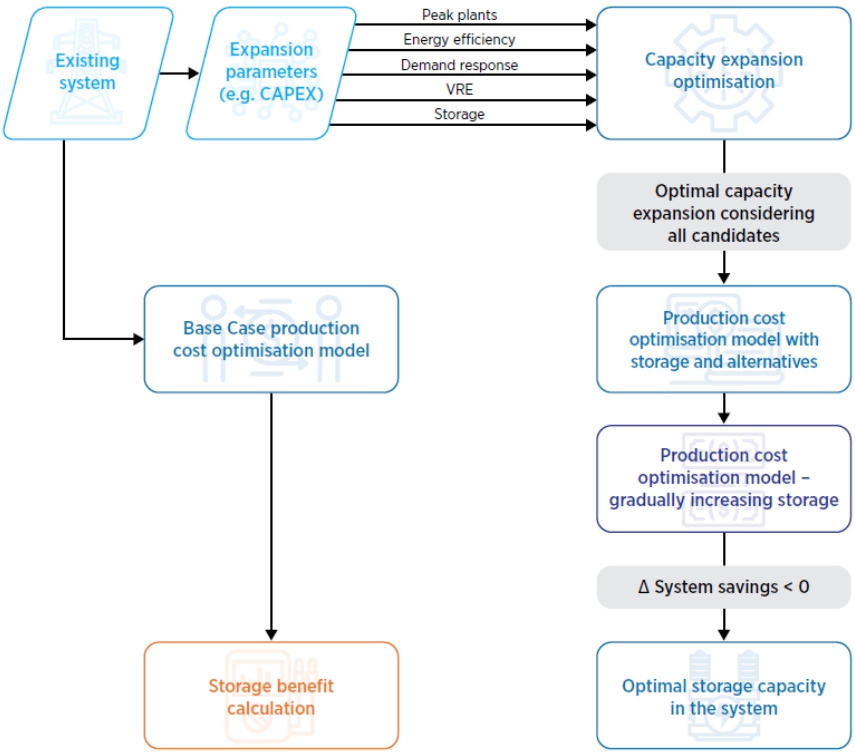
Stage 1 of the assessment is to identify the services provided by electricity storage to support VRE integration. This stage does not require specific modeling tools: Stage 2 is to analyze and create energy storage technologies that provide the required services. This involved scoring or ranking various energy storage technologies based on their suitability for providing the services identified. The analyses in this stage are consistent with those mentioned in the previous section on "assessing energy storage technologies", and specific steps include:

- Establish scoring criteria and score each energy storage technology based on its technical and economic parameters;
- For each application case, the energy storage system should be prioritized accordingly, reflected in the weight allocation of various technical and economic indicators;
- Construct an adaptability matrix of energy storage technologies to application case based on the specific requirements of application;
- Developing scoring by integrating the energy storage technology scores, weights, and adaptability matrix. The calculation process includes calculating the weighted sum of the scores for each energy storage technology according to the assigned weights, then multiplying it by the corresponding adaptability score from the adaptability matrix to obtain the final score of the energy storage technology;
- Rank the suitability of each energy storage technology based on the scoring results from above.

Stage 3 is to analyze the system value of electricity storage relative to other alternative solutions. System value analysis involves conducting a system-level assessment to calculate the total economic benefits of building energy storage facility. The baseline for calculation can be either an existing system or a future plan. This will serve as a reference for evaluating the deployment of energy storage systems to reduce overall system costs. Compared with other alternative solutions, such as improving energy efficiency, demand response, and building new fossil fuel power plants, electricity storage demonstrates effectiveness in delivering the aforementioned services. From the entire grid perspective, the total value of different services provided by energy storage is ultimately estimated using economic indicators such as capital expenditure (CapEx) and operational expenditure (OpEx). The system value analysis mainly uses two methods: capacity expansion optimization and production cost modeling, which include the following steps as shown in Figure 3-7:

- Capacity expansion optimization aims to minimize system investment and operating costs by optimizing the installed capacities of different resources (energy storage and generation). Taking energy storage as an example, the optimal power and energy capacities of the storage system need to be decided. It is noted that IRENA has developed FlexTool software for system-level analysis such as capacity expansion and production cost simulation. This software can be free downloaded from: https://www.irena.org/Energy-Transition/Planning/Flextool;

- Build a production cost model for the baseline system to estimate system operating costs;
- Build a production cost model for the newly added energy storage system. The power and capacity of the new energy storage system are obtained from in Step 1;
- Gradually increase the energy capacity (charge/discharge duration) of the energy storage system and run the production cost model to find the optimal storage duration while reducing production costs;
- Compare the generation costs from Steps 2 and 4, and analyze the potential benefits of energy storage.



Source: IRENA，Electricity Storage Valuation Framework: Assessing system value and ensuring project viability[R]. 2020-03

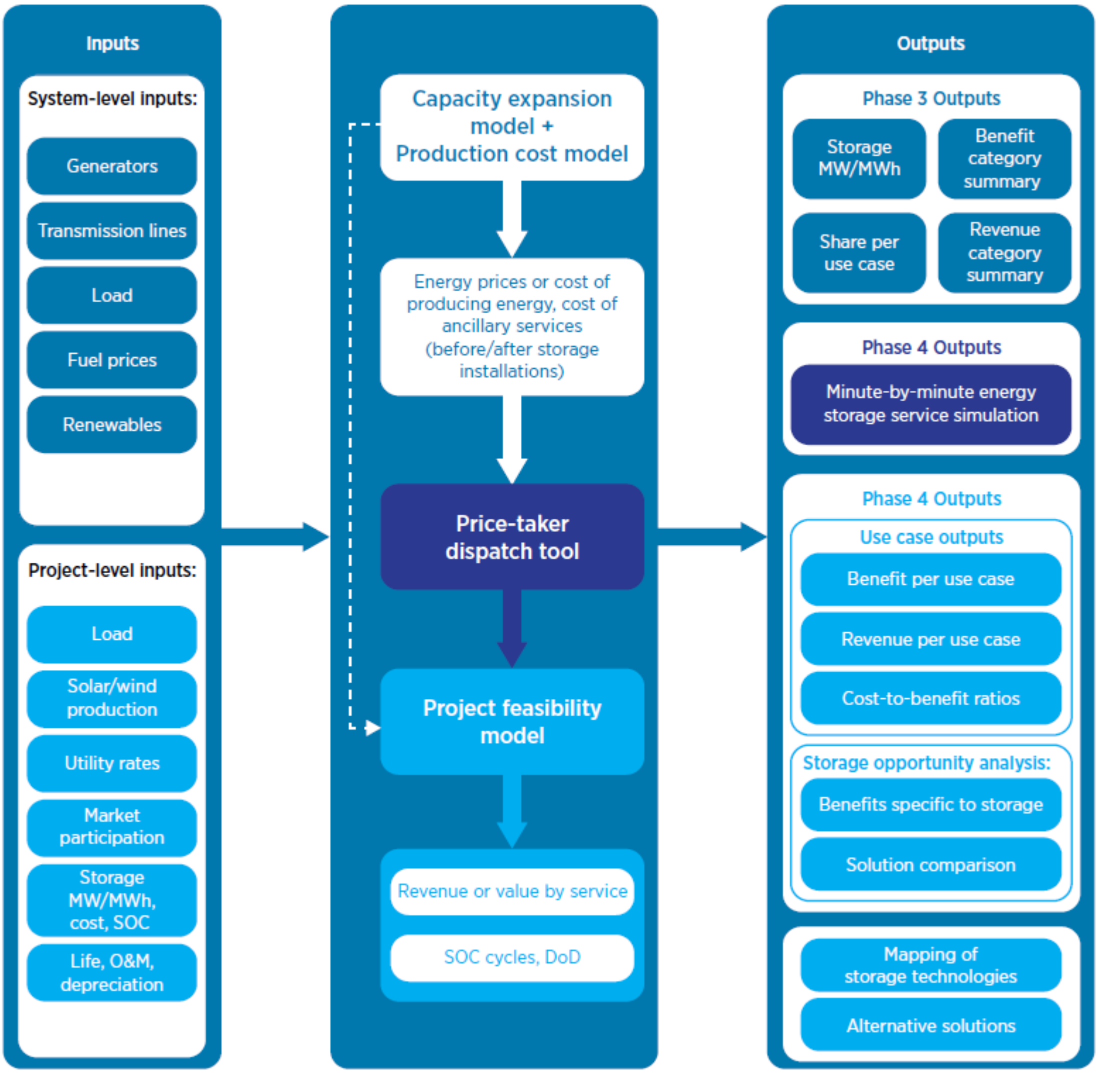
Figure 3-7 Energy Storage System Value Analysis

Stage 4 is Energy Storage Project Operation Simulation. The purpose of simulating an energy storage project's operation is to analyze how the energy storage system can maximize revenue by participating in multiple market transactions under the market environment simulated in Stage 3. This stage can employ a price-taker storage dispatch model. The price-taker storage dispatch model tool is applied to simulate how electric energy storage assets can efficiently enter power market bidding and optimize their operation schedules, thereby maximizing profits through combined revenue streams from markets such as the spot market, ancillary service market, and capacity market. When relevant data inputs are available, this dispatch tool can output energy storage operation status at hourly or sub-hourly intervals for further detailed analysis and optimization. The applied dispatch model tools should be suitable for local day-ahead markets, intraday markets, and other specific market time scales and application environments. If users do not have a dedicated price-taker storage dispatch model tool, they may choose StorageVET 2.0 software developed by the Electric Power Research Institute (EPRI), which is available at https://www.storagevet.com/.

Stage 5 is Feasibility Assessment of Energy Storage Projects. The full life cycle revenue of an energy storage project determines whether the project is economically viable in the end. If it is not feasible, what remedial measures can be taken. As the final stage, the project-level cost and revenue are analyzed, in which costs refer to the investment in constructing and operating the energy storage project, while the revenue refers to the total of project-level and grid-level revenues. For the analysis at this stage, the outputs are measured in monetary units, which may be higher or lower than the system value of the project.

This stage conducts a cost-benefit analysis for a specific energy storage project; therefore, the project feasibility model is essentially a cost-benefit model. It can be further divided into two parts: one is financial cost-benefit analysis, and the other is non-financial cost-benefit analysis, which mainly considers the benefits that the energy storage system brings to the power grid. In addition, the value of the energy storage system can be divided according to the various services it provides. The ESVF framework further breaks down system revenue into specific energy storage projects and services based on the charge/discharge rate (C-rate) of the energy storage system.

Figure 3-8 shows the data and information flow in the simulation and analysis in Steps 3 to 5 for the ESVF Framework.



Source: IRENA， Electricity Storage Valuation Framework: Assessing system value and ensuring project viability[R].2020-03

Figure 3-8 Information Flow in Simulation and Analysis for the ESVF framework

3.2 Technical standards and regulations for energy storage system

With the rapid development of renewable energy and the transition of the global energy landscape, energy storage technology will become a key enabler facilitating green energy utilization. The establishment of energy storage systems, especially new energy storage systems formed by deeply integrating multiple novel energy storage technologies with digital and information technologies, can effectively integrate multiple energy sub-systems such as electricity, heat, cold, gas, and hydrogen, promoting flexible, efficient, balancing energy supply and demand, achieving multi-energy complementary coordinated optimization of energy systems.

APEC economies, including Australia; China; and the United States, particularly China, have become leaders in energy storage technology R&D and demonstration and deployment globally. The formulation and implementation of energy storage technology standards and regulations are important in that they ensure the safe and efficient operation of energy storage systems, guarantee compatibility with current and future energy systems, and support the deployment of energy storage, accelerating the integration and utilization of renewable energy resources.

3.2.1 Technical specifications on the development of energy storage industry

(1) Technical standards for energy storage

i) IEC standards

The International Electrotechnical Commission (IEC) established Technical Committee TC120 on electrical energy storage systems in 2012, responsible for developing standards related to the connection of energy storage systems to the power grid. The committee established 5 working groups focused on terminology, unit parameters and test methods, planning and installation, environmental issues, and safety considerations to develop relevant standards. IEC started standard development from those urgently needed by the market. TC120 plays a crucial role in standardizing grid-integrated EES systems. Their work focuses on system-level aspects rather than individual devices, addressing the interaction between EES systems and electric power systems across various grid applications (transmission, distribution, islanded, and customer installations, including smart grids). Key areas of IEC's standard development for EES include defining unit parameters and testing methods (e.g., IEC 62933-2-1), planning and installation guidelines, environmental considerations (e.g., IEC/TS 62933-4-1), and comprehensive safety requirements for grid-integrated EES systems, particularly for electrochemical-based systems and those undergoing modifications (e.g., IEC 62933-5 series). This extensive body of work aims to ensure the safe, reliable, and efficient integration of diverse energy storage technologies into the global electrical infrastructure, supporting the growing penetration of renewable energy and grid stability.

ii) IEEE standards

The Institute of Electrical and Electronics Engineers (IEEE) published two standard development projects related to energy storage systems: *IEEE P2030.2 Guide for Interoperability of Energy Storage Systems Integrated with Electric Power Infrastructure* in 2014 and *IEEE P2030.3 Standard Test Procedures for Electrochemical Energy Storage Equipment and Systems Used in Power System Applications* in 2016. IEEE focuses on interconnection with larger-scale power grids and system requirements for various energy storage technologies.

IEEE 1679 provides a unified method for assessing performance, lifespan, and safety across different energy storage technologies, helping technology developers evaluate and compare their product performance. The evaluation results help users assess different energy storage technologies. It also outlines an evaluation framework, including performance requirements such as energy efficiency, self-discharge performance, storage performance, and calendar life, as well as safety requirements covering aging and failure mechanisms, safety design, labeling, and usage and abuse conditions. IEEE 1547 is a widely adopted general grid-connection specification for distributed energy resources in North America, specifying clear support functions such as voltage stability, reactive power support, and grid anomaly response.

IEEE 2800 was officially released on 22 April 2022, filling the gap in grid connection specifications for large-scale photovoltaic and energy storage power stations in North America. It specifies unified technical requirements for the capacity and full life cycle performance of inverter-based resources (IBRs) interconnected with transmission and sub-transmission systems. These include, but are not limited to, voltage and frequency ride-through, active and reactive power control, dynamic active power support under abnormal frequency conditions, dynamic voltage support under abnormal voltage conditions, power quality, negative sequence current injection, and system protection.

iii) UL standards

Underwriters Laboratories Inc. (UL) is a standards development organization in the field of safety. The UL 9540 standard for energy storage systems and equipment is the safety standard for energy storage systems in the North American market and serves as an effective pass for entering the North American energy storage market. UL focuses on safety testing standards for energy storage. In recent years, installation codes and standards have been updated to address modern energy storage applications that frequently employ new energy storage technologies. The 2018 editions of the *International Fire Code*, *International Residential Code*, and *NFPA 1 Fire Code* introduce requirements specifically tailored to modern energy storage system applications. The 2020 edition of NFPA 855 *Standard for Installation of Stationary Energy Storage Systems* further refines these requirements. All these codes and standards require electrochemical energy storage systems to be listed under UL 9540.

iv) Energy storage standards in selected APEC economies

In Japan, Japanese Industrial Standards Committee (JISC)'s JISC 8715-2 is a safety standard revised based on IEC 62619; The Korea Battery Industry Association (KBIA) released a certification standard SPS-C KBIA-10104-03-7312 in December 2018, replacing the previous two standards KBIA-10104-01 and KBIA-10104-02. These standards take relevant IEC standards as primary references. In March 2023, the Korean Agency for Technology and Standards (KATS) issued Announcement No. 2023-0027, releasing the new energy storage battery standard KC 62619.

In Australia and New Zealand, besides adopting international standards such as those from IEC, Standards Australia is also developing corresponding standard requirements to ensure energy storage safety. Among them, AS/NZS AS/NZS 5139:2019 *Electrical installations - Safety of battery systems for use with power conversion equipment*, published on 11 October 2019, fills the gap in safety guidelines for emerging residential energy storage industry, especially concerning potential fire hazards caused by batteries, ensuring the safety and reliability of battery energy storage systems, and sets out general installation and safety requirements for battery energy storage systems. Malaysia is accelerating its energy transition deployment through battery energy storage systems, planning to install five 100MW battery storage systems by 2034. The Malaysia Energy Commission (EC) has established the Malaysia Grid Code (MGC). However, as of 2022, due to the lack of near-term plans for installing energy storage at the transmission level, the EC had not yet issued interconnection guidelines for battery energy storage systems with the grid.

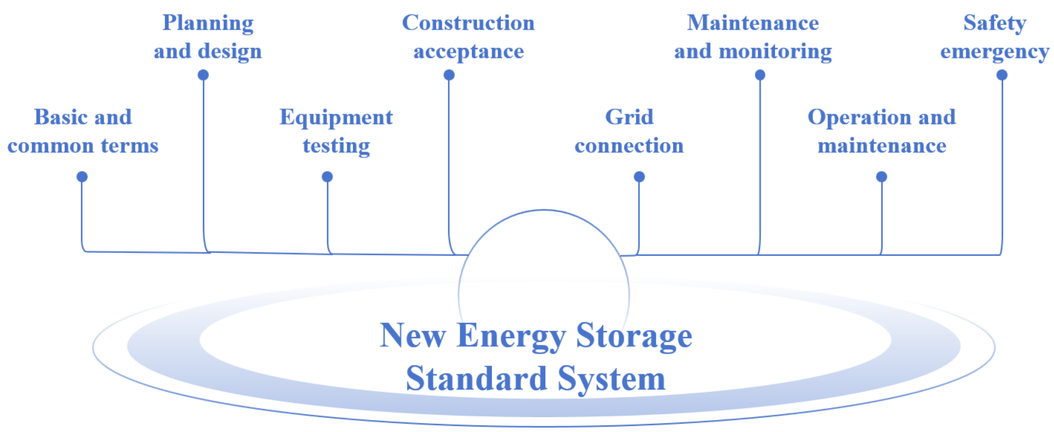
The United States relies on standards development organizations to create standards; government agencies mainly coordinate, participate in standard development, and adopt standards after publication. The US Department of Energy released the Energy Storage Safety Strategic Plan in 2014 and established the Energy Storage Safety Working Group in 2015, which includes three subgroups, one of which is the Standards Working Group, aimed at promoting and coordinating the development and revision of energy storage standards. National Fire Protection Association (NFPA) stipulated NFPA 70, known as the *National Electrical Code (NEC),* aims to reduce risks of electric shock or fire. The latest edition includes additional requirements for battery energy storage systems and aligns with NFPA 855. NFPA 855 was officially published in 2019 and was approved by American National Standards Institute (ANSI) as an American National Standard. It specifies deployment requirements for battery energy storage systems and lists various design and installation considerations, including spacing between battery modules, sprinkler system sizing, ventilation, and related fire protection system requirements. The 2023 edition of NFPA 855 was passed by the NFPA Technical Meeting in June 2022, approved and published by the NFPA Standards Council on August 2022, and became effective on September 2022.

Table 3-1 lists energy storage system related standards in selected APEC economies.

Table 3-1 Energy Storage Standards of Selected APEC Economies

Economy	S/N	Standard No.	Standard name
Japan	1	JIS C8715-1	Secondary lithium cells and batteries for use in industrial applications—Part 1: Tests and requirements of performance
	2	JIS C8715-2	Secondary lithium cells and batteries for use in industrial applications—Part 2: Tests and requirements of safety
	3	JIS C4412-1	Safety requirements for electric energy storage equipment, part 1: General requirements
	4	JIS C4412-2	Safety requirements for electric energy storage equipment, part 2: Particular requirements for Separation type power conditioner
	5	JIS F8102	Electrical installations in ships - Electric energy storage equipment using secondary lithium cells and batteries
	6	JIS F8103	Small craft - Electrical devices - Electric energy storage equipment using secondary lithium cells and batteries
Korea	1	KS C 8547	Redox flow battery for use in energy storage system - Performance testing
	2	KS C8548	Glossary of BESS (Battery Energy Storage System)— Secondary Lithium Battery Systems
	3	KBIA-10104-01	Secondary lithium-ion cell and battery system - Battery energy storage system Part 1: Safety test
	4	KBIA-10104-02	Secondary lithium-ion cell and battery system - Battery energy storage system Part 2: Performance test
	5	SGSF-025-3-1	Information Communication Between Internal Devices in Energy Storage Systems Part 1: General requirements
	6	JSGSF-025-4	General performance Testing requirement of PCS for energy storage systems
	7	SGSF-025-5-1	Energy storage system Part 1: General requirements
	8	SGSF-025-5-2	Energy storage system Part 2: Performance Test Methods
	9	SGSF-045-1-3	Electrical Energy Storage Systems -Part 3: General Requirements and Management and Test Method of Electrical Energy Storage System for Demand Side Management
	10	SGSF-045-1-4	Energy storage system Part 4: Requirements for Information Exchange in Energy Storage Systems
Australia	1	AS/NZS 4755.3.5	Demand response capabilities and supporting technologies for electrical products - Interaction of demand response enabling devices and electrical products-Operational instructions and connections for grid-connected electrical energy storage (EES) systems
	2	AS/NZS 4777.2	Grid connection of energy systems via inverters, Part 2: inverter requirements
	3	AS/NZS 5139	Electrical installations - Safety of battery systems for use with power conversion equipment
The United States	1	NFPA 1	Fire Code
	2	NFPA 70	National Electrical Code (NEC)
	3	NFPA 78	Guide on Electrical Inspections
	4	NFPA 791	Recommended Practice and Procedures for Unlabeled Electrical Equipment
	5	NFPA 855	Standard for the Installation of Stationary Energy Storage Systems
	6	NFPA 5000	Building Safety and Construction Code

In China, technical standards for energy storage play a dominant role in ensuring the quality and safety of battery energy storage applications.[64] Since 2013, China has begun developing domestic technical standards for power energy storage systems. Based on a series of industry standards issued for key components and system integration of lithium-ion battery energy storage stations, in February 2023, the Standardization Administration of China (SAC) and the National Energy Administration (NEA) jointly issued the *Guidelines for the Construction of New Energy Storage Standard System*.[65,66] As shown in Figure 3-9, the framework defines energy storage standard system into eight categories: basic general, planning and design, equipment testing, construction and acceptance, grid-connected operation, inspection and monitoring, operation and maintenance, and safety and emergency response. Among them, standards related to energy storage safety are categorized into six major types including planning and design. Additionally, the safety of energy storage systems extends beyond the battery system itself; the external sub-system, including the safety of the energy storage inverter, Power Conversion System (PCS) are also covered.[67]



Source: Guidelines for the Construction of New Energy Storage Standard System

Figure 3-9 Structure of China's New Energy Storage Standard System

(2) Advancement of performance standards

In recent years, lithium-ion battery energy storage technologies have continued to improve in key performance areas. The technical standard system and application management system oriented towards power system applications have become increasingly complete. Issues related to controllable safety applications have also gradually improved, making it one of the most promising energy storage technologies. Other new energy storage technologies, such as flywheel and compressed air energy storage, although having

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64 State Administration for Market Regulation, Standardization Administration. Lithium-ion batteries for electricity storage GB/T 36276—2018[S]. Beijing Standards Press of China, 2018

65 Hu Juan, Xu Shouping, Yang Shuili, et al. In-depth Study on the Power Energy Storage Standard System [J]. Distribution & Utilization, 2020,37(03): 27-33.DOI: 10.19421/j.cnki.1006-6357.2020.03.005

66 *Notice of the Standardization Administration and National Energy Administration on Printing and Distribution of the Guidelines for the Construction of a New Energy Storage Standard* System (sac.gov.cn) https://www.sac.gov.cn/xw/tzgg/art/2023/art_584bc1a52522490682d3b0482f5155f7.html

67 State Administration for Market Regulation, Standardization Administration. Lithium-ion batteries for electricity storage: GB/T 36276—2018[S]. Beijing Standards Press of China, 2018

relative advantages in certain technical performance, still have significant gaps compared to the needs of power system application in terms of comprehensive techno-economic performance. Corresponding technical standard systems and application management frameworks are not yet fully developed, and their grid connection performance and grid adaptability still need further verification and evaluation.[68] The figure below shows the technical standards in China related to energy storage systems from design and production to system installation, operation and maintenance.

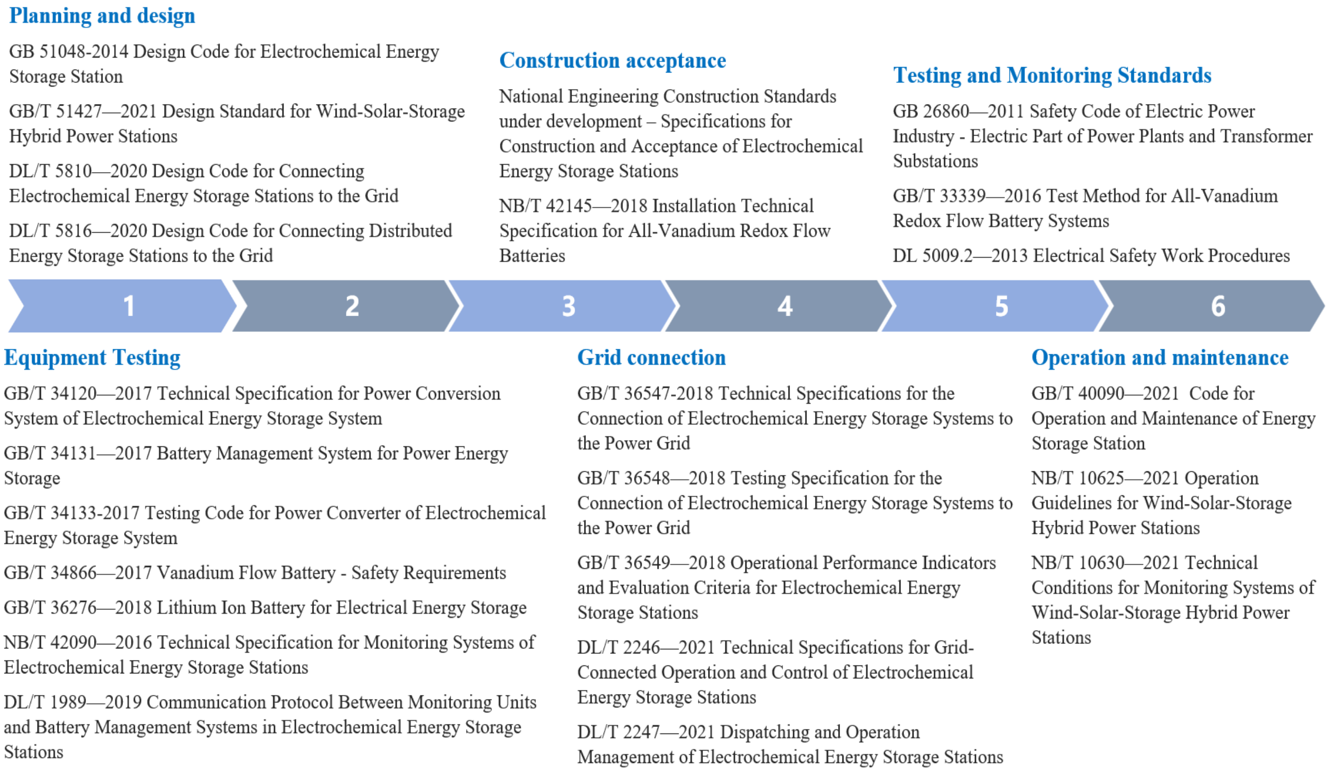

Figure 3-10 Relevant Technical Standards for Energy Storage in China

Performance standards for energy storage technologies, such as energy density, charge/discharge efficiency, lifespan, and reliability, are crucial for improving the economic viability and efficiency of renewable energy systems. For example, performance testing standards such as IEC 62933 and IEC 62056 not only cover battery performance but also include system-level performance evaluations, ensuring that energy storage systems can work efficiently with renewable energy systems. These performance standards encourage manufacturers to develop more efficient energy storage technologies capable of rapidly responding to changes in energy demand, improving energy conversion efficiency, and reducing energy losses. Moreover, high-performance energy storage systems can more effectively store intermittent energy generated by renewable sources such as solar and wind, enhancing the stability and reliability of the entire

[68] Guan Yibiao, Shen Jinran, Liu Jialiang, Qu Zhanzhan, Gao Fei, Liu Shiyang, Guo Cuijing, Zhou Shuqin, Fu Shanshan. Comprehensive Performance Evaluation Standards for Energy Storage Lithium-Ion Batteries Oriented toward Safe and High-Quality Applications [J]. E nergy Storage Science and Technology, 2023, 12(9): 2946-2953

energy system.

(3) Standardization and system operation

As more renewable energy is integrated into power grids, the standardization and interoperability of energy storage systems have become increasingly important. Interoperability standards such as IEEE 1547 and IEC 61850 define detailed protocols for how energy storage systems communicate and collaborate with other parts of the grid. They are two pivotal standards in the realm of grid modernization, particularly concerning Distributed Energy Resources (DERs). IEEE 1547, primarily an American standard, establishes the technical requirements for the interconnection and interoperability of DERs with the electric power system, focusing on aspects like voltage regulation, frequency response, power quality, and ride-through capabilities during grid disturbances to ensure safety and reliable operation. In contrast, IEC 61850 is an international standard defining communication protocols and data models for intelligent electronic devices (IEDs) within substations and increasingly for DERs, enabling seamless interoperability between different manufacturers' equipment through standardized logical nodes and communication services like GOOSE and MMS, thereby facilitating automation, protection, and control of the power system. While IEEE 1547 defines *what* DERs must do to connect to the grid, IEC 61850 provides the framework for *how* these devices communicate and are controlled within the broader grid infrastructure, often with profiles of IEC 61850 being developed to support the functional requirements of IEEE 1547.

These standards ensure that energy storage devices can be seamlessly integrated into broader energy management systems, supporting functions such as demand response, frequency regulation, and peak load shifting. Standardized interfaces and communication protocols simplify the integration of multiple technologies, enabling energy from renewables to be captured, stored, and dispatched efficiently. This not only enhances the flexibility and responsiveness of the energy system but also reduces the complexity and costs of technology implementation, promoting commercialization and large-scale deployment of storage systems.

3.2.2 Promotion of technological innovation through related performance standards

(1) Performance test standard

IEC 62619 focuses safety requirements for secondary cells and batteries, particularly targeting portable sealed secondary lithium-ion batteries. This standard specifies in detail the safety test methods for lithium-ion batteries, including tests for thermal runaway protection, short circuits, overcharging, and over-discharging. Such tests ensure the stability and safety of battery products under extreme conditions, providing technical assurance for their widespread usage. Through rigorous performance testing, IEC 62619 not only improves battery safety but also sets high requirements for battery performance metrics such as energy density, efficiency, and long-term reliability.

Batteries that can safely withstand these extreme conditions are inherently more robust and reliable, leading to longer lifespans and more consistent performance in their intended applications. Therefore, compliance with IEC 62619 assures that batteries are designed and manufactured to minimize risks and operate safely, which is a fundamental aspect of reliable and sustained performance, which makes energy storage system manufacturers continuously optimize product design and material selection, driving continuous innovation and improvement in battery technology.

(2) Manufacturers innovation

Driven by performance standards like IEC 62619, many energy storage technology manufacturers have made significant technological innovations in improving product performance and safety. For example, Tesla's Powerwall home energy storage battery was developed following performance testing standards, using advanced lithium-ion battery technology and a unique thermal management system to enhance product safety and efficiency. In addition, Tesla uses its own software platform to achieve real-time monitoring and management of battery performance, further improving the operational efficiency and lifespan of the battery systems. Another example is LG Chem, which made significant innovations in battery management systems (BMS), developing advanced algorithms to optimize battery charging and discharging processes, reduce energy loss, and extend battery life. These innovations not only meet the requirements of technical standards like IEC 62619 but also significantly enhance the market competitiveness of energy storage products, and facilitate the applications of storage systems.

(3) Impacts on storage system efficiency and lifespan

Performance standards have a direct impact on the efficiency and lifespan of energy storage systems. By establishing rigorous performance testing and requirements, these standards ensure that energy storage systems deliver maximum energy output while minimizing energy loss. For example, by improving battery chemistry and structural design, manufacturers can develop battery products with higher energy density and longer lifespans. This not only reduces energy loss during storage and conversion but also extends the overall service life of the energy storage system, reducing the frequency of maintenance and replacement. Furthermore, the implementation of performance standards promotes better integration of energy storage systems with renewable energy resources. High-efficiency and long-life energy storage solutions enable renewable energy systems to respond more effectively to production fluctuations and demand changes, enhancing the stability and reliability of the entire energy system. This is of importance for increasing the proportion of renewable energy in the energy mix.

3.2.3 Standardization and interoperability

The Electric Power Research Institute (EPRI) has conducted pioneering work in grid interoperability, developing a series of standards and guidelines aimed at facilitating seamless collaboration between energy storage systems and the grid. These standards cover multiple aspects, including device access, communication protocols, data exchange formats, and security requirements for energy storage systems. One important standard defines how energy storage systems communicate with the grid via Advanced Metering Infrastructure (AMI), specifying protocols and security measures for data exchange to ensure data accuracy and secure communication. The standards developed by EPRI also include guidance on how energy storage devices respond to grid signals, such as how to quickly and effectively release or absorb energy during demand response events to help balance grid load. The implementation of these standards helps enhance grid flexibility and reliability, especially in addressing grid stability challenges posed by the integration of high proportions of renewable energy.

As an example, the energy storage project implemented by Monterey Bay Community Power (MBCP) in California adopted interoperability standards developed by EPRI to integrate large-scale lithium-ion battery energy storage systems into the local grid. This system not only supports the storage of solar and wind energy but also provides necessary energy support during peak electricity demand, effectively alleviating pressure on the grid. This project ensured seamless integration of the energy storage system with existing grid management systems through EPRI's standards, enabling real-time data monitoring and management, thereby improving system responsiveness and operational efficiency. In addition, the energy storage system further enhanced grid reliability and economic benefits by participating in grid service markets such as frequency regulation and emergency backup services.

Standardization and interoperability of energy storage technologies are critical for integrating renewable energy. As more solar and wind energy projects are deployed, the grid must manage increasing amounts of intermittent and unstable energy sources. Energy storage systems provide an effective solution by balancing supply and demand. Interoperability standards developed by EPRI ensure that these systems can work efficiently with the grid and other energy systems, playing a vital role in load shifting, frequency regulation, and emergency response. For example, when solar power generation peaks do not align with periods of low consumption, energy storage systems can store excess solar electricity and release it during peak demand, reducing reliance on traditional power plants and lowering carbon emissions. The implementation of interoperability standards not only improves the efficiency of this process but also reduces operation and maintenance costs by ensuring seamless exchange of data and commands between different devices and systems and optimization of energy systems.

3.2.4 Standards promoting global market access for storage products

International standards such as the IEC 6248 series provide common technical specifications and safety guidelines for the sale and deployment of energy storage equipment in global markets. These standards not only help manufacturers optimize product design to meet regulatory requirements across economies but also promote global trade and technology transfer. By implementing internationally recognized technical specifications, energy storage solutions can more easily integrate into global energy markets, supporting economy renewable energy expansion plans. Such international coordination also helps promote harmonization of global energy policies, enhances global capacity to address climate change, and accelerates the transition toward low-carbon energy systems.

IEC 61427 is a series of international standards regarding the use of secondary batteries, particularly specifying performance and reliability requirements when used in conjunction with photovoltaic systems. It provides performance and durability test methods that batteries should meet in typical cycling applications within photovoltaic systems, ensuring stable and safe performance under various environmental and operating conditions. By establishing these standards, IEC helps manufacturers ensure their products perform consistently in similar applications worldwide, whether in hot deserts or cold northern regions. The implementation of these standards lays the foundation for the widespread acceptance and application of energy storage products, enhancing user confidence in product quality and reliability.

International standards have a profound impact on international trade in energy storage products. Firstly, these standards promote product compatibility and mutual recognition among economies by removing technical barriers, making it easier for energy storage products to be sold across borders. For example, the existence of standards like IEC 61427 allows importers and distributors around the world to trust product quality and performance, reducing additional testing and certification requirements imposed by importing economies, thus lowering transaction costs and time. Secondly, international standards help create a level playing field, promoting healthy development of the global market. Manufacturers no longer need to customize products for each target market, but can instead produce unified products that comply with international standards. This not only improves production efficiency but also strengthens global consumer confidence in the products.

3.3 Safety of battery energy storage systems

With the acceleration of energy storage system deployments, the safety of energy storage technologies has emerged among the top priority for ensuring the stable operation of the storage energy system and user safety. While energy storage systems are highly effective in regulating the grid, supporting renewable energy, and providing backup power, they pose safety risks such as thermal runaway, chemical leakage, and fire. Since 2011, approximately 50 electrochemical energy storage plant fires have been recorded globally. Battery energy storage stations face safety risks throughout all stages, including battery safety quality management, operations and maintenance, and end-of-life recycling.[69] After 2018, the global installed capacity of utility-scale battery energy storage systems increased rapidly. Through continuous accident analysis and active research into improvement, prevention, and mitigation measures, the failure rate of utility-scale battery energy storage systems dropped by 97%.[70] Addressing potential risks of energy storage systems is crucial to ensuring safety and reliability. How to avoid widespread power outages or even safety incidents caused by

[69] Li Yunsong, Cai Tianliang, Cui Jian, Zhao Yulong, Liang Hao, Wu Zheng. Safety Risks and Prevention Measures for Electrochemical Energy Storage Power Stations [J]. Electric Power Safety Technology, 2023, 25(12): 1-3，16.

[70] Insights from EPRI's Battery Energy Storage Systems (BESS) Failure Incident Database: Analysis of Failure Root Cause. https://www.epri.com/research/products/000000003002030360

system failures and improve the safety of energy storage systems is not only a necessary condition for maintaining infrastructure security but also a key step toward achieving a sustainable energy future.

3.3.1 Potential safety risks of energy storage systems

(1) Thermal runaway and fire risks

Thermal runaway is a major risk for battery-based energy storage systems, especially lithium-ion battery systems. The high heat generation rate during charging and discharging can easily cause overheating, affecting battery performance and lifespan. Under misuse conditions, thermal runaway may occur, leading to safety incidents.[71]

In September 2021, the Moss Landing 300MW/1200MWh energy storage project in California experienced significant battery overheating, which triggered the sprinkler fire suppression system and generated large amounts of smoke. The incident did not result in any casualties or affect nearby communities, but it damaged 7% of the battery modules. In September 2021, a fire broke out in the Tesla Megapack energy storage system at the Elkhor battery storage project in Monterey County (Moss Landing), California. The system included 256 Tesla Megapack battery units mounted on 33 concrete pads. In February 2022, the energy storage station experienced another incident, with about 10 battery racks melted. When the facility began operations on 11 December 2020, it was the world's largest battery energy storage system (BESS), equipped with 300MW/1200MWh of lithium-ion batteries. In April 2022, a fire occurred at an energy storage facility inside the Salt River substation in Arizona, which resulted in a fire that lasted five days. The affected energy storage project was located near Southeast 56th Street, close to Interstate 10 and Loop 202 in Chandler, Arizona. The project has over 3,200 lithium-ion batteries with a total storage capacity of 10MW/40MWh, is Arizona's first standalone energy storage project. The energy storage solution was provided by Fluence, and Mortenson was the EPC contractor. In May 2024, a fire occurred at the Otay Mesa (Gateway) energy storage station in San Diego, California (lithium-ion batteries), caused by thermal runaway.[72]

In July 2021, Australia's largest energy storage project — the Victoria Big Battery Storage Project — caught fire during equipment commissioning, with 13 tons of lithium-ion batteries fully ignited inside one container. The site housed over 200 Tesla Megapack containerized energy storage systems, each containing 3MWh of lithium-ion battery capacity. The fire destroyed two Megapack energy storage systems at the site. Investigations revealed that the fire was caused by a cooling system leak that led to a short circuit, which then triggered the energy storage fire. In January 2022, a fire occurred at an energy storage plant in Gyeongsangbuk-do, Korea. The energy storage plant began its commercial operation in August 2018, primarily performing functions such as renewable energy integration and load shifting. The energy storage

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[71] An Zhoujian. Study on Cooling and Thermal Safety of LiFePO4 Batteries Based on Flow Boiling [D]. Beijing Jiaotong University, 201 9.

[72] A Fire Incident Occurred at the Otay Mesa Gateway Lithium-Ion Battery Energy Storage Facility in the the United States - ENCN (esc n.com.cn) Source: https://www.escn.com.cn/20240522/7340a592053d4957803906866d35bfa0/c.html

project consists of a 450kW power conversion system (PCS) and lithium-ion batteries with a capacity of 1500kWh. The PCS was provided by Willings, and the batteries were supplied by LG Chem. Research report indicates that the cause of the incident was the rapid temperature rise of lithium-ion batteries due to internal short circuits caused by overcharging or defects, which subsequently led to a battery fire. In June 2024, a fire occurred at a lithium battery factory in an industrial complex in Hwaseong City, Gyeonggi Province, Korea. Professor Kim Jae-ho from Daejeon University, specializing in fire and disaster studies, stated that materials like nickel used in batteries are highly flammable, and compared to fires caused by other materials, people in the storage facility do not have enough time to react. In March 2024, an explosion occurred at a solar power plant in Isa City, Kagoshima, Japan.[73]

The unsafe conditions of batteries in energy storage systems include fire, explosion, overheating, swelling, and leakage. To prevent thermal runaway, safety prevention technologies should be enhanced from multiple aspects including battery safety, energy storage system design, operation and maintenance, and post-incident firefighting.[74]

(2) Electrochemical leakage risk

Lithium-ion batteries do not contain heavy metals such as mercury, cadmium, or lead, and are therefore generally considered environmentally friendly. However, they are also classified as batteries with characteristics such as flammability, leaching toxicity, corrosiveness, and reactivity. When lithium-ion batteries experience thermal failure or casing rupture, hydrolysis, decomposition, and oxidation reactions may occur. The substances produced from reactions mainly include 5%–30% hydrogen (H_2), 5%–30% carbon monoxide (CO), 20%–90% carbon dioxide (CO_2), and 0%–9% various hydrocarbons (such as methane, ethylene, propylene). These reactions can also produce multiple toxic substances that harm soil and water sources. Vapors or smoke may damage human respiratory system, and lithium-ion battery combustion releases harmful compounds such as hydrogen fluoride and other toxic gases. Therefore, it is critical and urgent to further standardize the use of fire-resistant battery casing encapsulation technology, leakage detection systems, and specialized fire suppression systems to ensure the safety of the operation of battery energy storage systems.

(3) Mechanical structural failure risk

Energy storage system components such as batteries, capacitors, and mechanical structures may degrade and potentially fail over time due to environmental stress, material fatigue, and operational wear. Faults in the management and control systems of energy storage systems (e.g., software failures, communication interruptions, or hardware faults) may cause sudden increases or decreases in energy output, thereby affecting

73 An Explosion occurred at a Solar Power Facility in Kagoshima, Japan, Injured Four People! Energy Information Center of IN-EN.com Source: https://m.in-en.com/article/html/energy-2331404.shtml

74 Deng Qixi. Current Status of Safety Technology Development for Lithium-ion Battery Energy Storage Systems [J]. Sino-Global Energy, 2022, Vol.27(11): 93-99

grid stability. Regular maintenance and advanced diagnostic techniques can effectively reduce the frequency and severity of such faults.

(4) System integration and grid stability risk

The risk associated with integrating energy storage systems with grid stability mainly refers to the failure of battery management systems or improper configuration of energy storage systems, which can result in abnormal charging and discharging of the storage units, thus affecting the overall grid's load balancing and frequency regulation. Energy storage system balance includes but is not limited to busbars, cables, enclosures, power conversion systems, transformers, fire suppression systems, HVAC systems, and liquid cooling systems. Therefore, grid operators need to carefully design and implement energy storage integration strategies to ensure system safety and stability. Static and dynamic security issues in power systems refer to the ability of the system to return to a stable state after being subjected to disturbances. The support of energy storage system for power system security is mainly reflected in its high-speed response capability when rapidly deployed and regulated after the disturbances, with the core feature being its fast response characteristics.[75]

3.3.2 Safety standards and regulations of battery energy storage systems

(1) Safety incidents and causes

As discussed before, with the development of electrochemical energy storage technology and the expansion of energy storage applications, safety incidents at energy storage plants have become frequent. Over the past decade, lithium-ion battery-based energy storage plants have experienced repeated safety incidents including more than 50 fire and explosion accidents. The safety of energy storage plants has drawn significant attention from both industry and society.[76] Based on publicly available information, these fire or explosion incidents at energy storage plants show several key characteristics:[77,78]

- From a battery type perspective, ternary lithium-ion battery-based energy storage plants have experienced the most safety incidents, accounting for more than 50%;
- From the geographical perspective, Korea has experienced the highest number of fire or explosion incidents at energy storage plants, which is closely related to the widespread use of ternary lithium-ion batteries in Korean energy storage facilities;
- From the incident phase perspective, more than half of the fires or explosions occurred during or

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75 Yu Pengfei, Zhu Jizhong, Xiong Xiaofu, Chen Hongzhou, Song Yonghui, Wang Wei. Security Control Methods for Power Systems Based on Energy Storage [J]. Power System Protection and Control, 2023, Vol.51(19): 173-186

76 Peng Peng, Lin Da, Wang Xiangjin, Qiu Yishu, Dong Ti, Jiang Fangming. Fault Diagnosis of Lithium-ion Battery Energy Storage Systems Based on Local Outlier Factor [J]. Zhejiang Electric Power, 2023, Vol.42(5): 11-17

77 Cao Wenjiong, Lei Bo, Shi Youjie, Dong Ti, Peng Peng, Zheng Yaodong, Jiang Fangming. Analysis and Reflections on Safety Accidents at Lithium-ion Battery Energy Storage Power Plants in Korea [J]. Energy Storage Science and Technology, 2020, Vol.9(5): 1539-1547

78 Chen Yin, Xiao Ru, Cui Yilin, Chen Mingyi. A Review on Early Warning and Suppression Technologies for Lithium-ion Battery Fires in Energy Storage Power Plants [J]. Journal of Electrical Engineering, 2022, Vol.17(4): 72-87

shortly after battery charging.

Currently, there are still gaps in the safety management of electrochemical energy storage facilities, including insufficient quality control of key components and equipment, defects in fault diagnosis and safety protection of battery management systems and core devices, inadequate safety protection measures, and unstandardized on-site operations and management. It is therefore necessary to strengthen safety management from perspectives such as battery manufacturing, early warning and safety testing of battery faults, and multi-level electrical isolation within the energy storage system. At the same time, the energy storage standards system should be further improved, with existing standards formulated or revised based on technological advancement. Safety-related fault detection items should be added to the standards to enhance the safety of energy storage systems connected to the power grid.[79]

A safer energy storage system means that renewable energy can be stored and dispatched more safely, especially during peak demand periods. In addition, through smart microgrid technology, the main grid and distributed generation systems can be effectively interconnected, enabling the integration and enhancement of their security, stability, and functionality to achieve efficient operation.[80] A reduction in safety incidents allows project developers to deploy energy storage systems across a wider range of geographic locations and different applications, further promoting the integration and utilization of renewable energy. Table 3-2 list some recent energy storage safety incidents in APEC economies.

[79] Meng Qinggeng. Investigation and Prevention Strategies for Fire Accidents in Energy Storage Systems [J]. Fire Science and Technology, 2023, Vol.42(1): 142-145

[80] Lv Zhimin. Application of Automatic Control and Energy Storage Technologies in Smart Microgrids [J]. Energy Storage Science and T echnology, 2023, Vol.12(11): 3581-3582

Table 3-2 Selected Energy Storage Plant Safety Incidents in APEC Economies

Economy	Type of energy storage	Scale	Building Type	Services of storage system	Date of accident	Cause
China	Ternary lithium battery	4.5MWh	Container	Frequency regulation	2017-03	Defects exist in the fault diagnosis and safety protection functions of the battery management system.
	Lithium iron phosphate battery	—— 25MWh	Container Concrete	Demands management Photovoltaic Energy Storage & Charging	2018-08 2021-04	On-site personnel negligence resulted in incorrect power line connections; Internal battery short circuits triggered thermal runaway; The responsible company failed to fulfill its safety obligations and did not develop emergency response plans based on actual site risks.
Japan	Sodium-sulfur battery	—— ——	Assembled Assembled	Demands management Demands management	2011-02 2011-09	Safety quality issues in battery cells caused internal short circuits
The United States	Lead acid battery	15MWh	Container	Wind power distribution and storage	2012-08	Lack of safety protection facilities at the energy storage plant.
	Ternary lithium battery	2MWh	Container	Demands management	2019-04	Design and manufacturing defects in the energy storage battery and system caused internal short circuits, and essential safety protections were lacking; Fire suppression systems could not effectively extinguish fires; On-site emergency management procedures were missing
Korea	Ternary lithium battery	1460MWh 8600MWh 14000MWh 18966MWh 18000MWh 5989MWh 18000MWh 17700MWh	Container Container Modular panel Modular panel Modular panel Modular panel Concrete Container	Wind + storage Frequency regulation Wind + storage Solar + storage Demands management Solar + storage Solar + storage	2017-08 2018-05 2018-06 2018-05 2018-09 2018-09 2018-09 2018-10	Manufacturing defects existed in the battery and protection system; Operation environment management was not standardized; Installation and commissioning procedures missing; The comprehensive protection management system was incomplete (may applicable to multiple incidents)

Economy	Type of energy storage	Scale	Building Type	Services of storage system	Date of accident	Cause
		46757MWh 3600MWh 50000MW	Concrete Modular panel Station building	Frequency regulation Demands management Solar + storage Solar + storage	2019-01 2019-05 2022-01	
Australia	Lithium iron phosphate battery	300MW/450 MWh	Container-type	Demands management	2021-07	Design and manufacturing defects in the battery system caused internal short circuits

(2) Battery energy storage system safety standards

The safety of energy storage systems directly affects consumer and investor confidence. Improved safety standards protect users' lives and property, reduce investment risks, and enhance project attractiveness. Investors are showing a growing preference for energy storage projects that adhere to rigorous safety standards, as these projects offer the promise of stable long-term returns while minimizing potential legal and remediation expenses. As related safety standards improve and the safety of energy storage technologies gains public acceptance, more consumers are willing to adopt energy storage systems to optimize their energy usage, especially in residential and commercial projects integrated with renewable energy technologies. This increased market demand further drives R&D, and manufacturing capability, large-scale deployment of energy storage technologies, and lowering the costs of storage systems.

i) IEC standards

International Electrotechnical Commission (IEC) stipulates a series of standards related to the safety of battery energy storage systems, such as IEC 62619 and IEC 62477. IEC 62619 specifies safety requirements for lithium-ion batteries, including design, testing methods, and safety measures. These standards aim to ensure battery performance and safety under abnormal conditions such as overcharging, over-discharging, and high temperatures. IEC 62619 specifies standardized battery testing methods, including temperature endurance tests, short-circuit tests, and overcharge tests, to ensure battery performance under extreme conditions.

ii) IEEE Standards

The standards of Institute of Electrical and Electronics Engineers (IEEE), such as IEEE 1679, provides recommended practices for stationary battery maintenance and management; IEEE 1547 outlined the requirements for interconnecting distributed resources with power systems, significantly enhancing the integration safety of energy storage systems with the grid.

iii) The US battery system safety standards

As a dynamical process, the US DOE provides a template for authorities which aim to procure BESS and highlights the relevant codes and standards including safety issues. The following standards has been added in the 2024 template:[81]

- NFPA 68: The standard deals with explosion protection through deflagration venting. In the context of BESS, this involves designing ventilation systems to safely release pressure in the event of an explosion, preventing catastrophic failure;

[81] The US DOE. 2023. Lithium-ion Battery Storage Technical Specifications. https://www.energy.gov/femp/articles/lithium-ion-battery-storage-technical-specifications .

- NFPA 69: This standard focuses on explosion prevention systems, such as those that detect and suppress explosions before they can cause significant damage. For BESS, this involves installing fire suppression systems, gas detection systems, and other measures to prevent fires and explosions within the battery modules;
- NFPA 72: The standard covers fire alarm and signaling systems. For BESS installations, it involves installing fire alarms, smoke detectors, and other early warning systems to detect fires and initiate appropriate responses, such as activating fire suppression systems or alerting personnel.

Other relevant codes and standards regarding BESS safety in the United Stated are summarized in Table 3-4.

Table 3-4 Relevant Codes and Standards Regarding BESS Safety in the United States

Code/standard	Description	Code/standard	Description
NFPA 70	National Electrical Code	UL 9540A	Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
NFPA 855	Standard for the Installation of Stationary Energy Storage Systems	IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electrical Power System Interfaces
UL 1642 UL 1973	Standard for Lithium Batteries Batteries for Use in Light Electric Rail Applications and Stationary Applications	UL 1741	Standard for Static Inverters and Charge, Converters, Controllers and Interconnection System Equipment
UL 9540	Energy Storage Systems and equipment	UL 62109-1	Safety of power converters for use in photovoltaic power systems - Part 1: general requirements

iv) Chinese standards

Chinese technical standards, such as GB/T 36276-2018, specify safety requirements for the installation, testing, and operation of energy storage equipment, including detailed provisions on environmental safety, electrical safety, and operator training. These standards cover the entire life cycle of battery manufacturing, transportation, installation, and operation and maintenance, ensuring end-to-end safety control from equipment manufacturing to system operation.

v) Japan Electrical Safety & Environment Technology Laboratory

Japan follows guidelines established by the Japan Electrical Safety & Environment Technology Laboratory (JET) to ensure that energy storage system products meet specific safety standards before entering the market. Japan's safety standards for Battery Energy Storage Systems largely align with and often adopt international standards, particularly those from the IEC. For industrial lithium secondary batteries, including those in stationary applications, Japan's JIS C8715-2 is based on IEC 62619, covering design guidelines for safe operation, product safety testing (e.g., short circuit, impact, overcharge), and functional safety requirements like thermal and voltage management systems. Additionally, for portable secondary batteries, Japan has updated its DENAN Standard to incorporate Appendix 12 of IEC 62133-2, which introduces more rigorous monitoring methods and enhanced testing for overcharging, aiming to prevent fire accidents and improve overall safety for manufacturers and importers. While these standards primarily focus on the battery units themselves, there's a broader emphasis on fire prevention, proper installation, and system-level safety within the context of grid integration.

3.3.3 Safety management strategies

Fire events underscore the importance of multi-front approaches in lowering the failure incidence rate of battery products. These include validating propagation-resilient designs, proactive measures in quality, working standards, handling, storage, emergency response, and safe disposal of end of life (EOL) lithium-ion batteries to mitigate fire risks. Active efforts and measures have been taken in major BESS markets in the region that have lowered the incident rates. Overall, energy system safety management involves a systematic engineering approach, including design and engineering controls, operations and committees, as well as training and education.

(1) Design and engineering controls

The state of charge (SOC), state of health (SOH), and state of safety (SOS) of battery energy storage units are monitored. An energy management strategy maintains SOC consistency among units help mitigate safety risks.[82] Alternatively, during the design phase of battery energy storage systems, battery safety research and development should be strengthened to improve thermal stability and safety. Fire protection designs for energy storage plants should be enhanced, employing multi-layered safety measures such as fire detection systems and emergency response protocols.[83,84] Regular electrical performance testing, thermal imaging monitoring, and physical inspections should be conducted to promptly identify battery aging, wear, or other potential issues; Adopting modular design would enable localized isolation of faults, preventing the spread of problems; Thermal management systems should be used to regulate battery temperature, automatically adjusting the charging status or cutting off power when abnormal temperatures are detected to prevent thermal runaway risks.

(2) Operation and maintenance

As for operation and maintenance of the storage systems, conduct regular maintenance and safety

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[82] Li Hanning, Li Xiangjun. Energy Management Strategy for Energy Storage Power Plants Considering Battery Safety Status [J]. Distribution & Utilization, 2023, 40(08): 21-27.DOI: 10.19421/j.cnki.1006-6357.2023.08.003

[83] Xiao Xianyong, Chen Zhifan, Wang Ying, Liu Qingshi, Zhang Hongyu, Wei Lingxiao, Xi Yanna, Tao Yibin, Feng Xinchen, Cao Tianzhi, Yi Shuxian, Chen Rui, Li Xuan. Multi-level Comprehensive Evaluation Method for the Safety State of Large-capacity Battery Energy Storage Systems [P]. Chinese Patent: CN113569402A,2021.10.29

[84] Li Wenyang, Fu Dongshe, Xiong Gang, Xiang Haifeng, Ni Dongxin. Fire Protection Control System for Prefabricated Energy Storage Systems [P]. Chinese Patent: CN116899149A,2023.10.20

inspections of energy storage systems and identify and address potential hazards in a timely manner; Carry out comprehensive safety assessments and regulatory oversight for both existing and new battery energy storage facilities; Develop and establish detailed emergency response plans, including initial fire response, evacuation routes, and designated emergency contacts. Conduct regular drills to ensure the operators are familiar with emergency procedures and can respond quickly and effectively in case of an incident.

Operation and maintenance of energy storage systems can be supported by AI-based battery safety maintenance management systems, which analyze maintenance timing based on operational faults and actual load conditions. Maintenance needs arising from different battery statuses should be prioritized, and maintenance routes are allocated accordingly based on priority levels and battery locations, improving both efficiency and timeliness of maintenance.[85] Additionally, embedded device-based battery energy storage monitoring systems can provide human-centric and visual alarm and protection functions through real-time screening and data analysis.[86]

(3) Training

Training on energy storage system safety should be dynamically updated according to the highest industry standards and robust safety protocols implemented to keep pace with evolving regulations and technological advancements. Emphasis should be placed on case studies, incorporating detailed technical explanations of on-site emergency response measures following explosions, as well as recommendations for improving regulations, standards, and emergency response training to better protect firefighters, maintenance personnel, and nearby communities.[87] Furthermore, by integrating and real-time outputting of multi-source heterogeneous data from video surveillance and condition monitoring at energy storage facilities, operation and maintenance digital-twin visualization training platform can be developed for energy storage systems. Three-dimensional visualization of power plant's equipment enables operation and maintenance personnel to learn and train relevant operations and maintenance in a virtual environment, enhancing training effectiveness and reducing risks during actual operations.[88]

In summary, establishing an overall strategy for energy storage systems safety risk prevention and control, focusing on accident mechanism research, establishing a relevant safety standards and regulations systems, adopting quantitative risk analysis methods to evaluate system safety, implementing safety engineering design and installation requirements, emphasizing operational safety and routine maintenance, developing emergency response plans for accidents, and strengthening training in handling such incidents

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[85] Liu Haohan, Cao Qin, Kan Guozhu, Xu Sitong. AI-based Safety Maintenance Management System for Energy Storage Batteries [P]. Chinese Patent: CN117438678A,2024.01.23

[86] Xue Zhong, Dong Bei, Ding Yi, Zhang Yao. Battery Energy Storage Monitoring System Based on Embedded Devices [P]. Chinese Patent: CN111478435A,2020.07.31

[87] UL Firefighter Safety Research Institute Publishes Report on Explosions of Lithium Battery Energy Storage Systems [J]. Fire Science and Technology, 2020, Vol.39(12): 1651

[88] Weng Zhoubo, Deng Yimin, Qian Ping, Huang Wentao, Yang Fan, Dai Zheren, Zhao Shanshan, Lü Hongfeng, Lai Shangfeng, Zhang Tianlong, Qi Yanwei. Construction Method for a Twin Visualization-assisted Operation and Maintenance Training System for Energy Storage Power Plants [P]. Chinese Patent: CN117422592A,2024.01.19

can comprehensively enhance the safety, reliability and emergency response capabilities of battery energy storage systems.[89]

As an example, Korea is thought of as one of the early and most mature energy storage markets in the APEC region, however between 2017 and 2019, the economy witnessed 28 battery storage fires (16 in 2018 alone) that brought Korea’s energy storage marketplace almost to standstill. The incidents were investigated by Korea's Ministry of Trade, Industry and Energy (MOTIE) and their report identified that potential manufacturing defects and poor installation practices were amongst the main causes. Another more significant lithium-ion battery fire in late 2022 knocked out a major data center which caused banking, ride-sharing and online delivery services to be out of action for a number of days. The Korean authority proposed a tightening of safety measures in 2022 to address the issue. The renewed focus on safety has led to a significant increase in demand for non-flammable, safe battery technology, including vanadium flow batteries, and relevant measures include revision of the law to force battery vendors in Korea to make sure that the energy storage fields have ground-fault detectors to prevent current flow from running on the ground, fire extinguishing systems, and devices to mitigate the internal pressure of battery cells in the event of a thermal runaway where the temperature rises sharply.

An incident is defined as an occurrence caused by a BESS system or component failure which resulted in increased safety risk, and for lithium-ion BESS, this is typically a thermal risk such as fire or explosion. Over recent years, with greater attentions and increased efforts, the overall rate of incidents has decreased rapidly, as lessons learned from early failures and incidents have been incorporated into new designs and best practices. According to a research of Electric Power Research Institute (EPRI), which performs am comprehensive analysis of operational incidents in operational BESS projects, as shown in Figure 3-11, between 2018 and 2023, the global grid-scale BESS failure rate has dropped 97%.[90] As the total installed BESS capacity has grown exponentially, the number of incidents remain relatively constant or a drop trend. Incidents by capacity now is at its lowest level, where the rate of is reflected by ratio of number of incident and installed storage capacity (GW), which is at its lowest since 2016, being 0.03 incidents/GW installed.

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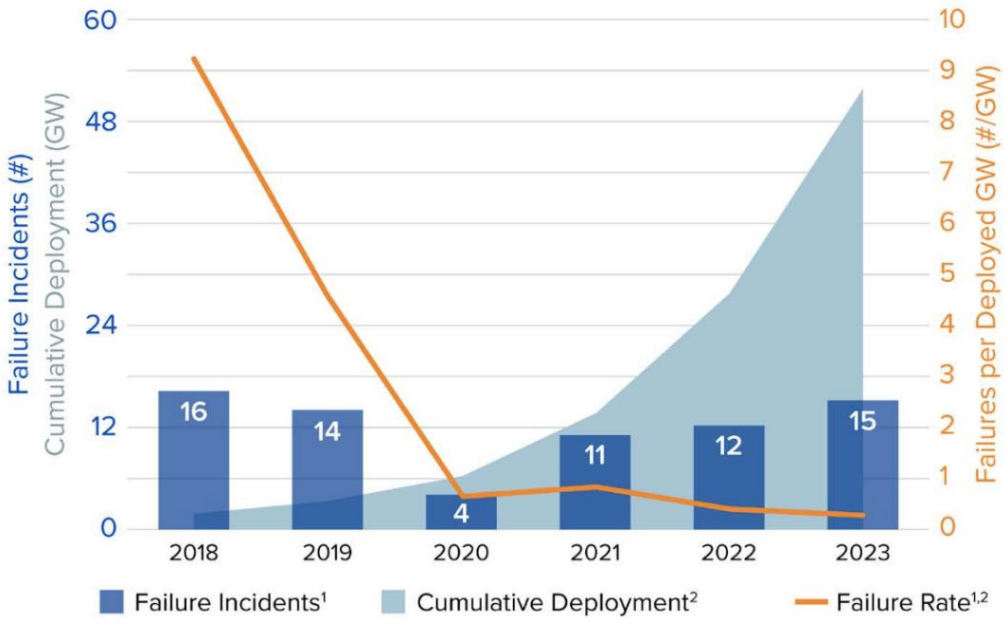
[89] Liu Zhong, Hao Zhenkun, Nan Jianglin. Study on Prevention and Control of Fire and Explosion Hazards in Lithium Battery Energy St orage Systems [A]. The 1st International Conference on Building Fire Safety [C], 26 September, 2022

[90] EPRI. 2024. Insights from EPRI's Battery Energy Storage Systems (BESS) Failure Incident Database: Analysis of Failure Root Cause. h ttps://www.epri.com/research/products/000000003002030360 .



Source: EPRI, Wood Mackenzie

Figure 3-11 Global Grid-scale BESS Safety Incidents

3.4 Chapter summary

With the ongoing energy transition and increasing adoption of renewable energy, energy storage technology has become a critical pillar of energy development. This chapter summarizes evaluation indicators for energy storage technologies from three dimensions—technical capability, performance, and costs—to serve as a reference for the development of energy storage projects. The evaluation indicators for energy storage technical capabilities mainly include seven second-level indicators, namely: moment of inertia, reactive power control, black start, grid adaptability, overload capacity, low voltage ride-through capability, and high voltage ride-through capability; The evaluation indicators for energy storage performance include six second-level indicators, namely: power/energy, basic energy charging/discharging indicators, lifespan, application, safety, environment, and site conditions. Each second-level indicator further includes several third-level indicators. The total lifecycle costs of an energy storage system mainly consists of capital expenditure (CapEx), operational expenditure (OpEx), and decommissioning costs. Correspondingly, energy storage cost evaluation indicators can be categorized into three secondary indicators: construction costs, operation costs, and decommissioning costs.

There are various types of emerging energy storage technologies, each with its own advantages and disadvantages in terms of costs, efficiency, scale, safety, and performance. Currently, the development and utilization of storage technologies are in a multifaceted situation, with significant differences in technical-economic advantages and applicable conditions across different technologies. Due to the fact that some energy storage technologies are yet mature, many characteristic parameters are still not fully established, the assessment would involve mixed qualitative and quantitative indicators and numerous fuzzy factors, making fuzzy evaluation methods a suitable method for evaluation. This chapter induces the implementation process of evaluating the applicability of energy storage technologies using the fuzzy comprehensive evaluation method and Electricity Storage Valuation Framework (ESVF) enveloped by IRENA. The ESVF framework is to assess the value that electricity storage brings to the power grid and the feasibility of energy storage projects.

Standards and technical specifications for energy storage system play a core role in promoting the safe and efficient operation of energy storage systems and their compatibility with existing and future energy systems. International standard organizations such as IEC, IEEE, and UL, as well as several APEC economies, have developed comprehensive technical standards and regulations for energy storage systems. IEC standards are developed through Technical Committee TC120, which formulates grid integration standards for energy storage, covering areas such as terminology, testing methods, planning, and installation; IEEE ensures that energy storage technologies meet grid requirements through performance evaluation frameworks and interoperability guidelines; UL has established safety standards for energy storage systems, such as UL 9540, which has become a necessary certification for entering the North American market. APEC economies such as Australia; China; Korea; and the United States have also developed or adopted systematic energy storage technology standards. For new energy storage technologies, such as lithium-ion batteries, sodium-ion batteries, and flow batteries, they are successfully promoted through the development of such standards and specifications. Performance standards such as IEC 62933 ensure that energy storage technologies meet efficiency and economic requirements, optimizing energy storage systems through indicators such as energy density and lifespan. The experience shows that standardization and interoperability are among the keys to advancing the commercialization of energy storage technologies. Through protocols such as IEEE 1547, energy storage devices can seamlessly integrate into energy management systems, enhancing demand response and frequency regulation capabilities. Furthermore, the harmonization of international standards makes it effective to promote energy storage products globally. For example, IEC 61427 establishes battery standards for photovoltaic systems, ensuring their performance across various environments and facilitating technical mutual recognition and international trade. The standardization supports the commercial and large-scale application of energy storage technologies, ultimately accelerating the global transition toward low-carbon energy systems.

With the acceleration of global energy storage system deployments, the safety of energy storage systems installed has been on the top priority for ensuring the stable operation of the entire energy system and user safety. On the trajectory of their development, electrochemical energy storage systems faced major safety risks such as thermal runaway, chemical leakage, and fires. Global energy storage accident data show that fire incidents caused by lithium-ion battery thermal runaway occur frequently, making them a key focus of safety concerns. Improving safety of energy storage systems requires great efforts from multiple aspects including design, operation, and management. During the design phase, modular structures and thermal management systems can be used to control battery temperature and prevent thermal runaway risks; During operation, enhanced maintenance and real-time monitoring systems should be implemented to detect and address potential issues promptly; At the same time, AI-based safety maintenance and system optimization management are among effective methods. Safety education and emergency training are essential for ensuring operational safety; virtual training and case analysis can enhance emergency response capabilities. With increased attentions and greater efforts from the authorities and technology advancement, safety records of energy storage systems have improved greatly in recent years. Improved safety directly impacts market confidence of energy storage products. Implementing high safety standards significantly reduces investment risks, increases consumer acceptance of energy storage technologies, and thus drives research, development, and commercialization of energy storage system. These not only ensure the deployment of energy storage systems but also provide safe and reliable supports for energy system stability and large-scale applications of renewable energy.

Chapter IV Policy Instruments for Energy Storage Development

Policy instruments play a crucial role in fostering the development and deployment of battery energy storage systems. Governments worldwide are employing a diverse set of mechanisms to incentivize investment, reduce costs, and create stable market conditions for energy storage projects. Financial incentives are a cornerstone, often taking the form of direct subsidies, tax credits, and rebates for both residential and commercial installations. Beyond financial support, regulatory frameworks are essential in unlocking the full potential of energy storage. Procurement targets, mandating utilities to acquire specific amounts of energy storage by certain deadlines, send strong market signals and reduce regulatory uncertainty. Interconnection policies that streamline the process for connecting energy storage facilities to power grid and fairly compensate energy storage for the grid services that provides are also vital. Furthermore, the establishment of clear safety standards and permitting processes helps to build public confidence and facilitate energy project development. Initiatives aimed at supporting domestic manufacturing and research and development efforts are crucial for long-term sustainability and cost reduction in energy storage sector.

The policy tools and measures that support and stimulate energy storage development in APEC economies are categorized into financial incentives, procurement targets and mandates, market-based mechanisms, research, development, and demonstration (RD&D) programs, safety and standards, and industrial development strategies, which are summarized in Table 4-1. In the following sections, related policies and development plans for energy storage in APEC economies are reviewed.

Table 4-1 Policy Tools and Measures Supporting and Stimulating Energy Storage Development

Economy	Policy tools and measures					
	Financial incentives	**Procurement targets & mandates**	**Market-based mechanisms & regulatory reforms**	**RD&D programs**	**Safety and standards**	**Industry development strategies**
The United States	Yes	Yes (Numerous states have set energy storage procurement targets)	Yes	Yes	Yes	Yes
Australia	Yes	Yes	Yes	Yes	Yes	Yes
Japan	Yes	No direct broad mandates/targets, but emphasis on integration through market incentives.	Yes	Yes	Yes	Yes

Economy	Policy tools and measures					
	Financial incentives	**Procurement targets & mandates**	**Market-based mechanisms & regulatory reforms**	**RD&D programs**	**Safety and standards**	**Industry development strategies**
Korea	Yes	Yes	Yes	Yes	Yes	Yes
China	Yes	Yes	Yes	Yes	Yes	Yes
Thailand	Emerging	Yes	Emerging	Yes	Developing	Yes
Malaysia	Emerging (No direct broad financial incentives for standalone energy storage, but policies supporting RE indirectly benefit storage)	Yes	Emerging	Yes	Developing	Yes
The Philippines	Emerging	Yes	Emerging	Yes	Developing	Yes
Viet Nam	Emerging (New FiT rates for solar power projects that incorporate BESS, reflecting a policy emphasis on grid flexibility)	Yes	Emerging	Yes	Developing	Yes
Chile	Emerging (Carbon credits for renewables-plus-storage; incentives in regulated market tenders for night-time injections)	Yes	Yes	Yes	Yes	Yes

Many APEC economies have set ambitious goals for energy storage development, recognizing its vital role in supporting renewable energy integration and ensuring grid stability. Economies like China and the United States have outlined significant expansion plans for energy storage, while others such as Australia; Japan; and Korea are also experiencing notable growth and have established substantial targets. The specific objectives for battery energy storage system development of selected APEC economies are summarized in Table 4-2.

Table 4-2 Plans and Targets for Battery Energy Storage Systems Development

Economy	Capacity target (GW)	Target year	Notes
California, the United States	35	2045	
New York, the United States	6	2030	
	1	2025	
Michigan, the United States	2.5	2030	
	4	2040	
Canada	8-12	2035	

Economy	Capacity target (GW)	Target year	Notes
Victoria, Australia	2.6	2030	
	6.3	2035	
Queensland, Australia	7	2032	
New South Wales, Australia	2	2030	
Japan	24 (GWh)	2030	
Korea	22.8 (GWh)	2036	
Thailand			In 2021, the total installed power generation capacity was 55GW, with renewable energy accounting for 22%. Wind power capacity was 1.57GW, and solar PV capacity was 3.15GW.
The Philippines			As of the end of 2021, the installed power capacity was 28 GW, with renewable energy installations accounting for 28%. The installed capacity of hydropower was 3.1 GW, and that of photovoltaic (PV) systems was 2.2GW.
Viet Nam			In 2021, the total installed capacity was 76GW, with renewable energy accounting for 56%. Solar PV capacity was 16.6GW, and wind power capacity was 4.3GW.
Singapore	1.5	2025	
	2	2030	
Chile	2	2030	
	6	2050	
China	30	2025	Guiding Opinions of the National Development and Reform Commission and the National Energy Administration on Accelerating the Development of New Energy Storage

4.1 Policies and plans of energy storage development

4.1.1 Industrialized APEC economies

(1) Australia

Policies at federal government level

i) Energy storage-related laws and regulations

On 13 September 2022, the Australian government passed the *Climate Change Act 2022*, which came into effect the same day, marking the first time carbon emission reduction targets were codified into law. The Act clearly sets a target for Australia to reduce greenhouse gas emissions by 43% below 2005 levels by 2030, and to achieve net-zero emissions by 2050. Additionally, the Act mandates that the Minister must prepare an Annual Climate Change Statement; The Climate Change Authority must provide advice to the Minister regarding the preparation of the Annual Climate Change Statement and recommend incorporating greenhouse gas emission reduction targets into new or revised Nationally Determined Contributions (NDCs); And the implementation of this Act must be reviewed periodically. Codifying carbon reduction targets into law strengthens the commitment of governments and the industry to these goals, promoting the long-term and stable development of renewable energy and energy storage.

In July 2022, the Australian government introduced the *Renewable Energy (Electricity) Amendment Act 2022 (Powering Australia).* The new legislation expands the mandate of ARENA (Australian Renewable Energy Agency), allowing the agency to support energy storage, energy efficiency and electrification technologies. Electrification technologies include EV chargers, heat pumps, and mining applications; energy efficiency technologies include demand reduction and management technologies, cost and emission reduction technologies, and technologies supporting a flexible power grid. ARENA continue to support large-scale energy storage, ultra-low-cost solar, demand flexibility, green hydrogen, and other renewable energy technologies.

ii) Financial support for emerging storage technologies

In October 2022, the Australian government announced new funding for ARENA under the 2022–2023 federal budget, covering four areas: advancing government funds, supporting energy security and reliability, residential solar community batteries, and indigenous community microgrid programs. Of this, AUD60 million was allocated to support energy security and reliability, specifically for large-scale grid-connected battery storage projects; AUD188.4 million was allocated to residential solar community batteries to help roll out 342 community battery projects across Australia; AUD83.8 million was allocated to the Indigenous Community Microgrid Program to develop and deploy microgrid technologies in indigenous communities. These new funds affirm ARENA's role in accelerating the energy transition and will further speed up Australia's transition toward achieving net-zero emissions.

In December 2022, ARENA announced conditional funding of AUD176 million for eight large-scale grid-connected battery storage projects economy-wide, with a total project value of AUD2.7 billion and a combined capacity of 2.0GW/4.2GWh. All batteries reach financial close in 2023 and become operational by 2025. The Large-Scale Battery Storage Support Program was launched in December 2021 with an initial allocation of AUD100 million. Due to the high quality of applications received, the funding was expanded to AUD176 million. This round of funding supports grid-connected battery storage projects equipped with advanced grid-forming inverter technology, enabling batteries to provide essential power system services similar to those traditionally provided by synchronous generators.

In addition to battery storage technologies, the Australian government also provides funding for the exploration of other energy storage technologies. For compressed air energy storage, in October 2022, ARENA conditionally approved AUD45 million in funding to support Hydrostor in building a 200MW/ 1,600MWh advanced compressed air energy storage project. Regarding hydrogen, in October 2022, ARENA announced AUD13.7 million in funding to Fortescue Future Industries Pty Ltd (FFI) and Incitec Pivot Limited (IPL) to support the deployment of a 500MW hydrogen electrolyzer to replace the current hydrogen source for IPL's Gibson Island ammonia plant; Previously, ARENA had announced conditional funding of AUD47.5 million to ENGIE for the construction of a 10MW hydrogen electrolyzer; Additionally, ARENA committed AUD88 million for renewable hydrogen projects, including feasibility studies, small-scale electrolyzer demonstrations, gas blending trials, and vehicle deployments. For thermal energy storage, in August 2022, ARENA announced AUD1.27 million in funding for MGA Thermal Pty Ltd (MGA Thermal) to support its innovative thermal energy storage technology and the construction of a 500kW/5MWh pilot facility.

State level polies

In September 2022, the Victorian government announced two statutory energy storage targets: a target of 2.6GW of installed storage capacity by 2030 and 6.3GW by 2035. In addition, Victoria has positioned offshore wind as central to its future clean energy mix, planning for 2GW of offshore wind capacity by 2032, 4GW by 2035, and 9GW by 2040. Offshore wind alone could power up to 1.5 million households over several decades. In September 2022, the Queensland government released a USD62 billion Energy and Jobs Plan, setting two new statutory renewable energy targets: 70% renewable generation by 2032 and 80% by 2035. To achieve these targets, 7GW of long-duration energy storage and 6GW of residential/commercial battery storage will be required, including a 5GW large-scale pumped hydro facility near Mackay. In New South Wales, the NSW government announced, in March 2020, its *Stage 1 Net Zero Plan: 2020-2030 Plan*. The plan laid the foundation for NSW's actions to address climate change, aiming to achieve net-zero emissions by 2050. In November 2020, the NSW government announced the commencement of the *Electricity Infrastructure Investment Act 2020*, legislating supports for the Electricity Infrastructure Roadmap. The *Electricity Infrastructure Roadmap* stipulates that: A target of 12GW of renewable energy capacity and 2GW of long-duration energy storage by 2030, with plans to retire four coal-fired power stations over the next 15 years, representing three-quarters of the state's electricity generation capacity. In September 2021, the NSW government released an update on the implementation of the Net Zero Plan, outlining a goal to reduce emissions by 50% from 2005 levels by 2030. An update on the implementation of the Net Zero Plan released in December 2022 outlines a goal to reduce emissions by 70% from 2005 levels by 2035.

(2) Canada

Canada views the opportunity to decarbonize the electricity sector as a vital step to achieving a net-zero emission economy and has introduced a suite of policies, regulations, investment mechanisms, and strategic programs and initiatives that help accelerate a clean and just energy transition. This includes seizing the opportunities and challenges of ensuring Canada's energy security, such as expanding and modernizing electricity infrastructure, including the use of energy storage.

Canada provides policy certainty to attract sustained investment by establishing clear regulatory frameworks, such as the Clean Electricity Regulations and regulations to phase out coal by 2030, and eliminating regulatory barriers that improve the efficiency of permitting processes for energy projects. Through the use of targeted programming to support the unique needs of sectors or projects of strategic significance, programs, such as the CAD4.5 billion Smart Renewables and Electrification Pathways Program, support the deployment of clean electricity infrastructure and aim to modernize and strengthen the electricity grid to ensure a reliable, affordable and decarbonized electricity system for all Canadians.

The most recent Budget 2024 continued to deliver on a suite of Clean Economy Investment Tax Credits (ITC), which provide a clear and predictable anchor regime that is broadly accessible to eligible organizations in the economy. These include ITCs on clean technology adoption and manufacturing, clean hydrogen, carbon capture, utilization and storage (CCUS), clean electricity, and electric vehicle supply chains. The Clean Technology ITC provides refundable tax credits equivalent to 30% of capital investment costs for electricity generation equipment, stationary electricity storage equipment and other clean technologies. Stationary electricity storage equipment that does not use any fossil fuel in operation are eligible, including but not limited to batteries and pumped hydro storage.

Canada also aims to enhance its competitiveness and attractiveness by leveraging strategic financing through the Canada Infrastructure Bank to provide at least CAD10 billion to clean power projects, including zero-emitting generation (including nuclear), energy storage, and transmission (including interties), as well as at least another CAD10 billion in green infrastructure. Additionally, Canada has established the Canada Growth Fund, a CAD15 billion independent and arm's length public fund that will help Canada to speed up the deployment of technologies in its efforts to reduce emissions, transform its economy and support the long-term prosperity of Canadians. With these investments, the authority of Canada has now committed more than CAD40 billion in potential support for Canada's clean electricity sector in the form of tax measures, public financing, and grants and contributions, while working closely with provinces and territories as well as industry to improve transmission capacity and regional integration across the territory of Canada.

(3) Japan

In October 2020, the Japanese government announced its goal of achieving carbon neutrality by 2050. Currently, energy-related emissions account for more than 80% of Japan's total carbon emissions. Achieving carbon neutrality by 2050 makes emission reductions in the energy sector critical. Among them, the power sector is steadily decarbonizing through the use of clean electricity, with increasing the share of renewables being a key strategy for decarbonization. Since announcing the carbon neutrality goal, the Japanese government has issued various policies and taken a series of measures to promote the widespread adoption of renewable energy resources.

Regarding energy storage subsidies, in December 2020, Japan's *Green Growth Strategy toward 2050 Carbon Neutrality* outlined a roadmap for industries to achieve this goal, requiring financial incentives, tax policies, and financial support to drive corporate innovation and green industrial development, including a requirement that solar PV installation costs be controlled at JPY70,000/kW (including construction costs) by 2030; It also called for expanding the market applications of solar panels in commercial and industrial buildings. In the *Sixth Strategic Energy Plan* issued in October 2021, Japan raised its 2030 renewable energy generation target from the previous 22–24% to 36–38%, with specific shares set as follows: solar at 14–16%, wind at 5%, hydropower at 11%, and biomass at 5%. The Plan requires the achievement of these renewable targets through optimized site selection, strengthened safety regulations, reduced generation costs, and promotion of technological innovation. To adapt to power system decarbonization while ensuring energy security, the Plan mandates that new investment approaches be provided to align power system decarbonization with stable electricity supply; As renewable energy penetration increases, the plan emphasizes enhancing power system flexibility and the important role of energy storage to ensure steady decarbonization.

With the wide deployment of variable renewable energy (VRE), technologies like battery storage that help balance supply and demand are essential for improving power system stability and flexibility. The Ministry of Economy, Trade and Industry (METI) has identified energy storage as a key technology for achieving Japan's mid- to long-terms carbon neutrality goals. In recent years, the Japanese government has encouraged investment, construction, and deployment of front-of-meter battery storage through various measures. In October 2021, the *Sixth Strategic Energy Plan* stated that widespread adoption of battery storage and hydrogen electrolyzers would be achieved through cost-reduction. Amendments to the *Electricity Business Act* in May 2022 classified grid-connected battery storage systems of 10MW or larger as eligible to register as power generation resources capable of participating in day-ahead markets and other trading opportunities. Their discharging operations of storage facilities are categorized as power generation activities, allowing them to connect to general transmission network and receive transmission services. Taking effect since April 2023, this legislation clarifies the position and roles of utility-scale battery systems in the power grid, broadens and diversifies their revenue models, and helps promote large-scale deployment of energy storage systems.

To reduce costs, both economy and local governments provide subsidies for energy storage facilities and establish innovation funds to promote cost-reduction through technological innovation. METI allocated part of the supplementary budget of JPY13 billion from FY2021, supporting battery projects at one-third to two-thirds of upfront costs, with subsidy levels linked to the application scope and technology used (including hydrogen electrolyzers). The New Energy and Industrial Technology Development Organization (NEDO) established the Green Innovation Fund to promote decarbonization technologies. The fund supports the "Next-Generation Battery and Motor Development" project aimed at advancing battery R&D and reducing storage costs through innovation. Japan aims to bring down the cost of utility-scale battery storage system to around JPY23,000 per kWh, which is comparable to pumped hydro.

In early 2022, Japan mandated that utilities open the grid to energy storage systems operated by third-party companies. In August, Japan called for further discussions on accelerating the introduction of stationary batteries while expanding the grid system to accommodate higher renewable energy penetration. In Hokkaido, where renewables have a high share in the power mix, the local grid operator introduced rules in 2015 requiring new renewable energy facilities to include storage, prompting the deployment of various battery projects. In 2023, the government allocated approximately JPY17 billion in subsidies for battery storage systems. The subsidies aim to support newly added battery storage projects to achieve supply-demand balance in electrochemical energy storage and meet transaction demands in the electricity spot market.

(4) Korea

In October 2020, Korea committed to achieving net-zero emissions by 2050. The power system is Korea's largest source of emissions, accounting for 37% of economy's emissions in 2019. Achieving net-zero emissions hinges critically on decarbonizing the power system. Korea aims to reduce emissions from the power system in a cost-effective manner while ensuring power security. Increasing renewable energy generation is one of the key pathways for Korea to decarbonize its power system. In January 2022, Korea clarified its Nationally Determined Contribution (NDC) target for 2030, aiming to increase renewable electricity generation to 185.2TWh, representing an average annual growth rate of 18% starting from December 2021. Under the *Ninth Basic Plan for Electricity Supply and Demand (2020–2034)*, solar and wind are the main drivers of renewable growth, contributing 83% to overall generation growth, with VRE expected to reach 20% of total electricity generation by 2034.

Korea's Carbon Neutrality Strategy (CNS) sets out principles for power system decarbonization, including: i) Promote carbon pricing through the Emissions Trading Scheme (ETS), increase the proportion of paid carbon quotas, and reflect carbon costs in electricity tariffs; ii) Accelerate the adoption of variable renewables by streamlining approval processes and regulatory frameworks for distributed renewable energy; iii) Ensure system stability by increasing flexible resources and energy storage, and introducing real-time and ancillary service markets into the electricity market; iv) Gradually phase out fossil fuel generation in consultation with affected communities, while converting to low-carbon fuels such as hydrogen and ammonia; v) Support the commercialization of R&D technologies, such as floating solar integrated with hydropower, hydrogen turbines, and ocean energy.

(5) The United States

The United States has provided strong policy supports for energy storage development. The US Federal Government and state governments have successively introduced policies to promote the development of energy storage. In terms of fiscal and tax subsidy supports, the United States started early, maintained long-term supports, and provided substantial assistance. In 2021, the US federal government further clarified in the *Build Back Better Act* that tax incentives (Investment Tax Credit, ITC), applying to solar investments and energy storage projects, extending the tax credit for ten more years. In 2022, under the *Inflation Reduction Act (IRA)*, the US federal government increased the previous ITC tax credit rate. For energy storage systems connected to solar PV, the ITC credit rate for commercial projects was raised to 30–70%. An overview of energy storage policies at federal and state levels is given in the following Table.

Table 4-1 Energy Storage Policies in the United States

Releasing time	Releasing region	Policy	Summary and key contents
2005	Federal	*Energy Policy Act of 2005*	Provides a 30% investment tax credit (ITC) or tax exemption for private entities that install photovoltaic systems along with energy storage. The ITC was extended, with the incentive at 26% in 2020, 22% in 2021, and by 2022, the tax credit for commercial and utility-scale projects will drop to 10%.
2013	California	*California Assembly Bill 2514* (CPUC)	Requires Investor-Owned Utilities (IOUs) to procure 1,325MW of energy storage by 2020 and have it operational by 2024.
2017	Arizona	Public Utility Incentive Program	Assists large commercial customers in deploying energy storage to reduce peak demand, offering an annual subsidy program of USD2 million.
2018	California	Self-Generation Incentive Program (SGIP)	A total of USD0.8 billion fund was granted to support the energy storage and other clean energy technologies. The investment for user-side energy storage was up to USD1.2 billion in total.
2019	Federal	Better Energy Storage Technology Act (BESTAct)	A total of USD1.08 billion was allocated over five years for energy storage, microgrids, and distributed energy resource projects.
2019	New York State	Energy Storage Incentive Program	The bridge incentive measures with a total value of USD350 million was authorized to accelerate the market development. Additionally, RGGI fund of USD53 million was granted.
2019	Massachusetts	Smart Solar Renewable Energy Program	Photovoltaic systems with a rated solar power capacity exceeding 25% must be paired with energy storage systems.
2020	Federal	Energy storage challenges roadmap (ESGC)	At both federal and state levels, combined efforts are made through tax incentives and subsidies to promote the development of the energy storage industry. Accelerate the transition of energy storage technologies from laboratories to markets, aiming to reduce the average cost of long-duration stationary storage to USD0.05 per kWh by 2030 — a 90% reduction compared to 2020 levels. Achieving this goal will drive commercial applications of energy storage across various fields, including: Meeting load demands during peak periods; Ensuring the grid can accommodate rapid electric vehicle charging; Ensuring the reliability of critical infrastructure, including information and communication technology. By 2030, the battery pack cost for electric vehicles with a 300-mile range is expected to fall to USD80 per kWh, 44% lower than the current USD143 per kWh of lithium-ion batteries. This will make electric vehicles cost-competitive and also benefit the technological development of stationary energy storage batteries.
2021	Federal	Build Back Better Act (BBBA)	For the first time, energy storage received standalone tax credits. Until 2026, energy storage systems above 5kWh capacity are eligible for up to a 30% tax credit.
2022	California	Fiscal Support Policies	California has announced USD380 million in fiscal support for long-duration energy storage projects, which could incentivize the deployment of 20 additional long-duration storage projects in the state, where demand for energy storage systems is high. The California Governor released the 2022–2023 government budget plan. The long-duration storage funding is part of California's USD2 billion clean energy investment plan, which also allocates funds for green ammonia, building decarbonization, pumped hydro storage at Oroville Dam, and other initiatives.

2022	Federal	Inflation Reduction Act (IRA)	The Inflation Reduction Act (IRA) increases the tax-exempt allowances available to energy storage systems, expands their application scope, and provides long-term incentives and market certainty for the US solar + storage industry. Residential solar Investment Tax Credit (ITC) remains at 30% until it begins to phase down in 2033; Residential energy storage systems with batteries larger than 3kWh qualify for a 30% ITC until it starts phasing down in 2033; Commercial solar projects are eligible for a 30% ITC until 2025. Credits after 2025 depend on whether the Treasury Department determines that carbon emission reduction targets have been met. For commercial projects, energy storage systems connected to solar PV qualify for ITC credits as high as 30–70%.

At the federal level, the *Inflation Reduction Act (IRA)* is the most significant policy for energy storage in 2022. For the first time, stand-alone energy storage systems were included under the Investment Tax Credit (ITC), allowing all storage applications — front-of-meter, industrial and commercial, and residential — to receive ITC subsidies of 30% or more for over ten years. The increased subsidy amount and extended duration significantly improve the economics of energy storage systems projects, paving the way for faster deployment of energy storage across the United States At the state level, Michigan became the 10th state of the United States establishing a clear energy storage development target.

Federal Policies

i) Inflation Reduction Act of 2022

On 16 August 2022, the US President Joe Biden signed the *Inflation Reduction Act of 2022* (H.R.5376, IRA) into law. Essentially a scaled-down version of the *Build Back Better Act* proposed by the Biden administration in 2021, the bill is also regarded as the largest climate investment legislation in United States history due to its planned USD369 billion investments in energy security and climate change areas. To promote the deployment of clean technologies in the United States, the IRA introduced a series of fiscal incentives, including major measures affecting energy storage such as inclusion of standalone energy storage in the Investment Tax Credit (ITC), extension and modification of existing ITC provisions.

- Standalone energy storage included in ITC: The ITC was originally formulated to support the commercialization and large-scale deployment of solar or solar-plus-storage systems. Each year, if an energy storage system is charged by solar power above a certain threshold, it could qualify for tax credits as part of the solar system. Standalone energy storage systems were previously ineligible for tax credits. The IRA updated the ITC to include standalone energy storage systems for the first time (commercial and industrial storage >5kWh and residential storage >3kWh), aiming at accelerating the deployment of standalone energy storage systems in the United States
- Extension and modification of ITC: The IRA extended the ITC subsidy period until 2035, with a phase-down starting in 2033, while increasing the credit cap. For residential energy storage, the maximum credit was increased from 22% to 30%. For commercial and industrial storage, in addition to the base 30% credit rate, there is potential for an additional 40% credit, bringing the total possible subsidy up to 70%. Regarding eligibility for base rate, new qualification criteria have

been introduced related to prevailing wage and apprenticeship requirements (with an exception for residential storage projects with output below 1MW). Developers who do not meet any of the additional provisions will only be eligible for a 6% base credit rate.

The *Inflation Reduction Act* extends the subsidy timeline, raises the credit cap, and for the first time includes standalone energy storage in the scope of support. This will significantly improve the deployment speed and return levels of the energy storage projects in the United States, ushering in a new stage of development and laying a foundation for rapid growth in the US energy storage industry over the decade to come.

ii) Funding supports

In April 2022, the US Department of Energy and the Washington State Clean Energy Fund (CEF) invested a total of USD75 million to support the Pacific Northwest National Laboratory (PNNL) in building the Grid Storage Launchpad — a research facility dedicated to exploring new energy storage technologies. It features with 35 research labs, office and testing spaces and 105 staff members, evaluating new energy storage technologies above 100kW under "real-world conditions", particularly focusing on long-duration energy storage technologies. The facility, became operational in 2023, promotes the deployment of clean energy in the United States and accelerate the development and deployment of low-cost, long-duration grid-scale energy storage systems.

In November 2022, the US government launched a USD350 million Long Duration Demonstration Program, selecting up to 11 demonstration projects to help achieve the US Department of Energy's long-term goal of reducing long-duration storage costs by 90%. The funding comes from the *Bipartisan Infrastructure Law* passed at the end of 2021 and will be managed by the Office of Clean Energy Demonstrations within the US Department of Energy (DOE). The program requires demonstration projects to provide 10 to 24 hours of energy storage duration and can cover up to 50% of project costs. Letters of Intent were required to be submitted before December 2022, and full applications started in March 2023.

State level policies

i) California AB2625 Act

On 29 August 2022, the Governor of California signed Assembly Bill 2625 (AB2625), which excludes leases and easements for qualified energy storage projects from the Subdivision Map Act ("Map Act"). The "Map Act" defines the authority of local legislative bodies to approve, disapprove, or set conditions for subdivision maps and any modifications to them. Under the "Map Act", local agencies are authorized to regulate and control the design and improvement of subdivisions. The Act and local ordinances enacted under its authority require the creation of accurate maps showing internal and external boundaries of subdivisions and the location of improvements. The new law exempts energy storage projects from the requirements of California's "Map Act", like how leases and easements for qualifying wind and solar projects are exempt.

Leases and easements related to financing, installation, and sale of energy storage projects are no longer subject to the "Map Act".

The subdivision processes increase project development costs, more time, may require public hearings, and leave potential litigation targets for project opponents, prolonging the project development cycles. After the passage of AB2625, energy storage projects in California can complete the development process without consulting local zoning authorities, therefore helping to accelerate the deployment of battery energy storage systems in the state.

ii) California NEM3.0

On 15 December 2022, the California Public Utilities Commission (CPUC) voted to adopt Net Energy Metering 3.0 (NEM 3.0), under which a net billing model replaces the previous net metering system. The new policy significantly reduces compensation rates for distributed solar exports to the grid. NEM 3.0 took effect on April 2023. Systems installed before this date will still be eligible for NEM 2.0, and users under NEM 1.0 and 2.0 will not be affected by the new policy.

Net billing replacing net metering improving economics of solar plus storage. The core changes in NEM 3.0 include replacing net metering with net billing, where customers are compensated based on a variable export rate rather than retail electricity prices. While the average export rate will be significantly lower, the new rate structure introduces a new time-of-use mechanism, further widening the peak-to-valley price spread (aligned with wholesale pricing). As a result, the economics of residential solar plus storage will improve under the new policy.

iii) New York's 6GW Energy Storage Roadmap

On 28 December 2022, the New York State Energy Research and Development Authority (NYSERDA) and the New York Department of Public Service (DPS) submitted the *New York's 6GW Energy Storage Roadmap: Policy Options for Continued Growth in Energy* to the Public Service Commission (PSC). The roadmap presents a comprehensive set of recommendations to expand New York's energy storage programs in a cost-effective manner, enabling rapid growth in statewide renewable energy deployment while enhancing grid reliability and customer resilience. The roadmap supports expanded energy storage deployment, with projections indicating that statewide electricity system costs could decrease by nearly USD2 billion. Additionally, reduced exposure to harmful fossil fuel pollutants would bring significant public health benefits and cut carbon emissions.

The roadmap proposes implementing NYSERDA-led initiatives to procure an additional 4.7GW of new energy storage across utility-scale, retails (community, commercial, and industrial), and residential sectors in New York. Combined with existing energy storage systems already contracted and moving toward commercial operation, these future procurements will enable New York to reach its energy storage target of 6GW by 2030. This energy storage roadmap builds upon existing policy efforts, including the 2018 New

York State Energy Storage Roadmap and the landmark Energy Storage Order issued by the PSC in December 2018 (Order Establishing Energy Storage Goal and Deployment Policy).

iv) The Michigan Healthy Climate Plan

On 23 September 2020, the Governor of Michigan signed *Executive Orders 2020-182 and 2020-10*, establishing the Michigan Healthy Climate Plan. The plan was officially launched on 21 April 2022, aiming to guide the state toward achieving carbon neutrality by 2050, with interim goals set for 2030. By 2040, Michigan plans to deploy 4GW of utility-scale energy storage, with a short-term target of 1GW by 2025 and an intermediate goal of 2.5GW by 2030. As mentioned, Michigan became the 10th state of the United States to establish a clear energy storage development target.

v) New Jersey Energy Storage Incentive Program

In September 2022, the New Jersey Board of Public Utilities (BPU) released a proposal for the Statewide Energy Storage Incentive Program (SIP), focusing on incentivizing standalone energy storage systems physically connected to New Jersey's distribution companies. The program applies to both front-of-meter ("grid-supplied") and behind-the-meter ("distributed" or "customer-level") energy storage systems, and separate market segments were created for each type of energy storage.

At least 30% of the incentive fee are paid as a fixed annual incentive based on the energy storage capacity (S/kWh), depending on satisfactory operating performance indicators. The remaining incentives are provided through performance-based payment mechanisms: Front-of-meter standalone energy storage system are compensated based on the amount of carbon emissions reduced through its operation, determined by measuring the marginal carbon intensity of the wholesale grid; For behind-the-meter distributed standalone energy storage, payments are made when the distribution company calls on the storage during specific operating windows established by the program and the system successfully delivers power to the distribution grid. To maximize private investment, in addition to the above incentives, private investors are allowed to own and operate energy storage systems.

The developers of storage projects are permitted to "stack" revenues from the wholesale electricity market, actively manage their energy usage at the distribution level using behind-the-meter resources to lower electricity costs, and participate in distributed energy resource (DER) aggregation services where available. In addition, as part of the *Inflation Reduction Act*, recent changes in federal tax policy allow standalone energy storage systems to qualify for Investment Tax Credits (ITC) for the first, which significantly enhance the supports for storage development, along with the state-level incentives.

4.1.2 Other APEC economies

(1) Chile

Chile aims to achieve an 80% renewable energy grid by 2030 and a 100% zero-emission grid by 2050, estimating that it needs 2000MW of energy storage every decade. Chile was one of the first economies to recognize that energy storage could provide value to transmission systems, allowing energy storage-as-transmission projects to be submitted for consideration and inclusion in Chile's National Transmission Plan. By evaluating the value of energy storage in the grid, it was found that energy storage is a flexible and reliable resource for addressing some issues in transmission and distribution networks. Therefore, in the process of promoting renewable energy power generation, Chile utilizes energy storage systems to enhance the reliability of power grid.

Chile's future energy mix includes 46% photovoltaic, 31% wind, 12% hydropower, and 8% flexible natural gas plants, along with 23% battery storage capacity, with the remaining 2% allocated to biomass, geothermal, and other less common energy sources. Additionally, Chile will need an estimated 9.5GW of new flexible capacity over the next decade to completely replace coal and achieve significant emission reductions necessary for meeting government climate targets.

Various energy storage technologies, including lithium-ion batteries, compressed air, cryogenic/liquid air, pumped hydro storage, and molten salt thermal storage have been used in Chile. Currently, out of the 129 large-scale energy storage projects under development in Latin America, 36 are in Chile, including 32 of the region's 71 early-stage projects. While many projects are under development, lithium-ion battery storage remains limited. Energy company AES Andes added 188MW of battery storage capacity to Chile's power system by 2023. With the additional 175MW currently under development, capacity will double to exceed 360MW.

Chile's regulations include capacity pricing for long-duration energy storage, intraday price differences, and ancillary services markets, providing multiple revenue streams for energy storage projects such as capacity, arbitrage, and ancillary services. In November 2022, Chile enacted the *Promotion of Electricity Storage and Electric Vehicles* law, which allows standalone energy storage (unrelated to power plants) to sell electricity to the power grids, including both retail and wholesale markets. It also allows electric vehicle storage capacity to be injected into distribution networks. Additionally, within one year of the policy's announcement, the Ministry of Energy issued compensation prices for energy storage systems directly connected to transmission and distribution networks, as well as price stabilization mechanisms applicable when participating in the electricity market, and methods for coordinating the dispatch of energy storage systems.

Chilean regulators introduced four remuneration schemes over the past decade to promote investment in energy storage projects. The first scheme targets independent battery systems, allowing asset owners to perform energy arbitrage and sell ancillary services. The second involves integrating energy storage systems with renewable energy plants, also rewarding power capacity. The third is that independent system operators in Chile can use energy storage to earn fees from providing ancillary services. The fourth is that Chile's energy regulatory body, Comisión Nacional de Energía or CNE, funds the purchase of energy storage assets to support grid infrastructure. Canadian compressed air energy storage company Hydrostor is targeting this last market, advancing a large-scale advanced compressed air energy storage project exceeding 2GW. ESS begun providing a 300kW/2MWh flow battery system for the Patagonia region in Chile.

(2) Indonesia

In 2021, Indonesia's installed power capacity was 74GW, with renewables accounting for 15%. Among renewables, hydropower made up 59% (6.5GW), and solar contributed 17% (1.9GW). The Indonesian government supports renewable energy deployment through low-interest financing to help accelerate project development. State-owned utility PLN signed a memorandum of understanding with other state institutions, including the Indonesian Battery Corporation, to establish battery energy storage systems before 2022. There is currently no information available regarding the specific locations or functions of these battery systems.

(3) Malaysia

By the end of 2021, Malaysia had an installed generation capacity of 39GW, with renewables accounting for 23%. Hydropower represented 70% of renewable capacity, and solar made up 20%, with no wind generation installed. The Malaysian government places great emphasis on the development of its domestic renewable energy industry, having introduced several favorable policies such as the *Renewable Energy Supply Agreement (SARE)* and the *Net Energy Metering (NEM) Scheme*. The economy aims to reach 12,916MW of renewable capacity by 2025, representing 31% of total generation, and increase this to 40% by 2035. Promoting energy storage is an important means to enhance the flexibility of low-carbon electricity, balance the grid, and contribute to a more sustainable power ecosystem. The Energy Commission of Malaysia’s *Peninsular Malaysia Generation Development Plan 2020 (2021–2039)* outlines plans to add 100MW/year of battery storage capacity in Peninsular Malaysia between 2030 and 2034.

(4) Mexico

Due to the continuous growth of renewable energy generation in Mexico and its transmission infrastructure failing to keep pace with rising electricity demand, the development of energy storage infrastructure has become increasingly urgent to maintain efficient and reliable power system operations. The development of energy storage projects in Mexico faces many challenges, including costs of energy storage systems, lack of unified standards and outdated regulatory policies, leading to slower progress in front-the meter energy storage investments. In Mexico, behind-the-meter energy storage systems do not require interconnection agreements or generation permits, and they can help adjust the consumption curves of large electricity users, saving electricity costs by avoiding peak period prices. Revenue sources from energy storage include arbitrage and serving as a backup power source. Energy storage systems help users comply with new, stricter grid regulations; failure to comply could result in losses of 2-10% of net income which drives the development of behind-the-meter energy storage.

(5) The Philippines

As of the end of 2021, the Philippines had an installed generation capacity of 28GW, with renewables accounting for 28% (3.1GW hydro, 2.2GW solar, and smaller shares of wind and others), with the rest coming from natural gas and coal. The Philippines has committed to halting the construction of new combustion-based power plants. As of August 2022, the Philippines had 27 operational battery storage projects, and the Board of Investments (BOI) had approved a total of 74 storage projects with total investments of PHP120 billion. To encourage faster deployment of energy storage, the Department of Energy (DOE) issued Memorandum No. DC2019-08-0012, recognizing the benefits and applications of energy storage in improving the reliability, quality, and security of the power system. In July 2020, the Philippines issued the Guidelines for the Green Energy Auction Program (GEAP), providing official implementation strategies for economy-wide bidding of renewable energy projects. This policy facilitates the steady increase in new renewable energy installations, the continuous reduction in renewable energy electricity generation costs, and the enhanced competitiveness of renewable energy projects in the Philippines.

Because large power companies are the main investors in large-scale storage in the Philippines, current rules hinder their willingness to invest. The DOE and regulators of the Philippines energy sector are considering revising ownership rules for grid-connected storage systems. Previously, power companies were prohibited from owning more than 30% of any grid segment or 25% of total capacity of the economy, and future ownership will no longer be subject to these restrictions.

According to the Philippines Energy Plan (PEP), which outlines the economy's low-carbon energy transition goals, renewables will account for 35% of electricity generation by 2030 and 50% by 2040. To achieve this, the Philippines will need to add 52.8GW of renewable energy capacity by 2040. To address challenges associated with rising renewable penetration, the DOE encourages technological innovation and promotes disruptive systems and technologies such as distributed generation, energy storage, and smart grids. The Philippines has received grant funding from the NAMA Facility to conduct research and development activities evaluating hydrogen as an efficient energy storage medium and energy carrier. To further investigate hydrogen feasibility, the DOE signed two memoranda of understanding with major Australian and Japanese companies. Locally, the Department of Science and Technology provides funding for the development and commercialization of innovative technologies through grants to academia and micro, small, and medium enterprises.

In the distributed energy space, the ERC of the Philippines approved new rules for DERs with capacities not exceeding 1MW, allowing owners of distributed renewable systems to inject surplus power into the grid and receive compensation for up to 30% of excess electricity output. At the same time, the government has mandated an annual 6% decline in the solar FiT tariff, driving economic viability for behind-the-meter storage systems.

(6) Singapore

Singapore has an installed generation capacity of 12GW, with renewables accounting for only 5%. Of this, 66% comes from solar PV, totaling 350MW. Currently, 95% of Singapore's electricity is generated from natural gas, mainly imported via pipeline from Malaysia and Indonesia. Due to its equatorial location and lack of other resources, solar energy is considered the most viable renewable option. Singapore plans to quadruple its solar deployment, reaching a peak capacity of 1.5GW by 2025 and 2.0GW by 2030. Currently, solar accounts for less than 1% of electricity generation, with a target of increasing this to 3% by 2030. To achieve these targets, Singapore focuses on exploring energy storage solutions, as geographical constraints and dense urban landscapes limit its ability to significantly expand solar or other renewables in the energy mix. Using storage to balance peak and off-peak demand can save significant infrastructure costs. In light of this, Singapore plans to add 200MW of energy storage capacity after 2025. At the same time, the economy envisions exploring a regional grid, similar to parts of Europe, to sell surplus electricity to neighboring economies.

In addition, the Singaporean government heavily invests in electric vehicles, virtual power plants and other innovations. It has allocated USD49 million for R&D in low-carbon energy to support a successful transition to a low-emission economy. The government encourages partnerships between people, the private and public sectors—known as 3P (People, Private, Public) collaborations—to develop climate action strategies. By leveraging real-time data from various distributed energy resources (DERs), the economy optimizes the power output of these resources on the island, promoting the development of VPPs and V2G technologies, maintaining grid stability while integrating more clean and distributed energy into Singapore's energy mix.

(7) Thailand

In 2021, the total installed power generation capacity of Thailand was 55GW, with renewable energy accounting for 22%. Wind power capacity was 1.57GW, and solar PV capacity was 3.15GW. Thailand has been steadily advancing its National Strategy 4.0, developing a climate-resilient economy, building a low-carbon society, and promoting green energy transition. According to the *Alternative Energy Development Plan (AEDP)* and *Power Development Plan (PDP 2018–2037)*, Thailand aims to raise the share of renewable electricity to 30% by 2037. The government recognizes that only by combining renewables with energy storage can the power system operate reliably and stably. It plans to invest THB200 billion by 2036 to build smart grids and promote energy storage investments to ensure continuity of renewable generation. The grid operator will purchase electricity from licensed generators to develop renewable energy plants totaling 5.2GW between 2022 and 2030. The 5.2GW allocation includes: biogas plants (335MW), wind farms (1,500MW), centralized solar farms (2,368MW), and solar-plus-storage plants (1,000MW). From 2024 to 2030, the annual solar quota will be 100MW. Solar and storage quotas are increasing: 190MW in 2024, 290MW in 2025, 258MW in 2026, 440MW in 2028, 310MW in 2029, and 390MW in 2030. So far, Thailand has limited utility-scale energy storage capacity, with only a few projects in the pipeline. The government encourages the integration of energy storage with renewables through power purchase agreements (PPAs) to accelerate deployment.

In 2021, Thailand's Ministry of Energy approved a THB2.4 billion investment in the "Solar for Villages" program, supporting the development of three types of power generation projects: community power stations, including solar, biomass, and biogas generation; solar-powered pumping systems; self-generation projects in unelectrified areas, creating necessary conditions for the development of energy storage. The Energy Regulatory Commission (ERC) published the *Renewable Energy Procurement Regulations under the Feed-in-Tariff (FiT) Plan 2022–2030*, effective from 28 September 2022, covering utility-scale solar, battery storage, wind, and biogas. The regulation introduced a 25-year FiT of THB21.679/kWh for solar-only and THB28,331/kWh for solar-plus-storage, allowing for a premium tariff when energy storage is added.

(8) Viet Nam

In 2021, the total installed capacity of Viet Nam was 76GW, with renewable energy accounting for 56%. Solar PV capacity was 16.6GW, and wind power capacity was 4.3GW. Between 2021 and 2024, Viet Nam's total electricity demand is expected to grow at an annual rate of 10%, with power shortages expected to intensify across different regions. According to reports from Viet Nam Electricity (EVN), it was estimated that Viet Nam would face a power shortage of nearly 400GWh in 2021, rising to a peak of 1,330GWh by 2023. In February 2020, Viet Nam's Central Committee of the Communist Party issued Resolution No. 55-NQ/TW *Viet Nam's National Energy development strategy direction for 2030 and Development Vision Outlook for 2045*, which encourages and promotes the development of renewable energy as an effective substitute for fossil fuels, and calls for research and assessment of geothermal, wave, tidal, and ocean current energy potentials. It also encourages the development of the hydrogen industry and approves a number of pilot projects.

After the Ministry of Industry and Trade submitted the draft *National Power Development Plan VIII (PDP8)* to the government in March 2021, which greatly promote investment and development of energy storage in Viet Nam. Among others, the Viet Nam Sustainable Energy Alliance submitted four recommendations, including encouraging private sector participation in grid development and environmentally friendly battery energy storage systems. Attentions were paid to balancing baseload and variable power sources to ensure energy security and emphasize the planning of flexible resources. Due to the rapid growth of solar PV exceeding grid transmission capacity, to avoid placing additional strain on an already overloaded grid, Viet Nam's National Power Transmission Corporation (EVN) studied how to deploy battery storage systems to enhance power system flexibility and achieve high levels of renewable integration. EVN has proposed pilot storage systems with capacities of 50–100MWh, aiming to validate equipment performance through frequency regulation, assess optimization effects on the grid, and accumulate operational experience. The energy storage pilot project is funded and supported by the US Agency for

International Development (USAID) through its Trade and Development Agency (TDA).

Based on the actual operation results of the pilot storage projects, data will be provided to support the formulation of policies related to the development and operation of energy storage systems. Empirical data validation shows that due to the currently low penetration of renewables in Viet Nam, investment in energy storage does not yield economic benefits unless the renewable penetration reaches at least 15%. In the long terms, energy storage is regarded as a key to increasing renewable share. Pumped hydro is seen as a suitable short-term solution for Viet Nam's energy system, while battery storage systems will help facilitate higher penetration of variable renewables. Therefore, supportive policies encourage investment in energy storage, especially more flexible battery-based systems.

4.2 Energy storage policies and plans in China

4.2.1 Economy-level policies and plans

For China, entering a new phase of development during the "14th Five-Year Plan" period, energy storage has become a top priority in energy system construction. A series of policies have been issued to guide planning and provide support for energy storage applications. The rise and development of the energy storage industry cannot be separated from the broader context of China's energy transition strategies. From the 8th Five-Year Plan (1991–1995) to the 12th Five-Year Plan (2011–2015), the economy agenda emphasized the promotion of new energy industries. Starting from the 13th Five-Year Plan through the 14th Plan, the state formally proposed the development of energy storage industry. In 2021, the *Outline of the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and Long-Term Goals for 2035* proposed implementing incubation and acceleration plans for future industries in frontier science and technology fields like hydrogen energy and energy storage, and planning to layout a number of future industries.

In recent years, a series of policies concerning new energy storage have been introduced at the economy level. The National Development and Reform Commission (NDRC), the National Energy Administration (NEA), the Ministry of Industry and Information Technology (MIIT), the Ministry of Science and Technology (MST), the Ministry of Education (MOE), as well as State Grid Corporation of China and China Southern Power Grid Co., Ltd., have issued guiding opinions, implementation plans, R&D projects, industry norms, and academic discipline constructions aimed at promoting the development of new energy storage, forming a foundational policy framework for new energy storage development.

Table 4-4 Policies Regarding Energy Storage Development at the Economy Level

Target areas	Policy documents
Top-level design	National Development and Reform Commission, National Energy Administration: Guiding Opinions on Accelerating the Development of New Energy Storage Implementation Plan for the Development of New Energy Storage during the 14th Five-Year Plan Period
Scientific and technological breakthroughs	Technology Department: Key Special Projects on Energy Storage and Smart Grid Technology NEA Planning for Technological Innovation in the Field of Energy during the 14th Five-Year Plan Period
Project management	National Energy Administration: Interim Management Standards for New Energy Storage Projects", "Technical Guidelines for Planning New Energy Storage Configuration for Cross-Provincial Transmission from New Energy Bases
Product specification	Ministry of Industry and Information Technology: Industry Normative Conditions for Lithium-ion Batteries, Interim Measures for Managing Announcements on Industry Normatives for Lithium-ion Batteries, Notice on Promoting Synergistic and Stable Development of the Lithium-ion Industry Chain and Supply Chain, Safety Requirements for Lithium Batteries and Battery Packs Used in Electric Energy Storage Systems (Draft for Comments)
Grid connection	National Development and Reform Commission, National Energy Administration, Power Trading Center, etc.: Regulations on the Management of Grid Connection Operation, Measures for the Administration of Ancillary Services in Electric Power, Notice on Further Promoting New Energy Storage Participation in Electricity Markets and Dispatch Operations, Notice Encouraging Renewable Energy Power Generation Enterprises to Build or Purchase Peak Load Regulation Capacity to Increase Grid Connection Scale, Model Text of Grid Connection Dispatch Agreement for Electrochemical Energy Storage Power Stations, Trial Guidelines for Registration Norms of New Energy Storage Entities, Notice on Strengthening Safety Management of Electrochemical Energy Storage Power Stations, Twenty-Five Key Requirements for Preventing Power Production Accidents
Technical standards	Design Code for Electrochemical Energy Storage Power Stations (GB51048-2014)， Safety Procedures for Electrochemical Energy Storage Power Stations (GB/T 42288-2022), Guidelines for Environmental Impact Assessment of Electrochemical Energy Storage Power Stations (GBIT42318-2023)， Guidelines for Environmental Impact Assessment of Electrochemical Energy Storage Power Stations (GBIT42318-2023)
Research fields	The Ministry of Education, National Development and Reform Commission, National Energy Administration: Action Plan for the Development of Specialized Disciplines in Energy Storage Technology (2020-2024), Results of Filing and Approval of Undergraduate Majors in Ordinary Higher Education Institutions in 2021

Energy storage industry development goals: NDRC and NEA issued the *Implementation Plan for the Development of New Energy Storage during the 14th Five-Year Plan Period*, further clarifying development goals and detailing key tasks. As shown in the following table, by 2025, new energy storage will transition from the initial commercialization stage to a scaled development phase, with conditions for large-scale commercial deployment. By 2030, new energy storage will enter into comprehensive market-oriented development.

Table 4-5 Goals of China's Energy Storage Industry

Year	Development goals of energy storage industry
2025	By 2025, new energy storage will move to a scaled development phase from the initial commercialization stage, with mature conditions for large-scale commercial application. Innovative capabilities in new energy storage technology will be significantly enhanced, core technologies and equipment will be largely domestically controlled, the standard system will be basically complete, the industrial system will become increasingly mature, and the market environment and business models will be basically mature.
2030	By 2030, core technologies and equipment for new energy storage will be independently controllable, technological innovation and industrial levels will rank among the world's top, market mechanisms, business models, and standard systems will be mature and well-established, deeply integrated with all aspects of the power system, basically meeting the needs of building a new type of power system and fully supporting the timely achievement of carbon peak targets in the energy sector.

As China's new energy industry continues to develop, the installed capacity of wind power and solar PV has significantly increased, making the construction of infrastructure for absorbing green energy an urgent task. The *2010 Amendment to the Renewable Energy Law* first mentioned the development of energy storage. Guided by this, economy agencies and local governments at all levels have successively introduced relevant laws, plans, and measures, providing financial support for the development of the energy storage industry.

Table 4-6 Economy-level Policies on Energy Storage Industry

Release time	Authority	Policy document	Key contents
2023.05	NDRC	Implementation Opinions on Accelerating the Promotion of Charging Infrastructure Construction to Better Support New Energy Vehicles Going to the Countryside and Rural Revitalization	Encourage research on key technologies such as bidirectional interaction between electric vehicles and the grid (V2G) and coordinated control of PV-storage-charging. Explore the construction of integrated PV-storage-charging infrastructure in rural areas with lower utilization rates of charging piles.
2022.12	Ministry of Industry and Information Technology and other three ministries	Guiding Opinions on Deepening Green Industrial Development in the Yellow River Basin	Encourage provinces such as Qinghai and Ningxia to develop molten salt thermal storage and supercapacitor technologies to cultivate new types of power storage equipment. Support regions rich in wind and solar energy, such as Qinghai and Ningxia, to develop rooftop PV, smart PV, distributed wind power, diversified energy storage, efficient heat pumps, etc., and carry out the construction of industrial green microgrids in provinces like Henan, promoting efficient complementary use of multiple energies to provide high-quality clean energy for industrial enterprises in the Yellow River Basin.
2022.08	Ministry of Industry and Information Technology	Action Plan to Expedite the Green and Low-carbon Development of Electrical Equipment	Significantly enhance the reliability of electrochemical energy storage equipment, accelerate the research and development of compressed air energy storage flywheel energy storage equipment, and develop multi-level fire safety guarantee technologies and equipment for energy storage power stations. Develop online detection status prediction and early warning technologies and equipment for energy storage batteries and systems.
2022.08	Ministry of Science and Technology and other eight ministries	Science and Technology Support Implementation Plan for Carbon Peak and Carbon Neutrality (2022-2030)	Research and development of efficient energy storage technologies such as compressed air energy storage, flywheel energy storage, liquid and solid-state lithium-ion battery energy storage, sodium-ion battery energy storage, and flow battery energy storage; R&D of large-scale energy storage applications for cascaded power plants and related safety technologies; study of advanced energy storage technologies such as solid-state lithium-ion and sodium-ion batteries that are lower cost, safer, longer-lasting, more energy-efficient, and not constrained by resources.
2022.08	Ministry of Industry and Information Technology and other two ministries	Implementation Plan for Carbon Peak in the Industrial Field	Breakthrough and promote a batch of key core technologies in efficient energy storage, energy electronics, hydrogen energy, carbon capture, utilization, and storage (CCUS), and moderate condition CO_2 resource utilization.
2022.06	National Development and Reform Commission	Notice on Further Promoting the Participation of New Energy Storage in Power Markets and Dispatch Operations	Local government departments and dispatched institutions of the National Energy Administration should study and refine regulatory measures, strengthen supervision over the dispatch operation of standalone energy storage, ensure that energy storage power stations invested by social capital receive fair dispatching, and have equal rights and comparable utilization rates.
2022.05	National Development and Reform Commission, National Energy Administration	Notice on Implementation Plan for Promoting High-Quality Development of New Energy in the New Era	Improve the compensation mechanism for peak shaving and frequency regulation power sources, intensify the flexibility transformation of coal-fired power units, hydropower expansion, Pumped hydro storage and solar thermal power generation projects, and promote the rapid development of new energy: Study cost recovery mechanisms for energy storage.
2022.04	State Council	Opinions on Accelerating the Construction of a National Unified Market	Optimize the structure of government-issued standards and market-driven standards, and integrate and streamline economy-wide and industry standards. Strengthen standard verification, implementation, and supervision, and improve the standard system in emerging fields such as modern logistics, big data, artificial intelligence, blockchain, fifth-generation mobile communication (5G), Internet of Things, and energy storage.
2022.04	State Council	Outline of the 14th Five-Year Plan for National Economic and Social Development and Vision 2035 of the People's Republic of China	In frontier science and industrial transformation fields such as brain-like intelligence, quantum information, gene technology, future networks, deep-sea and space development, hydrogen energy, and energy storage, organize and implement future industry incubation and acceleration programs, and plan to layout a number of future industries.
2022.03	National Development and Reform Commission, National Energy Administration	Implementation Plan for the Development of New Energy Storage during the 14^{th} Five-Year Plan Period	By 2025, new energy storage will move to a scaled development phase from the initial commercialization stage, with mature conditions for large-scale commercial application. Among them, electrochemical energy storage technology has seen further performance improvements, with system costs reduced by more than 30%. By 2030, new energy storage will enter into comprehensive market-oriented development.
2022.01	Ministry of Industry and Information Technology	Action Plan for Innovative Development of Smart Photovoltaic Industry (2021–2025)	Break through key technologies in smart photovoltaics and energy storage, stabilize PV power output fluctuations, track generation plans, shift electricity over time, and enhance support capabilities for the new power system. Promote integrated development of photovoltaic power stations with pumped hydro storage, electrochemical energy storage, flywheel energy storage, and other technologies; construct a number of power-side photovoltaic energy storage projects to ensure efficient consumption and utilization of

Release time	Authority	Policy document	Key contents
			photovoltaic power.
2022.01	Ministry of Industry and Information Technology etc.	Guiding Opinions on Strengthening Industrial-Financial Cooperation to Promote Green Development of Industry	Support breakthroughs and industrial development of key technologies such as high-efficiency energy storage. Accelerate the integration and innovation of electronic information technology with the clean energy industry, promote breakthroughs in the new energy storage battery industry, and guide the high-quality development of the smart photovoltaic industry.
2022.01	National Energy Administration	Implementation Opinions on Deepening "Delegation, Management, and Service" Reforms in the Energy Sector to Optimize the Business Environment	Ensure grid connection and interconnection services for projects such as new energy, distributed energy, new energy storage, microgrids, and incremental distribution networks. Provide necessary information for related project access system design, clarify query procedures and processing times for available transformer capacity and other information. Promote the establishment of an energy multi-type collaborative development promotion mechanism centered on wind, solar, hydro, thermal, and storage, and support distributed power generation in participating in market transactions.
2022.01	State Council	Notice on Issuing the "14th Five-Year" Modern Comprehensive Transportation System Development Plan	Plan and construct convenient, efficient, and moderately forward-looking charging and battery swapping networks. Focus on advancing charging infrastructure construction at transportation hubs, parking facilities, highway service areas, and other locations. Encourage the reasonable deployment of photovoltaic power generation and energy storage facilities along transportation hubs and highways, railways, and other routes.
2021.07	National Energy Administration	Guiding Opinions on Accelerating the Development of New Energy Storage	Uphold diversified energy storage technologies, and promote continued cost reductions and large-scale commercial applications of relatively mature new energy storage technologies such as lithium-ion batteries.
2021.11	State Council	Action Plan for Deepening Price Mechanism Reform During the 14th Five-Year Period	Improve the price formation mechanisms for wind power and photovoltaic power generation, implement the newly introduced pricing mechanism for pumped hydro storage, and establish a pricing mechanism for new energy storage to promote the development of new energy and related energy storage industries. Continue to advance reforms in transmission and distribution pricing, rationalize the structure of transmission and distribution prices, enhance the flexibility of electricity pricing mechanisms, and promote the local consumption of new energy as well as the optimal allocation of electric power resources over a broader scope.
2021.10	State Council	Circular of the State Council on Printing and Issuing the Action Plan for Carbon Dioxide Peaking Before 2030	Actively develop "New Energy + Energy Storage", source-grid-load-storage integration, and multi-energy complementarity to support the reasonable configuration of energy storage systems for distributed new energy. Formulate a new round of medium- and long-term development plans for pumped hydro storage power stations and improve policy mechanisms that promote the development of pumped hydro storage. Accelerate the demonstration and application of new energy storage technologies. Deepen power system reform and accelerate the construction of a unified economy electricity market system. By 2025, the installed capacity of new energy storage will reach more than 30 million kilowatts. By 2030, the installed capacity of pumped hydro storage power stations will reach around 120 million kilowatts, and provincial power grids will generally have response capabilities for peak load demand of more than 5%.
2021.10	State Council	Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Neutralization in Peak Carbon Dioxide Emissions and Carbon Neutrality	Accelerate the large-scale application of pumped hydro storage and new energy storage; Accelerate the formation of a new power installation development mechanism based on energy storage and peak-shaving capabilities; Adopt the "revelation and leadership" mechanism to conduct research on low-carbon, zero-carbon, negative-carbon technologies and new materials, new technologies, and new equipment for energy storage; Conduct in-depth research on smart grid technologies that support the large-scale and friendly grid connection of wind and solar power generation. Strengthen technological research, demonstration, and industrial application of new energy storage technologies such as electrochemical and compressed air energy storage.
2021.08	National Development and Reform Commission	Notice from the National Development and Reform Commission on Further Improving Time-of-Use Electricity Pricing Mechanisms	On the basis of maintaining the overall stability of retail electricity prices, further improve time-of-use pricing mechanisms to better guide users in peak shaving and valley filling, improve power supply-demand conditions, promote the absorption of new energy, and provide support for building a new power system dominated by new energy and ensuring the safe, stable, and efficient operation of the power system.
2021.07	State Council	Guiding Opinions on Accelerating the Construction of a New Standard System in the Energy Sector	In emerging fields such as smart energy, energy internet, wind power, solar energy, geothermal energy, biomass energy, energy storage, and hydrogen energy, take the lead in advancing the construction of a new standard system and play a demonstrative and leading role.
2021.03	State Council	Guiding Opinions on Promoting Source-Grid-Load-Storage Integration and Multi-Energy Complementarity in Power Systems	Rationally allocate energy storage, actively implement upgrades to existing "wind-solar-hydro-coal-storage integrated" systems, steadily promote incremental "wind-solar-hydro (storage) integration", explore incremental "wind-solar-storage integration", and strictly control incremental "wind-solar-coal (storage) integration".

Note: as for 2023.

Impacts of the 14th five-year plan on development of energy storage industry: Entering the 14th Five-Year Plan period, the energy storage industry needs to undergo top-level design at the economy level, break through market mechanism barriers, establish a suitable market environment for energy storage development, and change the situation of struggling for survival. The 14th Five-Year plans of energy development, electricity development, renewable energy, and energy technology innovation all include energy storage, with some directly setting up special targeted areas for research. The *Outline of the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and Long-Range Objectives Through the Year 2035* outlines specific policies and impacts as follows:

Table 4-7 Impacts of the 14th Five-Year Plan on the Development of Energy Storage Industry

Targeted areas	Specific contents
Accelerate the Application of the Energy Storage Industry	Accelerate the intelligent transformation of grid infrastructure and the construction of smart microgrids, improve the complementary and intelligent regulation capabilities of power systems, strengthen the integration of source-grid-load-storage, enhance the ability to absorb and store clean energy, and improve the capacity for power transmission and distribution to remote areas.
Promote the Development of Energy Storage Technology	In frontier science and industrial transformation fields such as hydrogen energy and energy storage, organize and implement future industry incubation and acceleration programs, and plan to layout a number of future industries.

Impacts of carbon peaking and carbon neutrality strategy on development of energy storage industry: Carbon peaking and neutrality became a key policy focus after the *2021 National Two Sessions*. China has solemnly pledged to the world to strive to achieve carbon peak by 2030 and endeavor to achieve carbon neutrality by 2060, which means achieving net-zero CO_2 emissions. Specific impacts of the carbon Peak and neutrality strategy on energy storage development are as follows:

Table 4-8 Impacts of Carbon Peak and Neutrality Strategy on Development of Energy Storage Industry

Targeted areas	Specific contents
Promote innovation in energy storage technology and expand market applications	The proposal of the carbon peak and neutrality goals has provided a clear roadmap for the energy revolution and set an overall timeline for energy transition, accelerating the transformation of the energy structure. As a key technology for promoting the development of renewable energy, the development of energy storage has become an increasingly urgent need for achieving carbon neutrality goals. Energy storage is an important technology and basic equipment supporting new power systems, playing a crucial role in promoting green energy transition and ensuring energy security.

Impacts of the *14th Five-year Plan of New Energy Storage Development Implementation* on Energy

Storage Industry: New energy storage is an important technology and basic equipment for building new power systems, serving as a critical support for achieving carbon peak and carbon neutrality goals, and it is also an important area for fostering new domestic energy formats and capturing international strategic high ground. The *14th Five-Year Plan of New Energy Storage Development Implementation* proposes that by 2025, new energy storage will move from its initial commercialization phase into a stage of scaled development, possessing conditions for large-scale commercial application.

Table 4-9 Main Targeted Areas in the 14th Five-Year Plan on New Energy Storage Development

Targeted areas	Specific contents and plans
Promote the Development of the Energy Storage Industry System	Strengthen top-level design, highlight scientific leadership, enhance coordination with relevant energy plans, and coordinate the upstream and downstream development of the new energy storage industry. For various application scenarios, develop diversely based on local conditions, and optimize the construction and layout of new energy storage.
Promote the Development of the Energy Storage Application Market	Focus on various application scenarios, pay attention to diversified technical routes, conduct pilot demonstrations of new energy storage in a steady and phased manner, and strengthen tracking and evaluation of demonstration projects. Accelerate pilot demonstrations in key regions, encourage localities to take the lead in piloting and demonstrating, promote technological progress and industrial upgrades in new energy storage through demonstration applications, improve the industrial chain, and enhance industrial competitiveness.
Promote the Development of Energy Storage Technology	Leverage both government guidance and market initiative, strengthen strategic layout and systematic planning of energy storage technology innovation, actively carry out key R&D on new energy storage technologies, adopt a "challenge-based leadership" mechanism to conduct breakthroughs in new materials, technologies, and equipment for energy storage, accelerate core technology autonomy, promote organic integration across production, education, research, and application, expedite the transformation of innovative achievements, and enhance innovation capabilities in the field of new energy storage.

4.2.2 Provincial and municipal levels energy storage policies

(1) Installed capacity targets for energy storage at provincial and municipal level

During the 14th Five-Year period, many provinces in China have also put forward development goals for the energy storage industry. As of January 2023, a total of 27 provinces and cities across the economy have set targets for new energy storage capacity during the 14th Five-Year period, with a total scale of approximately 71.55GW. It is noticed that the combined capacity planned by local governments exceeds the economy’s target of 30GW by more than double.

Table 4-10 Local Energy Storage Targets during the 14th Five-Year Period

Province or city	Release time	Policy document	Targets capacity (GW)
Beijing	2022.10	Beijing's Implementation Plan for Carbon Peak	0.7
Tianjin	2022.1	The 14th Five-Year Plan" for Renewable Energy Development of Tianjin	0.5
Hebei	2022.4	Hebei Province's "14th Five-Year" New Energy Storage Development Plan	4
Shanxi	2022.9	Implementation Plan for the Development of New Energy Storage during the th Five-Year Plan Period	6
Inner Mongolia	2021.12	Opinions on Accelerating the Development of New Energy Storage	5
Liaoning	2022.7	The 14th Five-Year Plan" Energy Development Plan in Liaoning Province	1
Jilin	2022.8	Notice on Jilin Province's Carbon Peak Implementation Plan	0.25
Jiangsu	2022.7	Implementation Plan for the Development of New Energy Storage during the th Five-Year Plan Period in Jiangsu Province	2.6
Zhejiang	2022.5	Zhejiang Province's "14th Five-Year" New Energy Storage Development Plan	3
Anhui	2022.4	New Energy Storage Development Plan (2022–2025)	3
Fujian	2022.8	Notice on Fujian Province's Action Plan for Promoting Green Economic Development (2022–2025)	0.6
Jiangxi	2022.7	Notice on Jiangxi Province's Carbon Peak Implementation Plan	1
Shandong	2022.12	New Energy Storage Engineering Development Action Plan of Shandong Province	5
Henan	2022.2	Carbon Peak Implementation Plan of Henan Province	2.2
Hubei	2022.5	The "14th Five-Year" Energy Development Plan of Hubei Province	2
Hunan	2022.10	Hunan Province's Power Support Capacity Enhancement Action Plan (2022–2025)	2
Guangdong	2022.4	The "14th Five-Year" Energy Development Plan of Guangdong Province	2
Guangxi	2022.6	The "14th Five-Year Plan" for Renewable Energy Development of Guangxi Province	2
Sichuan	2022.12	Sichuan Province's Power Grid and Generation Development Plan (2022–2025)	2
Guizhou	2022.11	Carbon Peak Implementation Plan of Guizhou Province	1
Yunnan	2022.12	Yunnan Province's Climate Change Response Plan (2021–2025)	2
Tibet	2022.7	Power Supply Guarantee Plan for This Winter and Spring and the 14th Five-Year Period	0.7
Shaanxi	2022.3	Shaanxi Province's 2022 New Energy Storage Construction Implementation Plan (Draft for Comments)	1
Gansu	2021.12	"14th Five-Year Plan" Energy Development Plan in Gansu Province	6
Qinghai	2021.7	Qinghai Province's Action Plan to Build a National Clean Energy	6

Province or city	Release time	Policy document	Targets capacity (GW)
		Industry Base	
Ningxia	2023.2	Implementation Plan for the Development of New Energy Storage during the Five-Year Plan Period in Ningxia Province	5
Xinjiang	2022.3	Implementation Plan for the Development of New Energy Storage during the Five-Year Plan Period	5
		Total	**71.55**

Among these plans, the configuration of energy storage with renewable energy is a key focus. According to statistics from the China Energy Storage Alliance (CNESA), more than twenty provinces have issued policies encouraging or mandating to pair energy storage with renewable energy projects, with storage to generation ratios ranging between 5% and 30%, and durations typically between 1 to 4 hours. For example, Hubei, Xinjiang, and other regions have introduced policies that calculate the proportion and capacity of renewable energy installations based on the scale of pumped hydro and new energy storage construction. In Anhui, Gansu, Ningxia, and other province, multiple batches of competitively allocated projects have been announced, where the ratio of energy storage to renewable energy has become an important scoring criterion in the project permission processes. The policies requiring energy storage to be integrated with renewable energy reflects the increasing demand for flexible resources as the penetration of renewable energy continues to rise. However, current one-size-fits-all and mandatory storage policies have increased the burden on developers. Additionally, due to the lack of proper cost recovery mechanisms and system-wide optimization, the utilization efficiency of energy storage paired with renewables remains low, and returns are generally less than expected. According to the *Survey Report on the Operation Status of New Energy Paired with Energy Storage* released by the China Electricity Council, the equivalent utilization factor of new energy paired with energy storage is only 6.1%.

To lower initial investment, improve system operation efficiency, and leverage the regulation role of energy storage in the power system, since 2019, Qinghai, Jiangsu, Hunan, and other provinces have begun exploring shared energy storage construction and operational models. In 2022, independent and shared energy storage facilities became one of the main models for renewable energy paired with energy storage installation across the regions. Compared with on-site energy storage within renewable energy generation, independent and shared energy storage can act as independent entities participating in the electricity market. Currently, independent shared energy storage projects primarily earn revenue by participating in regional ancillary service markets and spot markets, and receives payment from capacity leasing according to local renewable paired energy storage policies.

(2) Energy storage policies at provincial and municipal level

The Outline of the 14th Five-Year Plan and the 2035 Long-Term Vision proposes focusing on frontier science and industrial transformation fields such as energy storage. Provinces and cities have also launched local development policies and plans aiming at promoting the energy storage industry in line with the blueprint of *the 14th Five-Year National Plan*.

Table 4-11 Provincial and Municipal Policies on Energy Storage

Province or city	Release time	Policy document	Main contents
Guangdong	April 2023	Guangdong Province's Implementation Plan for New Energy Storage Participation in Electricity Market Transactions	Promote high-quality development of the energy storage industry, establish and improve mechanisms for new energy storage participation in the electricity market, accelerate the involvement of new energy storage in electricity market transactions, and gradually build a transaction system covering medium- and long-term contracts, spot markets, and ancillary services markets for new energy storage. Gradually improve the commercial operation model of new energy storage in Guangdong and establish a market-based pricing mechanism for new energy storage.
	March 2023	Several Measures on Accelerating the High-Quality Development of New Energy Storage Products	Clarify the main development directions for each link in the new energy storage industry chain, strengthen existing advantages, cultivate emerging industries, plan for future directions, and focus on developing key links such as components, equipment, systems, and comprehensive utilization.
Jiangsu	May 2023	Notice on Further Strengthening the Construction of Supporting Peak-Shaving Capacity for Photovoltaic Market-Oriented Grid Connection Projects	To ensure the overall safe and stable operation of the power grid and fully leverage the role of new energy storage, all newly included photovoltaic market-oriented grid connection projects in the implementation database should adopt methods such as self-construction, joint construction, or purchasing new energy storage (including electrochemical, compressed air, gravity-based storage, etc.) to meet the conditions for market-oriented grid connection.
	March 2023	Notice on the Implementation Plan for Promoting the Integrated Cluster Development of Strategic Emerging Industries	Promote continuous cost reduction and large-scale application of new energy storage technologies, accelerate the commercialization of long-duration energy storage technologies such as compressed air and flow batteries, and support R&D and large-scale pilot demonstrations of next-generation energy storage equipment such as flywheel and chemical energy storage.
Zhejiang	November 2022	Action Plan for Accelerating the Construction of Charging Infrastructure Along Highway Routes	Actively explore technical solutions for the integrated development of charging infrastructure along highways and the distribution of renewable energy and intelligent transportation in smart grids. Encourage the research and development of large-capacity energy storage technologies to enhance the grid's capacity for collection and transmission. Encourage highway service areas (stations), parking lots, passenger terminals, and logistics parks with suitable construction conditions to carry out integrated development of photovoltaic, energy storage, and charging/swapping facilities.

Province or city	Release time	Policy document	Main contents
	August 2022	Implementation Opinions on Supporting Carbon Peak and Carbon Neutrality Efforts	Support offshore wind power development through various policies including fiscal subsidies, government industrial funds, and financial guidance. Encourage regions with favorable conditions to develop new types of energy storage such as electrochemical energy storage and distributed natural gas generation according to local conditions, and accelerate the formation of a power system development mechanism based on energy storage and peak-shaving capabilities.
Hebei	April 2023	Notice on Issuing the Action Plan for Accelerating the Integrated and Clustered Development of Strategic Emerging Industries in Hebei Province (2023-2027)	Develop industrial chains such as energy storage technologies and equipment, accelerate the advancement of the new energy and smart grid equipment industries up the value chain, and focus on fields like vanadium-titanium extended processing and vanadium-titanium-based equipment manufacturing, achieving breakthroughs in key core technologies such as all-vanadium redox flow batteries.
	April 2022	Hebei Province's "14th Five-Year" New Energy Storage Development Plan	Widely apply new energy storage at the power generation, grid, and user levels to enhance source-grid-load-storage integration and safety supervision capabilities, promote deep integration of "new energy + energy storage" with unified planning, simultaneous construction, and joint operation, and strengthen the regulation capabilities of the power grid and end-user energy storage systems.
Inner Mongolia	December 2022	Notice on Issuing Several Policies to Support New Energy Storage Development in the Autonomous Region (2022–2025)	The autonomous region has introduced several measures to support the development of new energy storage, aiming to coordinate related work, accelerate the launch of demonstration projects, and promote the marketization, industrialization, and large-scale development of new energy storage across the region.
Shanghai	December 2022	Implementation Plan for Carbon Peak in the Industrial Field in Shanghai	Actively develop "source-grid-load-storage" integration and multi-energy complementarity, guiding enterprises and industrial parks to accelerate the development and operation of integrated systems such as distributed PV, diversified energy storage, high-efficiency heat pumps, waste heat and pressure recovery, and smart energy management, promoting green microgrid construction centered on distributed renewables plus energy storage, and developing efficient multi-energy complementary operating systems. Actively explore the application of new energy storage technologies and promote their demonstration use in scenarios such as renewable energy absorption and grid peak shaving.

Province or city	Release time	Policy document	Main contents
	August 2022	Shanghai's Implementation Plan for Carbon Peak in the Energy and Power Sector	Leverage the multiple functions of energy storage such as peak shaving, frequency regulation, emergency backup, and capacity support, encouraging energy storage to provide various regulation services to new energy sources and power users, and orderly advancing the coordinated development of energy storage and new energy.
Beijing	October 2022	Carbon Peak Implementation Plan of Beijing City	Deepen cooperation with Hebei, Inner Mongolia, and Shanxi in the development and utilization of renewable energy power, vigorously promote green power transmission channels into Beijing and the construction of peak-shaving and energy storage facilities, and build a new power system dominated by new energy.
	August 2022	Beijing's Energy Development Plan During the 14th Five-Year Period	Accelerate the construction of peak-shaving power stations around Beijing, promote deep peak-shaving retrofits for gas turbines, and advance the construction of new energy storage projects. By 2025, the city will have formed an emergency reserve and peak-shaving capacity of tens of millions of kilowatts, significantly enhancing the allocation capability of emergency power resources, and further improving the level of new energy absorption.
Hunan	June 2022	Hunan Province's Plan to Strengthen the "Three Capabilities" (2022–2025)	Accelerate the construction of pumped hydro storage power stations, study and explore hybrid retrofitting of conventional hydropower stations, and actively develop electrochemical energy storage.
	January 2022	Three-Year Action Plan for the Advanced Energy Storage Materials and Power Battery Industry Chain in Hunan Province (2021–2023)	By 2023, establish one core area (China Lithium Battery Valley, including the economy-level energy storage industry cluster zone in Xiangjiang New Area, advanced battery park and headquarters center, and regional testing center for new materials), and form a multi-point layout (battery manufacturing base relying on BAIC in Zhuzhou, industrial supporting bases centered in Xiangtan Economic Development Zone, Changde Economic Development Zone, Loudi Economic Development Zone, Yiyang Hi-Tech Development Zone, etc., and coastal energy storage material receiving bases and enterprise technology transfer/research centers represented by industrial parks in Yongzhou and Chenzhou).
Hubei	May 2022	The "14th Five-Year" Energy Development Plan of Hubei Province	Promote the application of energy storage technologies, construct a number of centralized energy storage power stations, guide the construction of energy storage on the power generation side, grid side, and user side, and encourage social capital investment in energy storage facilities.
	November 2021	Hubei Province's Manufacturing Industry High-Quality Development Plan for the 14th Five-Year Period	Promote the development of energy storage equipment industries such as all-vanadium redox flow battery systems and lithium-ion batteries. Intensify efforts to attract R&D and manufacturing companies in wind power equipment and promote the development of the wind power equipment industry.

Province or city	Release time	Policy document	Main contents
	April 2021	Outline of the 14th Five-Year Plan and the Vision 2035 of Hubei Province	Strengthen the R&D and application of energy storage technology and equipment, and implement a number of demonstration projects integrating wind, solar, hydro, thermal, and storage systems with integrated source-grid-load-storage operations.

Note: as for 2023.

(2) Incentive policies for energy storage

Economic viability is a major consideration for users when investing in and constructing energy storage projects. Currently, the initial investment costs for energy storage are still relatively high, and relying mostly on peak-valley arbitrage does not offer strong economic attractiveness. Therefore, the governments set out various subsidy policies to support energy storage projects.

As of 2024, there are a total of 32 energy storage subsidy policies being implemented across the economy. Among them, 20 were issued in 2022. The energy storage subsidy policies in 2022 mainly focused on the user side and emphasized integration with distributed PV. Local governments showed strong needs for investment promotion, particularly in Zhejiang, Jiangsu, Sichuan, Anhui, Chongqing, and Guangdong. The main forms of subsidies include discharge subsidies, capacity subsidies, and investment subsidies. Subsidy directions primarily focus on integration with distributed PV, energy-saving technological upgrades, low-carbon emission, and industrial project implementation.

In terms of operational subsidies, multiple provinces across China provide subsidies for the grid-connected electricity generated by user-side energy storage systems within their regions. For example, Qinghai Province offers a subsidy of CNY0.10/kWh for electricity sold to the provincial grid through self-generated and stored facilities in "new energy + hydropower + storage" projects. Projects that use locally produced energy storage batteries at a proportion over 60% receive an additional subsidy of CNY0.05/kWh, with a two-year subsidy period. Wenzhou City provides a subsidy of CNY0.8/kWh to energy storage operators based on actual power output for operational distributed energy storage projects, encouraging local governments to increase support for centralized energy storage projects. Yiwu City provides a subsidy of CNY0.2/kWh to energy storage operators based on peak-period actual power output for energy storage systems under coordinated dispatching by the power grid, with a two-year subsidy period. The subsidy policies for user-side energy storage in some regions are shown in Table 4-12.

Table 4-12 Subsidy Policies for User-end Energy Storage Projects

Subsidy type	Subsidy overview	Province and region	Subsidy level
Discharge subsidy	Provide subsidies to energy storage investment and	Yiwu City, Zhejiang Province	CNY0.25/kWh
		Longgang District, Wenzhou City, Zhejiang Province	CNY0.8/kWh

Subsidy type	Subsidy overview	Province and region	Subsidy level
	operation entities based on the actual power output from energy storage stations	Hefei, Anhui	CNY0.3/kWh
		Wuhu, Anhui Province	CNY0.3/kWh
		Suzhou Industrial Park, Jiangsu Province	CNY0.3/kWh
		Changsha, Hunan Province	CNY0.3/kWh
		Shenzhen, Guangdong	CNY0.2/kWh
Capacity subsidy	Provide subsidies based on the power rating or battery capacity of installed energy storage stations	Zhuji, Zhejiang	CNY0.2/kW
		Changzhou, Jiangsu	CNY0.3/kW
		Wuxi High-Tech Zone, Jiangsu Province	CNY0.1/kW
		Zhaoqing High-Tech Zone, Guangdong Province	CNY0.15/kW
		Chengdu City, Sichuan Province; Liangjiang New Area, Chongqing	CNY0.2/kW
		Tongliang District, Chongqing	CNY0.2/kW
		Xiaoshan District, Hangzhou City, Zhejiang Province	CNY0.3/kW
Investment subsidy	Provide subsidies based on the investment amount of energy storage projects	Putuo District, Zhoushan City, Zhejiang Province	Provide a subsidy of CNY300,000 for each new energy storage project completed and put into operation.
		Haiyan County, Zhejiang Province	Offer a one-time subsidy of up to CNY4 million at 10% of the actual equipment cost for manufacturing enterprises investing CNY3 million or more in new energy storage stations.
		Taiyuan, Shanxi Province	Provide a subsidy of 2% of the investment amount, with a maximum of CNY5 million.
		Beijing	For energy storage projects registered and constructed in Beijing, provide financial support equivalent to 30% of fixed asset investment, with a maximum of CNY10 million per project.
		Chaoyang District, Beijing City	Provide subsidies of up to 20% of the total investment for energy storage technology projects.
		Xi'an City, Shaanxi Province	For PV + storage systems, offer a 20% subsidy of the actual investment in storage equipment, with a maximum of CNY500,000. In Shaanxi Province, demonstration projects receive a compensation of CNY0.1 per kWh for charging electricity prices based on new energy transaction prices, and CNY0.1 per kWh for discharging electricity prices based on coal-fired benchmark prices.

Regarding demand response subsidies, multiple provinces across the economy provide subsidies for user-side energy storage systems that respond to grid demand. For example, Anhui Province offers the following response compensation: Scheduled peak shaving: CNY8/ kW per event; Real-time peak shaving: CNY12/ W per event; Valley filling: CNY3/kW per event; Capacity compensation: Scheduled standby capacity: CNY1/kW per month during peak season and CNY0.5/kW per month during off-season; Real-time standby capacity: CNY2/W per month during peak season and CNY1/kW per month during off-season. Zhejiang Province's electricity subsidies include: implementing precision smart control measures for day-ahead, hourly, minute-level, and second-level demand response. Day-ahead peak shaving price is capped at CNY 4/kWh, while hourly, minute-level, and second-level annual electricity subsidies have a fixed unit price of CNY4/kWh; Capacity subsidy: Hourly level CNY0.25/kW per month during peak season, zero during off-season; Minute-level CNY1/kW per month during peak season, zero during off-season; Second level CNY0.1/ kW per month during peak season, zero during off-season; Valley filling CNY5/kW per day.

With the implementation of energy storage subsidy policies across various regions, domestic energy storage commercialization and large-scale development experience significant growth. In 2022, local governments showed strong demand for investment promotion and project implementation in the energy storage projects. Local subsidy policies directly incentivize industrial expansion, reduce enterprise operating costs, and facilitate the investment and operation of energy storage projects. However, it is also necessary to take a calm and objective view of the impact of subsidy policies on storage development. Looking back at the development history of the solar PV and wind power industries, sound industrial support policies can help enhance the global competitive advantage of China's energy storage industry. However, continuous R&D investment, ongoing improvement of technical performance, enhancement of manufacturing capabilities, advancement in next-generation technologies, and optimization of the industrial chain and ecosystem are the fundamental factors that enable China's energy storage industry to thrive locally and in international markets.

4.3 Chapter summary

In the context of global low-carbon energy transition, the growing importance of energy storage has led to sustained growth in industry interest. With continuously increasing policy supports, government policies have become the most powerful driving force behind the development of energy storage. Major APEC economies have introduced various favorable policies related to the energy storage, promoting its development entry into a fast development phase. Taking the United States as an example, both the federal government and state governments have successively introduced policies to promote the development of energy storage; At the federal level, the *Inflation Reduction Act (IRA)* is the most significant policy for energy storage in 2022. For the first time, stand-alone energy storage systems were included under the Investment Tax Credit (ITC), allowing all application conditions — front-of-meter, industrial and commercial and residential — to receive ITC subsidies of 30% or more for over ten years. The increased subsidy amount and extended duration significantly improve the economics of energy storage systems, paving the way for faster deployment of energy storage across the United State; At the state level, for example, Michigan became the 10th state of the United States to establish a clear energy storage development target.

In China, the development of energy storage has been elevated to an economy-level strategy. Over 600 relevant policies at the economy and local levels have been released, directly facilitating the implementation of large-scale energy storage projects across various regions. As power market reforms gradually advance into deeper stages, the focus of energy storage policies has begun to shift toward market mechanisms and dispatching mechanisms. Under the current policy and market mechanisms, energy storage still lacks a stable and sustainable profit mechanism, which remains the main constraint on its commercial development. Regarding the allocation of energy storage with renewable energy: Policies should follow the principle of adapting measures to local conditions, coordinating the planning of energy storage integration with renewable energy sources to avoid inefficient investments; Accelerate the pace of full participation of new energy sources in various markets; Explore business models combining renewable energy with shared energy storage in joint operations. Regarding standalone energy storage: Further clarification is needed on the definitions and dispatching mechanisms of independent and non-standalone energy storage. The joint or independent operation mechanisms of shared standalone energy storage with renewable energy stations need further refinement. For the shared leasing market, corresponding operational rules or guidance schemes should be introduced, and a credible regional capacity leasing platform should be established to ensure transparent and fair transactions and protect the rights and responsibilities of both lessors and users. At the same time, it is recommended to introduce preferential fiscal and tax policies to support the development of new energy storage, reduce storage costs, and further intensify policy support for energy storage technologies, equipment, and manufacturing to enhance the competitiveness of the energy storage supply chain. In addition, safety policies should take into account technological advancements and the needs of large-scale development, further standardizing the construction and operation management of energy storage projects. Since 2024, China's energy storage industry continues to maintain a rapid growth trend. In the context of fierce international market competition, China holds an absolute leading advantage globally in new energy storage technologies represented by lithium-ion batteries. At the same time, other major energy storage technologies are also at the forefront internationally in terms of R&D and manufacturing. Sustained policy support for the new energy storage industry requires, on one hand, precision and depth to break through market access barriers. On the other hand, policies across sectors including industry, academia, research, application, finance, taxation, and finance should work in synergy to form a systematic framework. This will create a healthy market environment for the development of new energy storage, promote its healthy and sustainable growth, and help China maintain and expand its hard-earned international competitive advantage in this field.

Australia; Canada; Japan; and Korea are all actively pursuing energy storage development, primarily driven by the need to integrate growing renewable energy sources, enhance grid stability, and achieve decarbonization targets, though their approaches vary. Australia is experiencing a "big battery boom" with supportive government policies like the Capacity Investment Scheme (CIS) and the Cheaper Home Batteries Program, offering long-term underwriting contracts and discounts to accelerate the deployment of utility-scale and small-scale battery systems, aiming for significant renewable energy penetration by 2030. Canada incentivizes energy storage through refundable investment tax credits for clean technology manufacturing and clean electricity, including for grid-scale energy storage equipment, alongside a Clean Electricity

Strategy and funding for smart renewables and electrification pathways to modernize its grid and achieve net-zero by 2050. Japan's energy storage market is rapidly expanding, supported by its "Green Transformation" policy strategy, which includes an economy-wide subsidy scheme offering capital expenditure support for projects and market opportunities in balancing, wholesale, and capacity markets, with a focus on diversifying beyond lithium-ion to include sodium-sulfur batteries for enhanced grid stability and resilience. Korea's "Energy Storage System Industry Development Strategy" aims for a 35% global market share by 2036, emphasizing a flexible power system with diverse energy storage technologies (including lithium-ion, redox flow, and sodium-sulfur batteries), supported by the 11th Basic Plan for Long-Term Electricity Supply and Demand to significantly increase renewable energy capacity and stimulate domestic investment while addressing safety standards.

Southeast Asian economies, facing rapidly growing energy demand and ambitious decarbonization targets, are increasingly turning to energy storage solutions to integrate burgeoning renewable energy capacity and enhance grid stability. While specific policies vary, common themes include feed-in tariffs (FITs) that incentivize renewable energy coupled with storage, the development of economy power development plans (PDPs) that explicitly set energy storage targets (e.g., Viet Nam's PDP8 targeting 2.7GW by 2030), and efforts to reduce red tape for distributed solar PV and storage projects (as seen in Thailand). There's also a growing recognition of the need for advanced grid infrastructure and market mechanisms to facilitate the integration of intermittent renewables. Notably, the economies like the Philippines are leveraging privatization and free competition to unlock energy storage potential, while Indonesia is pursuing investment plans like the Just Energy Transition Partnership (JETP) to accelerate its energy transition, including dispatchable renewable energy. Pumped hydro storage is also gaining attention in the region due to its geographical advantages.

Chile stands out as a leader in energy storage development within Latin America, largely driven by its rapid build-out of solar and wind power and the consequent need to address grid constraints and ensure system stability, especially during periods of low solar electricity yields. The economy has implemented a carbon tax and emissions standards for coal-fired facilities, alongside the recently enacted Energy Transition Law, which aims to accelerate investments in the power grid and battery storage infrastructure. Chile has set an ambitious target of 2GW of energy storage by 2030, with significant operational and under-construction capacity already in place. Its regulatory framework is considered progressive, with ongoing efforts to refine wholesale power market mechanisms and rules for remunerating ancillary services provided by energy storage systems. The focus is on integrating large-scale battery energy storage systems (BESS), often co-located with solar PV projects, to mitigate renewable energy curtailment and enhance grid flexibility, making Chile a pioneering example in the South America for energy storage regulations and deployment.

Chapter V Development and Deployment of Battery Energy Storage Systems

5.1 Battery technologies for energy storage

5.1.1 Battery technologies

At present, lithium-ion (Li-ion) batteries are the dominant technology for energy storage across various applications, from consumer electronics and electric vehicles to grid-scale energy storage installations, owing to their high energy density, relatively fast charging capabilities, and long cycle life. However, other technologies are gaining traction, especially for long-duration energy storage (LDES), including flow batteries (such as vanadium and iron flow, which store energy in liquid electrolytes, offering scalability and extended lifespan), and emerging alternatives like sodium-ion batteries, which leverage abundant and low-cost materials for stationary storage.

The chemistries available for lithium-ion batteries used in storage applications are the same as those available for the EV markets. However, energy storage applications have different technical requirements and characteristics such as costs, capacity to charge/discharge frequently, safety and overall lifetime are prioritized over energy density of the batteries. Currently Lithium-ion occupies approximately 98% of the battery energy storage system (BESS) applications, with a dominant position in bankability, round trip efficiency (RTE), and product offerings. It is expected that Lithium-ion batteries are set to remain a key part of short-duration storage. Over the recent years, the desire for lower costs and higher cycle lives as well as safety considerations have led to a shift of chemistry towards Lithium-iron Phosphate (LFP) batteries for storage applications. LFP has now overtaken Nickel Manganese Cobalt (NMC) battery as the dominant stationary energy storage chemistry, accounting for over 80% of total capacity of battery energy storage system (BESS) installed in 2023. The technology of BESS is currently predominantly based on LFP chemistry. LFP batteries are currently produced almost exclusively in China for both domestic and overseas storage markets, but it has been observed that the battery manufacturers in other economies have started to develop their manufacturing capability.

In terms of performance, in general, Lithium-ion BESS is cost-effective for short duration in the following two use cases: i) Demand-supply matching from few seconds up to 8 hours; ii) Energy arbitrage (i.e. buy energy/charge when it's cheap, sell/discharge during higher-price hours). Lithium-based BESS are suboptimal for long-duration storage due to costs, degradation, and sustainability challenges. Normally, Lithium-ion battery is not cost effective over 8 hours at current prices for either use cases, which have driven the research and investigation for alternative battery chemistries. To satisfy the needs, alternative battery chemistries are being developed either to compete with LFP or to complement it. Innovation in lithium chemistries, such as iron-phosphate, solid-state, may improve their viability in the future. Emerging technologies like flow batteries, hydrogen, and hybrid systems are better positioned to address multi-hour to seasonal storage, and long duration needs.

Besides lithium chemistry, in recent years there are several competing chemistries vying to become leaders based on improvements in costs, safety performance and duration and other technical indicators. Sodium-ion batteries have been emerged and developed rapidly, which do not use lithium, are constructed from less expensive materials than lithium-ion batteries, and need fewer critical mineral materials that is a great advantage particularly considering the increased attentions on the supply chain issues. They attracted a lot of attention since 2023 thanks to the good market performance of the sodium-ion powered EVs produced by main EV manufacturers, particularly in China. Sodium-ion batteries are less energy dense than lithium-ion batteries, but they could be 20-30% cheaper than equivalent LFP batteries if produced at the similar scales and conditions. However, this cost advantage largely depends on the current prices of lithium and also needs to be weighed against a potentially shorter service life of Solium-ion batteries compared to the LFP batteries. The research and innovation efforts in the related areas have been very active, which will shape the trajectory of market conditions of the battery sector in the years to come.

Neither lithium-ion or sodium-ion batteries are likely to be able to serve significant shares of longer duration storage (across days) because of the costs and technical challenges arising from prolonged high states of charge. Long duration energy storage battery deployed globally as of 2024 is approximately 2GW, or approximately 1% of total installed BESS capacity. Other battery chemistries may be more suitable for requirements of longer storage durations, which are illustrated in Table 5-1.

Table 5-1 Selected Battery Technologies for Energy Storage Applications

Battery technology	**Storage duration**				
	4-hour or less	4-8 hour	days	Weeks	Seasonal
Lithium-ion	suitable	suitable	unsuitable	unsuitable	unsuitable
Sodium-ion	suitable	suitable	unsuitable	unsuitable	unsuitable
Redox flow	marginal	suitable	suitable	unsuitable	unsuitable
Iron air	unsuitable	unsuitable	marginal	suitable	unsuitable

● suitable ● marginal ● unsuitable

Source: Adapted form IEA

An alternative battery chemistry that could provide longer (multi-day) storage is redox flow batteries.

Redox flow battery can use different chemistries, and vanadium is the most used while its supply chain is still small at the present. Flow batteries offer 6-24 hours energy storage that could be used to stabilize grid and provide peak shifting/load shifting capability. Redox flow batteries based on vanadium are already technically relatively mature. The main challenge is the ability to scale up rapidly over the coming years. However, it is expected that this is likely to happen only in response to adequate market condition and price signals, for example through the emergence of longer duration storage markets.

Iron-air and other metal-air battery technologies that potentially could enable the storage of electricity over longer durations measured in weeks, and even provide dispatchable capacity for seasonal storage, which are still in the early stage of research and development. While solid-state batteries are still largely in research and development, they are widely considered the future of battery technology due to their potential for even higher energy density, increased safety, and longer lifespan, though challenges in mass production and cost remain. Currently it is not quite clear whether those technologies can be developed and deployed so as to provide the storage services required in a cost-efficient and commercially viable manner.

5.1.2 Battery costs

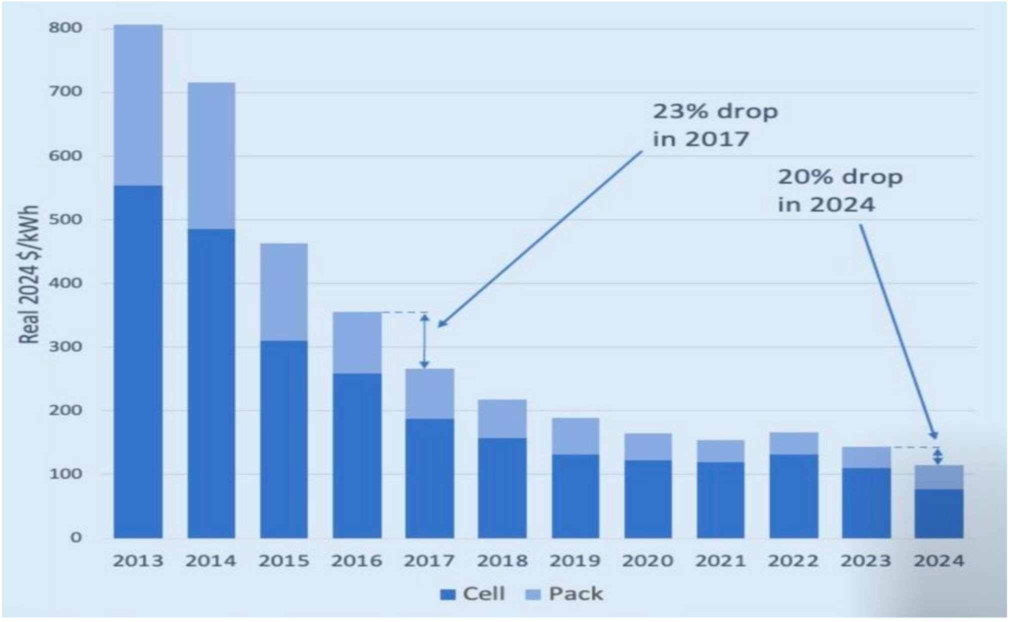
(1) Cell and pack costs

A battery cell is the fundamental, individual electrochemical unit that stores and releases electrical energy. These cells, typically with a low voltage (e.g., 3-4 volts for lithium-ion), are then connected in series and/or parallel to form a battery pack. A battery pack is a complete energy storage system, comprising multiple cells (often organized into modules for better management) along with a Battery Management System (BMS) for monitoring and control, thermal management, safety features, and an enclosure, all designed to deliver the required voltage and capacity for a specific application like an EV or energy storage system.

The battery has undergone a dramatic transformation in costs over the past decade, both lithium-ion battery cells and packs costs have experienced substantial declines, significantly impacting the landscape of EVs and energy storage systems applications. Battery cell costs have decreased by approximately 65% from 2014 (USD290/kWh) to 2023 (USD103/kWh). When considering the longer timeframe since 1991, the reduction is even more dramatic, at around 97%. Similarly, battery pack costs have also seen significant reductions. While precise pack cost data for 2014 vary, it is estimated that a decrease of roughly 60% from around USD280-300/kWh in 2014 to a record low of USD115/kWh in 2024. Battery prices at the pack level saw the largest drop since 2017, by 20% from 2023. It is estimated that the global average cost for turnkey battery storage systems falls to USD165/kWh in 2024, 40% drop compared to 2023.[91] These substantial reductions in both battery cells and packs costs have been instrumental in making electric vehicles and energy

[91] BloombergNEF, 2025. Lithium-Ion Battery Pack Prices See Largest Drop Since 2017. https://about.bnef.com/blog/lithium-ion-battery-pack-prices-see-largest-drop-since-2017-falling-to-115-per-kilowatt-hour-bloombergnef/.

storage solutions increasingly more economically viable, and more competitive comparing with traditional technologies.



Source: BloombergNEF

Figure 5-1 Costs of Lithium-ion Battery Cell and Pack

The key elements influencing battery costs include:

- Technological advancements in cell chemistry and materials science have been paramount, leading to improved performance and lower material usage;
- One significant driver is the decrease in lithium prices, which have plummeted by over 85% from their peak in 2022. This drop in raw material costs has a direct impact on battery prices;
- The increasing scale of battery manufacturing, which leads to economies of scale and lower production costs. Improved manufacturing efficiency and intensive market competition among the battery manufacturers, particularly in China, have driven prices down;
- The growing adoption of Lithium Iron Phosphate (LFP) battery chemistry, which are generally cheaper than other lithium-ion chemistries, is also contributing to the overall cost reduction in the battery sector. Furthermore, advancements in battery technology and manufacturing processes continue over the years to improve efficiency and lower costs.
- Innovations in battery pack design, such as cell-to-pack architectures, have helped to optimize the overall system cost.

Global battery manufacturing capacity increased from 1.05 TWh to 1.45 TWh in 2024. China continues to dominate the supply chain, owning more than 80% of key cell components and cells manufacturing capacity. In addition, supply chain efficiency has been come along with manufacturing excelling, which is among the key reasons for the manufacturer in China achieving very low production cost. The main blocks of battery cell production costs are cathode, anode and processing. It is the supply chain efficiency and technical innovation are the main forces and lay the foundation to pull these production costs down, which give top manufacturers an additional edge over rest of the battery industry. Table 5-2 outlines several key technical factors contributing to the cost reduction for manufacturers in China.

Table 5-2 Key Factors Contributing to Reduced Battery Manufacturing Costs in China

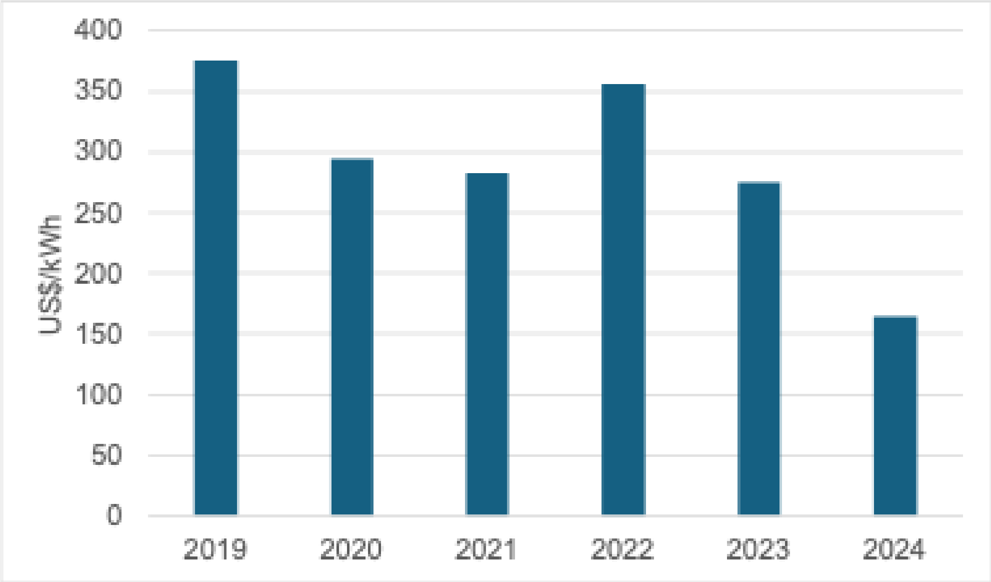
No.	Category	Factors lowering the cost of battery manufacturing
1	Vertical integration	● Allows downstream companies to source raw materials at cost price; ● Ability to pass on any high cost of operations down the value chain; ● More and effective control over technical specifications over the manufacturing process.
2	Upstream cost reduction	● Manufactures have secured low-cost mineral resources; ● Refineries in China are some of the lowest cost operations globally, which mitigate the largest cost component for battery cells.
3	Midstream price pressure	● Intense competition in the midstream is leading to thinner margins; ● Cell manufacturers are pressuring cathode and anode producers for lower prices.
4	Capex leverage	● Economies of scale in the downstream, including EV and battery storage, enables lower unit Capex; ● Cheaper financing in the upstream (mining/refining). ● Mechanism hedges investment risk.
5	Technical innovation	● Prioritize scaling-up of manufacturing capacity; ● Appropriate approach of incrementally optimizing proven technologies; ● Support R&D and explore disruptive new technologies along the industry value chain.
6	Factory yields & automation	● Widespread automation reduces labor costs and enables higher yields; ● Yields and production processes have been well optimized, and only incremental improvements being made.
7	Effective planning and industrial ecosystem	● Through effective policy and planning foster and support the development of the battery industry in a coherent and comprehensive manner; ● Chinese companies tend to operate in integrated industrial parks where there is always a consumer for by-products or waste from adjacent, which raise the overall efficacy of battery manufacturing sector.

Along overcapacity across the battery supply chain, the cell price lowers to the new low level of USD50/kWh for China-made LFP cells in 2024. More recent Chinese industrial policy aimed at phasing out low-quality capacity added further pressure. For battery producers navigating this challenging pricing environment, current industry strategic focuses include: further costs reduction through better management and efficiency, technological innovation, vertical integration of production, and diversification into overseas markets.

In comparison, battery costs are significantly higher outside of China. For instance, the average production costs for NMC 811 battery cells in Korea, the European Union, and the United States are 19%, 52%, and 57% higher than those in China, respectively. Higher cost of production outside China is influenced by initially lower production yields and relatively less factory automation level, differences in energy and labor costs in different economies, higher margines commanded by the suppliers, as well as import tariffs and local premiums on raw materials supply.

(2) Battery energy storage system costs

A battery energy storage system is a comprehensive solution that captures electricity from various sources, such as renewable energy or the grid, and stores it in large-scale rechargeable batteries for later use. Beyond just the battery cells and packs, a BESS includes critical components like a Battery Management System (BMS) for monitoring and safety, a Power Conversion System (PCS) to convert power between AC and DC for grid compatibility, a thermal management system to regulate temperature, and an Energy Management System (EMS) to optimize charge/discharge cycles based on demand and pricing. The costs of lithium-ion battery packs for battery energy storage systems have seen a substantial decrease, which has made BESS technology significantly more accessible for various applications. Figure 5-2 shows the average costs of BESS in recent years. Costs of BESS have fallen dramatically, according to BNEF, costs per kWh of BESS fell on average to USD165/kWh in 2024, down 40% from 2023, which is less than half of the 2019 value. An uptick in prices in 2022, as shown in the Figure 5-2 was driven by constrained supply, high Lithium prices and lingering pandemic supply chain issues over the period then. The prices listed in the diagram is based on unit of usable energy capacity, including DC-block battery enclosures and power conversion system, but exclusive of EPC and grid connection costs. Balance of System (BoS) of BESS encompasses all necessary components and civil works of a storage system, such as Enclosure/Container: Housing for the batteries and other equipment, often with thermal management; Thermal Management System: Cooling, heating, and air conditioning to maintain optimal operating temperatures for the batteries; Electrical Wiring and Cabling: Connecting all components within the system and to the grid; Safety Systems: Fire suppression, smoke detection, security systems (CCTV, restricted access) and Civil Works: Site preparation, foundations, fencing.



Note: The costs are in 2024 Real Dollars.

Source: BloombergNEF

Figure 5-2 Costs of Battery Energy Storage Systems

Significant regional variations exist in terms of BESS costs. China currently boasts the lowest prices, with system-level costs reported as low as USD82 per kWh in the third quarter of 2024.[92] This is reflected in the average battery pack prices in China, which was USD94/kWh in 2024. It is reported that a December 2024 bid for 16GWh of battery enclosures plus power conversion system (PCS) had an average price of USD66/kWh. In contrast, battery pack prices in the United States and Europe were considerably higher, at approximately 31% and 48% above the level China, respectively[93], and these differences highlight the impacts of manufacturing scale and strong market competition in battery industry.

5.2 Deployment of BESS in APEC economies

5.2.1 Trends overview

The term "*battery decade*" refers to a period of significant growth and impact for battery technology, particularly in energy storage and electric vehicles, driven by factors like falling prices of battery technology, increasing demand, the need for grid stability, and regulatory shifts towards sustainability. This decade, between 2020 and 2030, is expected to see a massive expansion of battery applications and a crucial role in the transition to renewable energy.[94]

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[92] S&P Global. 2025. Where are EV battery prices headed in 2025 and beyond? https://www.spglobal.com/automotive-insights/en/blogs/2025/01/where-are-ev-b attery-prices-headed-in-2025-and-beyond.

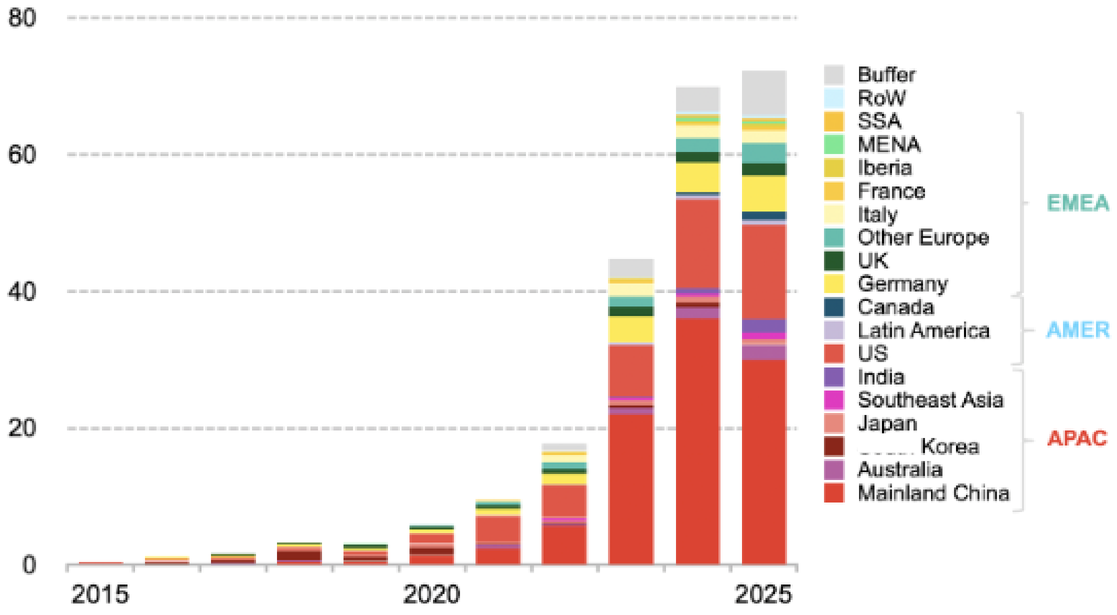
[93] Electric vehicle economics. 2025. How lithium-ion cell costs impact EV prices.

[94] McKinsey & Co. 2023Battery 2030: Resilient, sustainable, and circular. 16 January 2023.

The dominant application of battery is electric vehicles, while battery energy storage system (BESS) deployments have grown more quickly than the battery industry as a whole. The BESS deployment continues to increase in recent years, with 55% growth globally over 2023-24, being regarded as "*the fastest-growing energy technology in 2024*"[95], with significant growth in both grid-scale and behind-the-meter (BTM) battery systems. About 65% of the storage capacity additions are for utility-scale storage systems, with behind-the-meter battery storage responsible for about 35% of the annual additions on average. BESS now account for 15% of total battery deployments, up from 7% in 2020, highlighting its rapid adoption and deployment. In terms of battery technologies, as mentioned above, globally Lithium-ion batteries accounted for 98% of battery installations in 2024. Primary drivers in the surge of the storage applications include falling battery costs, government policy incentives, and a massive uptick in investments in BESS technology and projects to support renewable energy development and green energy transition. About 65% of the capacity additions are for utility-scale systems, with behind-the-meter battery storage responsible for about 35% of the annual additions on average. New BESS installations in 2024 alone contributed over 45% of the current cumulative global capacity of 150GW/363GWh, underscoring BESS's significance as one of the most promising and fast-growing sectors in the battery industry landscape. Looking forward, IEA projects a massive 35-fold increase in grid-scale battery storage capacity between 2022 and 2030 in their Net Zero Scenario (NES) of energy outlook.

Geographically, battery storage projects are surging around the globe, dominated by a few APEC economies, including China (36GW), the United States (13GW), Australia (2GW), as well as Europe (10GW), which collectively accounted for nearly 90% of the capacity added globally. Figure 5-3 shows the BESS capacity over the period 2015-25.

[95] The Economist. 2024. Grid scale storage is the fastest growing energy technology. https://www.economist.com/the-world-ahead/2024/11/20/grid-scale-storage-is-the-fastest-growing-energy-technology. 20 November 2024.



Source: BloombergNEE

Figure 5-3 Installed BESS Capacity by Economies

According to the BloombgerNEF, China and the United States are the top two leaders when it comes to BESS deployment, and collectively these two markets account for approximately 70% of all BESS projects world-wide in 2024. China added 36 GW/84GWh in 2024, up 64% on a GW-basis from 2023. The energy storage deployments in the United States across all segments reaches 13GW/41GWh in 2024, up 72% on a GW-basis from 2023. Other APEC economies on the top list of BESS deployment include Australia; Korea; and Japan. The following sections provide an overview of the BESS development, market environment, representative projects in Australia; China; Japan; Korea; and the United States as well as the BESS deployment in urban areas in these economies.[96]

5.2.2 Australia: From early pilots to an economy-wide ambition

(1) BESS Deployment

Australia is on the cusp of a major BESS boom, primarily driven by the pressing need to replace its aging coal-fired power plants and to effectively manage the increasing intermittency associated with higher levels of variable renewable electricity generation. The development and deployment of BESS can be divided into the following two phases:

- Early deployments (2015–2020): Australia's BESS journey began with small-scale pilot projects,

[96] Sources of the data and information in the chapter include, but are not limited to, annual reports, government documents, statistical dat abases, news articles and press releasees.

such as the 2MW/1.3MWh King Island Renewable Energy Integration Project in 2015, which demonstrated the viability of lithium-ion batteries for off-grid applications. By 2017, the landmark Hornsdale Power Reserve (100 MW/129 MWh) in South Australia-colloquially known as the "Tesla Big Battery", which set a precedent for grid-scale storage applications, achieving rapid frequency response and arbitrage capabilities. However, installed capacity remained below 500 MW in the economy during this period due to limited policy support and market mechanisms.

- Accelerated growth (2021–2024): The National Electricity Market (NEM) saw a surge in BESS deployments post-2020, driven by planned coal plant retirements and achieving renewable energy targets. By 2024, installed capacity of BESS reached 2.3GW, with projects like the Waratah Super Battery (1,096 MW) in New South Wales dominating the storage fleets. Utility-scale projects accounted for nearly 60%, with high price spreads on the wholesale electricity market and high ancillary service prices driving investment, suggesting a strategic approach to deploying storage specifically for providing crucial grid services for stabilization and facilitating the integration of renewable energy.

Behind-the-meter storage capacity rose strongly as well, in part thanks to financial incentives that encourage the pairing of residential solar PV systems with batteries. Looking ahead, within the National Electricity Market (NEM), installed BESS capacity is expected to more than double in 2025 and then double again by the end of 2026. It is projected to increase to 18GW by 2035, representing about eightfold increase in capacity.[97]

(2) Market environment

A primary driver for BESS adoption in Australia is the anticipated retirement of coal-fired power plants, with nearly 70% of the economy's long-dominant coal fleet expected to cease operations by 2035.[98] This necessitates the deployment of alternative power sources and grid stabilization mechanisms, where battery storage is seen as a crucial component in ensuring a smooth transition to a cleaner energy mix. Coal plants have historically provided baseload power and essential grid stability services. As they retire, BESS is well-positioned to offer fast-response frequency regulation and energy smoothing capabilities. The increasing penetration of renewable energy, particularly wind and solar, has led to increased value of flexible capacity in Australia's National Electricity Market (NEM). The inherent intermittency of these renewable resources creates volatility in wholesale power prices, presenting business opportunities for battery systems to engage in price arbitrage. The economic incentive strengthens the BESS deployment. The Australian federal government is actively promoting battery uptake through its Capacity Investment Scheme (CIS), which

[97] BNEF. 2025. Australia's utility-scale BESS uptake to expand eightfold to 18GW in 2035. https://about.bnef.com/blog/australia-on-the-cusp-of-big-battery-boom-according-to-bloombergnef-report/#:~:text=Uptake%20of%20utility%2Dscale%20batteries%20in%20Australia%20could%20expand%20eightfold,research%20provider%20BloombergNEF%20(BNEF). 24 March 2025.

[98] BNEF. 2025. Australia on the Cusp of Big Battery Boom, According to ..., accessed May 3, 2025, https://about.bnef.com/blog/australia-on-the-cusp-of-big-battery-boom-according-to-bloombergnef-report/.

involves a series of tenders held every six months between 2024 and 2027, aiming to secure 9GW of new clean storage capacity by 2030. This scheme provides long-term underwriting contracts with agreed revenue floors and ceilings to the successful applicants, playing a crucial role in de-risking BESS investments and accelerating deployment by offering revenue certainty to storage project developers.

Australia is witnessing a shift towards longer duration energy storage, with projects featuring 4 to 8 hours of storage capacity emerging. This increasing focus on longer duration systems indicates a growing recognition of the need for storage solutions that can provide power for extended periods, thereby enhancing grid resilience and enabling greater time-shifting of renewable energy to meet demand across more hours of the day, and potentially over the weeks. While shorter duration batteries are effective for frequency regulation and short-term arbitrage, longer duration systems are essential for addressing more prolonged periods of low renewable output or high electricity demand.

Recently, there is development in DC-coupled hybrid projects in Australia, which integrate battery storage directly with solar generation at the DC level for more streamlined energy management. This approach aims to improve the overall efficiency of the whole system, renewable generation and storage, and potentially reduce system costs compared to traditional AC-coupled systems by minimizing energy conversion losses.

(3) Notable BESS Projects

Australia is developing several large-scale battery energy storage projects. Origin Energy's Eraring BESS in New South Wales is undergoing expansion to reach a capacity of 700MW/2,800MWh, making it the economy's one of the largest approved battery storage projects. New South Wales is also home to the Waratah Super Battery, with a significant capacity of 850MW/1,680MWh. Another notable project in New South Wales is the Richmond Valley BESS, an 8-hour battery project with a capacity of 275MW/2,200MWh, being developed through a collaboration between Ark Energy and Hanwha Energy.

Origin Energy is behind the Mortlake BESS in Victoria, with a capacity of 300MW/650MWh.[99] Quinbrook Infrastructure Partners and GE Vernova are collaborating on the Supernode BESS project in Queensland, planned to have a total capacity of 750MW (with a storage duration of 2-4 hours) across three stages.[100] Neoen's Blyth BESS in South Australia has a capacity of 238.5MW/477MWh. Octopus Australia and Wärtsilä are working on the Fulham Solar Battery Hybrid project in Victoria, a DC-coupled system with a capacity of 64MW/128MWh[101].

The development of these large-scale BESS projects signifies a strong commitment in Australia to

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[99] Energy Council. 2025. Battery Storage: Australia's current climate. https://www.energycouncil.com.au/analysis/battery-storage-australia-s-current-climate/

[100] Quinbrook. 2025. Quinbrook to Build Advanced Long Duration Battery Storage in Australia. https://www.quinbrook.com/news-insights/quinbrook-to-build-advanced-long-duration-battery-storage-in-australia/

[101] Wartsila. 2025. Wärtsilä will deliver one of Australia's first DC-coupled energy storage projects. https://www.wartsila.com/media/news/09-04-2025-wartsila-will-deliver-one-of-australia-s-first-dc-coupled-energy-storage-projects-3571733

utilizing battery storage as a fundamental component of its future energy system. The increasing size and duration of these projects are particularly noteworthy, indicating a strategic move towards leveraging storage for more than just short-term grid services. Large-scale and long duration storage are crucial for Australia's energy transition, enabling the seamless integration of abundant but intermittent renewable energy sources like solar and wind into the grid. By storing excess power during high generation and discharging it during peak demand or low renewable output, BESS enhances grid stability, reduces reliance on fossil fuel "peaker" plants, lowers electricity costs, and ultimately accelerates Australia's path to a reliable, clean, and secure energy future.

(4) BESS development in cities

BESS projects are gaining significant traction in Australian cities as a crucial component of the economy-wide energy transition. Several notable BESS initiatives are underway or have recently been completed in major Australian cities, demonstrating the commitment to a cleaner and more resilient energy future.

In Sydney, several BESS projects are in various stages of development. Iberdrola Australia is developing the Smithfield BESS, a 65 MW/130 MWh system expected to be operational by December 2025. This project, co-located with an existing gas peaker plant, aims to power 20,000 homes during peak demand. Ausconnex is planning a network of 12 BESS across Greater Western Sydney, including four high-voltage sites with a capacity of up to 100MW each and eight medium-voltage sites up to 5MW each.[102] These projects are designed to support the increasing integration of renewable energy in the region. Additionally, EnergyAustralia received approval for a significant 500MW/2,000MWh BESS near the Mount Piper coal-fired power plant, slated for completion in 2026, which will aid in the transition as coal power being phased out.[103] Ausgrid is proposing two large-scale 200MW/400MWh BESS projects in Newcastle and Homebush, aiming to facilitate over 1.5GW of distribution-connected grid-scale storage on its network by the early 2030s.[104]

Melbourne is also witnessing substantial developments in battery storage. The State Electricity Commission (SEC) of Victoria has contracted Energy Vault to deliver a 100MW/200MWh BESS near Horsham, northwest of Melbourne, as part of a 100% publicly owned renewable energy park. This project is expected to be online by 2027 and will supply renewable electricity to the government facilities in Victoria. The SEC is also pursuing the Melbourne Renewable Energy Hub, which includes a 12.5MW solar PV plant and a co-located 1,200MW/2,400MWh BESS, with construction underway and the first phase involving 444 Tesla Megapack installations. Furthermore, ACEnergy is developing the Little River BESS, a 350MW/700

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[102] Great Western Battery. 2025. Greater Western Sydney Battery Program. https://greatwesternbattery.com.au/

[103] EnergyAustralia. 2023. EnergyAustralia secures planning approval for large-scale battery near Lithgow. https://www.energyaustralia.com.au/about-us/what-we-do/new-energy-projects/mt-piper-battery-energy-storage-system

[104] Ausgrid. 2024. Future Grid. https://www.ausgrid.com.au/About-Us/Future-Grid.

MWh standalone system in southwest of Melbourne, expected to be operational by late 2026, supporting Victoria's clean energy transition. Eku Energy and Shell Energy have jointly developed the Rangebank BESS, a 200MW/400MWh project in Melbourne's southeast, completed in late 2024, which enhances renewable energy hosting capacity. AusNet Services is also developing a 300MW/600MWh BESS in Thomastown, north of Melbourne, with operations planned to commence in early 2026.

In general, the BESS projects across major Australian cities signify a strong commitment to integrating renewable energy, improving grid reliability, and transitioning towards a sustainable energy future. BESS development in Australian cities is rapidly advancing, focusing on both large-scale grid support and smaller, community-level applications. Major urban centers are seeing the commissioning of significant projects while various cities are also deploying "community batteries" to allow households, including those without rooftop solar, to access stored renewable energy, reduce electricity bills, and enhance local grid stability. This dual approach aims to optimize renewable energy integration, manage peak demand, and improve energy security within urban environments. By providing crucial energy storage capabilities, these initiatives are paving the way for a cleaner and more resilient urban energy landscape in Australia.

5.2.3 China: Globally dominant and rapidly evolving

China's BESS development strategy is multifaceted and ambitious. One of key focuses is on boosting the entire manufacturing value chain, fostering the growth of leading enterprises, and enhancing innovation capabilities in high-end, intelligent, and green technologies. The strategy involves significant technological innovation, including upgrading lithium and other batteries and supporting disruptive technologies, while also emphasizing the importance of cost reduction to facilitate widespread adoption of battery technologies. To support this growth, China has been intensifying the exploration of domestic mineral resources like lithium, cobalt, and nickel and others, and promoting the use of recycled materials in manufacturing. Furthermore, the strategy aims to integrate BESS into various sectors such as power, industry and transportation applications have been systemically stipulated and effective implemented across the regions and provinces.

(1) Deployment of BESS

China is a dominant player in BESS deployment, accounting for 70% of global deployments in 2024. In general, the deployment of BESS can be divided into the following phases:

- Policy-driven expansion (2015–2020): China’s BESS market grew incrementally in the second half of the 2010s, supported by the economy’s targets for renewable energy expansion and grid integration. By 2020, installed capacity reached approximately 3.2GW, primarily through pilot projects in regions like Qinghai and Inner Mongolia. The 14th Five-Year Plan (2021–2025) marked a key turning point, prioritizing energy storage as a strategic industry and catalyzing investments in lithium-ion, sodium-ion, and flow batteries and other battery technologies[105], and support the applications across the sectors.

- Unprecedented scaling-up (2021–2024): Exponential growth of BESS capacity has been observed since 2021. China is currently the global leader in the deployment of BESS, demonstrating an extraordinary pace of capacity growth. By the end of 2024, China's installed capacity of new energy storage had reached a remarkable 73.8GW/168GWh, marking a twentyfold increase since the end of 2021 and an impressive 130% annual growth rate compared to 2023.

This is supported by the strategies and policies prioritizing energy storage and China's dominant lithium-ion battery manufacturing capacity, as reviewed in the previous Chapter. Some of specific examples that fuels the exponential growth include:

- Provincial mandates: Inner Mongolia (10.23GW), Xinjiang (8.57GW), and Shandong (7.17GW) led BESS deployments, aligning energy storage with wind and solar farms development in provinces or regions;
- Technology innovation and diversification: While lithium-ion dominated, projects like the Dalian Flow Battery, in Dalian City (Phase I, 100MW/400MWh), commissioned in 2022, showcased vanadium redox flow (VRFB) technology. The planned storage capacity of the system is 200MW/800MWh;
- Manufacturing scale: China accounted for over 70% of global lithium-ion battery production, enabling cost reductions through economies of scale.

In 2024 alone, China added 42.4GW/101.1GWh of new storage capacity (excluding pumped hydro). It is expected that there would be more than 20GW new additional capacity in 2025, and the total capacity will exceed 100GW, highlighting the continuing rapid expansion.[106]

China's rapid energy storage expansion aligns with the economy's broader strategy for renewable energy integration, green energy transition and carbon neutral goal. According to the "*Implementation Plan for the Special Action to Optimize the Regulation Capacity of the Power System (2025–2027)*" issued by the National Development and Reform Commission (NDRC) and the NEA[107], China aims to support an annual addition of 200GW of new renewables between 2025 to 2027. The expansion of energy storage has been driven by the growth of both utility-scale and customer-end distributed storage applications.

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[105] XinhuaNet. 2025. The installed capacity of new energy storage in China exceeded 70 GW. https://baijiahao.baidu.com/s?id=1822095076336511263&wfr=spider&for=pc. 24 January 2025.

[106] China Energy Storage Industry Technology Alliance 2025. White Paper on Energy Storage Industry. April 2025. Beijing.

[107] NDRC and NEA. 2024. Notice on Issuing the Implementation Plan for the Special Action to Optimize the Regulation Capacity of the Power System (2025-2027). https://www.nea.gov.cn/20250106/6a9d8a6e621d495db0ca2ba14196f00f/c.html.

(2) Market environment

The rapid growth of storage in China has been fueled by strong government support and a strategic focus on energy storage as a critical component of its electricity infrastructure as an integral dimension in developing of *new type of power system*. The projection of exceeding 100GW in 2025 further underscores the continuing rapid expansion of China's BESS infrastructure, solidifying its global leadership in this vital sector across the industry value chain.

A prominent trend in China's recent BESS development in China is the shift towards large-scale systems, with a clear preference for utility-scale assets boasting power outputs greater than 100MW. The large-scale projects account for 74% of the new storage capacity added in 2024. The strategic focusing on large, centralized BESS projects reflects China's aim to efficiently integrate substantial amounts of renewable energy into its power grid and to provide robust support for grid-level stability. Utility-scale batteries are particularly effective in managing the variability of large renewable energy farms and ensuring overall grid reliability. Deployment is also characterized by regional concentration, with 10 provinces in China contributing over 80% of the new capacity, which are primarily concentrated in the northern and western regions, aligning strategically with the locations of major renewable energy resources such as solar and wind. The geographical concentration reflects a strategy to address local grid constraints and maximize the utilization of renewable energy generated across the regions. Placing storage facilities near renewable generation sources minimizes transmission losses and provides localized power grid support. On distribution level, behind-the-meter storage capacity has been raising in China as well, with large-scale commercial entity and industry rather than residential users driving the uptake of storage deployment, underpinned by subsidies and increasing applications of time-of-use electricity tariffs in China, so the commercial benefits from the storage projects.

In terms of battery technology, LFP batteries overwhelmingly dominate the Chinese market, comprising over 96% of the installed capacity. This strong preference for LFP batteries suggests a significant emphasis on cost-effectiveness and safety, as LFP technology offers advantages in these critical areas compared to other lithium-ion chemistries. LFP batteries are generally more affordable and safer, making them a preferred choice for large-scale stationary energy storage applications. The average discharge duration of energy storage projects in China has been also increasing, reaching 2.3 hours in 2024, up from 2.1 hours in 2023. Furthermore, a growing share of projects now has storage durations exceeding 4 hours.[108] This trend towards longer discharge durations indicates a growing need for BESS to provide more sustained power and support the grid for extended periods, moving beyond short-term frequency regulation to address more prolonged periods of low renewable output or high demand.

While lithium-ion technology remains dominant, as mentioned before, China is actively pursuing

[108] XinhuaNet. 2025. Total installed capacity of new energy storage in China will exceed 70GW by 2024. https://baijiahao.baidu.com/s?id=1822095076336511263&wfr=spider&for=pc. 24 January 2025.

technological diversification, with the integration of non-lithium storage technologies such as sodium-ion, compressed air, and flow batteries also occurring. This exploration and deployment of alternative battery chemistries, particularly sodium-ion, is largely driven by concerns regarding the long-term security of the lithium supply chain and the potential for lower costs associated with more abundant materials. Diversifying the battery technology portfolio can lead to more resilient and cost-effective energy storage solutions in the future.

(3) Notable BESS Projects

China is at the forefront of deploying innovative and large-scale BEES projects. On December 25, 2024, the largest BESS project in China, supporting the Gansu Longdong to Shandong UHVDC transmission project, began construction in Qingyang City, Gansu Province.[109] The project is configured based on 10% of the renewable energy capacity and a 4-hour storage duration, with a total storage capacity of 600MW/2400MWh. Scheduled commission of the project is in the first half of 2025 in conjunction with the Longdong to Shandong UHVDC transmission project. After its completion, the project is able to absorb approximately 840GWh of green electricity annually, store approximately 2.4GWh in one charge.

The world's largest sodium-ion BESS has commenced operation in Qianjiang city, Hubei province in 2024, with an initial capacity of 50 MW and 100 MWh, representing the first phase of a larger planned project aiming for 100 MW and 200 MWh.[110] Another significant project is a large-scale hybrid lithium-sodium-ion BESS in Yunnan province, employing grid-forming technology with a total capacity of 200MW/400MWh, which includes 20M/40 MWh of sodium-ion batteries.[111] The commissioning of the project can effectively stabilize the regional power system, provide strong support for the construction of new power systems and regional efforts towards low carbon development. China has also seen the successfully connection to the grid at full capacity and official commencement of commercial operation of a significant compressed air energy storage facility with a capacity of 300MW/1,500MWh in Yingcheng City, Hebei province.

These example projects highlight China's strong commitment to technological innovation in the energy storage sector and its proactive approach to support renewable energy penetration and development of integrated new type of power system, in which storage plays a pivotal role.

(4) BESS development in cities

China is undertaking a massive and multifaceted deployment of BESS within its sprawling urban

[109] CNR. 2024. The largest electrochemical energy storage project in China has started construction in Qingyang, Gansu. https://baijiahao.baidu.com/s?id=1819464872722282971&wfr=spider&for=pc. 26 December 2024.

[110] Wuhan Municipal Government. 2024. The world's largest sodium-ion battery energy storage power station is put into operation. https://www.wuhan.gov.cn/sy/whyw/202407/t20240716_2428881.shtml.

[111] Yunnan Electric Power Industry Association. 2025. The new energy storage pilot demonstration project in Yunnan Province is connected to the grid for operation. https://mp.weixin.qq.com/s?__biz=MzU4NjI0MDk0Mw==&mid=2247523212&idx=1&sn=dfec1fc98e4519186e9aab7b2e2c711c&chksm=fcfc8181cbadda0f130fd206f118dbb9b2432302d6b652453b1243ccc406c9c74d7b50a0e036&scene=27. 7 April 2025.

landscapes, driven by a confluence of factors including its ambitious renewable energy targets, the urgent need to modernize its distribution power grid, and the imperative to ensure energy security for its vast and rapidly growing urban populations. The scale of China's urbanization presents unique challenges and opportunities for energy management, and BESS are seen as a critical solution for integrating the massive influx of intermittent renewables such as solar and wind power, which are often located far from major consumption centers. Government policies at both economy and local levels are providing significant financial incentives, subsidies, and regulatory support to accelerate the adoption of energy storage technologies in urban and peri-urban areas.[112] This proactive approach aims to create more resilient, efficient, and sustainable energy systems capable of supporting China's continued economic growth and environmental goals.

Within the densely populated Greater Bay Area, encompassing megacities like Shenzhen and Guangzhou and other cities, a diverse range of BESS projects are being actively developed and implemented. These initiatives serve multiple purposes, including providing crucial peak shaving capabilities to alleviate strain on the grid during periods of high electricity demand, offering rapid frequency regulation services to maintain grid stability as more variable renewable sources come online, and enhancing the overall resilience of the local power distribution network disruptions.[113] These relevant projects often involve collaborative partnerships between state-owned energy enterprises, private sector companies specializing in battery technology and energy management, and leading academic and research institutions. The data and operational insights gleaned from these pioneering projects are invaluable in informing the development of best practices and scalable deployment strategies that can be applied to other urban centers across China with similar energy challenges and renewable energy integration goals.

In Beijing and Shanghai, the integration of BESS is closely linked with the expansion of renewable energy generation in their surrounding regions. These megacities are strategically investing in energy storage solutions to effectively utilize the clean electricity generated by large-scale solar and wind farms located in neighboring provinces. By storing excess renewable energy during periods of high generation and lower demand, and then dispatching it during peak consumption times, these BESS installations help to maximize the utilization of renewable resources and reduce the cities' reliance on traditional coal-fired power plants, contributing to air quality improvements and carbon emissions reductions. Furthermore, recognizing the rapid growth of the EV market, Beijing, Shanghai and other cities are exploring the synergistic benefits of BESS in managing the increasing electricity demand from EV charging infrastructure and in providing grid services through vehicle-to-grid (V2G) technologies, ensuring more stable and efficient integration of electric mobility into the urban energy eco-systems.[114]

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[112] NDRC and NEA. 2021. Guiding Opinions on Accelerating the Development of New Energy Storage (No.1051). https://www.gov.cn/gongbao/content/2021/content_5636148.htm.

[113] China Energy Storage Alliance. 2005. China Energy Storage Project Database. https://www.esresearch.com.cn/project/.

[114] CNEV Post. 2024. Shanghai to build more energy storage facilities to support EV charging, grid stability. https://cnevpost.com. June 2

Beyond the first-tier cities, other urban centers throughout China are also recognizing the strategic importance of BESS and are implementing projects tailored to their specific industrial profiles and energy needs. Cities with substantial manufacturing sectors, for example, are increasingly deploying industrial and commercial BESS to ensure a consistent and reliable power supply for critical industrial processes, mitigating the economic risks associated with power outages and voltage fluctuations.[115] As China continues its ambitious trajectory of expanding its renewable energy capacity economy-wide, the role of urban BESS to support renewable integration and grid stability has become more critical. With right business and commercial model, the storage capability enhances the overall efficiency and reliability of the power systems and security of electricity supply.

In summary, China's approach to deploying BESS in its cities is characterized by its scale, ambition, and strategic integration with broader energy and environmental goals. Driven by strong government support, technological advancements, and the pressing needs of its rapidly urbanizing society, China is making substantial and accelerating progress in leveraging energy storage technologies to modernize its power grid, facilitate the deep penetration of renewable energy, enhance energy security, and improve the sustainability and resilience of its urban energy systems. Notably, integrated approaches addressing electricity generation, distribution, storage and consumption have been formed to establish the new type of power system. The diverse applications and the sheer volume of BESS projects being implemented across Chinese cities underscore the nation's commitment to making energy storage a fundamental pillar of its future energy infrastructure.

5.2.4 Japan: Accelerating with strong government incentives and utility-led efforts

(1) Deployment of BESS

Japan was among the early economies recognizing the importance of energy storage. As early as 2016, the installed energy storage system capacity in Japan had reached 254.6MW.[116] In 2018, Japan held a significant 11.8% share of the global annual BESS installations. Utility-scale battery storage capacity additions in Japan increased substantially in 2023 rising to more than 400MW. In 2024, Japan saw a surge in BESS capacity and BESS capacity auction in Japan awarded is 1.37GW. According to IEA, Japan has also added over 300MW of behind-the-meter battery storage annually over the period of 2020-2023.

Japan's 7th Strategic Energy Plan aims for 40-50% renewable energy by 2040, achieving Net Zero emissions by 2050, indicating a continued focus on BESS and other renewable energy technologies. The economy is actively investing in BESS to enhance grid efficiency and energy security, focusing on residential, commercial, and industrial applications. Looking forward, taking a measured approach, it has

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[115] S&P Global Commodity Insights. 2024. China's energy storage buildout to accelerate in 2024 on policy support, falling costs. 10 May 2024.

[116] Flowbatterieseurope. 2025. https://flowbatterieseurope.eu/wp-content/uploads/2024/11/FBE-Reports-on-Regions_Asia-Pacific.pdf.

planned that expansion in BESS capacity in Japan's energy systems will continue to increase, from 1GWh to about 5GWh from 2024 to 2027.

(2) Market environment

The Japanese government is actively fostering the growth of the BESS market through various supportive policies and financial incentives. Ministry of Economy Trade and Industry (METI) implemented CAPEX subsidy schemes for grid-scale battery developers and other financial support mechanisms to reduce the initial investment burden.[117] METI allocated a budget to provide 66% cost subsidies for households and businesses installing lithium-ion batteries, and for factories and small businesses to improve energy efficiency, which also aims to encourage the use of energy storage systems in solar power plants and substations. To promote the adoption of new energy solutions among households, the government provides subsidies for families implementing zero-energy home retrofits. These subsidies come from both central and local governments, supporting accounts for 40–50% of the retail price of batteries.

In addition to financial support, the Japanese government has taken a proactive policy stance in the new energy market: it requires utility-scale solar independent power producers to install a certain proportion of batteries to stabilize power output; it mandates grid operators to install batteries on transmission networks to stabilize frequency or purchase ancillary services from suppliers; at the distribution level, distribution networks and microgrids offer incentive programs to encourage battery adoption, and they may also outsource battery operations to third parties; consumers are also allowed to install their own solar panels and batteries, and even sell stored electricity back to the grid. In the electric vehicle sector, companies like Tesla, Mercedes-Benz, BMW, and Nissan are promoting combinations of EVs, solar panels, and batteries, which could become a mainstream direction for future battery sales in Japan and hold strong potential.

Japan's energy storage policies mainly include industrial development plans, electricity price incentives, renewable energy development, distributed energy system development, and equipment investment incentive policies. Among them, the industrial development planning policies mainly include the "Sunshine Plan", the "Moonlight Plan", and the "New Sunshine Plan"; Electricity price incentive policies mainly include policies promoting pumped hydro storage and similar technologies. Renewable energy development policies mainly include special measures laws such as the Act on Special Measures Concerning Procurement of Renewable Energy by Electricity Utilities and similar legislation for power utility operators. Policies for the development of distributed energy systems mainly include amendments to the *Energy Conservation Act*. Equipment investment incentive policies are primarily represented by subsidy programs for lithium-ion battery storage systems. Overall, Japan's energy storage policies are characterized by forward-looking vision, comprehensiveness, efficiency, and sustainability. The Japanese government and regulatory authorities have also formulated a series of battery energy storage policies and a regulatory framework to improve the

[117] Ministry of Economy, Trade and Industry. 2022. Clean Energy Strategy Interim Report.

technical capability for the deployment of battery storage systems.

Behind-the-meter storage takes the lead for storage deployment in Japan. Due to its land area restriction, high population density, and topographical characteristics, the development of rooftop PV and distributed generation facilities has shown a significant upward trend in recent years compared to large-scale solar power plants. At the same time, Japan has implemented incentive measures to encourage residential adoption of energy storage systems to address grid management challenges caused by the rapid growth of distributed solar PV, leading to a continuous increase in demand for battery storage systems.

The Feed-in Tariff (FIT) system for solar PV and Zero Energy House (ZEH) subsidies have driven rapid growth in residential energy storage. Japan launched its FIT program in 2012, offering high grid-connected electricity prices for solar PV, which spurred rapid growth in PV installations and created new use cases for residential energy storage; In addition, the Japanese government began implementing the ZEH program in 2018 and provided subsidies. In 2019, the ZEH subsidy budget was JPY55.18 billion, covering 208 models of residential energy storage products. Subsidies for energy storage under the ZEH program significantly improved the economic viability of residential storage investments, further driving sustained high growth in this segment. Additionally, local mandatory battery installation policies and the approaching deadline for front-of-meter solar PV grid connection requirements boosted demand for energy-shifting storage installations. In 2015, regions such as Hokkaido and Okinawa introduced mandatory battery installation policies for large-scale solar projects, requiring all PV projects above 2MW to install energy storage systems. This directly drove high growth in front-of-meter energy-shifting storage installations from 2015 to 2016; Furthermore, in 2018, METI required that front-of-meter solar PV projects (approximately 23.5GW in total) that had signed FIT contracts between 2012 and 2014 but remained uncompleted must be connected to the grid and begin operation by 2020; otherwise, their FIT rate would be reduced to JPY21 per kWh. This led to a rush of front-of-meter solar installations in 2020, driving a 914% year-on-year increase in front-of-meter energy-shifting storage installations.

For the policy implementations, for instance, more recently, Tokyo's FY2024 subsidy program awarded JPY13 billion to 12 grid-scale BESS projects. Furthermore, the government has amended the Electricity Business Act to categorize standalone BESS businesses as Electricity Generation Businesses, enabling them to connect to power grids, allow them to participate in the electricity market and offer system services. The introduction of the Feed-in-Premium (FiP) scheme also incentivizes the use of BESS by allowing developers to modify their business plans to include battery storage without altering the base subsidy prices, encouraging power export during peak demand.[118]

Technological advancements and strategic partnerships are further propelling the BESS market in Japan. Innovations in battery technologies, including lithium-ion, flow, and sodium-sulfur batteries, are enhancing

[118] Japan External Trade Organisation. 2023. Strengthening Market Competitiveness in Green Transformation and Energy to Achieve De-carbonization, Stable Energy Supply, and Economic Growth.

energy density, efficiency, and longevity. The exploration of alternative battery technologies like solid-state and sodium-ion batteries is gaining traction due to concerns over lithium supply chain vulnerabilities and price volatility. Collaborations among key market players, both domestic and international, are deemed crucial for technological advancements and market expansion. For example, partnerships involving companies like main players in industry namely Panasonic, Mitsubishi Materials, and LG Energy Solution are strengthening Japan's BESS capabilities.

The development of revenue streams through wholesale, capacity, and balancing markets provides a robust framework for investment in energy storage projects. Moreover, the increasing focus on energy self-sufficiency and resilience against natural disasters further underscores the strategic importance of BESS deployment across various sectors in Japan. The Long-Term Decarbonization Auction (LTDA) mechanism, introduced in 2024, awarded 1.4GW of BESS contracts in its second round, signaling integrating battery storage as a key component of Japan's energy infrastructure. It is noted that BESS projects with durations exceeding 6 hours accounted for 22% of the awards, reflecting a focus on energy shifting towards more solar electricity integration.

Japan is strategically deploying BESS within its urban centers as a critical component of its energy infrastructure modernization. The Tokyo Metropolitan Government, recognizing the importance of energy storage, has implemented a significant subsidy program to accelerate the development and deployment of grid-scale BESS projects within and around the capital. In Fiscal Year 2024, this subsidy program awarded a substantial JPY13 billion to support the development of 12 distinct BESS projects. Cumulatively, these projects represent a total capacity of 180 MW/595.3 MWh. The geographical distribution of these subsidized projects spans across several prefectures in the greater Tokyo metropolitan area, including Tokyo itself, as well as neighboring prefectures such as Kanagawa, Chiba, Saitama, Ibaraki, Tochigi, and Gunma.[119] This wide distribution suggests a comprehensive strategy to follow, enhancing grid stability and reliability across a significant portion of the Kanto region, which is home to a substantial portion of Japan's urban population and economic activities.

Several key players in the energy sector are actively involved in these urban BESS developments, leveraging the financial support provided by the Tokyo Metropolitan Government. According to Japan Energy Hub, Tokyo Century, a prominent financial services company, is developing two of the subsidized projects, located in Kanagawa and Tokyo prefectures. NTT Anode Energy and Renewable Japan, both significant contributors to Japan's renewable energy landscape, have also secured the maximum available subsidy amount for their respective large-scale BESS projects in Tochigi and Saitama respectively. These investments highlight the growing recognition of battery storage as a vital technology for enabling green

[119] Japan Energy Hub. 2025. 12 grid-scale BESS projects totalling 180MW/595MWh secure 13B yen from Tokyo's FY2024 subsidy schem e. https://japanenergyhub.com/news/tokyo-grid-scale-bess-subsidy-recipients-fy2024/#:~:text=The%20subsidy%20covers%20up%20to,released %20in%20February%202025%20shows. 7 March 2025.

energy transition. Beyond the immediate vicinity of Tokyo, other major urban areas in Japan are also witnessing notable BESS deployments. In Sendai City, located in the Miyagi Prefecture, a Tesla Megapack battery storage system with a capacity of 10.8 MW/43 MWh has been installed at the Sendai Power Station. This advanced system actively participates in Japan's recently established ancillary services markets, playing a crucial role in maintaining the delicate balance of the power grid frequency, which is essential for reliable power delivery. Furthermore, in Hokkaido, Sumitomo Corporation is operating an innovative large-scale energy storage facility known as the "EV Battery Station Chitose". This facility, with capacity of 6 MW/23 MWh, uniquely utilizes repurposed batteries from used electric vehicles, demonstrating a sustainable and circular economy approach to urban energy storage solutions.[120]

These diverse BESS projects across Japan's urban landscape underscore the nation's strong commitment to integrating advanced energy storage technologies into its power infrastructure. Driven by government support, private sector innovation, these initiatives are contributing to enhancing grid resilience, facilitating the greater adoption of renewable energy sources, and ultimately ensuring a more reliable and environmentally friendly energy supply for urban areas and other areas in Japan.

5.2.5 Korea: Synergistic public policy and private innovations

(1) Deployment of BESS

Korea was one of early adopters of energy storage policies in the 2010s, which initially led to rapid growth of BESS deployment, with Korean companies holding a significant share of the global lithium-ion battery BESS market by 2018. However, a series of lithium-ion BESS-related incidents caused a slowdown in storage deployment after a peak in 2018.[121]

Addressing the safety concerns, the government has enhanced the related regulations, established mechanism and set up the goals to revitalize the storage industry in Korea, with a particular emphasis on long-duration storage solutions in line with *the 9th Basic Electricity Supply and Demand Plan* issued in 2022, achieving renewable target of 21.6% by 2030, and 40% by 2034 respectively. Utility-scale battery storage capacity additions in Korea, including project development in an advance stage, reached around 1GW in 2024. Korea's BESS deployment also leverages its strong domestic battery manufacturing sector, with a focus on both lithium-ion and exploring longer-duration technologies like flow batteries, while also prioritizing enhanced safety measures.

(2) Market environment

The Korean government is actively supporting the revitalization of its BESS industry through a range

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[120] Sumitomo Corporation. 2025. Transforming Energy Storage Into Core Infrastructure: New Storage Battery Challenges for Sumitomo Cor poration in Hokkaido. https://www.sumitomocorp.com/en/jp/enrich/contents/0073. 28 February 2025.

[121] Flowbatterieseurope. 2025. https://flowbatterieseurope.eu/wp-content/uploads/2024/11/FBE-Reports-on-Regions_Asia-Pacific.pdf.

of initiatives and ambitious targets, including significant financial investment and the establishment of market mechanisms. This active government intervention is considered crucial for driving the rebound and future growth of the BESS market by creating demand, incentivizing investment, and addressing existing barriers to deployment, particularly those related to safety. There is a strong emphasis on Long-Duration Energy Storage (LDES), with the government setting a target of 20.85GW of LDES deployment by 2036 to effectively compensate for the inflexibility of renewable energy sources. This strategic focus on LDES highlights Korea's recognition of the need for energy storage solutions capable of providing power for extended periods, thereby enhancing grid reliability in the face of increasing renewable energy penetration in power system.

Following the past fire incidents involving lithium-ion BESS, there is an increased focus on enhanced safety measures within the Korean BESS market. These include implementation of stricter regulations and technological advancements in safety systems. The government has also introduced a central contract market for BESS, offering long-term contracts for projects, with the first tender launched for projects on Jeju Island in 2023, targeting 260MWh of battery energy storage systems. The winning bid secured a 15–20-year contract, determining price and volume through the bidding process, aiming to stabilize Jeju's power grid by storing surplus power from renewable resources. The establishment of such a market provides revenue certainty for BESS projects, encouraging investment, particularly in regions with high renewable energy penetration like Jeju Island, which often experience excess energy generation and curtailment.

Korea has been actively exploring flow battery technology, with KEPCO increasingly deploying flow battery demonstration projects and providing supports for flow batteries paired with renewable generation projects. The longer lifespan and lower capacity degradation of follow battery compared to lithium-ion batteries, aligning well with Korea's focus on LDES applications. Behind-the-meter capacity additions in Korea peaked in 2018, but the market crashed following the withdrawal of subsidies and has yet to regain its 2018 level.

(3) Notable BESS Projects

In September 2024, Korean Electric Power Corporation (KEPCO) completed a significant 978MW/889 MWh BESS portfolio across 6 substations in Miryang, Gyeongsangnam-do Province. The Bubuk Substation (336MW) alone represents one of Asia’s largest grid-stabilizing BESS. The portfolio represents a significant operational deployment in Korea. A more recent initiatives include a government tender for 540MW/3,240MWh of BESS capacity in May 2025, part of a broader USD29 billion market goal by 2038. This builds upon major projects like KEPCO's completion of Asia's largest 978MW/889MWh BESS portfolio for grid stabilization, with further installations planned. Currently, Samsung and Korea Southeast Power are collaborating on a project to develop a 300MW BESS as an integral part of a hydrogen-powered data center, and this project is planned for commercial operation by 2032.[122] On the other front, H2 Inc., a Korean vanadium flow battery manufacturer, is planning to scale up its production capacity significantly, aiming for 1.2GWh of annual manufacturing capacity by 2026.[123] LG Energy Solution, a major Korean battery manufacturer, supplied its innovative TR1300 system to Vistra's 300MW/1.2GWh Moss Landing Energy Storage Facility in the United States, highlighting Korea's role as a key technology provider in the regional BESS market.[124]

KEPCO's portfolio and other projects demonstrate the development of large-scale BESS capacity in Korea, and the economy's strategic focus appears to be on future long-duration energy storage projects and leveraging its strong battery manufacturing sector to supply both domestic and international markets. The planned hydrogen-powered data center project with a substantial BESS component indicates an interesting future direction for energy storage applications in Korea.

(4) BESS development in cities

Korea recognizes the crucial role of battery energy storage systems in enhancing grid stability and integrating its growing renewable energy capacity, and the overall trend and government support for BESS deployment in cities are evident. One significant development indicating the scale of BESS deployment in Korea is the completion of what is billed as one of Asia's largest battery energy storage systems for grid stabilization in Miryang, Gyeongsangnam-do Province. While Miryang is not a major metropolitan city like Seoul or Busan, the project taken by KEPCO, highlights the economy commitment to large-scale energy storage to support the grid. Such large-scale installations, even if not directly within the largest cities, provide critical grid support that benefits urban centers by ensuring a more stable and reliable power supply.

The government's *10th Basic Plan for Electricity Supply and Demand* emphasizes the need for energy storage to complement the increasing share of renewables. This plan anticipates a significant need for energy storage capacity by 2036, implying ongoing and future BESS deployments that would likely include installations in or near major demand centers like Seoul, Busan, and Incheon in order to optimize grid management and resilience. Furthermore, the focus on developing a robust local energy storage system industry, with Korea aiming to become a major player in the global BESS market by 2036, indicates a strong drive for innovation and deployment of BESS technologies, including in urban areas.[125]

In summary, the overarching policy framework and the existence of large-scale grid-connected BESS projects demonstrate Korea's commitment to leveraging energy storage to support its cities' energy needs and

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[122] DataCenterDynamics. 2025. Samsung and Korea Southeast Power to develop fully integrated hydrogen-powered data center in Korea. https://www.datacenterdynamics.com/en/news/samsung-and-state-owned-utility-to-develop-fully-integrated-hydrogen-powered-data-center-in-south-korea/.

[123] H2ACE. 2025. H2 secures funds for new Korean factory. http://www.h2aec.com/eng/main.do?ref=ctvc.co.

[124] MultiVu. 2025. LG Energy Solution's New TR1300 Operational at World's Largest Battery -, https://www.multivu.com/players/English/8886951-lg-energy-solution-tr1300-worlds-largest-utility-battery-energy-storage-project/.

[125] Businesskorea.2023. Korea Aims to Secure 35% of the Global ESS Market by 2036. https://www.businesskorea.co.kr/news/articleView.html?idxno=204775. 1 November 2023.

its broader economy-wide renewable energy transition. The government's strategic plans and industry ambitions suggest a continued and growing deployment of BESS in and around major cities to enhance grid reliability and facilitate the integration of renewable energy sources, contributing to a more sustainable and resilient urban energy future for Korea.

5.2.6 The US: Incentivized and renewable integration driven expansion

(1) Deployment of BESS

The United States witness a surge in the development and deployment of BESS, expanding the scope to include all market segments from grid scale to end-users owned facilities, and the installed BESS capacity in the United States reached 27GW in 2024, marking a remarkable increase of over 10 times since 2020, with 10.4GW of new capacity added during that year alone.[126] Among these, utility-scale projects accounted for about 90% of the additional capacity, with California, Texas and other states in the southwest leading the deployments. The EIA expects a record 18.2GW of utility-scale battery storage additions in 2025, signaling an acceleration in deployment, and with expected capacity exceeding 170GW by 2030, representing a further 525% increase from the 2024 levels.

The trend towards hybrid renewable projects, combining battery storage systems with renewable electricity generation like solar and wind, has also gained momentum. Co-locating BESS with renewable generation enhances the value and reliability of these projects by allowing for the storage of excess renewable energy, which can then be dispatched when needed, thereby optimizing capacity factors and reducing curtailment risks. Distributed battery storage systems, installed residential, community, industrial and commercial sector have also showed strong growth. These significant increases of BESS deployment confirm a strong upward trajectory, driven by declining battery costs and the increasing imperative to integrate renewable energy sources into the grid. The rapid expansion signifies a strong commitment to leveraging battery storage as a crucial mean in green energy transition.

(2) Market environment

Improving economics of storage system in the United States are the results of market reforms, falling equipment costs and incentives such as investment tax credit introduced as part of the Inflation Reduction Act. This has allowed utility-scale batteries to make inroads into electricity market, as well as ancillary service markets, where they are increasingly tapped to provide balancing services and secure capacity in states with high shares of variable renewables generation in power system. A clear trend of the BESS market in the United States. is the focus on revenue stacking, where operators are actively diversifying their income streams by participating in multiple markets. These include energy arbitrage, capitalizing on price differences between peak and off-peak periods, providing ancillary services like frequency regulation to maintain grid

[126] EIA. 2025. U.S. battery capacity increased 66% in 2024. https://www.eia.gov/todayinenergy/detail.php?id=64705. 12 March 2025.

stability, and securing capacity payments through resource adequacy agreements. The multi-faceted approach to revenue generation has become increasingly important for the financial viability of BESS projects, especially as market dynamics fast evolve and competition intensifies. Diversifying income sources of the projects also helps mitigate risks associated with price volatility in any one particular market.

Technological advancements play a significant role, with ongoing innovations in battery chemistries. While Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) currently dominate as in other economies, emerging technologies such as solid-state and sodium-ion batteries promise higher energy densities, longer lifespans, and improved safety has been pushed in the different stage of development. Notably, the increasing adoption of LFP batteries for stationary energy storage installations suggests a growing emphasis on cost-effectiveness and safety of storage stations.[127] It is expected that the development of next-generation storage technologies including solid-state and sodium-ion batteries holds the potential to further enhance the performance and increase the deployment, and address supply chain issues of battery industry that becomes a primary concern regarding lithium and other critical mineral materials in the United States.

Furthermore, the integration of Artificial Intelligence (AI) and machine learning into Energy Management Systems (EMS) of BESS has been becoming increasingly prevalent. AI-driven EMS enables real-time market participation, accurate load forecasting, and optimized dispatch decisions, signifying a move towards smarter and more efficient operation and management of BESS facilities. The intelligent control helps maximize revenue generation while also considering battery degradation, optimizing and ultimately improving the overall economic performance of these systems. In addition, supportive regulatory frameworks are essential for accelerating the adoption of BESS by reducing bureaucratic hurdles and timelines associated with connecting to the grid. Regulatory reforms in the United States, such as FERC Order 2023, streamlines the interconnection processes for BESS projects, reducing delays and facilitating faster deployment.[128]

With some high-profile safety incidents occurred in the past, there is an increased focus on safety innovations in BESS, including advancements in fire suppression, thermal management, and real-time hazard detection. Ensuring robust safety protocols is paramount for gaining public acceptance, securing insurance coverage of the projects, and maintaining investor confidence in BESS technologies. It is noticed that the US energy storage industry has made a significant commitment to domestic manufacturing, pledging to invest USD100 billion in building grid scale battery systems with the goal of meeting 100% of domestic project demand with locally produced batteries by 2030. This initiative indicates a strategic push towards strengthening the domestic battery manufacturing supply chain, enhancing energy security, and creating jobs within the economy.

[127] NREL. 2024. Utility-scale battery storage: electricity.
[128] Federal Energy Regulatory Commission. 2024. Improvements to Generator Interconnection Procedures and Agreements.

(3) Notable BESS projects

Individual BESS installations are becoming more operational. As of November 2024, the largest operational BESS is the Edwards & Sanborn BESS in California, with a capacity of 821MW/3,280 MWh. For project development, many storage systems are built in several phases, adjacent to one another, and are commonly under separate interconnection applications. The United States is home to several of the world's largest BESS projects when it was put in operation in early 2024. While China leads the United States in deployed BESS capacity by end of 2024, the United States leads in construction of large individual projects, with 9 of the world's 11 operational projects greater than 300MW. Currently there are multiple projects in development breaking the 1GW mark by end of 2024. The Edwards & Sanborn solar-plus-storage project in California stands out with its 875 MW of solar capacity and 3,287MWh of BESS capacity, among the world largest. Another significant project in California is Vistra's Moss Landing Energy Storage Facility, with a capacity of 750MW/3,000MWh. In Nevada, the Gemini solar-plus-storage project combines 690MWac/966MWdc of solar PV with a substantial 380MW/1,400 MWh BESS capacity.[129] California also hosts the Menifee Power Bank, with a capacity of 620 MW and 2,480 MWh, and the Manatee Solar Energy Center in Florida with 409MW. Other examples of notable projects include Plus Power's Sierra Estrella Energy Storage in Arizona (250 MW/1,000 MWh) and Ørsted's Old 300 Storage in Texas (250MW/500MWh).[130]

The concentration of these large-scale projects in states like California and Texas, which have high renewable energy penetration, highlights the strategic role of BESS in supporting clean energy integration. These projects demonstrate the technical feasibility and growing adoption of BESS as a vital component of a modern and resilient power grid.

(4) BESS development in cities

Cities are recognizing the multifaceted benefits of BESS in the United States, from facilitating the integration of intermittent solar and wind power, enhancing the resilience of power grids to providing essential grid services, and ensuring a stable and reliable power supply in densely populated urban environments.[131] This momentum is further amplified by the federal incentives and research initiatives aimed at accelerating the adoption of clean energy technologies. The development and deployment of BESS in cities represent a dynamic and increasingly vital aspect of the green energy transition. The increasing electrification of transportation sector and buildings will further drive the need for flexible grid resources that BESS can provide. With projects emerging in diverse urban environments, the trend indicates a widespread recognition of the value of energy storage. The projects deployed in cities showcase increasing capacities,

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129 PrimergyGemini. 2024. Project Overview. https://www.primergygemini.com/project-overview.

130 Orsted. 2025. Ørsted Announces New Battery Energy Storage System in Fort Bend County. https://us.orsted.com/news-archive/2025/04/orsted-announces-new-battery-energy-storage-system-in-fort-bend-county.

131 American Clean Power Association. 2024. Energy Storage. https://cleanpower.org/energy-storage/.

diverse applications ranging from grid stabilization to peak shaving and renewable integration, and a growing interest from both established energy companies and new developers. It is noted that community engagement and addressing safety concerns remain crucial for successful deployment, particularly in densely populated urban areas. Continued technological innovation, supportive policies, and proactive engagement with communities will be essential to fully realize the potential of BESS in creating more resilient, sustainable, and equitable urban energy systems in the United States.

Examining specific projects provides a clearer picture of this urban BESS landscape. On the East Coast, several significant BESS projects are underway. In New York City, the East River Energy Storage Project, located in Astoria, Queens, stands out with a capacity of 100MW. This project, developed by Power Global, has the potential to power tens of thousands of households. Operational as of the summer of 2024, with the expectation of construction commencing in the first quarter of 2025, it is poised to become the largest battery storage installation in New York City and one of the largest in New York State. Its purpose is to provide stability and resilience to the city's power grid, particularly during periods of peak demand. Notably, the project is located on the site of a former fossil fuel plant, representing a strategic repurposing of land and infrastructure that supports the green energy transition. This approach leverages existing grid connections, potentially streamlining development and providing a tangible example of moving away from traditional fossil fuel power generation.

Beyond the large-scale initiative, NineDot Energy is developing multiple smaller, community-focused BESS projects across the five boroughs of New York City. With plans for 20 projects, each around 5MW20MWh in output and capacity, the total reaches 100MW/400MWh. These projects focus on community-scale ("retail-end") energy storage, utilizing incentives from the New York State Energy Research and Development Authority (NYSERDA). Additionally, Catalyze launched its first standalone BESS project in the Bronx, with a size of 4.29MW/8.58MWh, which was approved through New York City's updated permitting process. Furthermore, ArcLight and Elevate Renewables announced a 15MW/60MWh project at the Arthur Kill Power Station in Staten Island, anticipated to be New York City's largest upon its expected completion in late 2025. This combination of large utility-scale projects and numerous smaller-sized installations represent a comprehensive strategy to enhance grid resilience at various levels and cater to both broad and localized energy management needs. These strategically located urban batteries can alleviate transmission bottlenecks and provide backup power during outages, directly benefiting local communities.

The Boston Metropolitan Area is also witnessing significant BESS developments. The proposed Trimount Energy Storage Facility in Everett, near Boston, has a capacity of 700MW/2,800MWh, potentially making it the largest in New England. Developed by Jupiter Power, this project is currently in the permitting phase, aiming for commercial operations in the latter half of the decade. Its purpose is to improve electric reliability by connecting to Eversource's Mystic Substation and to support the region's clean energy objectives. Trimount is planned for a former oil terminal site, which will also support environmental remediation efforts in urban areas. The sheer scale of the proposed Trimount project underscores the significant commitment to energy storage in the Boston area and its potential to substantially bolster regional grid stability, providing a considerable capacity to manage fluctuations in renewable energy supply and ensuring power supply during the periods of high energy demands. In Brighton, Boston, Flatiron Energy has proposed a 300MW/1,200MWh indoor BESS project named Lite Brite Storage. This project has received approval from ISO New England and is currently seeking local permits, with a target operation date of 2028. Its goals are to enhance grid reliability and support clean energy initiatives. The indoor design is a notable feature, likely due to the dense urban environment of the proposed location, which could provide a showcase for the storage projects with similarly location.

In California, the Los Angeles Metropolitan Area features several significant BESS projects. While located near Mojave in Kern County but supplying Los Angeles, the Eland Solar-plus-Storage Center boasts a capacity of 400MW of solar generation and 1200MWh of energy storage. Developed by Arevon, Phase 1 of this project has completed, with Phase 2 expected in late 2025. Fully approved in 2019, Eland aims to provide power for over 266,000 Los Angeles homes, significantly contributing to the city's clean energy goals. As Los Angeles Department of Water and Power (LADWP)'s first utility-scale integrated solar and battery project, it represents a crucial step in the transition to renewable energy resources. Projects like Eland, although situated outside the immediate urban core, demonstrate the trend of developing large-scale renewable energy and storage facilities to serve major metropolitan areas. The availability of land and solar resources in surrounding regions often makes them ideal locations for such extensive projects, with the generated power then transmitted to the city, showcasing the interconnectedness of urban and regional energy infrastructure. In Lancaster, within Los Angeles County, AES operates the Luna and LAB Energy Storage facilities, which together provide 227MW/908MWh of storage capacity. These storage facilities deliver flexible and reliable clean energy to California, helping to manage peak loads and ensure grid stability. They store renewable electricity generated from nearby AES solar facilities, and serve customers of Clean Power Alliance and PG&E.

Despite the promising advancements, challenges remain in the widespread adoption of BESS in the US cities. Public perception and safety concerns, particularly regarding thermal runaway in lithium-ion batteries, necessitate robust safety protocols and community engagement.[132] Ensuring robust safety standards and regulations, and effective public communication to address potential concerns are paramount.[133] Streamlining permitting processes and establishing clear regulatory frameworks at the local and state levels are crucial for facilitating deployment. Additionally, addressing supply chain vulnerabilities for critical

[132] National Fire Protection Association. 2023. NFPA 855: Standard for the Installation of Stationary Energy Storage Systems. https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=855.

[133] Electric Power Research Institute. 2023. Energy Storage Safety.

battery materials and promoting equitable access to the benefits of energy storage system in all urban communities are regarded among important considerations for sustainable and inclusive growth of the BESS sector.

In summary, significant BESS projects have been developed and deployed across major the cities in United States, reflecting an economy-wide trend towards enhancing grid resilience and integrating renewable energy. These projects showcase increasing capacities, diverse applications ranging from grid stabilization to peak shaving and renewable integration, and a growing interest from both established energy companies and new developers. The repurposing of former fossil fuel plant sites for BESS projects is a notable strategy, leveraging existing infrastructure and supporting the green energy transition narrative. These urban BESS projects play a vital role in the ongoing green energy transition, supporting renewable energies, contributing to the development of a more reliable, sustainable, and resilient energy infrastructure for cities. However, community engagement and addressing safety concerns remain crucial for successful deployment of the projects, particularly in densely populated urban areas.

5.2.7 Other APEC economies

The development of BESS in other APEC economies have been also active. In Chile, over less than two years, BESS capacity surged from negligible levels to nearly 1000MW, notable considering the economy's peak demand of approximately 11,000MW. Chile added nearly 250MW of utility-scale storage in 2023, making it the first economy in Latin America to deploy battery storage at scale. By December 2024, BESS projects under construction reached around 2000 MW, demonstrating robust investment momentum for battery energy storage systems. Initially driven by key market players such as AES, Enel, and Engie, the BESS market in Chile has recently attracted international companies like Grenergy, Innergex, Atlas, and Pacific Hydro, reflecting the dynamism and rapid diversification of infrastructure investments. Most BESS installed in Chile are hybrid projects coupled with renewable generation, predominantly photovoltaic. Under Chilean regulations, these systems charge either from renewable sources or from the grid, dispatched by the system operator, Coordinador Eléctrico Nacional (CEN), primarily to meet nighttime demand and support the grid. It has been estimated that 5,000MW of projected capacity of BESS will be installed by 2030, positioning Chile as a leader in Latin America.[134]

In Southeast Asia, Malaysia; the Philippines; Singapore; Thailand; Viet Nam, are among the other economies in APEC set the goals for BESS development, with Singapore having already exceeded its 2025 BESS deployment target, launching Southeast Asia's largest storage system. The goals are to address the issues regarding rising renewable energy generation capacities, upgradations of existing grid, and improving power supply security. Some of the examples of recent developments in the BESS sector Southeast Asia

[134] Carlos Toro Ortiz and Belén Muñoz Zurita. 2023. Chile's Action Plan for Power Sector Decarbonisation. Delivered for the 14th Clean Energy Ministerial (CEM14).

include:

- Sembcorp Industries announced a joint venture with PT PLN Nusantara Renewables for the development of a 50MW solar power facility and a 14MWh BESS in Nusantara, Indonesia;
- In November 2024, the government of Malaysia announced a new BESS project for the installation of 400MW BESS installation. The project will be conducted in four phases, each with a capacity of 100MW/400MWh. This project is expected to become commercially operational by Quarter one in 2026;
- American Energy Storage Innovations Inc (AESI) announced plans for its new manufacturing facility in Malaysia along with new partnerships, inducing an expanded cell supply deal with a Chinese firm and an over 1.5GW BESS delivery pact in the UK.

The current and projected installations of BESS are expected to drive market growth within the region. There is a notable shift towards integrated solar PV and BESS solutions, with innovative methods such as the deployment of compact sodium-ion batteries in urban areas. Despite the significant potential for these systems, widespread adoption faces challenges including the need for harmonized policies, regulatory frameworks, and increased investment across various ASEAN economies.

5.3 Chapter summary

Battery energy storage systems are rapidly becoming a cornerstone of the global energy transition, offering solutions to the inherent intermittency of renewable energy sources and enhancing overall grid resilience, secure energy supply and enable green energy transition. The significant growth and varying development trends of BESS in each economy has been driven by factors such as renewable energy targets, government policies, technological advancements, and the need to enhance power networks.

Policy recommendations, to foster battery technology innovation and manufacturing, thereby increasing the performance and lowering the costs of BESS, should prioritize a concerted efforts across the innovation lifecycle. This includes significant and sustained government investment in fundamental and applied R&D to explore novel battery chemistries (e.g., solid-state, sodium-ion, flow batteries) that offer higher energy density, longer cycle life, enhanced safety, and reduced reliance on critical minerals. Alongside R&D, policies should implement targeted manufacturing incentives, such as production tax credits, investment tax credits, and grants for domestic gigafactories and supply chain development, to scale up efficient and cost-effective production of advanced battery cells and components. Furthermore, streamlined regulatory approvals and collaborative initiatives between research institutions, industry, and government are crucial to accelerate the translation of R&D breakthroughs into commercially viable products.

The United States; China; and Australia are the current fronter runners regarding BESS deployment. Australia and the United States are experiencing rapid growth, driven by ambitious renewable energy targets, supportive government policies, and the imperative to replace retiring fossil fuel power plants. China stands out as the global leader, with an extraordinary pace of deployment and a strong focus on large-scale, utility-connected systems. Korea, one of early adopters, is now aiming to revitalize its market with a strategic emphasis on long-duration energy storage and enhanced safety measures following past challenges. Japan, while possessing significant technological expertise, appears to be pursuing a step-by-step path in terms of near-term BESS capacity expansion compared to other economies. The overall trends clearly indicate a significant increase in BESS deployment, recognizing its critical role in enabling green energy transition. Technological advancements in battery chemistries, coupled with decreasing costs and supportive regulatory frameworks, are expected to further accelerate this trend in the coming years. As renewable energy penetration continues to rise and the need for grid flexibility and resilience becomes more pronounced, BESS will undoubtedly play an increasingly pivotal role in shaping the future of the global energy system. The diverse approaches and growth trajectories observed across these key markets highlight the varied priorities and challenges each economy faces in integrating energy storage into their unique energy landscapes.

In urban environments, BESS are becoming increasingly vital, serving as crucial infrastructure for modernizing power grids and facilitating the transition to cleaner energy sources. The BESS projects play a multifaceted role, enhancing grid stability by providing rapid response capabilities to balance supply and demand fluctuations, particularly with the growing integration of intermittent renewable energy like solar PV. Furthermore, BESS can improve the reliability of electricity supply in cities, supporting distribution network, reducing the frequency and duration of power outages. They also enable more efficient use of existing grid infrastructure by storing energy during periods of low demand and releasing it during peak times, potentially deferring the need for costly upgrades. The cities across the region are actively pursuing and implementing BESS projects to address their specific energy challenges and sustainability goals. In Australia, cities like Sydney, Melbourne, and Brisbane are witnessing significant investments in large-scale battery storage to support renewable energy integration and grid resilience. Similarly, in Japan, the Tokyo Metropolitan Government is heavily subsidizing grid-scale BESS projects, while other urban centers in the region are exploring innovative solutions like repurposing EV batteries for energy storage. Korea demonstrates a strong commitment to BESS deployment, evidenced by the completion of massive grid-stabilization projects that benefit urban centers by ensuring a more reliable power supply at the economy level.

All these highlight a trend towards recognizing the indispensable role of BESS in shaping the future of urban energy systems. By providing essential energy storage capabilities, cities are better equipped to manage the complexities of modern power grids, integrate higher penetrations of renewable energy, and ensure a secure and sustainable energy future for their residents and economies. The continued innovation and deployment of BESS technologies in urban areas therefore will be critical in achieving ambitious climate goals and building more resilient and efficient energy infrastructures.

Chapter VI System Integration and Operation of Energy Storage

6.1 Energy storage in urban power system

6.1.1 Changing landscape of urban energy system

(1) Urban energy system in transition

Conventional power system, based mostly on large scale centralized generation, has been disrupted by the pervasive and rapid penetration of renewables, both utility-scale and distributed ones, and which is particularly the situation in the context urban energy system. Renewables inherently bring about a host of new challenges for the conventional power systems. As the share of renewable generation participation in the existing power system increases, technological advancements and alternative technology adoption and management are among the must to ensure a reliable and secure future power system, which is largely the consequence of renewables such as solar PV and wind power being of internment nature, with great variation and less predictability in terms of energy yields.

On the one hand, the power transmission has evolved to effectively move the power from the generation sources to the load centers, particularly the cities which are far away from the resource centers as the situation in many economies. On the other hand, at the distribution level, the grid connection of distributed generation (DG) in urban power system may reverse the direction of the power flows, affect the existing protection systems and create a potential threat to the system operation and equipment safety. Furthermore, the intermittent nature of variable renewables likely induces more voltage and frequency deviation as far as the system stability is concerned, which results in the challenges regarding reliability and quality of power supply for the end-users. Furthermore, due to the geographically unbalanced locations and particularly unmatched timing of generations and loads, it would be of maximum interest for the related urban areas to enhance coordination to balance the renewable variations, ensuring better reliability and security of the urban power system. Furthermore, with the rising pace of electrification and re-electrification in end-use sectors, as well as increased penetration of electric vehicle in transport sector, the changing load profiles and consumption patterns results in challenges for the urban power system as well. Against these backdrops, the power generation assets and the power network needs be planned, designed, and operated in order to maintain the system voltage within accepted bounds of magnitude and frequency; avoid equipment overloads; maintain the system stability; and satisfy the need at the end-use level with quality of power supply.

(2) Resilience of urban energy system

Urban power grids in general are characterized by a bulky concentration of different load zones, such as these in industrial, commercial and residential sectors, and strict requirements on the grid reliability of power supply from distribution systems. The increasing power demand, due to economic growth and demographic changing, particularly in developing economies, along the increasing proportion of variable renewable electricity, has been pushing the operation of urban power network to its boundaries, and resilience becomes a critical aspect that needs to be considered for the development and modernization of urban power systems.[135]

Resilience of urban power system normally refers to the ability of power system planners and operators to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions to the power sector through adaptable and holistic planning and technical approaches and solutions[136]. As opposed to reliability, which typically focuses on routine events with shorter timescales and smaller impacts, resilience is also focused on low-probability, high-risk events with large-scale and long-duration consequences.[137] Resilience is a function of time, showing power grid's ability to degrade gradually under a disturbance, recovers to its pre-disturbance normal state, as illustrated in the Figure 6-1.

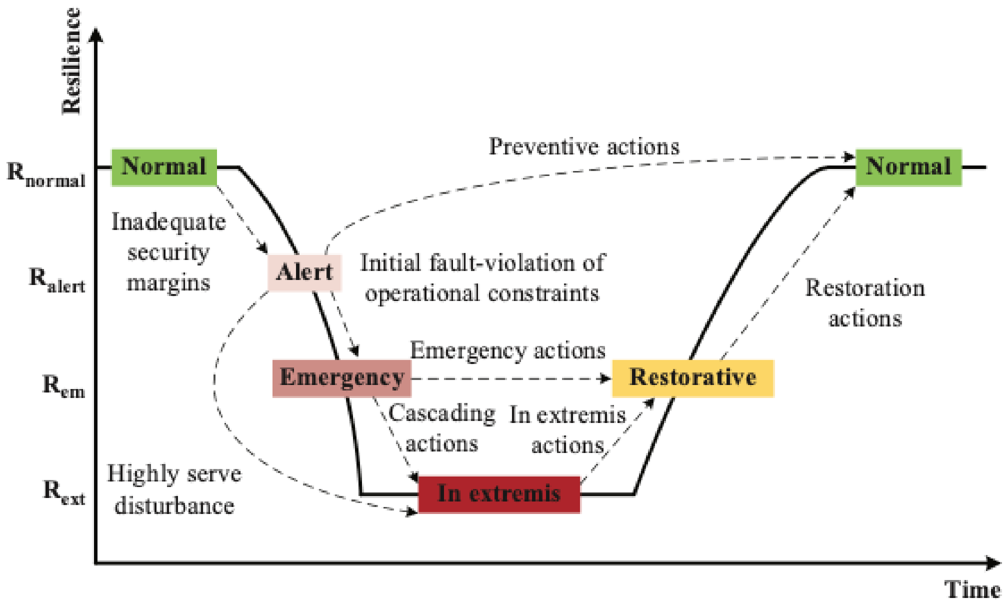


Figure 6-1 Illustration of Urban Energy Grid Resilience

The definition of resilience types has been evolving and varied depending on system ability to cope with disturbances. It can be divided into short-term and longer-term resilience. A short-term resilience refers to: i) the ability to detect the faults and disconnect the most critical parts of the urban power grid to operate in

[135] ARUC. 2025. Principles for Enhancing Electric System Resilience. National Association of Regulatory Utility Commissioners.

[136] Stout, Sherry R, Nathan Lee, Sarah L Cox, James Elsworth, and Jennifer Leisch. 2019. "Power Sector Resilience Planning Guidebook: A Self-Guided Reference for Practitioners." Guidebook NREL/TP-7A40-73489. Resilient Energy Platform. Golden, CO: NREL. https://doi.org/10.2172/1529875.

[137] Anderson, K., X. Li, S. Dalvi, S. Ericson, C. Barrows, C. Murphy, and E. Hotchkiss. 2020. "Integrating the Value of Electricity Resilience in Energy Planning and Operations Decisions." IEEE Systems Journal, 1–11. https://doi.org/10.1109/JSYST.2019.2961298.

isolated mode in which the loads are continuously supplied by local generations and storage units; and ii) ability to identify the abnormal voltage dynamic and implement countermeasures to bring the voltage back to pre-fault condition after disturbance.[138] Long-term resilience in energy system refers to the ability of the system to learn from previous events and adapt to changing conditions, and respond to future disturbances in the system. In practice, urban power system resilience is more about the planning process to upgrade the system to counteract with future predictable and unpredict disturbances. Whereas the short-term resilience of energy systems is the ability to prevent (precondition), effectively and rapidly react to (during), and restore the power service after a disturbance or critical event. The ability to provide ancillary services from distributed and dispatchable sources to support optimal, reliable grid operation, and maximize the benefit from these sources are increasing important to improve resilience of urban power system.

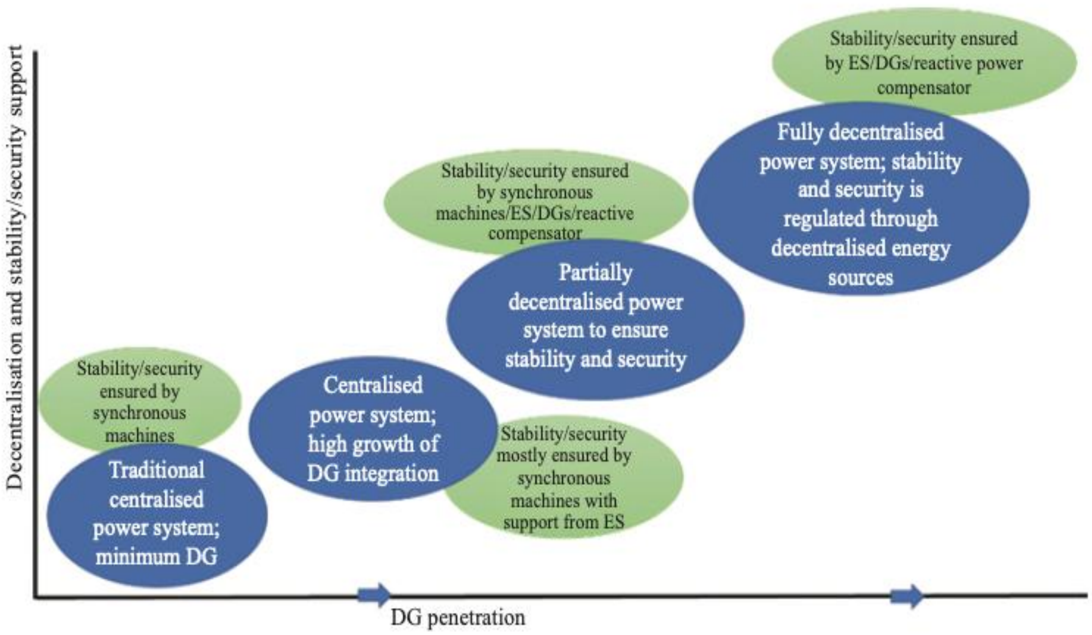
Enhancing urban power system resilience is crucial for minimizing economic losses, ensuring public safety, and supporting the overall well-being of urban populations in the face of uncertainties. To deal with growing climate change threats, having resilient distribution systems will prove essential to ensuring critical infrastructure that can still function as the power system recovers after severe events, reducing risks to customers, and more broadly minimizing negative impacts to the economy.

6.1.2 Roles of energy storage in urban power system

Energy storage can play significant role in providing the reliability services to the urban grid, particularly with increasing proportion renewable capacity in the power system, owing to its operational flexibility and fast-acting nature. The short-term and long-term energy storage technologies offers great flexibility to select the best option according to the city's power grid requirements, such as long-term storage facilities such as pumped storage hydropower and compressed air energy storage as well as fast response from battery energy storage system. Furthermore, energy storage technologies are capable of relieving stress from the transmission and distribution network when deployed in an integrated approach.

Figure 6-2 illustrates the issues of urban energy system with increased penetration of distributed generation, and the roles of energy storage in maintaining system resilience, providing ancillary services, acting as backup, facilitating the deployment of distributed generators, and bringing the power system back online after a disturbance.

[138] Yonghua Song et al. 2022. Resilient power grid for smart city. iEnergy. https://doi.org/10.23919/IEN.2022.0043.



Note：DG - distributed generation; ES – energy storage

Figure 6-2 Illustration of the Evolvement of Urban Power System

A reliable and secure power system can be achieved via combining the best attributes of renewables along with energy storage through coordinated control. At the same time, this would enable extracting the maximum technical benefit of the renewables and storage facilities, with both technologies operating in parallel to maximize their benefits. A coordinated dispatch of renewables and energy storage lower the costs of power purchase of the customers by reducing renewable resource curtailment, lowering network energy losses, as well as avoiding the likely penalty from power quality issues such as voltage deviation etc.[139] Nevertheless, an economic dispatch strategy is also imperative to ensure sufficient commercial returns from energy storage facilities which is achieved by exploiting the power injection from energy storage to balance uncertainties of renewable electricity generation and variation of load conditions, and provision of other services. In terms of power system operation, energy storage can be used in numerous ways to support the supply of safe, reliable and cost-effective electricity as urban energy transition and evolve over time, which include but not limited to:

- Distribution loss reduction: distribution-connected storage could reduce the distance power must flow by enabling excess energy from distributed generation to be locally stored and delivered to serve demand when needed. Energy storage suffers from bi-direction line losses need be considered in this situation;

[139] Kalantar N.M. and Cherkaoui R. 'Coordinating distributed energy resources and utility-scale battery energy storage system for power fle xibility provision under uncertainty'. IEEE Transactions on Sustainable Energy, 2021;12 (4):1853–1863.

- Time shifting energy: storage is able to shift energy supply to match later periods of demand. With increasing level and proportion of variable renewables, storage helps firm the supply of variable renewable power by storing energy at high-generation (low-price) periods and saving it for use at low-generation (high-price) periods;
- Avoiding or deferring transmission and distribution investment: storage and transmission and distribution (T&D) are complementary that can be optimized together to help more efficient network development. This is important given the scale and pace of change required to support energy transition in cities;
- Network support: storage supports grid stability by managing changes in energy supply or demand across the network. As levels of variable renewables increase across urban power major grids, there is increased needs for network support services, such as frequency control ancillary services (FCAS). Storage can help balance the short-term supply and demand and maintain grid voltage and frequency, as well as support network stability by correcting longer-term imbalances between generation and demand;
- Seasonal storage: as the power grid shift to more renewables, which may present a risk that there is a net surplus or deficit of energy supply over long periods of time. Some of these events requires the support from high-capacity, long-duration or seasonal storage capacity;
- Demand side management and response: at the distribution level, a variety of new consumption have emerged, including use of EV, and local, shared, and aggregated use by residential, commercial, and industrial electricity customers. Storage can help to form demand side management and response programs.

The Figure 6-3 shows the categories of system services that can be provided by grid-connected energy storage systems. These potential services are provided over different timescales. Some power system issues require near-immediate service provision to be addressed, whereas others might be resolved over the course of hours, days, or even seasons. The duration of an energy storage device often determines which services it can provide.

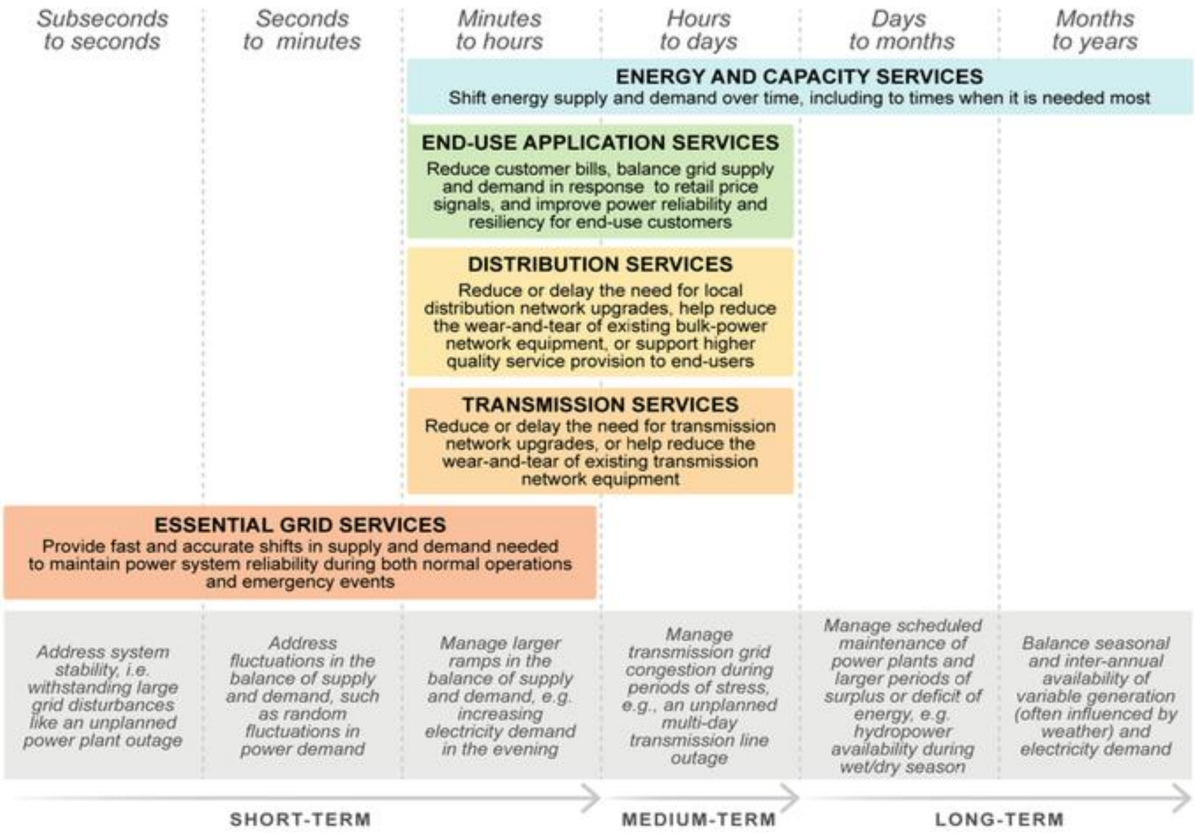


Figure 6-3 Services Provided by Energy Storage

As shown in above figure, different storage durations and technology options are used to serve the needs. As far as storage duration is concerned, from power system operation perspective, the energy storage technologies can be categorized as follows:

- Short-duration storage (between 1 and <4 hours) can play multiple support roles on the grid, offering value-stacking opportunities in the electricity market. Short-duration storage can be used for applications discussed earlier, such as network support, time shifting energy and helping avoid or defer T&D investment;
- Medium-duration (from 4 to <12 hours) storage systems can play an important role providing major grids with the flexibility to manage any imbalances between supply and demand, as well as supporting grid capacity. Medium-duration storage systems can be used for applications such as network support, time shifting energy and helping avoid or defer T&D investment;
- Long intraday (from >12 to 24 hours) storage is used for network support to help stabilize day-to-day variation in electricity supply and the time shifting of energy to manage differences between peak VRE generation and peak energy use times each day;

- Multiday (from >24 to 100 hours) and seasonal (>100 hours) storage can play a role managing significant and long-term imbalances between electricity supply and demand, discussed earlier as seasonal storage.

6.1.3 Applications of energy storage

As for the location on the power grid, and capacity of energy storage facilities, energy storage projects are generally categorized into:

- Grid-scale or utility-scale storage: these need a substantial storage capacity as dispatchable generation leaves the grid required. It needs to be of varying durations to be able to deal with changes in supply and demand in the system. The include hydrogen storage system, pumped storage plant, and BESS, installed mostly in transmission grid, including some long-term energy storage systems;
- Distributed storage: storage systems such as BESS or flywheels and others directly connected on distribution systems, which include household, community, industrial and commercial instillations. Typically have several hours of storage intended for daily cycling;
- Mico-grid and off-grid: off-grid application currently are mostly short-duration storage associated with hybrid generation in remote areas. The use of storage in a microgrid with renewables can reduce a community or industrial park's reliance on fossil fuels and help achieve high levels of decarbonization.

Furthermore, according to their mobility, the storage units sometimes are also divided into stationary and mobile storage systems. Mobile storage system are the transportable battery storage modules located on train cars or trucks. As an innovative solution, they can provide the same utility services as stationary storage does, but with more flexibility to suits for needs in different locations across the urban areas. The versatility and growing cost-effectiveness of utility-scale BESS are positioning them as a cornerstone technology for the future of resilient and sustainable power systems.

6.2 Planning and operation of storage system

6.2.1 Considerations of energy storage deployment

Energy storage, particularly, BESS, can help provide various grid services due to its fast time-response and diverse power and energy density in different technologies. In urban power system, the radial distribution network has a different risk structure compared to the transmission system. As a result, optimal placement, and optimal sizing of distributed energy resources, including energy storage, has becoming an emerging significant aspect for the distribution system operator (DSO) in planning the distribution network, especially along with the specific issues, such as power exchange between grid and distributed energy resources owners, high initial capital investment costs associated with distributed energy resources, and increased bi-directional power flow led by energy storage integration.

In general, the simplified energy planning methods in distribution network used in earlier stage have two drawbacks: i) the production cost simulation does not account for the detailed operation strategy; and ii) probabilistic modelling approaches cannot fully address the uncertainties of multiple distributed energy resources and loads. To address these two issues, the advanced planning methods have been used, considering the increased role of energy storage, which are enabled by the development of two-stage stochastic optimization techniques, accurate uncertainty modelling techniques and others. The planning of energy storage installation on the distribution system is usually formulated as an optimization process, and solved by using one or more techniques, including analytical approach, conventional optimization techniques, and meta-heuristic approach.[140]

(1) Energy storage to support urban energy system

The unique technical characteristics of BESS offer a range of supports to distribution network operators in cities, with proper control and coordination mechanisms, to improve grid reliability and resilience, as mentioned above. At the distribution level, the installation of energy storage close to the load centers helps reduce the stress of network components, enhance the continuity of supply for the critical loads and areas during emergency islanding. The deployment of BESS needs to consider the characteristics of BESS to achieve expected results. Table 6-1 lists some typical services and applications of energy storage provided along the resilience type on urban power system.

Table 6-1 Applications of Energy Storage for Resilience Enhancement

Resilience	Service areas	Technical applications
Long-term	Economic efficiency	• Renewable energy curtailment prevention • Loss reduction • Unit commitment
	Frequency restoration reserve (FRR)	• Frequency containment reserve (FCR) • Automatic FRR • Manual FRR
	Power balancing service	• Load following, load peak shaving, load valley filling • Generation/demand balance
Short-term	fault-initiated islanding FII)	• Provide backup power for critical, vulnerable loads, areas during a loss of a main supply
	Frequence regulation	• Support the system operator to control the frequency in a short period
	Voltage support	• Provide voltage support by modulating active and reactive power

140 V. B. Venkateswaran, D. K. Saini, and M. Sharma. 2020. "Environmental constrained optimal hybrid energy storage system planning fo r an Indian distribution network," IEEE Access, vol. 8, pp. 97793–97808, 2020, doi:10.1109/ACCESS.2020.2997338.

Small-signal stability	• Stabilize the power system in response to small perturbations (e.g., inter-area oscillations)
Renewable energy capacity ramp rate	• Smooth the power generation from intermittent renewable energy (i.e., ramp rate control)
Grid-forming	• provide artificial inertia and perform frequency regulation[141]

Energy storage facilitates the intermittent renewable electricity generation and secure revenue of the generators. Energy storage systems could increase the resilience of the grid and provide the black-start capability that is necessary to restore a system to normal operation after a disruptive event. The blackout in Spain on 28 April 2025 exposed vulnerabilities in the power grid and highlighted the need for energy storage. Spain's grid struggles to integrate growing renewable energy without disruption due to a lack of flexible storage options. The blackout underscores the critical role of energy storage systems in building resilient and sustainable power networks.

On the other hand, the increasing penetration of renewables with power electronic interfaces into the generation, transmission, and distribution areas has great impacts, which exposes new technical challenges and risks on existing urban power grid control, operation, and stability. More sophisticated coordination, energy, and information management are required. Further storage technology advancement, using advance planning method, and development of innovative control strategies for energy storage system become important to support resilience enhancement of the next generation urban power system.

(2) Characteristics of energy storage and its applications

There are many considerations to make when deciding on how to plan and deploy energy storage system, including technical configurations of the storage solutions, and level of deployment (generation, transmission, distribution and end-use), technical performance and costs of the system as opposed to other grid solutions[142,143]. Table 6-2 lists some main system characteristics of potential roles for energy storage.

Table 6-2 Key System Characteristics regarding Energy Storage Application

[141] It has been noticed that in the end of April 2025, the German regulator published a rule on the market based procurement of inertia in Germany. German TSOs will start to pay BESS for inertia services, starting 2026.

[142] Green the Grid. 2022. Energy storage decision guidebook. https://greeningthegrid.org/energy-storage-toolkit/energy-storage-decision-guidebook/power-system-characteristics#_ftnref1.

[143] Rose, Amy, Claire Wayner, Sam Koebrich, David Palchak, and Mohit Joshi. 2020. “Policy and Regulatory Environment for Utility-Scale Energy Storage.” NREL/TP-6A20-78101, 1756708, MainId:32010. https://doi.org/10.2172/1756708.

Characteristics	Potential role for BESS
Rapid growth in peak electricity demand and ramping requirements	• While the shape and duration of peak demand periods influences its efficacy, energy storage can be evaluated as an alternative to conventional flexibility and peaking power resources such as gas-fired combustion turbines.
Spiking power prices	• Periods of high energy production prices indicates insufficient power system flexibility to meet demand. Energy storage can be utilized to meet demand during high-priced periods with previously stored energy, a function often referred to as arbitrage.
Renewable energy curtailment	• High levels of variable renewable energy curtailment can be caused by an insufficient ability to back down conventional generators or transmit electricity during periods of high availability and high renewable energy yields. Energy storage can be charged with this excess energy in the system to meet demand at a later time, reducing curtailment.
Local and/or regional power disruptions	• Disruptions to electricity supply can be indicative of technical and/or operational issues that can potentially be alleviated with energy storage. Energy storage devices can be used to maintain reliable power supply during system disturbances (i.e., transmission voltage issues and/or generator outages) as well as during extreme weather events.
High targets for renewable electricity in the system, such as solar PV	• Power sector transformation toward low-carbon and high renewable energy power systems in cities, particularly with high shares of solar PV generation, can necessitate a transition to highly flexible and nimble system operations. Energy storage is one tool in the toolbox for system operators as they manage increasing variable and uncertain electricity supply from variable renewables, which is particular the case of solar PV.

(3) Value stack and deployment of BESS

In the assessment for the deployment of a commercial project, value stack refers to a framework for understanding and organizing the diverse ways a product, service, or organization adds value to its customers. It encompasses both the core offering and also supplementary elements such as integrations that enhance the overall experience of a system. It's normally a layered approach to value creation, moving beyond the primary function to address broader customer needs and goals. In terms of BESS project, value stacking approach can be used to help improve overall energy storage utilization and the economics of energy storage projects by maximizing value for providing a range of services, rather than just a narrow subset[144], so to make the project technically and financially attractive.

The framework of value stacking approach of BESS project is illustrated in Figure 6-4. It should be noted that the higher utilization of from value stacking might lead to faster degradation in energy storage

[144] Behnam Mohammadi-Ivatloo, et. al. 2021. Energy Storage in Energy Markets: Uncertainties, Modelling, Analysis and Optimization. Aca demic Press (Elsevier).

systems, as they are charged and dispatched more often than if they only arranged to provide a narrow set of services. It is also to be noted that despite the cost-benefits of value stacking, it is also important to prioritize critical reliability services and consider technical constraints when evaluating and designing the appropriate energy storage system, therefore a system optimizing approach is needed for the deployment of BESS.

In general, the optimal value stack for a BESS project is highly dependent on factors such as geographic location and specific market condition and rule as different electricity markets have varying regulations, tariffs, available ancillary service markets, and types of application, i.e. whether the BESS is connected directly to the grid or "behind-the-meter". The characteristics and performance of battery, such as discharge duration, power rating, and response time needed to be examined, as well as integration with other assets, especially when co-located with renewable electricity generation.

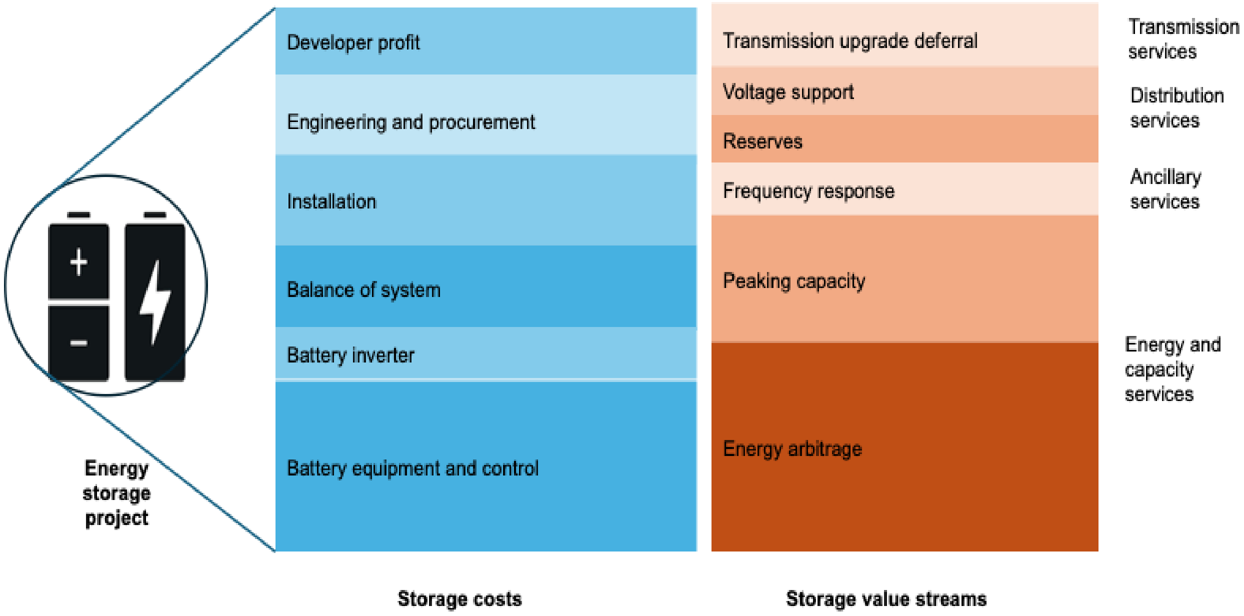


Figure 6-4 Illustration of Value Stack of BESS Project

The deployment of energy storage involves a cycle of a few key components, once the role and need for the energy storage are fully understood for a specific network or end-use application, stakeholders assess deployment considerations that may influence technology selection and deployment efforts. As stated previously, these considerations are highly site specific, varying even among similar end-use applications and sectors, and must consider the entire energy system for a given location. The main process of energy storage project development is illustrated in Figure 6-5.

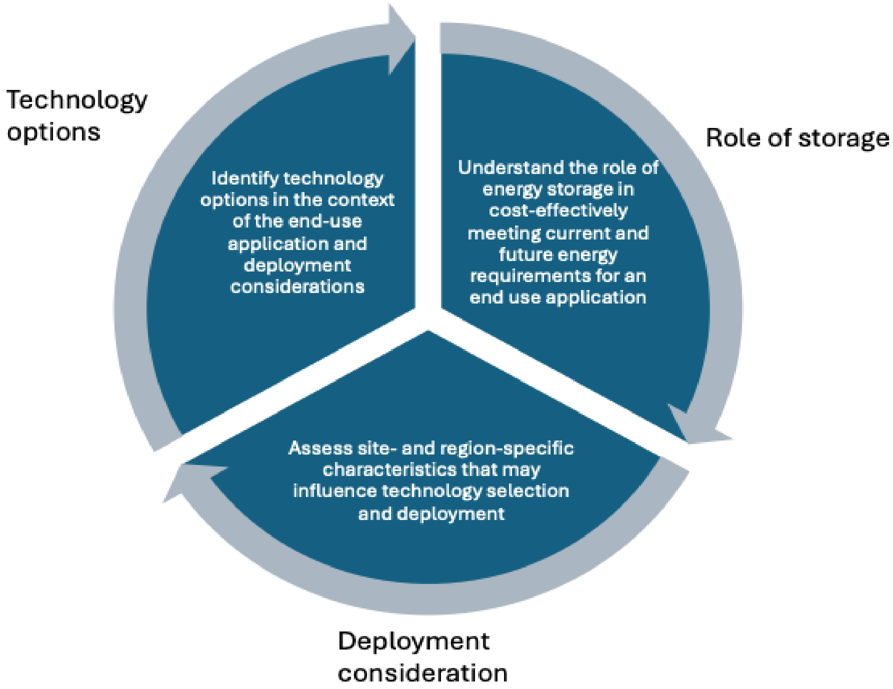


Figure 6-5 Illustration of the Processes of Storage Project Deployment

A main consideration for grid-connected BESS project development, particularly in urban areas, is robust grid integration. This encompasses a range of technical and regulatory requirements essential for the seamless and stable operation of BESS within the existing electricity network. Key technical aspects include ensuring the BESS's power conversion system (PCS) meets stringent grid codes and interconnection standards (e.g., IEEE 1547 in the US, or specific regional requirements in Australia) for voltage, frequency, reactive power control, and fault ride-through capabilities. Delays in grid connection studies and approvals can be consequential, especially in areas with limited grid capacity or outdated grid infrastructure.[145]

Developers must also consider the optimal sizing and location of BESS within the grid to maximize its benefits, avoid congestion, and ensure efficient energy arbitrage, as well as addressing potential export and import constraints, particularly when co-locating with renewable energy assets. Compliance with these complex requirements, often involving coordination with project developer, network owner, and independent system operators, which paramount for successful and impactful BESS deployment.

6.2.2 Planning and deployment of BESS

(1) Strategies and planning

Planning energy storage, including BESS, hinges on several key principles to ensure effective

[145] Electrical Engineering Portal. 2025. Grid Application & Technical Considerations for Battery Energy Storage Systems. [https://electrical-engineering-portal.com/grid-application-technical-considerations-battery-energy-storage-systems]

integration and optimal performance within the energy grid. Firstly, economic viability and value stacking are paramount. Projects must demonstrate a clear return on investment through various revenue streams, such as arbitrage, frequency regulation, capacity services, and avoided grid upgrades.[146] The scale and location of the storage system should be strategically chosen to maximize these benefits, considering factors like electricity market dynamics, grid congestion, and renewable energy penetration levels.[147] Furthermore, technical feasibility and grid compatibility are crucial. This involves selecting appropriate battery technologies based on the desired application (e.g., lithium-ion for fast response, flow batteries for long duration), ensuring seamless integration with existing grid infrastructure through robust power conversion systems and control mechanisms, and adhering to relevant grid codes and safety standards.[148]

System resilience and reliability are fundamental design considerations. Energy storage should enhance grid stability by providing rapid response during faults, smoothing out fluctuations from renewable sources, and offering backup power during outages.[149] Planning must account for factors like battery degradation, thermal management, and redundancy to ensure long-term operational reliability and safety.

i）Planning of energy storage in the US

A cornerstone good practice for the US power network operators in planning energy storage development is the adoption of a comprehensive, multi-faceted approach that strategically integrates identified grid needs, rigorous economic and technical analyses, and proactive stakeholder engagement. This process often initiates with a meticulous assessment of grid deficiencies and opportunities where energy storage can provide optimal value. Operators leverage sophisticated analytical tools, including advanced power flow and dynamic stability simulations, alongside production cost modelling, to pinpoint issues such as peak demand constraints, transmission congestion, voltage fluctuations, and the necessity for ancillary services like frequency regulation and reserves. A critical aspect here is the recognition of storage's role in facilitating higher penetrations of intermittent renewable energy sources, by firming output and managing variability. For instance, the Midcontinent Independent System Operator (MISO) utilizes its annual Transmission Expansion Plan (MTEP) to identify system needs, where energy storage projects are increasingly considered as viable alternatives or complements to traditional infrastructure investments, demonstrating a proactive approach to grid modernization and resilience.[150]

Following the identification of specific grid needs, operators typically engage in a detailed technical and economic evaluation phase. This involves conducting comprehensive benefit-cost analyses that compare energy storage solutions against conventional alternatives, considering a wide array of factors. These factors

146 IRENA. 2020. Electricity Storage Valuation Framework. International Renewable Energy Agency.
147 IEA. 2023. World Energy Outlook 2023. International Energy Agency.
148 Rrompton Greaves. 2022. Grid Integration of Battery Energy Storage Systems: Technical Considerations.
149 EIA. 2024. U.S. Battery Storage Market Trends. The US Energy Information Administration.
150 MISO. 2024. Transmission Expansion Plan (MTEP). Midcontinent Independent System Operator. https://www.misoenergy.org/planning/transmission-expansion-planning/.

include capital expenditures, operational and maintenance costs, potential revenue streams from participation in wholesale energy and ancillary service markets, and the avoided costs of traditional infrastructure upgrades. Furthermore, scenario analysis is a crucial component, where various future conditions, such as different levels of renewable energy penetration, projected load growth rates, and evolving carbon emission policies, are modelled to assess the robustness and long-term viability of storage investments under uncertainty. This rigorous evaluation helps ensure that the selected energy storage projects provide optimal value to the grid and ratepayers. For example, the New York Independent System Operator (NYISO) incorporates detailed market efficiency and reliability analyses into its planning processes, explicitly modelling the economic benefits and grid contributions of energy storage resources in various future scenarios.[151]

Finally, a critical good practice in the US power network operators' energy storage planning is robust stakeholder collaboration and regulatory alignment**.** This involves continuous engagement with a diverse group of stakeholders, including state regulatory commissions, utility companies, energy storage developers, environmental advocacy groups, and local communities. This collaborative approach ensures transparency throughout the planning process, allows for the integration of diverse perspectives, and helps address potential concerns related to siting, interconnection, and market participation. Furthermore, operators work closely with regulatory bodies to develop appropriate market rules, interconnection procedures, and compensation mechanisms that fairly value the services provided by energy storage. This ensures that energy storage resources can effectively integrate into the grid and contribute to its reliable and efficient operation. *The Federal Energy Regulatory Commission (FERC) Order 841*, which mandated that regional transmission organizations and independent system operators revise their tariffs to remove barriers to energy storage participation in wholesale markets, exemplifies the regulatory push that has significantly influenced and guided operators' planning practices across the United States.[152]

ii）Planning energy storage development in Australia

When development of the storage development plan in Australia, technologies is assessed based on the levelized cost of storage estimated, which is used to groups storage technologies by maturity to improve understanding as to which technologies can be used to meet short-term requirements and those that may be more appropriate for long-term needs. In Australia, during the planning process, maturity levels of technology is predominantly assessed using the commercial readiness index (CRI), the technological readiness level (TRL) is used to understand the nuances between technologies that are at a lower CRI level.[153] The definition of CRI and TRL used is given in Table 6-3, and the result of the evaluation is shown in Figure 6-6.

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151 NYISO. 2023. System Planning. New York Independent System Operator. https://www.nyiso.com/system-planning.

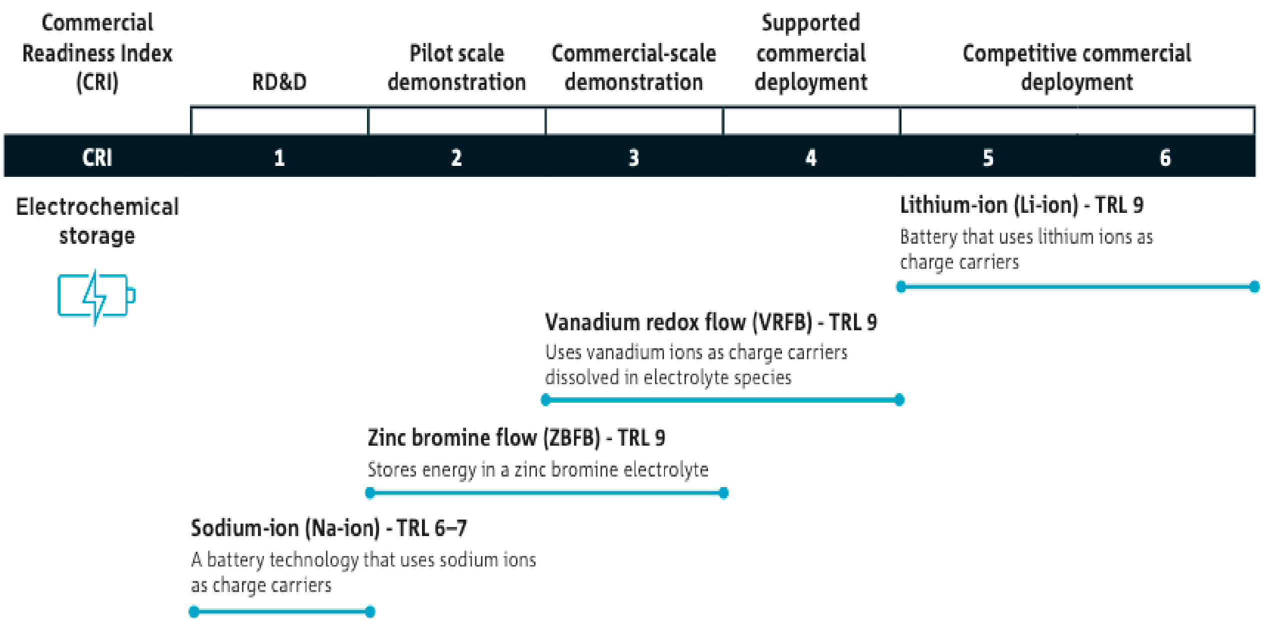
152 FERC. 2018. Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Opera tors (Order No. 841). Federal Energy Regulatory Commission. https://www.ferc.gov/news-events/news/ferc-actions-promote-electric-storag e-participation-markets.

153 CSIRO. 2023. Australia Renewable Energy Storage Roadmap. Canberra.

Table 6-3 Index Used for Assessment of Storage Technology

CRI/TRL Index	Stage of deployment	Definition
CRI 5–6	Competitive commercial deployment	Bankable asset class or market competition driving widespread deployment
CRI 4	Supported commercial deployment	Deployment of multiple commercial applications with government support
CRI 3	Commercial-scale demonstration	Commercial scale up supported by equity finance and government support
CRI 1–2 TRL 7–9	Pilot-scale demonstration	Commercial trial supported by equity and government support, or technically ready but commercially untested
CRI 1 TRL 2–7	RD&D	Research, development and demonstration

Source: CSIRO



Source: CSIRO

Figure 6-6 Assessment of Electrochemical Energy Storage Technology

A multi-layered planning mechanism is used for Australia's energy storage development, with the

Australian Energy Market Operator (AEMO) at its core.[154] AEMO's bi-annual Integrated System Plan **(ISP)** serves as the central roadmap for the National Electricity Market (NEM), outlining the optimal development pathway for generation, storage, and transmission infrastructure out to 2050, crucial for maintaining reliability as coal-fired power stations retire.[155] Starting with the assessment of various storage technologies, the 2024 ISP expects significant increases in required storage capacity, projecting a need for at least 22GW by 2030 and 49GW by 2050, encompassing a mix of batteries, pumped hydro, and coordinated consumer energy resources (CER). More specifically, regarding grid development and operation, some key considerations outlined in the 2024 ISP include:[156]

- In primary energy supply, coal retiring, renewable energy connected with transmission, firmed with storage and backed up by gas-powered generation is the lowest cost way to supply electricity to homes and businesses throughout Australia’s transition to a net-zero economy;
- Low-cost renewable energy will take advantage of the abundant wind, solar and hydro power resources that Australia has to offer;
- Firming storage technologies like pumped hydro, battery energy storage systems, as well as gas-powered generation will play a role of smoothing out the peaks and fill in the gaps from the variable renewable electricity;
- New transmission and modernized distribution networks will connect these new and diverse low-cost sources of generation, including distributed resources to end-use customers in the towns, cities and industry;
- Upgraded power systems will be capable of running, at times, entirely on renewable energy.

At the state level, specific policies and programs further drive BESS development; for instance, New South Wales has its Electricity Infrastructure Roadmap, which includes tenders for long-duration storage projects, while Victoria has set ambitious energy storage targets of at least 2.6 GW by 2030 and 6.3 GW by 2035, supported by initiatives like its Development Facilitation Program to fast-track planning approvals[157]. It is noted that the overarching framework is set by AEMO and state-level policies, actual project approvals often involve navigating local planning schemes.

iii) Energy storage and system operation in Korea

Korea is one of early economies in the APEC region that developed and deployed battery energy storge systems.[158] Overtime, Korea has made significant strides in battery energy storage systems (BESS),

[154] Clean Energy Council. 2024. The future of long duration energy storage. https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf.
[155] AEMO. 2024. 2024 Integrated System Plan (ISP). https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp.
[156] Australian Energy Market Operator (AEMO). 2024. Integrated System Plan for the National Electricity Market. https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp
[157] Energy Victoria. 2025. Energy Storage. https://www.energy.vic.gov.au/__data/assets/pdf_file/0015/721401/victorias-investment-prospectus-storage.pdf.
[158] The World Bank. 2020. Korea’s energy storage system development: the synergy of public pull and private push. The World Bank, Washington D.C.

particularly with the development of large-scale projects for grid stabilization and renewable energy integration. The Korea Electric Power Corporation (KEPCO) has completed a 978MW BESS project in Miryang in 2022, billed as one of Asia's largest for grid stabilization. Korea is also exploring long-duration and large-capacity ESS for its renewable energy targets. In terms of energy security, energy storage has been raised to a higher priority for power system operation and development, and Korea categorizes its power grid infrastructure into three key components, namely, i) power network, including transmission and distribution; ii) energy storage; and iii) interconnections.

Since January 2017, the installation of an energy storage system in Korea has been mandatory for newly built public buildings. Batteries are associated with small-scale solar PV and KEPCO regulates system frequency using its energy storage system. KEPCO has heavily invested in BESS as part of its broader grid modernization and renewable energy integration strategies. Regarding grid modernization in Korea, BESS are used for various purposes, including grid stabilization, peak shaving, and facilitating the integration of renewable energy sources. KEPCO planned to install 1.4GW of new battery energy storage systems.[159]

In the Korean power system, large-scale generation complexes are established in the east and west coastal regions because of economical and available location issues, e.g. to supply the load demand of Seoul metropolitan area which exceeds 50% of the total load demand. However, the required transmission reinforcement is delayed due to public complaints and environmental issues, therefore stability problems occur in the events of large-capacity outgoing transmission lines from the generation complexes. As countermeasures against the stability problems, a combined strategy based on generator tripping and generation curtailment are employed as a short-term operation strategy. This problem, which is to secure transient and frequency stability associated with under-frequency relay (UFR) actions, is expected to sustain until the required transmission reinforcement is expected to accomplish in 2026. From a short-term perspective, the operation purpose of the BESS is to replace a portion of generation curtailment, which has been a precautionary measure in the normal state of the system.

With a large amount of renewable energy generation is injected into lightly loaded system conditions and the corresponding generators are converter-interfaced, the equivalent inertia constant of rotating conventional machines might be critically low because a number of synchronous generators are necessarily out of service. In particular, when a large active power imbalance occurs in a critically low inertia case, the system frequency might change more steeply than it experiences in the current system. In order to suppress this, BESS facilities have been used as one of most important countermeasures by providing a level of system flexibility with their fast responses. A BESS with its fast response characteristic is considered capable to support system stability. Supporting flexibility of the system can be adopted as a long-term application of the BESS, which is among the energy policies in Korea as mentioned previously.

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159 KEPCO, 2021. The 9th Long-term Transmission and Substation Facility Plan, 2021.

(2) Distribution network initiatives

With more renewables coming onto the grid, taking the advantage of energy storage technologies, distribution network operation in many cities have taken actions to modernize distribution network, providing cleaner, reliable and affordable electricity, and enabling customers to access the services. Endeavour Energy, a distribution operator in Australia indicates that with energy storage, the shift from traditional network operation to a flexible modern grid allow customers more control on how they use and receive energy, and these include:[160]

- Ensure greater reliability of the grid;
- Reduce power system costs which translates into lower electricity bills for customers;
- Enable more renewable energy onto the grid to provide customers with more choice;
- Ensure customers can reap the benefits of solar without risking the stability of the network;
- Reduce emissions from the energy system;
- Support the electrification of industries and contribute to building sustainable communities.

Distribution network operators in urban areas are playing an increasingly proactive role in supporting BESS development, moving beyond traditional grid operation to embrace a more active management of distributed energy resources (DERs). Key initiatives include incentivizing behind-the-meter BESS through programs that reward customers for participating in demand response or virtual power plants (VPPs). Furthermore, more distribution network operators are investing in smart grid technologies and Distributed Energy Resource Management Systems (DERMS) to enhance their visibility and control over BESS assets, allowing for optimized charging and discharging based on real-time network conditions and wholesale market signals. By actively engaging with BESS, distribution network more towards a more resilient, flexible, and efficient grid that can seamlessly accommodate the growing penetration of renewable energy.

A prominent good initiative by distribution network operators (DNOs) in the United Stats to support energy storage development is the implementation of targeted incentive programs for customer-sited and grid-sited storage. These programs are designed to accelerate the deployment of energy storage by providing financial incentives to customers who install batteries, often paired with solar PV, and to developers of larger-scale distribution-connected storage projects. The incentives can come in various forms, such as upfront rebates, monthly bill credits for participation in demand response programs, or performance-based payments. For example, Duke Energy in North Carolina offers its PowerPair program, which provides upfront incentives for solar-plus-battery installations and ongoing monthly bill credits for battery owners participating in their EnergyWise® Home or Power Manager® Battery programs. This allows the utility to

[160] Endeavour Energy. 2024. https://www.endeavourenergy.com.au.

dispatch these batteries during peak demand periods, reducing strain on the grid and potentially deferring costly infrastructure upgrades.[161] Such programs not only encourage customer adoption but also provide the DNO with a valuable distributed resource for grid management.

Another practice is the development and utilization of Hosting Capacity Analyses (HCAs) and Integrated Distribution System Planning (IDSP). DNOs are increasingly using HCAs to identify locations on their distribution feeders that can accommodate new distributed energy resources (DERs), including energy storage, without requiring significant upgrades or causing reliability issues. This provides transparency to developers and customers, indicating where storage projects are most beneficial and can be interconnected more easily and cost-effectively. IDSP, building upon HCAs, takes a holistic view of distribution system planning, integrating DERs as viable alternatives to traditional solutions (e.g., wires and poles). This involves evaluating the full range of benefits that energy storage can provide at the distribution level, such as voltage support, feeder relief, peak shaving, and improving grid resilience. Lawrence Berkeley National Laboratory highlights the importance of accurately valuing all potential solutions, including DERs, to optimize distribution system costs.[162]

Case 1：Network operators' efforts in New York City

In New York State, with its aggressive climate goals, energy storage plays an integral role in the transition to a clean energy future. The state's Climate Leadership and Community Protection Act (CLCPA) calls for 100% clean electricity by 2040, 3GW of storage by 2030, 6GW of solar by 2025, and 9GW of offshore wind by 2035.

Con Edison, the energy company that serves New York City and Westchester County, N.Y., has been supporting the state's climate goals and is committed to leading the clean energy transition.[163] For Con Edison, energy storage is among keys. To meet the challenges of the CLCPA, Con Edison identified 2 projects that would expand the amount of storage on its distribution network. The company deployed a 100MW/400MWh, transmission-connected battery project at the site of a former fossil fuel plant in Astoria, Queens in 2022. The project is among world's larger battery storage projects then in an urban setting, and the largest so far in New York State. Con Edison has been also enabling distribution-connected energy storage on several fronts, including pairing the systems with other distributed energy resources (DER) and critical loads. The goal for these projects is to increase the reliability and the resilience of the local network while proving a positive business case. Over time, the objective is to demonstrate that storage systems can be standard equipment at substations to enhance local system reliability, such as peak shaving, Volt/VAR optimizations, renewable energy integration, and auxiliary services.

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[161] Duke Energy. 2025. Solar + Battery Incentives. Retrieved from https://www.duke-energy.com/home/products/powerpair.

[162] Lawrence Berkeley National Laboratory (LBNL). 2025. Integrated Distribution System Planning. Retrieved from https://emp.lbl.gov/projects/integrated-distribution-system-planning

[163] Con Edison. 2025. Our Energy Future. https://www.coned.com/en/our-energy-future/our-energy-vision/our-energy-future-commitment.

Energy storage can provide additional value for utilities and their customers by participating in wholesale market services and producing revenues. For instance, as shown in Figure 6-7, Con Edison installed a 2-MW/11-MWh storage system in Ozone Park, Queens to help meet peak load in a distribution network. It also developed a 7.5MW/30MWh storage system at its Fox Hills substation on Staten Island.

Source: Con Edison

Figure 6-7 Con Edison's 2MW/11MWh Storage System in Ozone Park

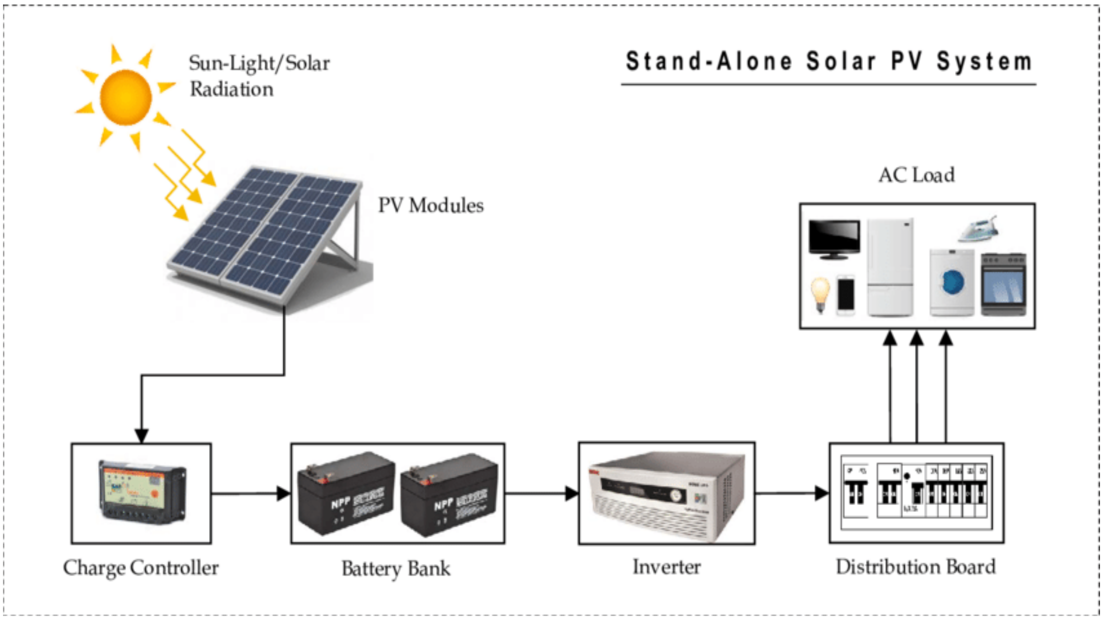
The company has been seeking to demonstrate that it can manage emerging duck curves due to increased PV, develop restricted sites in constrained territory, and potentially use the ESS for market participation. In an innovative demonstration project, Con Edison placed 1MW/1MWh systems on customer properties on the North Shore of Staten Island and on City Island in the Bronx. This project empowers Con Edison to select sites in areas where its electric-delivery system could use some relief at peak times. The customers receive lease payments for their space, Con Edison has the right to dispatch the batteries as needed, and the developer bids services from the batteries into the wholesale market. These systems provide peak load shaving, voltage support and frequency regulation.

As another example, Con Edison enabled energy storage at a site in Brooklyn and trying to lower the interconnection hurdles by providing the land, along with electrical infrastructure, and offsetting the cost of interconnection. The site also has EV quick-charging stations to provide significant operational value, grid benefits, and multiple value streams. In addition, the company has been fostering higher penetration of DERs through the release of hosting capacity maps and the Non-Wires Solution (NWS) programs, allowing third parties to develop projects in zones identified with load constraints.

Case 2: Stand-along power system programs in Melbourne

In Australia, CitiPower and Powercor are two of the five electricity distributors in Victoria, supplying customers with power through an integrated network of poles and wires to customers across more than half of Victoria's geographical area across the western suburbs of Melbourne, central and western Victoria, Melbourne's CBD and inner suburbs. The distribution networks include built-up medium to high density urban areas as well regional, rural, and remote locations where density of customers is low and can include isolated or remote customers whose property is supplied by extended lines.

An innovative product is developed as an off-the-grid electricity system that typically includes the construction of a solar array and battery energy storage system with a backup energy generator. A stand-along power system (SAPS) provides individual property owners, particularly those at the end of line or in difficult to access terrain, with greater reliability of their energy supply and remove their dependency on the standard network of poles and wires.



Source: Citi Power

Figure 6-8 Configure of a Stand-along Power System

SAPS works in the following ways: i) solar panels generate electricity during the day; ii)Solar energy then powers the customer's property, with excess energy stored in a battery; iii) The battery provides power at night, when the sun isn't shining, or to help regulate peak demand; and iv) A diesel generator might provide backup power for extended periods of low to no solar generation. SAPS may be a suitable solution for customers who are serviced by end-of-line network connections; positioned in a challenging geography vulnerable to unplanned outages driven by severe weather events; located within an area of high bushfire risk; or in remote locations. For eligible customers, the network Citi Power is responsible to install, maintain and operate this system at no extra cost.[164]

With sections of the distribution networks reaching their end of service, a Stand-alone Power System (SAPS) is an innovative and cost-effective alternative to a standard network connection, improving the ongoing reliability, safety and affordability of electricity supply for regional and remote customers. Some key feature of SAS include:

- modular and adaptable to your needs: SAPS are modular and adaptable, precisely tailored to your individual energy needs and your environment;
- cost-effective: switching to a SAPS incurs no additional cost, allowing customers to continue paying bills to the retailer of choice, while improving network efficiency and operating costs for all customers;
- renewable and environmentally sustainable: embracing renewable energy, SAPS reduce carbon emissions by relying on solar energy and battery storage. Backup generators ensure reliability during extended periods of adverse weather;
- comprehensive support: disconnected from the network doesn't mean you're on their own. The network company manages the SAPS. Regulated SAPS give customers the continuous support of monitoring, regular maintenance, and swift repairs if needed.

6.2.3 Operation of grid connected BESS

Utility-scale BESS are playing an important role in modern power systems in cities by offering a diverse range of applications that enhance grid stability, reliability, and efficiency. One application is frequency regulation, where BESS can rapidly inject or absorb power to maintain the grid's operational frequency within tight limits, crucial for preventing blackouts and ensuring the stable operation of interconnected generators.[165] Furthermore, more often now, BESS facilitates the integration of variable renewable energy sources like solar PV by smoothing out their intermittent output and providing firm capacity when needed. This capability helps to reduce curtailment of clean energy and ensures a more consistent and predictable power supply.[166]

Another significant application of BESS lies in providing grid support services such as voltage control and reactive power compensation. BESS can dynamically inject or absorb reactive power to maintain voltage stability, particularly in areas with weak grids or high penetration of distributed renewables.[167] Additionally, large-scale batteries can offer black start capabilities, enabling the restoration of power after a complete

[164] Citi Power. 2025. Standard Along System. https://www.citipower.com.au/network-planning-and-projects/network-innovation/stand-alone-power-systems/
[165] Kundur, P., Balu, N. J., & Lauby, M. G. 1994. Power system stability and control. McGraw-Hill.
[166] IEA. 2020. World Energy Outlook 2020. International Energy Agency.
[167] Machowski, J., Bialek, J. W., & Bumby, J. R. (2020). Power system dynamics: stability and control (3rd ed.). John Wiley & Sons.

system shutdown by providing the initial power needed to start generators[168]. These services are becoming increasingly important as power systems become more complex and decentralized.

Beyond these technical applications, utility-scale BESS offers economic benefits through energy arbitrage and peak shaving. By charging during periods of low electricity prices (often when renewable generation is high) and discharging during peak demand periods when prices are high, BESS can help reduce overall energy costs and improve power system economics.[169] This capability not only benefits utilities and consumers but also creates market opportunities for energy storage business.

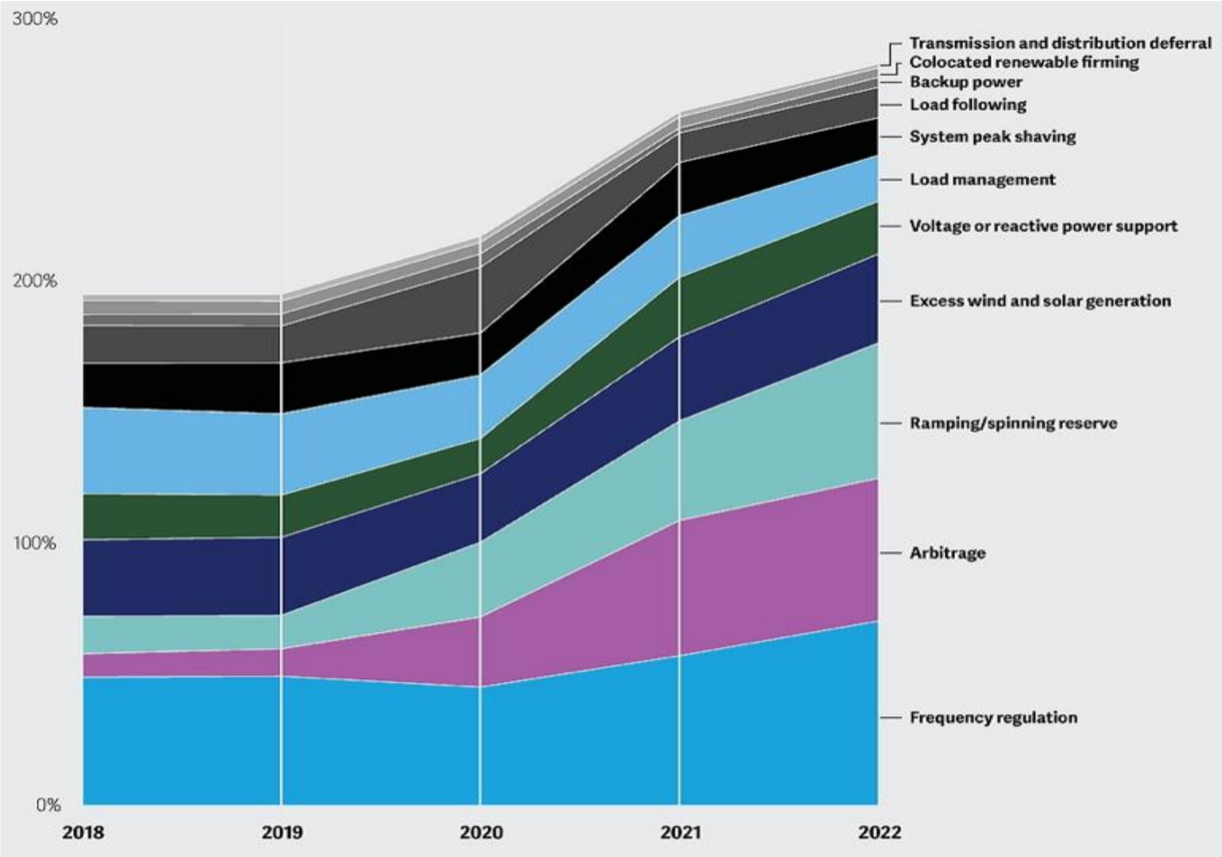
(1) Practices of supporting power grid operation in the United States

To strengthen the grid stability, the United States pays the three interlinked dimensions that guide the role and of energy storage in the power grid, namely: i) renewable energy integration: minimize curtailment, maximize utilization, and optimize the penetration of renewable electricity in the power grid; ii) grid optimization: enhance grid flexibility, reliability, and resilience to accommodate the growing complexity of balancing supply and demand; and iii) electrification and decentralization support: facilitate electrification of end-use sectors and support the integration of distributed energy resources (DER) to create a more decentralized power grid.

Energy storage has increasing provided variety of roles across the electric grid. Base on the data in 2022, while frequency regulation remained the most common energy storage application, 57% of the utility-scale energy storage capacity was used for price arbitrage, up from 17% in 2019 in the United States. Similarly, the capacity used for spinning reserve has also increased multi-fold. As illustrated in Figure 6-9, which shows the changing landscape of energy storage applications as the power sector adapts more market demands and compensation rules for these additional services and explores new use cases.

[168] EPRI. 2019. Black Start with Battery Energy Storage Systems. Electric Power Research Institute.

[169] Ela, E., O'Malley, M., & Hodge, B. M. 2017. The impact of increased price volatility on the economic viability of energy storage. Ap plied Energy. 185, 133-142.



Note: Total is greater than 100% as energy storage systems can provide multiple applications.

Source: Deloitte

Figure 6-9 Roles of BESS in the US Power Systems

Building upon the fundamental roles of BESS in grid operation, several examples in the United States demonstrate their diverse applications. In Texas, the Electric Reliability Council of Texas (ERCOT) benefits significantly from BESS, particularly in managing the critical evening peak demand. For instance, in August 2024, when ERCOT set a new peak demand record, BESS played a crucial role by contributing 3,927MW of output during the evening hours. This highlights their ability to quickly inject power when most needed and mitigate extreme price spikes, helping to balance the grid and reduce the strain on traditional power plants, especially during periods of high electricity consumption.

Beyond energy arbitrage and peak shaving, BESS are increasingly being deployed for crucial ancillary services and to enhance grid resilience. For example, some large-scale BESS projects in California are designed to provide resource adequacy, ensuring there's enough firm capacity to meet demand even as more intermittent renewables come online[170]. Utilities like United Power in Colorado are strategically placing battery arrays across their service territory to balance local load and integrate distributed renewable resources, totaling approximately 78 MW/323MWh. These systems can provide rapid frequency regulation to maintain

[170] California ISO. 2025. Energy Storage. https://www.caiso.com/generation-transmission/generation/storage.

grid stability and can also act as black start resources, meaning they can help restore power to the grid after a widespread outage without relying on external power. This multi-functional capability makes BESS a vital tool for ensuring a reliable and adaptable grid in the face of evolving energy demands and climate challenges.

(2) Operation of BESS project in Australia

Australian Renewable Integration Study (RIS) recommends maximum distributed solar PV penetration and minimum central electricity generation load shedding as a back stop measure due to the increasing distributed energy sources penetration, electrification and EV uptake.[171] Under all integrated system plan (ISP) scenarios, recommendations include large increases in grid-scale and distributed energy storage to support grid operation and stability. Based on the ARENA and AEMO.[172,173] and the result of a market study, the issues of urban distribution network faced and the functions that energy storage projects played by 2023 to support grid operation in Australia are grouped in Table 6-4.

Table 6-4 BESS Projects Supporting Distribution Network Operation in Australia, 2023

Network operational issues	Number of BESS projects	Description
Low voltage distribution network (LVDN) hosting capacity	12	The amount of distributed renewables such as roof-top solar PV that can be cost effectively and safely connected to the distribution network while remaining in its technical limits is called hosting capacity.
Distribution transformer (DT) overload	3	Distribution transformers which sit between medium voltage and the LVDN is subject to overloading during peak solar and peak demand as consumption increases over time. Overload can be characterized by excess current draw leading to increased heat and significantly reduced lifespans. When DTs are increasingly operating above 150%, life span is significantly decreased and an upgrade to the DT and all associated equipment is required.
Reverse flow	1	Reverse flow in the LVDN is usually characterized by excess distributed renewables solar PV where the net of all 3 phases of a DT is negative current.
Phase balancing	1	Households with PV have a single-phase connection to the grid. Multiple households with PV may connect to the same phase which may result in imbalance of current. Out of balance can affect the hosting capacity of a LVDN and grid stability.
Deferred augmentation	7	Installing a BESS can effectively defer the upgrade until the next price reset or eliminate the requirement thus saving costs compared to upgrading DTs, insulators,

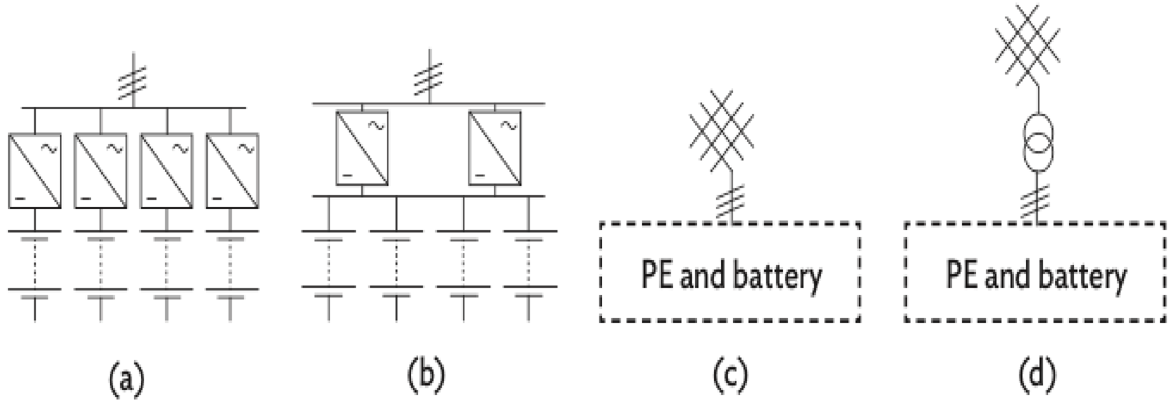
[171] AEMO.2020. Renewable Integration Study: Stage 1 report. Melbourne: AEMO
[172] ARENA. 2025. Battery storage. https://arena.gov.au/knowledge-bank/?technology=battery-storage.
[173] AEMO. 2023 Electricity Statement of Opportunities (ESOO). Annual statement, Melbourne: AEMO. 2023.

Network operational issues	Number of BESS projects	Description
		poles, conductors, power equipment and protection.
Fast frequency support (FFS)	21	Storage can sign up to and operate to provide fast acting injection of power to quickly assist short term frequency transient events. This is usually caused by sudden or unplanned loss of generation or power system outage.
Frequency control ancillary services (FCAS)	28	FCAS service requested by AEMO to keep the national energy market (NEM) frequency within technical specifications. FCAS is a short-term frequency support service.
System integration protection scheme (SIPS)	2	Contract formed between AEMO and a battery firm on behalf of a state to reserve battery capacity for the use of grid stability.
Time shifts peak solar	9	Energy storage systems could be used to increase demand during the day and reduce the severity of the “duck curve” by time shifting the energy.
Microgrid islanding	6	Microgrids islanding allows a LVDN circuit to isolate itself from the main network with the use of a BESS to maintain uninterrupted power. This is usually a protective measure in the case of a network outage, the isolated LVDN circuit can remain operational until the network is restored when the microgrid can reconnect.
Energy arbitrage	24	This is not necessarily a grid operational issue but a market driven mechanism to match supply of electricity generation to demand. When BESS’ perform energy arbitrage, it contributes to the stability of the grid because prices are high when supply is low, and demand is high and prices are low or negative, and when supply is high and demand is low.
Virtual inertia	7	More renewables in the grid result in the inertia of frequency is weakened which can affect the resilience of the grid. BESS’ and other non-synchronous generators such as PV or wind follow synchronous generator frequencies.
Off grid	1	Backup if there is a BESS outage or insufficient PV generation.

Source: ANREA, AEMO, and MarketInsignt

6.3 Grid integration of BESS

Figure 6-10 gives an overview of grid connection topologies for utility-scale BESS, which typically consist of multiple battery packs and inverter units, all adding up to the total system energy and power. Power electronics units dedicated to individual battery packs can be installed (a) as shown in the figure, or the battery packs can be connected in parallel to a common direct-current (DC) bus (b). An example of grid connection to a low-voltage level is given in (c), and connection to higher grid levels via a transformer is (d).[174]



Note：PE - power electronics

Figure 6-10 Illustration of Grid Connections of Battery Energy Storage Systems

Grid integration of BESS involves various processes of connecting and coordinating BESS facilities with the existing electrical power grid infrastructure. This deals with not only the physical interconnection at appropriate voltage levels but also the implementation of advanced control and communication systems to enable the BESS to provide a wide range of grid services. These encompass the deciding optimal sizing, placement, and operational strategies for BESS within the dynamic grid environment, considering factors such as power quality, stability, renewable energy integration, peak shaving, frequency regulation, and arbitrage, all while adhering to relevant grid codes and market regulations.

6.3.1 Challenges for integration of BESS to urban power grid

Standards and codes have a direct impact on the cost of an ESS and its installation, and administrative burdens and time to approval issues affect the ability to deploy the technology and cost. The lack of specifics limits progress until appropriate standards and codes are available; for the outdated standards and codes can be conservatively applied to the technology, affecting the cost of the installation, or limiting its application.[175] In this sense, the US DOE recognizes four key challenges to the widespread deployment of BESS:[176]

- Performance and safety: Grid operators must be confident that ESSs will perform as intended within the larger network. Advanced modeling and simulation tools can facilitate acceptance, particularly if they are compatible with utility software;
- Regulatory environment: ESSs provide divergent functions to their owners and the grid, often

[174] Hesse et al. (2017). Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Ap plications in Modern Power Grids, 2017.

[175] Conover. D. Overview of Development and Deployment of Codes, Standards and Regulations Affecting Energy Storage System Safety i n the the United States," Pacific Northwest National Laboratory.

[176] Transitions. O., Spotlight: Solving Challenges in Energy Storage. The US DOE.

leading to uncertainty as to the applicable regulations for a given project. Regulatory uncertainty poses an investment risk and dissuades adoption;

- Cost-competitive systems: Actual energy storage technology (e.g., the battery) contributes 30%–40% to total system cost; the remainder is attributed to auxiliary technologies, engineering, integration, and other services;
- Industry acceptance: Energy storage investments require broad cooperation among electric utilities, facility and technology owners, investors, project developers, and insurers. Each stakeholder offers a distinct perspective with distinct concerns.

Experience in many economies shows that grid operators and utilities so far have limited experience with storage and face technical challenges integrating storage into existing systems. Grid operators yet have sufficient experience considering planning for the integration and operation of storage, and they typically use models based on traditional resources. Moreover, storage can be more challenging to integrate than other resources because of changes in the system function from charging to discharging to generating electricity.[177] Some other challenges of storage deployment are related to uncertainty about the performance of storage technologies over time and their operating conditions.

6.3.2 Framework for grid integration

Successful integration of BESS into transmission and distribution networks requires a comprehensive understanding of technical aspects such as grid code compliance, power conversion system (PCS) dynamics, state-of-charge optimization, and thermal management strategies to ensure operational efficiency and longevity.

(1) Technical requirements

Voltage and frequency stability are fundamental to grid reliability, and BESS can play a important role in their regulation by providing fast and accurate response to deviations. Some key functions of BESS in voltage and frequency management include:

- Dynamic frequency response: BESS can provide instantaneous frequency regulation by injecting or absorbing active power to counteract sudden frequency fluctuations caused by renewable energy variability or load changes. This helps in maintaining the grid frequency within operational limits;
- Reactive power compensation: Through advanced power electronics, BESS can supply or absorb reactive power to regulate grid voltage, ensuring compliance with permissible voltage limits and

[177] The U.S. GA Office, "Energy Storage: Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," the United States Government Accountability Office, 2018.

improving power factor performance;

- Inertia emulation: In the absence of synchronous generators, BESS can emulate system inertia using fast-acting inverters to provide synthetic inertia, enhancing grid robustness during transient events such as faults or large load changes.

Implementing these capabilities allows BESS to provide essential grid support services, preventing cascading failures and enhancing overall system resilience. In addition, the interface between BESS and the power grid relies on sophisticated power electronic converters, including inverters, rectifiers, and bidirectional converters. These components are responsible for bidirectional power flow control, grid synchronization, harmonic mitigation etc. Furthermore, the Energy Management System (EMS) is a critical component that ensures the optimal operation of BESS by intelligently managing energy dispatch and coordinating grid interactions, and implementing real-time monitoring and control, optimal energy dispatch, ancillary services provisioning and cybersecurity measures.

(2) Regulatory framework for grid integration

The regulatory landscape for Battery Energy Storage Systems (BESS) is a critical factor in their successful integration into power grid. Governments and grid operators play a central role in defining the policies, standards, and compliance requirements that ensure BESS deployment aligns with broader energy transition goals. Effective regulatory frameworks needed to address grid reliability, market participation, and the evolving role of storage in supporting renewable energy penetration. Regulatory frameworks provide a structured set of rules and guidelines for the interconnection of BESS to the grid. These frameworks cover various aspects such as technical standards, grid impact assessments, interconnection agreements, and operational compliance requirements. Key components of regulatory frameworks include:

- Technical codes or standards: regulatory authorities establish grid codes and interconnection standards that define the performance, protection, and operational characteristics BESS must adhere to when connecting to the transmission or distribution network;

- Grid impact assessments: Before integration, BESS projects are subject to grid impact assessment to evaluate their effect on power quality, fault levels, and system reliability and others;

- Interconnection agreements: Legal agreements between BESS operators and grid operators outline responsibilities, operational constraints, and revenue-sharing mechanisms, ensuring that BESS provides reliable services without disrupting grid stability.

Based on the same principles, while the requirements vary, Table 6-5 lists some main requirements for grid integration of BESS projects in the selected APEC economies.

Table 6-5 Grid Integration Requirements in Selected APEC Economies

Economy	Main grid integration requirements for BESS	Description & context
The United States	• FERC Order 841 Compliance: Federal Energy Regulatory Commission (FERC) Order 841 requires regional grid operators (ISOs/RTOs) to remove barriers to electric storage participation in wholesale markets, including streamlined interconnection. • IEEE 1547 standard: widely adopted standard (IEEE 1547-2018) for interconnection and interoperability of distributed energy resources, including BESS, with electric power systems. This covers voltage and frequency ride-through, reactive power capabilities, and communication protocols. • UL Standards: UL 9540 (Energy Storage Systems and Equipment) and UL 9540A (Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems) are crucial for safety and fire suppression. • State-specific interconnection rules: State Public Utility Commissions (PUCs) establish rules, often based on FERC and IEEE guidelines, but with variations.	The US has a mature framework for BESS integration, with federal and state regulations aiming to standardize interconnection procedures and ensure reliable operation. Safety standards are also a high priority.
Australia	• National Electricity Rules (NER): BESS must comply with the NER, specifically Chapter 5 (Network Connection and Access) and Schedule 5.2 (Connection Requirements), covering technical performance standards like reactive power, frequency control, voltage control, and fault ride-through. • Australian Energy Market Operator (AEMO) Requirements: AEMO issues specific guidelines and tests for BESS to ensure they can provide Frequency Control Ancillary Services (FCAS) and other critical grid services. • System strength & inertia: specific requirements for BESS to contribute to or manage impacts on system strength and inertia, particularly in areas with high inverter-based generation. • Model validation: technical modeling and validation of BESS performance are required for grid connection approval.	Australia has a highly evolved grid code that places stringent technical requirements on new grid connections, including BESS, to ensure grid stability in a system with increasing renewable penetration.
Japan	• Grid Codes of TSOs: Compliance with the specific grid codes of the regional Transmission System Operators (TSOs) (e.g., TEPCO, Kansai Electric) covering interconnection standards, voltage and frequency stability, and control capabilities. • Balancing market requirements: BESS must meet the response time and accuracy requirements for participation in Japan's various balancing market products (Primary, Secondary-1, Secondary-2). • Safety standards: adherence to domestic safety regulations for battery installations. • Direct grid connection: sor subsidies, BESS must be directly connected to the grid and capable of market participation.	Japan's grid integration requirements are evolving to support the increased penetration of renewables and market-based operation of BESS, with clear rules for participation in balancing and capacity markets.
Korea	• K-BESS Standard (KPX/KEPCO): compliance with specific standards set by Korea Power Exchange (KPX) and Korea Electric Power Corporation (KEPCO) for BESS connection and operation, particularly for frequency regulation. • Performance requirements: high accuracy and fast response capabilities for ancillary services like frequency regulation.	Korea has a strong focus on utilizing BESS for grid stability and supporting renewable integration, with clear technical guidelines and

Economy	Main grid integration requirements for BESS	Description & context
	• Safety & certification: adherence to the safety standards and certification processes for BESS installations. • Grid reinforcement: the 11th Basic Plan on Electricity Supply and Demand emphasizes enhancing grid capacity to support increased renewable energy deployment, which includes BESS integration.	procurement mechanisms driving their deployment.

It has been noted that developing APEC economies has been making progress regarding technical regulation for grid integration of BESS projects. the Philippines' grid integration requirements are well defined, with a clear grid code and active involvement from NGCP and ERC to ensure BESS contribute effectively to grid stability, especially amidst growing renewable energy. Thailand's BESS integration framework is under development, with a focus on adopting robust technical standards to ensure safe and reliable deployment. Malaysia is in the early stages dealing with large-scale BESS integration, with current requirements being shaped by ongoing projects and the evolving grid code. Indonesia's diverse grid, particularly its numerous islands, necessitates tailored BESS integration requirements to manage grid stability, integrate renewables, and provide reliable power in remote areas.

(3) Grid integration assessment

For grid integration assessment of energy storage, approaches and methods applied, both technical and economic, vary across different economies and network operators, the main aspects of the assessment are listed in Table 6-6. These are normally in line with the codes and standards stipulated in or adopted by the authorities, which are discussed in the next sub-section. The assessments are usually performed by the third-party technical advisors.

Table 6-6 Methods for Grid Integration Assessment

Assessment and method	Applications
Capacity expansion models (CEM)	Create technically sound, least-cost investment plans for the power system to meet demand and reliability constraints over time by creating scenarios of cost-optimal portfolios of the future mix of generation, storage, and transmission capacity expansion. Multiple future scenarios are then used as a baseline for more detailed production cost models (PCM). However, because CEMs examine questions of optimal investment over long periods, they are limited in their ability to characterize the short-term flexibility and reliability attributes of grid solutions.
Production cost models (PCMs)	Simulate the technical and economic operation of the power system, typically for a period of 1 year, and can characterize the flexibility and reliability attributes of various grid solutions with relative accuracy, from timescales of minutes to months. This helps the project developer compare the operational value of various grid solutions, including storage.

Assessment and method	Applications
Power flow models (PFMs)	Used to simulate the physical movement of electricity through the power system during both normal steady-state operations and during periods of system stress. For the purposes of comparing grid solutions, PFMs are an important tool for validating the technical feasibility of portfolios of grid solutions from CEM and PCM analyses. Given the high granularity of PFMs and related tools, they are typically only used to analyze a snapshot (of up to several minutes) of power system operations.
Avoided network infrastructure valuation assessments	Help grid operators compare costs between "non-wires alternative" grid solutions, like storage, and traditional network infrastructure investments in locations where existing network capacity is not sufficient to meet expected electricity demand. This approach can be used to create a cost savings metric associated with each NWA that can help inform investment decisions.
Project-level techno-economic assessments	Used to design individual grid solutions and characterize their expected technical operation and financial performance, most used by project developers. Policymakers and regulators also use these tools to evaluate projects and benchmark contract prices for proposals received from utilities and/or the private sector, and to design new forms of DER compensation to understand the customer economics implications of new schemes.
End-use adoption models	The assessment provides an estimate of the levels of distributed energy resources investment that are likely to occur in each region and time. Such models can also relate important information on how certain factors like cost reductions, compensation mechanisms and other policy interventions are likely to impact when and where BTM energy storage will be adopted.

6.3.3 Code and standards for grid integration of BESS

(1) Technical requirements

Codes and standards help to drive down soft costs related to planning, purchase, financing, deployment, commissioning, operations, and de-commissioning. Well-established grid codes help improve the grid overall reliability and resilience. In general, there are five categories of codes that should be noted, including the definition of documents, grid codes or interconnection requirements, certification and compliance standards, and performance tests. These codes impact the core requirements for grid performance, such as voltage and frequency control, protection to ensure safety, preventing cascading events and damage to equipment, system stability, and continuity of service.[178]

The technical requirements dedicated to BESS control in cooperation with the power system requirements seek to support the power system operation and its reliability. One way of ensuring continuous and sufficient access to electricity is to store energy when it is in surplus and feed it into the grid when there is an extra need for electricity. BESS should be able to:

[178] T. Sikorski, M. Jasin´ ski, E. Ropuszyn´ ska-Surma, et al., Determinants of Energy Cooperatives' Development in Rural Areas Evidence from Poland. Energies, vol. 14, no. 2, p. 319, 2021.

- Maximize energy generation from intermittent renewable energy sources;
- Maintain power quality, frequency and voltage in times of high demand for electricity;
- Absorb excess power generated locally for example from a rooftop solar panel. Storage is an important element in microgrids where it allows for better planning of local consumption.

Despite relatively less impact on power system at low penetration levels, issues regarding transmission line loading, grid voltage, and system frequency can still occur as the penetration level increases during both normal and disturbed operations, therefore, constant revisions of the standards and codes, and lessons learned on the following key characteristics including active power control, reactive power supply and voltage support, power quality, frequency and voltage levels, short-circuit current contribution, fault-ride-through capability and ride-through capability etc.

(2) Codes and standards

The regulatory landscape governing grid interconnections presents challenges related to compliance with technical standards such as IEEE 1547, IEC 62933, and local grid connection codes, which define parameters for safe and reliable operation. Grid codes define the operational parameters and performance obligations that BESS installations must meet to ensure safe, reliable, and efficient grid integration. Compliance with these codes is essential to prevent adverse grid impacts, facilitate interoperability, and maintain power quality. Internationally, main international codes and standards applicable to BESS integration include:

- IEEE 1547: Establishes interconnection and interoperability standards for distributed resources, addressing voltage regulation, response to abnormal grid conditions, and protection schemes for BESS systems;
- IEC 62933 Series: Provides a comprehensive framework for the design, integration, and testing of BESS, ensuring compliance with international standards for safety, performance, and efficiency.

Adhering to these standards ensures that BESS units can support grid resilience, respond to disturbances, and operate harmoniously with other grid assets. The relevant codes and standards applied in Australia; Singapore; and the United States are discussed below.

Australia

In Australia, energy storage systems are rapidly being deployed in the region within an ever-changing landscape of market entrants and industry players. The integration issues primarily deal with: i) grid integrated; and ii) stand-alone storage systems installed at the small-scale commercial and residential level.

The Council of Australian Governments (COAG) identified a need for energy storage standards to cover the increasingly diverse range of energy storage technologies, and thus sought to work with Standards Australia to develop the Roadmap for Energy Storage Standards. The roadmap identifies standards needed to facilitate the safe installation, connection, maintenance, operation and disposal of batteries. The municipal energy systems follow the relevant standards.

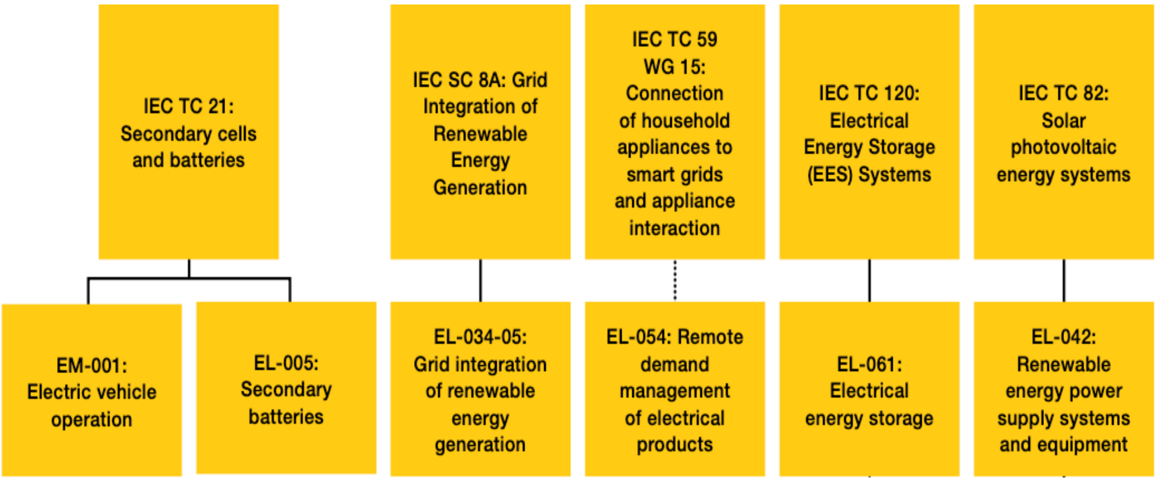
Outlining the need for technical standards covering installation, product safety, and product performance, Standard Australia developed 'Roadmap for Energy Storage Standards' in 2017, which acts as a guidance helping stakeholders navigate the future for electrical energy storage standards.[179] The focuses of which is grid integrated, and stand-alone storage systems installed at the small-scale commercial and residential level. Some of the outcomes of this Roadmap are also relevant to grid-scale storage installations. In general, the following areas require standards to support the rollout of energy storage in Australia: i) installation including labelling; ii) product safety including marking; iii) performance measurement; and iv) Energy storage system operation i.e. operational control of the system. The priority documents regarding the development of energy storage include Installation including labelling: AS/NZS 5139; Product safety including marking; and Performance measurement of products.

Regarding grid integration and operation of BESS, main domestic standards, such as AS/NZS 5139:2019 (Electrical installations – Safety of battery systems for use with power conversion equipment) and AS/NZS 4777 series (Grid connection of energy systems via inverters), provide crucial guidelines for safety, installation, and inverter requirements for both residential and utility-scale BESS. These standards address aspects like system capacity, fire safety, location restrictions, demand response capabilities, and the performance of grid-forming inverters, ensuring grid stability and reliable operation as BESS increasingly contribute to the National Electricity Market (NEM).

International alignment and engagement have been considered pivotal on relevant issues, and international participation has been identified as critical, given Australia is deemed as a net importer of energy storage products. Influencing international standards through participation in their development has also been regarded as an important approach[180]. Figure 6-11 shows the structure of the engagement with IEC.

[179] Standards Australia. 2017. Release of Roadmap for Energy Storage Standards. https://www.standards.org.au/news/release-of-roadmap-for-energy-storage-standards

[180] Standards Australia. https://www.standards.org.au/news/release-of-roadmap-for-energy-storage-standards.



Source: Standards Australia

Figure 6-11 Structure of Energy Storage Engagement for Standard Development

In general, regarding grid integration and operation of BESS, Australia's participation in the current international efforts has been activities, specifically with IEC TC 120 (Electrical Energy Storage Systems) and IEC SC 8A (Grid integration and renewable energy integration), and the priorities areas include: Participation on IEC SC 8A to ensure effective management of renewable energy sources and their connection to the grid; and Demand response management (AS/NZS 4755 series) was identified as mid-to-high priority for certain stakeholders, including networks, retailers, and battery manufacturers.

The United States

In the United States, there are requirements to enhance the safe development of energy storage systems by identifying codes that require updating and facilitation of greater conformity in codes across different types and usages of energy storage technologies. For energy storage systems interconnected at the distribution level, the IEEE 1547TM family of standards applies, as listed in Table 6-7 below. The base standard of this family is IEEE Std 1547- 2018TM, which lays out the interconnection requirements. IEEE Std 1547.1-2020TM gives the requirements for the tests needed to verify compliance with IEEE Std 1547-2018TM. Another 1547-family standard that is particularly relevant to energy storage is IEEE Std P1547.9, which, as of this writing, is nearing the end of the balloting process and is expected to be published in 2022. IEEE Std P1547.9 is a guide for the application of IEEE Std 1547-2018TM and IEEE Std 1547.1-2020TM to distribution-connected energy storage systems.

For energy storage systems interconnected at the transmission or sub-transmission levels via a power electronic (inverter) interface, the IEEE 2800TM family of interconnection standards apply. The base standard of this family is IEEE Std 2800-2022, which defines the interconnection requirements for all inverter-based resources connected at the transmission and sub-transmission levels. As of this writing, IEEE Std 2800-2022TM has been approved for publication in 2022. Standards P2800.1 and P2800.2 will then spell out the testing requirements to demonstrate compliance with P2800.

Table 6-7 Standards for Grid Integration of Storage System in the United States

Standards Development Organizations	Standard	Title	ESS Relevance
IEEE	IEEE 2800-2020	Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Systems	Standard sets interconnection, performance, capability, and interoperability requirements for all inverter-interfaced systems (including ESS) connected to transmission and sub-transmission systems.
IEEE	IEEE 1547-2018	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces	Standard for interconnection of DER with EPS. DER, as defined in IEEE 1547, includes ESSs capable of exchanging real power (kilowatts, megawatts) with the local distribution utility grid. IEEE 1547 also defines the performance requirements that are the basis for UL 1741 listing.
IEEE	IEEE 1547.2-2008	Guide for IEEE Standard 1547-IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems	Provides technical background and application details to support applying the basic requirements of IEEE [Institute of Electrical and Electronics Engineers] 1547-2003. This is done by characterizing various forms of distributed resource (DR) technologies and their associated interconnection issues. The IEEE 1547 series of standards is cited in the Federal Energy Policy Act of 2005.
IEEE	IEEE 1547.3-2022	Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems	Facilitates the interoperability of DR and helps DR project stakeholders implement monitoring, information exchange, and control to support the technical and business operations of DR and transactions among the stakeholders. Document being updated to provide guidelines for Cybersecurity of Distributed Energy Resources (DER) interconnection with Electric Power Systems (EPS).
IEEE	IEEE 1547.9-2022	Guide for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems	Guide provides information on and examples of how to apply IEEE Standard 1547 with associated EPS interfaces that result in interconnection of energy storage DER, including those connected to EPS capable of bidirectional real power exchange with the EPS.

The National Electrical Code (NEC), or NFPA 70, is a regionally adoptable standard for the safe installation of electrical wiring and equipment in the United States

Singapore

In Singapore, planning and performance assessment of electrical energy storage system is stipulated in the Technical Reference TR 77-1:2020 (2023),[181] which is applicable to BEES systems designed for grid-connected indoor or outdoor installation and operation. The TR considers the following key areas of an BEES system: necessary functions and capabilities of EES systems; test items and performance assessment methods for EES systems; requirements for monitoring and acquisition of EES system operating parameters; exchange of system information and control capabilities required.

Stakeholders of this document comprise personnel involved with EES systems, which includes planners of electric power systems and EES systems, owners of EES system, operators of electric power systems and EES systems, constructors, suppliers of EES system and its equipment and aggregators. For the safety consideration of grid-integrated EES system, Singapore follows the Technical Reference 77-2:2020, which specifies safety considerations, including hazards identification, risk assessment, risk mitigation, applicable to EES systems integrated with the electrical grid. This TA is compatible with IEC/TS 62933-5-1:2017. Overall, the TR provides criteria to foster the safe application and use of electric energy storage systems of any type or size intended for grid-integrated applications.

Japan

Japan's technical standards for BESS grid integration are also designed to ensure safety, reliability, and efficient operation within its grid, which operates at both 50Hz and 60Hz depending on the region. The Ministry of Economy, Trade and Industry (METI) oversees the Electrical Appliances and Materials Safety Act, which dictates technical requirements for batteries and related equipment. Japan has largely adopted IEC standards, such as IEC 62133-2 (2017) for portable secondary lithium-ion cells and batteries, replacing older local standards to enhance safety. For stationary BESS, specific safety designs, measures to prevent and respond to accidents (e.g., fire or smoke), and public safety measures are increasingly emphasized in project business plans. Furthermore, the Japan Electrical Safety & Environment Technology Laboratories (JET) certification plays a critical role in ensuring that BESS can safely and reliably connect to the grid, covering tests for voltage and frequency regulation, and anti-islanding protection. Japan's grid codes also incorporate technical requirements for BESS participation in various balancing products within its electricity markets, demanding specific response times and stability contributions from these systems.

6.4 Distributed energy storage systems

In urban power system, the term *distributed energy storage* is typically defined to include all storage systems connected to the power distribution system. This includes systems connected on the primary distribution lines owned by the electric power companies as well as those connected to customer owned

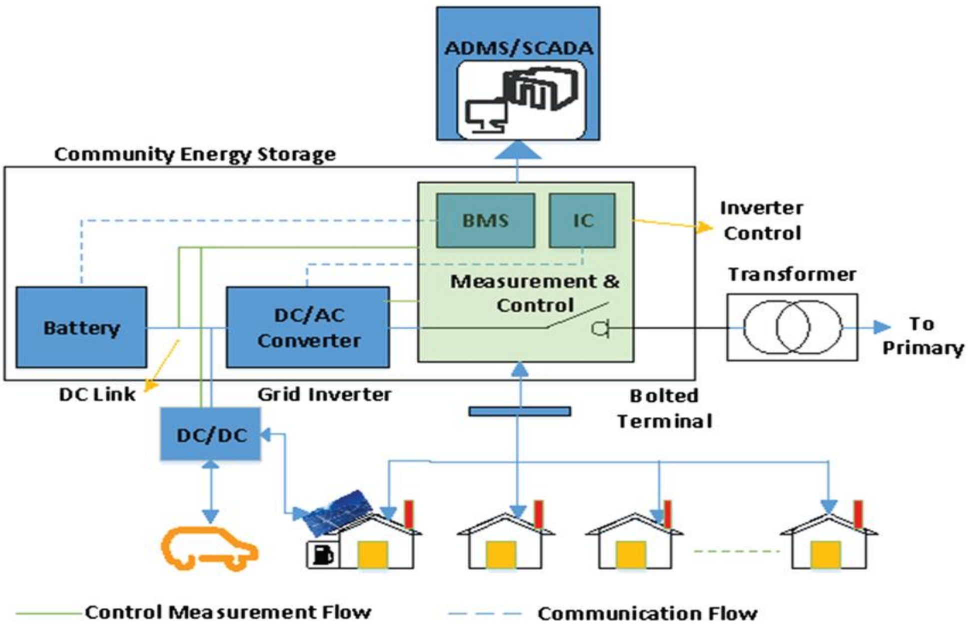
[181] TR 77-1:2020(2023) is compatible with IEC/TS 62933-3-1:2018.

systems at the service voltages. These storage systems installed on customer premises are often referred to as "behind-the-meter (BTM)" systems.

6.4.1 Community battery program

Besides the technical and economic advantages raised at the grid level, the collective use of battery ES at the local level potentially is a game changing strategy for the energy transition and decarbonization of the sector in cities, while accommodating the needs and expectations of households and local communities. The community energy storage (CES) involves the accomplishment of either individual households all hooked into one large battery deployed at the neighborhood level, or with smaller household batteries linked together so that neighboring customer units could borrow and lend power as needed.

The concept of CES embodies many facets to deliver a more equitable distribution of benefits and control of the local grid. There are multiple definitions of CES in practice that can lead to different interpretations. A generic concept structure of CES is illustrated in Figure 6-12.[182] In the United States, the California Public Utility Commission (CPUC) defines community storage as storage connected at the distribution feeder level, associated with a cluster of customer load.[183]



Source: Singh et al.

Figure 6-12 Schematic Layout of Community Energy Storage System

[182] Shailendra Singh S. P. Singh Vijay Babu Pamshetti. 2019. Energy efficiency and peak load management via CVR and distributed energ y storage in active distribution grid. International Transactions on Electrical Energy Systems. 2020;30:e12224.

[183] DeShazo J, Gattaciecca J, and Trumbull K. The Growth in Community Aggregation Choice: Impacts on the California's Grid. Universit y of California, Los Angeles, Luskin School of Public Affairs, 2018.

Typically, a CES consists of a battery, a four-quadrant inverter, and a measurement/control system that includes a battery management system (BMS), an inverter, and a monitoring/control (IC) unit. The main difference between CES and DGs lies in the fact that CES is normally equipped with a fully dispatchable four-quadrant inverter that enables it to bi-directionally exchange active and reactive powers. CES can regulate voltage and frequency and inject/ absorb reactive power to/from the grid on demand. In practice, the CES systems in urban distribution network can perform peak-shaving, smoothing DER's intermittencies (output shifting/levelling), energy management such as power quality improvements, supporting islanding during outages, and maximizing self-consumption of local renewable resources.

Importantly, besides battery, community storage can encompass a wide range of storage technologies, including EVs, as well as thermal storage such as ice storage, electric space heaters, and water heaters.

(1) Community battery program in Australia

The Australia Government's Community Batteries for Household Solar Program is to install 400 batteries to provide shared storage for households across Australia.184 The program aims to lower electricity bills; support more households to install rooftop solar; allow households who cannot install solar panels to enjoy renewable energy; reduce pressure on the electricity grid; and absorb excess energy that might cause voltage spikes in the electricity grid. The AUD200 million program delivers grants through the Department of Industry, Science and Resources' Business Grants Hub[185], and the Australian Renewable Energy Agency's (ARENA) Community Batteries Funding.[186] The Business Grants Hub is administering AUD29 million of grants to install batteries in 58 locations. ARENA administers AUD171 millions of grants for the community batterie programs through two rounds. Over 30 batteries are in operation under this program with more to be deployed in 2025.

In Sydney, several community batteries are in operation, contributing to city's net-zero goal by 2040[187]. Endeavour Energy, a distribution network operator in Sydney, works with local councils and communities to find a suitable location for their community batteries. The Bungarribee Community Battery commissioned in July 2023, is the first for Western Sydney. The program allows households access lower-cost renewable solar power without the cost of installing a battery or solar system. It stores surplus energy from local solar installations, which is made available to participating customers to use: whether they have solar PV panels installed or not. For customers without a solar power system, capacity was made available for a monthly fee, and their allocation is charged with surplus solar electricity from the area. Likewise, those with roof-top PV rent a portion of the battery to virtually store and access energy generated in the neighborhood. An initial

[184] Department of Climate Change, Energy, the Environment and Water. 2024. Community Batteries for Household Solar program. https://www.dcceew.gov.au/energy/renewable/community-batteries.

[185] Australia Government. 2024. Grants to install Community Batteries. https://business.gov.au/grants-and-programs/community-batteries-for-household-solar-stream-1.

[186] Australian Renewable Energy Agency. 2024. Community Batteries Funding. https://arena.gov.au/funding/community-batteries-round-1/.

[187] City of Sydney. 2023. Net zero by 2040: Ambitious new emissions target set. https://news.cityofsydney.nsw.gov.au/articles/net-zero-by-2040-city-of-sydney-ambitious-new-carbon-emissions-target-set.

battery capacity limit was set at 4 kWh per household per day, and this costs AU$15 per month. In comparison, 4kWh is less than a third of the useable capacity of a fully charged Tesla Powerwall (13.5kWh). The battery is charged from the grid during the shoulder/off-peak timeframes when demand and wholesale electricity costs are much lower. Participants receive a rebate directly to their bank accounts reflecting the savings made sourcing some of their energy needs from their allocation rather than the grid. Feed-in tariffs for solar PV owners are not affected.

Endeavour Energy Chief Executive Officer Guy Chalkley said that community batteries are one of the ways distribution network's efforts helping shape Western Sydney as a green energy hub. "It is an exciting innovation that will see our customers both be a part of, and benefit from the green energy transition in city, whether they have rooftop solar PV installed or not." [188] and "The installation of community batteries supports our target of net-zero by 2040 and is part of our transition to a modern, clean power grid that meets the changing needs of the customers with customers being able to generate, store and share their energy", said Mr Chalkley. The Mayor of Blacktown City, Tony Bleasdale welcomed the battery to Bungarribee and both environmental and commercial wins for the community, and said, "Blacktown City Council strongly supports the use of community batteries, which will support our residents in reducing their household energy costs and lowering their households carbon footprints."

Source: Endeavour Energy

Figure 6-13 Site of Bungarribee Community Battery, Sydney

(2) Community battery programs in the United States

Community battery programs are rapidly gaining traction in US cities, and various approaches are being

[188] Endeavour Energy. 2023. https://www.endeavourenergy.com.au/news/media-releases/endeavour-energy-switches-on-western-sydneys-first-community-battery

explored, ranging from utility-led initiatives that integrate storage for grid stability and peak shaving to community-choice aggregation (CCA) models that empower local entities to procure and manage energy resources, including shared batteries, tailored to their constituents' needs.

Across the US cities, diverse community battery initiatives are taking shape, showcasing the adaptability of this concept to different local contexts and energy goals. For instance, cities are actively partnering with CCAs and municipal utilities to launch innovative programs. San Diego Community Power (SDCP), a prominent CCA, has introduced programs that incentivize homeowners with batteries to discharge energy during on-peak hours, but more critically, they are also exploring broader community-scale storage solutions that serve multiple customers without requiring individual home battery installations.[189] Beyond homeowner incentives, some city-led efforts, like those spearheaded by Ava Community Energy (formerly East Bay Community Energy) in California, are strategically deploying solar-plus-battery systems at critical municipal facilities, such as fire stations, police departments, and community centers. These installations are designed to ensure the continuity of essential services during grid outages, thereby bolstering overall community resilience and providing a direct benefit to the public[190]. Such projects demonstrate how community batteries can serve a dual purpose: supporting grid stability and acting as localized emergency power hubs.

The evolution of community battery programs in the US cities currently is increasingly moving beyond simply aggregating individual residential batteries to encompass larger, purpose-built systems that serve a collective. This shift acknowledges that while individual home batteries contribute to decentralization, shared community batteries can offer more significant economies of scale, more effective grid support, and equitable access to clean energy benefits. These larger systems can be strategically placed to address specific localized grid constraints, integrate distributed renewable generation from community solar projects, or provide critical services during extreme weather events. The growing recognition of these multifaceted benefits is spurring cities to explore and invest in diverse community battery models, laying the groundwork for more resilient, sustainable, and democratized urban energy landscapes.

6.4.2 Shared virtual energy storage

Shared virtual energy storage is a model where the benefits of a centralized energy storage system are distributed among multiple participants without each needing their own physical battery. This is often achieved through a utility-scale battery or a network of distributed energy resources (DERs) aggregated to function as a single entity. Participants can purchase "shares" or virtual capacity, entitling them to a portion of the storage system's benefits, such as reduced energy costs through peak shaving or access to backup power. This approach lowers the barrier to entry for individuals and businesses to benefit from energy storage, as it eliminates the need for upfront investment, installation space, and maintenance responsibilities

[189] SolarInsure. 2025. Unlock Money-Saving Benefits with San Diego Community Power's Solar Battery Program. https://www.solarinsure.com/san-diego-community-power-solar-battery-program

[190] Ava Community Energy. 2025. Resilient Municipal Facilities. https://avaenergy.org/community/municipal-programs/resilient-facilities/

associated with on-site batteries.[191] One prominent good of shared virtual energy storage is the Sacramento Municipal Utility District's (SMUD) “Energy StorageShares” program in California, the US, which allowed commercial customers to invest in a utility-scale battery and receive on-bill credits reflecting their share of the battery's savings.

For large electricity market players, such as transmission and distribution utilities, aggregators, and local system operators, the control of multiple energy storage assets concurrently, acting as a single entity, enables new sorts of benefits. Among these, lie the ability to aggregate and control the existing distributed resources like rooftop solar PV, home batteries and electric vehicles as in a virtual power plant (VPP) to operate as a single, larger traditional power plant and provide grid services. Sunrun's CalReady system in California, which networks thousands of residential batteries, exemplifies this model.[192] In this sense, the aggregated management of distributed energy storage allows small energy sources to participate in wholesale and retail markets to sell electricity or provide ancillary services. The aggregation allows homeowners to contribute to grid resilience and potentially earn revenue for their stored energy. Similarly, the US Department of Energy has provided a loan guarantee to Sunwealth for "Project Polo," which aims to deploy commercial-scale solar and battery storage across multiple states, operated and managed a VPP[193] .

(1) The practices in the California

An example is Sunrun's "CalReady" VPP in California, which has scaled to connect approximately 75,000 home batteries from over 56,000 customers, offering up to 375 megawatts (MW) of backup power to the grid, particularly during summer heatwaves. This not only helps prevent blackouts but also lowers electricity bills for participants who get compensated for sharing their stored solar energy. Other notable projects include pilot programs in Texas and Vermont utilizing Tesla Powerwall batteries, and a multi-technology VPP by SDG&E in San Diego County, which leverages smart thermostats, well water controllers, and batteries to reduce demand and supply power during peak hours. The US Department of Energy has also been actively supporting VPP deployment through initiatives like a USD289.7 million loan guarantee for a project to deploy commercial-scale PV and BESS across 27 states, forming integrated VPPs[194].

(2) Australian cities

Australian cities are at the forefront of VPP development with BESS, largely due to high rooftop solar

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[191] Clean Energy Group. 2020. SMUD's Energy StorageShares Program: The First Virtual Energy Storage Program in the US. Retrieved fr om https://www.cleanegroup.org/smuds-energy-storageshares-program/. 21 September 2020.

[192] Sustainability Times. 2025. “56,000 Homes Become a Power Plant”: California Firm Creates Largest Virtual Energy Source in US With Revolutionary Grid-Sharing Tech. https://www.sustainability-times.com/energy/56000-homes-become-a-power-plant-california-firm-creates-largest-virtual-energy-source-in-us-with-revolutionary-grid-sharing-tech/

[193] DOE. 2025. DOE Announces $289.7 Million Loan Guarantee to Sunwealth to Deploy Solar PV and Battery Energy Storage, Creating Wide-Scale Virtual Power Plant. Retrieved from https://www.energy.gov/lpo/articles/doe-announces-2897-million-loan-guarantee-sunwealth-deploy-solar-pv-and-battery-energy. 16 January 2025.

[194] DOE 2025. 2025. U.S. Department of Energy Loan Programs Office. DOE Announces $289.7 Million Loan Guarantee to Sunwealth to Deploy Solar PV and Battery Energy Storage, Creating Wide-Scale Virtual Power Plant. https://www.energy.gov/lpo/articles/doe-announces-2897-million-loan-guarantee-sunwealth-deploy-solar-pv-and-battery-energy. 16 January 2025.

penetration and a strong focus on grid stability in the National Electricity Market (NEM). As an example in Australia, in late 2016, a VPP involving residential behind-the-meter batteries was developed with installation of 1,000 batteries in metropolitan Adelaide. The project, up to 2.765GWh of total capacity.[195] The South Australian Virtual Power Plant (SA VPP) is a leading example, developed by Tesla and electricity retailer Energy Locals with government support. This network aims to integrate up to 50,000 solar and Tesla Powerwall home battery systems across South Australia, working together to provide more affordable and reliable electricity. The SA VPP has demonstrated its capability to stabilize frequency levels in the grid and provide crucial supply during transmission interruptions.[196] Beyond residential deployments, community batteries are also forming the backbone of VPPs in cities like Melbourne, with the Yarra Energy Foundation (YEF) deploying community batteries managed by Diamond Energy's VPP to deliver value to the grid and local communities.

The application of VPPs, virtual storage in particular, with BESS in urban environments could help transform how cities interact with their energy grids. These systems provide crucial flexibility and resilience, enabling urban areas to better integrate renewable energy, manage peak demand, and reduce reliance on traditional, often fossil fuel-based, power plants. By aggregating distributed energy resources, VPPs defer the need for costly grid infrastructure upgrades and offer a more cost-effective way to enhance grid reliability. As policy support and technological advancements continue, the scale and sophistication of VPPs are expected to grow in urban energy system. This will lead to more robust, decarbonized, and decentralized urban energy systems, empowering consumers to actively participate in the energy transition and creating a more resilient future for cities.

6.4.3 Industrial and commercial storage

Industrial and commercial (I&C) customers can suffer significant losses during momentary events and/or sustained interruptions, which can be mitigated by energy storage facilities. Unlike residential applications, the power and quantity of electricity I&C loads have larger dimensions, requiring the use of technologies adapted to the specific needs, such as high demand, life cycle, and cost.

For I&C applications, the BESS is connected to the load using an AC–DC converter, connecting in three phase system, and ranging range in size from 100’s kW to GW level in capacity. It can also be connected in parallel with a second-generation source, such as solar panels. A controller is needed in these cases to define when it will be necessary to charge the batteries, managing the energy that comes from the grid and the distributed generations. BESS, in this case, mitigate power fluctuations occurring in PV power generation,

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[195] AGL Energy. Virtual Power Plant in South Australia. Australian Renewable Energy Agency, 2020. https://arena.gov.au/assets/2020/10/virtual-power- plant-in-south-australia.pdf.

[196] Clean Energy Finance Corporation. 2023. SA creates Australia's largest virtual power plant. https://www.cefc.com.au/case-studies/sa-creates-australia-s-largest-virtual-power-plant/.

which leads to increased stability and quality of the overall system[197,198].

I&C BESS can be used to help regulate grid frequency, and power conversion system (PCS) uses special inverters to convert DC battery power into three-phase AC voltage. The AC voltage is smoothed by filter elements and then increased to mains voltage by a transformer. The PCS can also be used as a Statcom device for the network, supplying and absorbing reactive energy (VAR) to the grid, improving the power factor or regulate the voltage on the grid. Currently, a primary driver for I&C BESS adoption is peak shaving, where stored energy is discharged during periods of high electricity demand, reducing demand charges imposed by utilities[199]. The storage owner could bid directly into wholesale and ancillary services for market participation, where market allows, generating financial benefits from the services. Beyond cost savings and power quality improvements, I&C BESS plays a vital role in integrating on-site renewable energy generation, such as solar PV systems. By storing excess solar energy generated during the day, businesses can utilize this clean power during evening peak demand or periods of low solar output, maximizing self-consumption and reducing reliance on the grid.[200] This capability not only lowers operational expenses of I&C business, but also contributes to sustainability goals and can potentially generate revenue through net metering or participation in demand response programs. Additionally, I&C BESS can provide backup power during grid outages, ensuring business continuity and preventing financial losses associated with downtime.

In APEC region, I&C BESS are seeing rapid adoption in Australia; China; Korea; and the US, primarily driven by the need for peak demand management, cost reduction through energy arbitrage, and enhanced grid resilience during outages. Table 6-8 list the main drivers, typical applications and relevant incentives for I&C BESS project in some APEC cities.

Table 6-8 Industrial and Commercial BESS in APEC Cities

Economy	Main drivers for C&I BESS adoption	Typical C&I BESS applications	Example project	Relevant incentive programs/policies
The United States	• Peak shaving • Demand charge Management: Avoiding high charges from utilities based on peak consumption. • Backup power	• Manufacturing facilities • Commercial buildings (offices, retail, hotels) • Data centers • Hospitals • Educational institutions	• Large BESS deployments in California are increasingly common, including those co-located with renewables. • New York: Focused on market acceleration and enhancing grid reliability. • Texas: BESS projects for grid support and energy arbitrage, often paired with renewable generation.	• California Self-Generation Incentive Program (SGIP): Offers substantial funding and support for energy storage projects. • New York's Energy Storage Roadmap & Incentives: Aims for 6 GW of energy storage by 2030 with nearly $2 billion in incentives, including upfront rebates

197 Devassy S and Singh B. Performance analysis of solar PV array and battery integrated unified power quality conditioner for microgrid systems. IEEE Transactions on Industrial Electronics. 2021.
198 IEEE Std 519-2014. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.
199 Energy Storage Association. 2023. The Benefits of Energy Storage.
200 SEIA. 2024. Solar + Storage. Solar Energy Industries Association.

Economy	Main drivers for C&I BESS adoption	Typical C&I BESS applications	Example project	Relevant incentive programs/policies
	• Renewable energy integration. • Sustainability goals: reducing carbon footprint and achieving corporate sustainability targets. • Grid services: participating in demand response and ancillary services markets.	• Agricultural operations		based on system capacity and performance. • Federal Investment Tax Credit (ITC): Provides a significant tax credit for BESS projects, particularly when paired with solar.
China	• Grid Stability & Modernization: Addressing grid stability issues arising from increasing renewable energy penetration. • Energy Cost Optimization: Reducing electricity costs for industrial and commercial users. • Policy Support & Investments: Strong government backing and large-scale investments in energy storage. • Demand Response & Load Shifting: Optimizing energy use and maximizing ROI across diverse settings.	• Industrial parks • EV charging hubs • Factories • Shopping centers	• Nanjing, Jiangsu: A behind-the-meter facility generates significant annual revenue through grid incentives. • Dingxi City, Gansu: A combined compressed air and lithium-ion battery shared energy storage power station. • Beijing, Shanghai, Shenzhen, Guangzhou: Major economic hubs with increasing C&I BESS adoption.	• Provincial/City-level Policies: Many provinces and cities offer specific pilot demonstration proposals and support for BESS deployment, including for vanadium batteries and combined energy storage technologies. • National Energy Administration (NEA) Targets: Driving significant growth in energy storage capacity. • Financial Incentives: Although specific C&I BESS incentives vary by region, overall government support and large-scale investments propel the market.
Australia	• Support renewable energy targets. • Grid stability & security. • Peak demand management & cost savings: • Off-grid and fringe-of-grid applications. • Innovative funding models	• Farms and agricultural operations • Industrial facilities • Commercial enterprises • Businesses participating in demand response programs	• South Australia: Home to some of Australia's largest BESS projects (e.g., Templers BESS, Blyth BESS). • Western Australia: Initiatives like Horizon Power's federally funded BESS project reducing diesel reliance in remote towns. • New South Wales, Victoria: Increasing BESS deployments across various industries.	• Capacity Investment Scheme (Federal): Supports construction of new generation and flexible capacity, offering long-term revenue guarantees. • Long-term Energy Supply Agreements (New South Wales): policy supporting clean generation and dispatchable capacity. • Cheaper Home Batteries Program (Federal): While primarily residential, also accessible by small

Economy	Main drivers for C&I BESS adoption	Typical C&I BESS applications	Example project	Relevant incentive programs/policies
				businesses and community facilities.
Korea	• Support emission and RE targets. • Energy management: costs and reliability. • Renewable energy grid integration. • Enhancing operational resilience for energy-intensive industries.	• Large-scale commercial applications • Manufacturing hubs • Data centers • Industrial facilities	• Seoul: High demand for BESS in large-scale commercial applications. • Namwon (Jeollabuk-do): Location of a significant 336MW BESS for grid services.	• Subsidies and Incentives: Substantial government subsidies and incentives to promote BESS adoption for commercial and industrial users. • KEPCO plan for large scale BESS installation for grid stabilization and frequency regulation.

In the United States, high demand charges and robust incentive programs like California's SGIP, alongside the federal ITC, are catalyzing deployments in manufacturing, data centers, and commercial buildings. China dominates the global BESS market, with its carbon neutral goals and extensive government support accelerating I&C applications in industrial parks and factories for grid stability and energy cost optimization. Korea is a strong adopter, propelled by economy's decarbonization policies and key utility tenders, supporting large commercial and industrial facilities in cities like Seoul and Namwon. Finally, Australia, with ambitious renewable energy targets and grid modernization efforts, leverages I&C BESS for peak shaving, renewable energy self-consumption, and energy independence in various industrial and agricultural settings, supported by initiatives like the federal Capacity Investment Scheme.

6.5 Summary and recommendations

(1) Regulatory and policy supports

Achieving the full potential of energy storage may require changes to operating practices or regulations for the deployment of the technologies. Policymakers should implement and consistently update clear, streamlined permitting that account for the unique characteristics of BESS, avoiding outdated regulations designed for traditional generation or loads. Market mechanisms and financial incentives are crucial; this includes establishing clear valuation for the multiple services that BESS provide and offering direct subsidies, tax credits, or performance-based incentives to de-risk investments and improve project economics. In addition, robust and adaptable safety codes and standards must be uniformly adopted and rigorously enforced, coupled with ongoing training for first responders and public awareness campaigns to ensure community acceptance.

With rapid advancement of battery technologies, policymakers and regulators can encourage familiarization with storage through the development of more pilot projects. These projects allow stakeholders to experiment with various technical, operational, and regulatory options to incorporate energy storage in urban energy systems. Such pilot projects could be important when determining how to use distribution-level storage facilities to meet the needs of both distribution and the transmission systems. The pilots will also help regulators determine the better ownership models to provide the most benefits to the grid at least cost and can help utilities familiarize themselves with providing services with the storage facility they own or procuring it from third parties.

(2) Technical rules and standards

Integrating energy storage into the power system and accessing its full value require technical regulations that ensure reliable, predictable behavior from the asset during both normal operations and in response to contingency events. Such regulations could cover myriad topics from communication capabilities, level of observability over the storage system for system operators, and various operational characteristics such as minimum response times to signals from a system operator. Although existing technical codes standards may adequately cover most of the technical requirements, energy storage systems that provide power to both the distribution and transmission system may need additional review and capabilities. To support the safe and effective integration of BESS into the power grid, focused areas include:

- Technical rules should ensure BESS are installed and operated safely, addressing risks like fires or chemical leaks. Standards should also require batteries to communicate smoothly with the grid, helping to stabilize voltage and frequency during outages or sudden changes in energy supply.
- From a grid operator’s perspective, regulations and standards for BESS should prioritize reliability, simplicity, and fairness. Connection rules shall ensure batteries can respond quickly and safely to grid needs. Standards must address safety risks like fires or overheating by mandating proven designs, emergency shutdown features, and regular inspections. Grid operators need straightforward protocols for how batteries connect to the grid, reducing delays and technical conflicts.
- Policies should be prepared helping batteries compete fairly in energy markets while supporting grid stability. Remove outdated rules that penalize batteries for charging from the grid or limit how they can earn revenue. Grid operators need flexibility to use batteries for multiple purposes, like easing congestion on overloaded power lines or delaying costly grid upgrades.

(3) Improve network planning and operating practices

Long-term energy storage targets and integrated resource planning can provide critical policy certainty, signaling a stable market for developers and investors while accelerating the integration of BESS into urban energy system. Alongside renewables development, utilities need to fully include energy storage in long-term grid planning of urban energy system, ensuring integrated considerations of batteries for various power system services. Such requirements can help make sure more novel approaches to power system needs are considered on an even playing ground with more traditional investments. The ability of batteries to provide both network services and market services means that both networks and other parties can lead the roll-out of energy storage infrastructure. Distribution network service providers in cities could effectively support scaling up BESS deployment by:

- Fully embedding BESS into the planning and design of networks, for example, due to network operator's intimate knowledge of evolving electricity demand and future infrastructure augmentation requirement, as well as related replacement and operational needs of the network;
- Taking the advantage to use existing land assets of the urban network operators, such as land adjacent to zone substations, to host batteries, lowering the cost of delivery. This also avoids the social license cost of procuring new land within communities and effectively navigating change of its use;
- Partnering with market facing third parties, including BESS developers and integrators, which can reduce the barriers for those parties to manage wholesale electricity market risks and sustain the BESS project development;
- Leveraging existing processes and workforce for the operation and maintenance of energy storge assets to maximize the values and benefits of BESS.

(4) Support grid integration

To accelerate the grid integration of BESS project, policy recommendations should prioritize streamlining and standardizing interconnection procedures. This involves developing clear, efficient, and transparent processes for connecting BESS to both transmission and distribution networks, which are often characterized by significant delays and uncertainties. Key policy actions include establishing firm deadlines for grid operators to complete interconnection studies and approvals, implementing "cluster study" approaches instead of serial processing to manage backlogs, and requiring higher readiness requirements for projects entering the queue to ensure only mature proposals proceed. Furthermore, policies should promote the provision of granular and accessible grid data, such as hosting capacity maps and circuit strength information, enabling developers to identify optimal interconnection points and design more effective projects, thereby reducing speculative applications and subsequent withdrawals.

Additionally, policies should address the technical and financial aspects of interconnection to facilitate BESS deployment. This includes updating technical standards to specifically accommodate the unique operational characteristics of BESS, such as their fast response times and ability to provide grid-forming services, rather than treating them solely as traditional generators. Policies should also clarify cost allocation mechanisms for necessary grid upgrades associated with BESS interconnections, ensuring that these costs are allocated fairly and do not disproportionately burden BESS developers. Finally, encouraging innovative connection models, such as co-location with existing renewable generation or shared connection points, can further optimize grid infrastructure utilization and reduce the need for extensive new transmission or distribution investments, thereby accelerating project timelines and reducing overall costs for BESS integration.

(5) Develop long-duration energy storage technology

Another challenge or obstacle is the lack of long-duration batteries currently available. Currently, battery system can provide short-term reliability of power system. However, the seasonal variation of renewables requires longer-duration batteries for system operation, which highlights a challenge that will need to be overcome to achieve carbon neutral goal. At the moment, pumped-hydro offers a long-storage storage, however, more of this will be required as more dispatchable generation is phased out in the power system, and alternative long duration energy storage (LDES) will be required, and these this could include redox flow battery, compressed air, thermal storage and others. The policy support could be on research and development, organising demonstration and pilot projects, and fostering the development of industry chain aiming at wide commercial applications of the technology.

(6) Facilitate distributed storage systems

Supporting the widespread adoption of distributed BESS, including community battery programs, industrial and commercial storage, and virtual energy storage, requires a multi-faceted approach. Governments and regulators should prioritize targeted financial incentives such as grants, low-interest loans, and performance-based payments that specifically encourage the deployment of these systems at various scales. Concurrently, regulatory frameworks need to be updated to fairly value the diverse grid services offered by distributed BESS, including peak shaving, demand response, and frequency regulation, ensuring they can fully participate and monetize their benefits in electricity markets. Cities can streamline local planning and permitting processes for these installations, reducing administrative burdens and accelerating deployment. Clear guidelines for community engagement and benefit-sharing, such as discounted electricity rates for participants, will also foster public acceptance and drive widespread adoption. Clear and streamlined interconnection rules are also essential to reduce project development times and costs, facilitating faster deployment.

In cities in developing economies, where industrialization and energy demand are soaring, policies can encourage I&C BESS through demand charge reduction incentives, preferential grid access for BESS-integrated renewable energy, and support for microgrids in industrial parks. These in industrialized economies cities should continue to leverage existing tax credits and relevant mandates for storage projects. Fostering the growth of virtual energy storage and I&C BESS necessitates regulatory innovation. This involves developing sophisticated market mechanisms that allow aggregated smaller storage units to participate in wholesale energy markets and provide ancillary services, effectively creating VPPs. These VPPs can optimize distributed BESS assets across a city, enhancing grid stability and efficiency, allowing them to provide demand response and grid services to the local network. For industrial and commercial users, policies should incentivize the integration of BESS with on-site renewable generation through tax credits or specific tariffs that reward self-consumption and grid support. continued investment in research and development, alongside public education on technology advancement and safety of distributed BESS.

Chapter VII Energy Storage Participation in Electricity Markets

Battery Energy Storage Systems are crucial for electricity market participation primarily due to their ability to provide flexibility and stability to the grid, especially with the increasing integration of intermittent renewable energy sources like solar and wind. Their significance lies in their capacity to store surplus energy during periods of high generation and low demand, and then discharge it when demand is high or renewable output is low. This capability not only reduces the curtailment of valuable renewable energy but also transforms these intermittent sources into more reliable and dispatchable power options. The fast response capability of batteries makes them highly valuable for power system services, which are crucial for integrating intermittent renewable energy sources and system operation and stability. By participating in the related electricity markets, BESS helps maximize the value of renewable energy, enhance grid reliability, reduce electricity costs, and ultimately accelerate the transition to a more sustainable and resilient energy system.[201]

7.1 Mechanisms of market participation

BESS have been actively integrating into electricity markets by leveraging their operational flexibility across various market segments. A primary role of BESS in electricity markets is the enhancement of grid stability and reliability. These systems possess the capability to rapidly inject or absorb power, responding to deviations in grid frequency within milliseconds, a speed unmatched by traditional power generators. This quick response is crucial for maintaining the delicate balance between electricity supply and demand on the market, thereby preventing potentially disruptive outages and damage to grid infrastructure.

BESS can participate in electricity markets through various mechanisms. A primary market participation strategy is energy arbitrage, where BESS charges during periods of low electricity prices and discharges when prices are high, thereby profiting from price differentials in spot and day-ahead markets.[202] This strategy is particularly effective in markets with high renewable energy penetration due to increased price volatility. A significant benefit of BESS market participation is their ability to facilitate the seamless integration of intermittent renewable energy sources like solar and wind. BESS can store excess energy generated during periods of high renewable output and release it when generation dips, effectively smoothing out the inherent variability of these sources. This strategy is particularly lucrative in markets that experience high price volatility, often driven by the increasing integration of renewable energy sources. Successful

[201] NREL. 2023. Clean Energy Ministerial Supercharging Battery Storage Initiative. Battery Storage Unlocked: Lessons Learned From Emerging Economies. National Renewable Energy Laboratory, DOE.

[202] Padmanabhan, N., Ahmed, M., & Bhattacharya, K. 2020. Battery Energy Storage Systems in Energy and Reserve Markets. IEEE Transactions on Power Systems, 35(1), 215-225.

energy arbitrage requires forecasting of market prices and efficient battery management systems to optimize charging and discharging schedules.

BESS contributes to improved overall electricity market efficiency and cost reduction through strategies like peak shaving and energy arbitrage. By storing energy during off-peak periods when electricity prices are typically lower and discharging it during peak demand times when prices are higher, BESS operators can engage in energy arbitrage. This process helps to reduce the reliance on expensive and often less efficient peaking power plants, ultimately leading to lower energy costs for consumers. Peak shaving, another cost-saving strategy, involves using stored energy to decrease the overall demand on the grid during peak hours, which can help businesses and utilities avoid incurring high demand charges.[203]

Another significant being the provision ancillary services, such as fast frequency response (FFR) and primary frequency response (PFR). These services are becoming increasingly vital as the grid's overall inertia decreases due to the replacement of conventional, synchronous generators with less inertial renewable energy sources. The fast and precise response of BESS can effectively compensate for this reduction in inertia, acting as a virtual stabilizer for the grid, as well as voltage support and operating reserves. The services also include voltage support, and operating reserves, which are essential for maintaining the stability and reliability of the power grid. The rapid response times of BESS make them particularly well-suited for providing these services, as they can quickly adjust their power output to match fluctuations in demand and supply. Revenue generated from participating in ancillary service markets can be a substantial component of a BESS project's overall profitability.

BESS also plays a critical role in providing essential backup power offering capacity reserves to prevent outages, enhancing grid resilience, particularly during unexpected outages. This capability ensures business continuity and provides vital support for critical infrastructure such as hospitals and emergency services. In regions susceptible to extreme weather events, strategically deployed BESS can significantly bolster grid resilience.[204] Furthermore, some advanced BESS offer black start capabilities, providing the initial power needed to restart generators and restore the grid following a major blackout.

Furthermore, BESS participates in capacity markets, receiving payments for ensuring power availability to the grid, which helps meet peak demand and enhance long-term resource adequacy. BESS can also offer reliable capacity services to meet peak demand and ensure resource adequacy. By participating in capacity markets, BESS can provide a guaranteed availability of power during periods of high electricity consumption, helping grid operators maintain resource adequacy and prevent blackouts, which facilitates "peak-shaving" and reduce reliance on fossil fuel-based peaker power plants. Capacity payments, received for this

[203] Montel. 2025. Cons and Applications of Battery Energy Systems (BESS) - Montel Group, accessed May 1, 2025, https://montel.energy /blog/advantages-applications-and-challenges-of-battery-energy-systems-bess

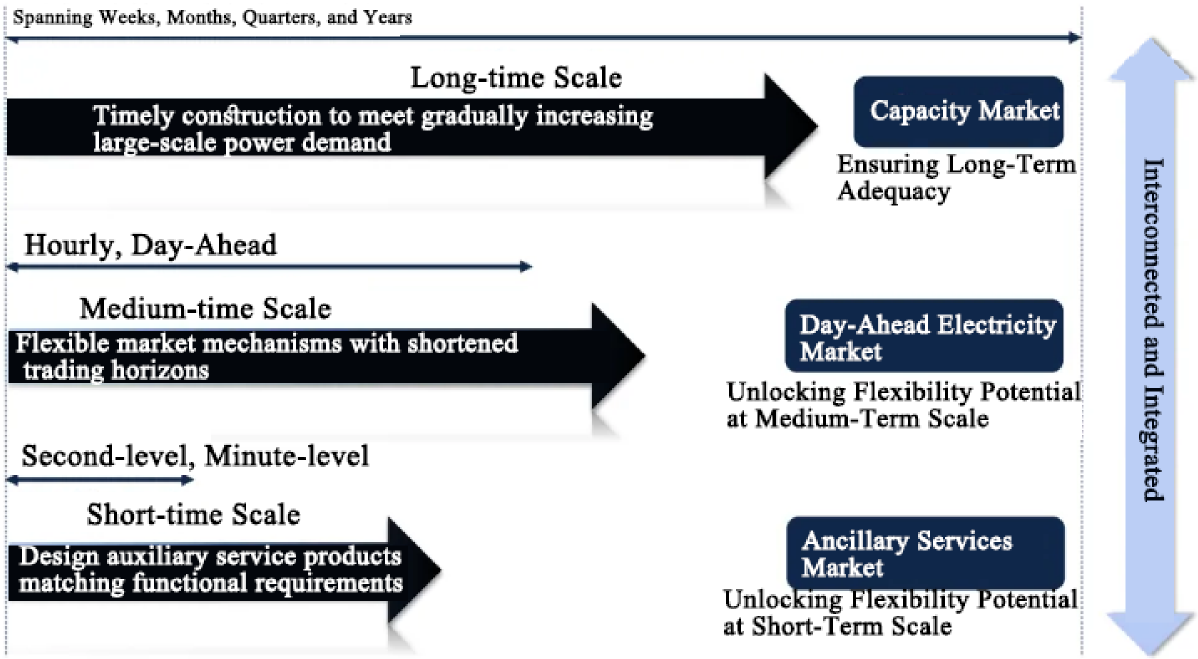
[204] NREL. 2023. Clean Energy Ministerial Supercharging Battery Storage Initiative. Battery Storage Unlocked: Lessons Learned From Emer ging Economies. National Renewable Energy Laboratory, DOE.

commitment, offer a more stable and predictable revenue stream for BESS projects.

BESS actively participate in day-ahead and real-time wholesale energy markets. They can bid into these markets, optimizing their charging and discharging schedules based on both predicted (day-ahead) and actual (real-time) market conditions.[205] A Direct engagement in these markets allows BESS to generate revenue from energy sales in addition to the income derived from other grid services.

7.1.1 Types of electricity markets

The market itself does not provide additional flexibility. However, through carefully designed market transaction mechanisms, the value of flexibility can be effectively conveyed via price signals, thereby guiding the release of existing flexible resources within the system or encouraging investment in such flexible resources.[206]



Source: https://mp.weixin.qq.com/s/JmNyzso5nPBqNUYlcMFyJQ

Figure 7-1 Schematic Illustration of Electricity Markets

As a flexible resource, energy storage can bring many benefits to the power system and energy storage facilities can generate profits by participating in the electricity market. As mentioned previously, the role of energy storage in the power system is demonstrated through its participation in different markets, including the energy market, ancillary services market, and capacity market. An effective electricity market mechanism

205 American Clean Power Association. 2025. Market Reforms to Harness Energy Storage and Strengthen Regional Grid Reliability. The American Clean Power Association (ACP).

206 Energy Academic Research and Progress, Building a Multi-Level Electricity Market System to Enhance System Flexibility: Strategic Analysis from Spot Markets to Capacity Markets [EB/OL]. https://mp.weixin.qq.com/s/JmNyzso5nPBqNUYlcMFyJQ , 2024-12-09.

is critical to ensure reasonable returns for energy storage projects and is essential to promote its large-scale application and commercial development of storage assets.

In general, electricity markets are composed of several sub-markets. From a time perspective, electricity markets can be divided into medium- and long-term markets and spot markets, which can be further categorized into annual, quarterly, monthly, day-ahead, and real-time markets; The medium- and long-term markets and spot markets serve different purposes: the former locks in revenues, while the latter discovers prices. From the perspective of product types, electricity markets can be divided into capacity markets, energy markets, ancillary services markets, and financial transmission rights markets. Among these, the ancillary services market can be further subdivided into frequency regulation ancillary services and reserve services markets. Due to its fast response characteristics and bidirectional charging/discharging capabilities, energy storage is most suitable as a demand response resource and a good ancillary service resource. Accordingly, storage most commonly participates in the energy and ancillary services markets under the spot market framework.

Energy storage can both charge and discharge, thus acting either as a generation entity or as a load/consumption entity. By exchanging energy with the grid through charging and discharging, energy storage can participate in the energy market. On the other hand, due to its fast response characteristics, energy storage is highly suitable to act as a frequency regulation resource and provide frequency regulation services to the system. Although energy storage can provide various types of ancillary services, its participation in the frequency regulation market currently yields the best economic benefits. With the increasing integration of renewable energy sources, the power system's demand for frequency regulation services continues to grow, and the corresponding compensation mechanisms have established and become mature. Compared to traditional generators, energy storage offers better performance in frequency regulation.[207]

- To participate in electricity trading, energy storage needs first define its charging and discharging strategy. Energy storage devices can charge during off-peak hours when electricity prices are low, storing energy; and discharge during peak hours or periods of high demand, releasing stored energy. This "buy-low-sell-high" strategy not only helps energy storage operators capture profits from price differences but also effectively alleviates supply-demand imbalances in the power system and improves the operational efficiency of the electricity market. The charging and discharging strategies of energy storage need to be closely aligned with market price signals and supply-demand conditions. Electricity markets typically include multiple time dimensions such as long-term markets, medium-term markets, short-term (spot) markets, and real-time markets. The charging and discharging plans need to be based on price and demand forecasts across different time horizons to maximize their economic returns.

[207] Analysis of Market Mechanisms and Models for Energy Storage Participation in Electricity Trading [EB/OL]. https://mp.weixin.qq.com/s/7Q6KG0kquwF37-UOz6ScCA, 4 November 2024.

- Participation of energy storage in electricity trading requires consideration of network constraints and dispatching rules of the network. Due to often limited transmission capacity and stability criteria of the power grid, the charging and discharging behaviors of energy storage systems may be subject to constraints and dispatching instructions from grid operators, therefore storage operators need to maintain close communication with grid dispatching authorities to ensure that their charging and discharging activities comply with the requirements for safe and stable grid operation.

Energy storage can directly participate in these markets or indirectly through agents/brokers. Electricity markets usually impose minimum entry requirements on participants (e.g., PJM's frequency regulation market has a threshold of 0.1MW). Some distributed energy storage systems, due to limited capacity, can only participate through an agent or broker. Aggregating more energy storage units through agents enables centralized and coordinated dispatching, often leading to higher profitability. An agent can either own the energy storage units or simply be responsible for aggregating, managing and dispatching them to participate in the market. For the former case, the agent's interests align completely with those of the storage units. For the latter, the operational and control models between the agent and the storage units influence the agent's market participation strategy. Besides determining optimal bidding strategies in the market, the agent must also establish management strategies for the energy storage assets.[208]

There are various models for energy storage participation in the electricity market, among which standalone energy storage model and integrated model are two relatively common approaches.[209]

- Standalone energy storage model: Under this model, the storage operator owns both the assets and the right to operate, and can independently decide on charging and discharging strategies based on market price signals and supply-demand conditions, and participate in electricity market bidding and transactions. The advantage of the standalone energy storage model lies in its flexibility and independence. Storage operators can quickly adjust charging and discharging strategies based on market conditions to maximize economic returns. At the same time, this model helps promote competition and vitality in the electricity market and improves its overall operational efficiency. However, the standalone energy storage model also faces certain challenges. For example, the construction and operation costs of energy storage systems are relatively high, requiring longer payback periods;
- Integrated storage model: The integrated storage model refers to the integration of energy storage systems with entities such as power generation companies or grid operators, jointly participating in electricity trading. Under this model, energy storage systems function as supporting infrastructure

208 Chen Dapeng. Research on Operation Strategies and Bidding Mechanisms for Energy Storage Participating in Electricity Markets Based on Flexible Energy States [D]. South China University of Technology, 2020)

209 Analysis of Market Mechanisms and Models for Energy Storage Participation in Electricity Trading [EB/OL]. https://mp.weixin.qq.com/s/7Q6KG0kquwF37-UOz6ScCA, 4 November, 2024

for power generation or grid companies, integrated with their core operations to jointly provide stable and reliable power supply to the power system. The advantage of the integrated storage model lies in its synergy and complementarity. Energy storage systems can be coordinated with the power generation units to smooth out the volatility of renewable energy sources; they can also be integrated with the transmission and distribution facilities to enhance the flexibility and stability of the power system. At the same time, the integrated storage model also helps reduce the construction and operating costs of storage systems, improving their economic efficiency. However, the integrated storage model also requires consideration of coordination and compatibility between the energy storage systems and the core business operations. The charging and discharging strategies of energy storage systems need to be aligned with the operational plans of power generation or grid companies to ensure the overall safety and stable operation of the power system.

The fundamental principle of electricity markets is technology neutrality — that is, different types of resources should receive equal compensation if they provide the same service. When mechanisms such as time-of-use pricing, ancillary services, and capacity markets are well-established — fully accounting for the time-based value of electricity, the value of flexibility regulation, and ensuring scientifically reasonable cost allocation — energy storage can participate in various markets through generation, grid, load-side, or independently. In such cases, the revenue obtained should not depend on how it participates. However, during the early stages of market development when mechanisms are not yet mature, cross-subsidies may exist across multiple stages, and the value of certain services may not be fully reflected, resulting in significant differences in revenue depending on how energy storage participates in the market.

7.1.2 Capacity and energy markets

(1) Capacity market

System operators calculate and determine the total capacity requirement based on metrics such as Loss of Load Expectation (LOLE) and Value of Lost Load. The lower the LOLE, the higher the system reliability, and consequently, the greater the total required capacity. This total capacity requirement is then transformed into a responsibility for capacity procurement, which is allocated to demand-side market participants (or directly purchased by the system operator). The supply side of the capacity market includes existing and new capacity providers, as well as demand-side response resources, thereby establishing the supply-demand relationship in the capacity market. The capacity markets designs vary significantly across regions.[210]

As electricity markets continue to develop, the power generation mix is constantly being optimized and adjusted. The sharp increase in the share of renewable energy generation has crowded out generation space previously occupied by traditional thermal power units. On the other hand, rising coal prices have led to

[210] Energy and Electricity Market Research, Analysis and Reflections on International Electricity Market Capacity Mechanisms [EB/OL]. https://mp.weixin.qq.com/s/Ga36zUGgcU1e_LQvD22xiQ, 19 July, 2024

situations where thermal power units generate insufficient revenue or even suffer losses, causing some units to face survival challenges. The functions of the capacity market are mainly reflected in the following aspects: i) Achieving long-term equilibrium in the power system and ensuring sufficient available capacity; ii) In the capacity market, both existing and new generation units compete on the same platform, to some extent curbing market power and reducing the influence of any single generation source on price formation; iii) The capacity market works in coordination with the energy market and ancillary services market to ensure full cost recovery for generation units, without affecting the energy market's objective of minimizing generation costs.[211] Capacity markets are generally composed of bilateral markets, primary auction markets, and supplementary auction markets. Taking the PJM capacity market in the United States as an example, the capacity market consists of multiple auction markets, including one base auction market and three supplemental auctions.

The purpose of a capacity market is to help power plants recover construction costs, encourage investment, and ensure the system has sufficient available capacity. Some generation capacity exists only for rare peak periods; if new energy storage systems are built, they can achieve the same effect through peak shaving and valley filling. Therefore, energy storage systems can, to some extent, substitute for *peaker* plants in the capacity market and earn revenues from the services. In the capacity market, different types of energy storage receive varying levels of capacity compensation, and storage systems with longer charge-discharge cycles and larger capacities are considered more reliable and thus receive higher compensation.

(2) Energy market

The energy market primarily involves transactions of electrical energy between generators and loads. Due to its charging and discharging characteristics, energy storage can participate in the energy market either as a generator or as a load. Based on the characteristics of energy storage, different markets impose different bidding requirements. These include quantity-only bidding, quantity-and-price bidding, and fully dispatched modes. The table below compares the bidding methods used by energy storage in energy markets, including those operated by PJM (Pennsylvania-New Jersey-Maryland Interconnection), CAISO (California Independent System Operator), and ERCOT (Electric Reliability Council of Texas).[212]

Table 7-1 Bidding Methods for Energy Storage in the Energy Market

Quotation method	Application region	Content	Market clearing methods	Characteristics
Quantity-Only Bidding	PJM, CAISO, ERCOT	Energy storage only submits its output profile, without	The output profile is entered as a boundary	This simplifies the market clearing model but does not guarantee the maximization of social welfare; It is a general market

[211] A Brief Discussion on Capacity Compensation Mechanisms and Capacity Markets [EB/OL]. https://mp.weixin.qq.com/s/Eg94gliuaczKE1DbuZUZfg)

[212] Lou Jiashu, Li Jihong, Xue Bike, et al. Bidding and Revenue Models of Virtual Power Plants with Energy Storage Participating in Foreign Electricity Markets and Their Implications for China [J]. Distribution & Utilization, 2023.

		submitting a price bid.	condition in the market clearing model.	participation method that can be chosen by energy storage systems with different characteristics.
Quantity-and-price bidding	Pumped hydro storage in PJM and other US markets often uses this approach.	Energy storage submits its operational status, physical parameters, and charging/discharging prices.	Based on these submissions, the market clearing process determines the charging and discharging schedules for the energy storage units.	Ensure the maximization of social welfare; In the PJM market, the state of charge (SOC) of energy storage is managed by the storage operator, which may lead to an infeasible output plan; This method is applicable to both pumped hydro storage and electrochemical energy storage.
	CAISO	Energy storage submits physical parameters and charging/discharging prices.		Ensure the maximization of social welfare; This ensures the feasibility of the clearing results; It is particularly suitable for electrochemical energy storage.
Fully Dispatched Mode	PIM	Energy storage fully transfers control authority and does not submit quantity-and-price bids.	The output profile is entered as a boundary condition in the market clearing model.	This is a highly regulated approach, primarily applied to large-scale pumped hydro storage units; It increases the complexity of the market clearing model and is not well-suited for future market environments.

Source: Lou Jiashu, Li Jihong, Xue Bike, et al. Bidding and Revenue Models of Virtual Power Plants with Energy Storage Participating in Foreign Electricity Markets and Their Implications for China [J]. Distribution & Utilization, 2023.

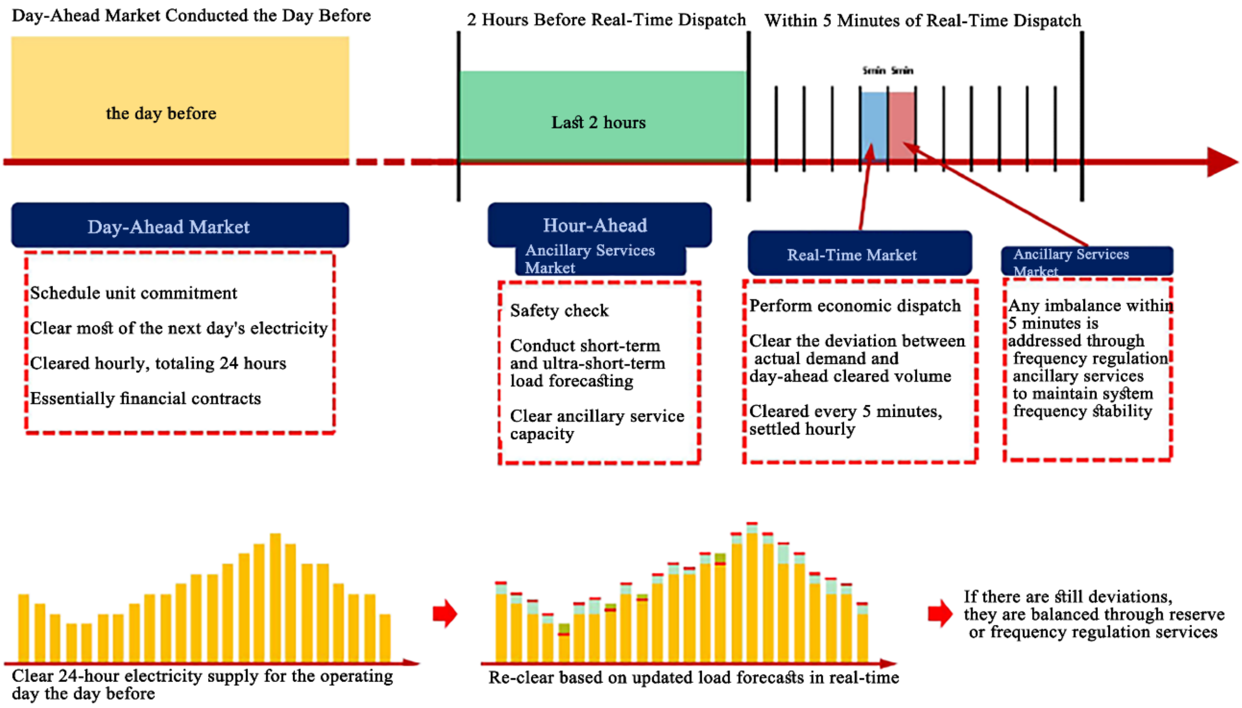
- Quantity-only bidding means that energy storage submits quantities (i.e., charging and discharging electricity levels for each time period) without specifying prices. This method is mainly used in the early stages of energy storage development when capacity is relatively small. It provides greater flexibility to operators who act as price takers, enabling them to determine charging and discharging schedules more freely while ensuring feasibility. Under this method, accurate market price forecasting is critical; significant forecast errors may result in revenue losses for the storage operator. For energy storage operators, strategies typically include optimizing charging/discharging schedules based on predicted 24-hour electricity prices or using historical price data to generate probabilistic price functions for optimization.

- Quantity-and-price bidding refers to a bidding method where both the quantity and price are submitted — that is, participating in the energy market by submitting a quantity-price curve. Under this method, the storage operator must submit charging/discharging bids along with the system's physical parameters. The market operator then determines the charging/discharging schedule based on the market clearing model, and the storage unit earns revenue according to the cleared prices.

7.1.3 Spot market and ancillary services market

(1) Spot market

The spot market in electricity markets generally consists of two components: the day-ahead market and the real-time market. The day-ahead market also falls under the category of forward markets. Both the day-ahead and real-time markets trade in energy and ancillary services (primarily frequency regulation and reserve services). The day-ahead market typically conducts joint clearing of energy, frequency regulation, and reserves. Based on generation offers, demand bids, ancillary service offers, and bilateral contracts submitted to the market, hourly clearing prices for the following day are calculated. The real-time market essentially serves as a balancing market. It performs security-constrained economic dispatch based on actual operating conditions and calculates settlement prices every five (or ten or fifteen) minutes. The day-ahead and real-time markets usually have separate pricing mechanisms.



Source: Chen Dapeng. Research on Operation Strategies and Bidding Mechanisms for Energy Storage Participating in Electricity Markets Based on Flexible Energy States [D]. South China University of Technology, 2020

Figure 7-2 Operational Process of the Spot Market

The Pennsylvania-New Jersey-Maryland (PJM) and California Independent System Operator (CAISO) electricity markets allow energy storage to participate in the spot market through quantity-and-price bidding or self-scheduling methods. In China, in the spot markets, Shandong allows standalone energy storage systems to participate in the market through quantity-only bidding, and over 20 standalone energy storage plants are participating, with a total capacity of approximately 2GW; Shanxi allows standalone energy storage to choose either quantity-and-price bidding or quantity-only bidding on a monthly basis for participation in the spot market.[213]

[213] Southern Energy Observer. Key Mechanism Discussion on Standalone Energy Storage Participating in the Electricity Spot Market [EB/

(2) Ancillary services market

Ancillary services are essential for the safe and reliable operation of the power system and serve as the foundation for the reliable supply and consumption of electricity. Ancillary services can be categorized into three types based on system operating conditions and functions:

- Primary service is active power balancing services, which mainly include frequency regulation, reserve capacity, and ramping services. The essence of these services is that generating units reserve a portion of their capacity to adjust output up or down when needed, in order to meet the system's active power balance requirements;
- The second category is reactive power balancing services, also known as voltage control services. These primarily include automatic voltage control (AVC), phase-shifting operation, and other related services;
- The third category includes emergency response and recovery services, such as stable generator tripping, load control, and black start capabilities during large-scale outages or other emergencies.

Table 7-2 Functions of Power System Ancillary Services

Category	Type	Function and Role
Active Power Balancing	Peak shaving	Address renewable energy integration challenges
	Frequency modulation	Ensure the safety and stability of the power system frequency
	Backup	Reserve generation capacity to respond to system contingencies
	Flexible ramping capability	Respond to short-term significant changes in net load
Reactive Power Balancing	Reactive Power Regulation	Supply reactive power to maintain voltage stability
	Automatic voltage control	Automatically regulate to achieve proper voltage distribution across the grid
Emergency response and recovery	Black start	After a large-scale blackout, power system restoration is provided by generating units with black-start capabilities

Most energy storage systems possess physical characteristics such as fast response times and limited energy capacity. Different types of energy storage vary significantly in terms of response speed, energy density, efficiency, lifespan, and economic cost, enabling participation in various markets and provision of different service offerings. New energy storage technologies, represented by electrochemical energy storage, offer fast response capabilities and can provide multiple ancillary services such as frequency regulation

OL]. https://mp.weixin.qq.com/s/MSu441uKIMzrWgLXcDt2pg, 24 August 2023 (including primary and secondary frequency control), peak shaving capacity, reserve capacity, and rapid ramping support.

Table 7-3 Energy Storage Technologies and Their Applicable Ancillary Service Markets

Energy storage technology	Response speed	Energy density	Efficiency/%	Cycle life/times	Suitable applications
Pumped hydro storage	Second-to-minute level response time	Very low	75~85	>10 000	Large-scale energy storage, peak shaving and valley filling, improving power supply reliability
Electrochemical energy storage (e.g., lithium-ion batteries)	Millisecond level	Very high	90~100	2 000~3 000	Used as standby and for frequency modulation and improve the reliability of power supply
Electrochemical energy storage (e.g., lead-acid batteries)	Millisecond level	High	60~95	2 500~3 000	Used as standby and for frequency modulation and improve the reliability of power supply
Mechanical storage (e.g., compressed air energy storage)	Second-to-minute level response time	Relatively low	80	>10 000	Peak shaving and valley filling, improve power supply reliability
Thermal energy storage	Second-to-minute level response time	Moderate	50~90	>10 000	Absorbing renewable energy, performing peak shaving and valley filling
Hydrogen storage	Second level	Relatively high	25~85	About 1000	Absorbing renewable energy, seasonal energy storage

Source: Chen Qixin, Fang Xichen, Guo Hongye, et al. Mechanisms for Energy Storage Participation in Electricity Markets: Current Status and Future Outlook [J]. Automation of Electric Power Systems, 2021

7.2 Practices of market participation

The BESS sector is currently experiencing rapid growth, driven by several key trends. Technological advancements continue to play a crucial role, with ongoing improvements in battery chemistry, energy density, and overall system efficiency. While lithium-ion batteries remain the dominant technology, emerging alternatives such as sodium-ion, flow batteries, and solid-state batteries are gaining traction, offering potential advantages in terms of cost, safety, and suitability for longer-duration storage applications. The integration of artificial intelligence (AI) is also becoming increasingly prevalent, enabling optimized battery performance, enhanced efficiency, and predictive maintenance capabilities. Furthermore, the development and deployment of grid-forming inverters are enhancing the ability of BESS to provide crucial grid stabilization services, particularly in power systems with a high penetration of renewable energy resources.[214,215]

The structure of electricity markets is also undergoing significant shifts, creating new and expanding opportunities for BESS. Wholesale electricity markets are evolving to better integrate energy storage resources, with the development of new market products and rules that recognize their unique capabilities as introduced above. The increasing penetration of variable renewable energy is driving greater price volatility in these markets, leading to more opportunities for profitable energy arbitrage. The rise of virtual power plants (VPPs) is enabling the aggregation of distributed BESS, allowing smaller-scale systems to participate in wholesale markets and provide valuable grid services. Furthermore, there is a growing focus on the development and deployment of longer-duration energy storage (LDES) technologies to support deep decarbonization goals and ensure grid reliability over extended periods. Mian market mechanism implemented and market operation in selected APEC economies are list in Table 7-4.

Table 7-4 Main Market Participation Mechanism of BESS

Economy	Key market participation mechanisms for BESS	Description and context
China	• Ancillary Services Markets: BESS primarily participate in frequency regulation, voltage support, and reserve markets. • Peak Shaving/Load Leveling: Utilized to manage demand peaks and reduce reliance on traditional generation. • Renewable Energy Integration: Co-located with wind and solar to smooth output and participate in grid connection requirements. • Emerging Capacity Markets: Moving towards market-based mechanisms and capacity compensation for standalone energy storage.	China's market is transitioning from mandatory storage allocation to more market-oriented mechanisms. While ancillary services remain key, the focus is shifting towards incentivizing standalone energy storage through capacity mechanisms and competitive bidding.
The United States	• Electricity Markets (Energy Arbitrage): BESS buy power during low-price periods and sell during high-price periods. • Ancillary Services Markets: Active participation in frequency regulation (primary and secondary), spinning reserves, and non-spinning reserves. • Capacity Markets: BESS offer capacity to ensure resource adequacy, receiving payments for availability. • Congestion Relief: Dispatched to alleviate transmission constraints. • Demand Response Programs: Can participate by reducing or shifting demand.	The US has a highly developed market for BESS, with various ISOs/RTOs (e.g., PJM, CAISO, ERCOT) providing multiple revenue streams. FERC Order 841 facilitated market participation by removing barriers for storage.
Australia	• Control Ancillary Services (FCAS): Dominant revenue stream, BESS provide rapid response to maintain frequency	Australia's NEM is highly conducive to BESS participation due to its 5-

[214] BESS Market Size & Growth: Trends Shaping the Energy Storage Landscape | PCI, accessed 1 May, 2025, https://www.pcienergysolutions.com/2024/12/06/bess-market-size-growth-trends-shaping-the-energy-storage-landscape/

[215] Grid-Forming Battery Energy Storage Systems, accessed 1 May, 2025, https: //www.esig.energy/wp-content/uploads/2025/03/ESIG-GFM-BESS-brief-2025.pdf

Economy	Key market participation mechanisms for BESS	Description and context
	across various FCAS markets. • Wholesale Energy Market (Energy Arbitrage): Exploiting price volatility in the National Electricity Market (NEM) by charging during low prices and discharging during high prices (5-minute settlement). • Network Support Services: Contracted by network service providers for voltage support and congestion management. • Capacity Mechanisms (e.g., Capacity Investment Scheme): Emerging schemes to incentivize firm capacity, including BESS. • Virtual Power Plants (VPPs): Aggregation of distributed BESS to participate in wholesale and ancillary services markets.	minute settlement period, which rewards fast-response capabilities. FCAS and energy arbitrage are primary revenue drivers, with increasing focus on capacity.
Japan	• Wholesale Electricity Market: Participation in day-ahead, intra-day, and forward markets (Japan Electric Power Exchange - JEPX). • Balancing Market (Supply and Demand Adjustment Market): Offers services for real-time balancing, including new products with varying response times (Primary, Secondary-1, Secondary-2). • Capacity Market: Provides payments to secure reserve capacity through T-1 and T-4 auctions. • Long-Term Decarbonization Auctions: Fixed-price, long-term contracts to promote investment in large-scale decarbonization assets like BESS.	Japan's market reforms aim to increase competition and integrate renewables. BESS can generate revenue across wholesale, balancing, and capacity markets, supported by CAPEX subsidy schemes for grid-scale projects.
Korea	• Frequency Regulation Market: BESS play a significant role in maintaining grid frequency, often through dedicated contracts with KEPCO. • Load Shifting/Peak Shaving: Utilized for demand management, participating in programs that encourage shifting consumption to off-peak hours. • Renewable Energy Certificate (REC) System: Historically, co-located BESS with renewables received higher REC weights as an incentive. • Competitive Bidding Markets: The government is increasingly introducing competitive solicitations for BESS capacity to address grid shortages and support renewable integration.	Korea has heavily incentivized BESS, particularly for frequency regulation and load shifting. The market is evolving towards competitive bidding for new capacity, with a strong focus on enhancing grid capacity for renewable deployment.

The ancillary services market is an important channel for energy storage to recover its costs. Most US market operators allow energy storage to participate in frequency regulation, reserve, and black start ancillary service markets; Australia allows energy storage to participate in both scheduled and emergency frequency regulation ancillary service markets. In China, provinces including Shandong, Shanxi, Gansu, Qinghai, Zhejiang, Fujian, Hubei, and Hunan allow standalone energy storage systems to participate in peak-shaving markets; Shandong, Shanxi, Fujian, Sichuan, Chongqing, Jiangsu, Hubei, Anhui, Gansu, Ningxia, and the

Southern region allow standalone energy storage to participate in frequency regulation markets; Shanxi allows standalone energy storage to participate in primary frequency regulation markets; Zhejiang and Shanxi allow standalone energy storage to participate in provincial reserve markets; The Southern region allows standalone energy storage to participate in inter-provincial reserve markets.[216]

7.2.1 The United States

The US electricity markets are overseen by the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) at the federal level, and by Public Utility Commissions (PUCs) at the state level. The US power system is divided into three major interconnections: the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection. Within these interconnections, multiple regional markets are established. The entities operating these markets are Regional Transmission Organizations (RTOs) or Independent System Operators (ISOs). RTOs are responsible for organizing the buying and selling of electricity within the power market. ISOs manage the final market and organize the real-time market to balance generation and load demand. Power generation, transmission, distribution, and sales are handled by independent or integrated companies within the market. Power generation companies are responsible for producing and selling electricity, as well as providing ancillary services. Transmission companies own transmission assets and operate them under the dispatch instructions from ISOs. Distribution companies are responsible for operating the distribution network. On the consumer side, large users can purchase electricity directly from power generation companies through competitive bidding in the wholesale market. Some large users can also participate in ancillary services as load management resources, while others may buy electricity from retail suppliers. Small users who are unwilling or unable to participate in the wholesale market can purchase their required electricity from retail suppliers.

Evolving policy changes, government incentives, and regulatory frameworks are also significantly shaping the BESS market in the United States. For example, the Inflation Reduction Act (IRA) has provided substantial financial incentives for BESS deployment, driving significant investment in the sector. Regulatory orders at the federal level, such as FERC Order 841 and Order 2222, continue to facilitate the participation of BESS in wholesale electricity markets and the aggregation of distributed energy resources. Additionally, various state-level policies and mandates are playing a crucial role in accelerating the adoption of BESS across different regions. In response to growing safety concerns, new standards and regulations are being developed and implemented to ensure the safe and responsible deployment of BESS. Federal acts are guiding and principle-based policies. As each regional market is relatively independent, the policies for each regional market are formulated by each Regional Transmission Organizations or Independent System Operators (RTOs/ISOs). Individual states independently manage and revise the rules related to energy markets, capacity markets, ancillary service markets, transmission assets, and the introduction of aggregators. The following

[216] Southern Energy Observer. Key Mechanism Discussion on Standalone Energy Storage Participating in the Electricity Spot Market [EB/OL]. https://mp.weixin.qq.com/s/MSu441uKIMzrWgLXcDt2pg, 24 August 2023.

section uses the California Independent System Operator (CAISO) and the PJM Interconnection (representing Pennsylvania, New Jersey, and Maryland) as cases for analysis.

(1) California electricity market

In the California Independent System Operator (CAISO) market, energy storage operator can submit price bids, initial state-of-charge (SOC) for the day, and the desired end-of-day SOC. The ISO applies a multi-period coupled economic dispatch model to determine nodal prices and the charging/discharging schedule for the storage units in each time period. Under this model, the state-of-charge constraints of energy storage are considered uniformly by the ISO in the market clearing process, ensuring that the resulting schedules are feasible for the storage systems. In addition to submitting separate bids for charging and discharging, CAISO is also considering allowing storage to submit price differential bids for complete charge-discharge cycles, which provides greater flexibility for storage participation in the market. Besides this specialized market design for storage, storage units can also choose to participate by submitting self-scheduling plans. In this mode, they manage their own state-of-charge but must act as price-takers in the market. In its most recent market reforms launched in 2020, CAISO has also paid attention to the potential exercise of market power by energy storage. In practice, since the costs of discharging depends on the prices at which the storage was charged and the opportunity costs of not being able to discharge during other periods, it is difficult for the ISO to determine the cost range of storage as with conventional generation units. This makes it easier for storage to evade regulatory oversight or bid artificially high prices. To address this, CAISO plans to develop a module to evaluate the discharging costs of storage. The module calculates energy costs, opportunity costs, and degradation costs separately, and then sum them up to obtain the total costs. If the ISO determines that the storage unit may be exerting market power, it will replace the submitted bid price with the calculated costs for market clearing. CAISO requires that energy storage have a minimum discharge duration of 4 hours. A storage system with an energy capacity of 4MWh and a power capacity of 1MW can discharge continuously for 4 hours, so its capacity value is 1MW and its capacity factor is 100%. While a storage system with an energy capacity of 2MWh and a power capacity of 1MW can discharge continuously for 2 hours only, so its capacity value is 0.5MW and capacity factor is 50%.

CAISO already included energy storage as one of the alternative transmission asset options in its *2017–2018 Transmission Expansion Plan*, and has supported the development of energy storage projects.

(2) PJM electricity market

In the PJM electricity market, energy storage must submit price bids and its current operating status. Like other market participants, the price bidding is presented in the form of a quantity-price stepwise curve. The operating status is a special physical parameter submitted by the storage unit, including four modes: charging, discharging, continuous (capable of both), and unavailable. The "continuous" mode indicates that the storage can either charge or discharge. Under the PJM model, the storage unit itself is responsible for managing its state-of-charge to ensure the feasibility of its charging and discharging schedule. If the market clearing result is infeasible, the storage unit can revise its bid up to 65 minutes before real-time operation to trade imbalance energy in the real-time market.

From a dispatch perspective, PJM adopts a centralized scheduling approach. By collecting the physical parameters of energy storage and interactively invoking pumped hydro optimization modules and the market clearing model, PJM obtains the market clearing results that maximize social welfare along with the charging/discharging schedules for the storage units. Under this model, energy storage cannot reflect its operational costs through its bidding strategy.

In discussions on revising the capacity market rules, PJM considers using Effective Load Carrying Capability (ELCC) to measure the capacity value of energy storage—that is, the increase in peak load that a 1MW storage unit can support without compromising system reliability. Since this 1MW storage can have different energy-to-power ratios, ELCC is actually a function of the energy-to-power ratio. By building a market simulation model with inputting parameters such as load curve shapes and distributions, generation mix, and storage configurations, the ELCC value can be derived. This method has already been applied to determine the capacity values of wind and solar PV, but has not yet been widely used for energy storage.

The comparison of energy storage participation across typical electricity markets is shown in the table below.

Table 7-5 Energy Storage Participation in Electricity Markets

<table>
<tr><th rowspan="2">Market</th><th colspan="3">Electric energy</th><th rowspan="2">Capacity confirmation</th><th colspan="2">Transmission & Distribution</th></tr>
<tr><th>Bidding object</th><th>SOC management</th><th>Scheduling method</th><th>Procures</th><th>Markt participation</th></tr>
<tr><td>CAISO</td><td>Charging and Discharging Energy or Cycling Price Difference</td><td>Report Initial and Desired End States, Managed by ISO</td><td>Self-Dispatch</td><td>Base on 4 hours of continuous discharge; otherwise, apply a capacity discount</td><td>Evaluate energy storage as an alternative transmission asset</td><td rowspan="2">No longer provide market services</td></tr>
<tr><td>PJM</td><td>Charging and Discharging Energy</td><td>Self-management</td><td>Self-Dispatch, ISO Dispatch</td><td>Base on 10 hours of continuous discharge; otherwise, apply a capacity discount</td><td>Consult with market participants</td></tr>
</table>

It should be noted that market developments and BESS deployment vary across different geographical regions in the United States. California (CAISO) and Texas (ERCOT) continue to be leaders in the United States, with distinct market structures and primary revenue streams. Other regions in the United States, such as New England (ISO-NE) and PJM, are also making strides in integrating energy storage into their electricity markets.

7.2.2 Australia

The Australian National Electricity Market (NEM) is a single energy-only market, using zonal pricing. It is currently divided into five regions, roughly aligned with state boundaries. In the NEM, energy storage systems have a dual identity, and they are both electricity suppliers and consumers.

In November 2016, the Australian Energy Market Commission (AEMC) issued the *National Electricity Amendment Rules 2016*, which proposed opening the ancillary service markets to new participants. This rule significantly increased opportunities for energy storage to participate in Australia's ancillary service markets, not only enhancing the supply of frequency control services but also helping to lower their prices. In August 2017, AEMC released the *National Electricity Amendment Rules 2017*, aimed at defining the ownership and usage rights of customer-side resources, clarifying the services they can provide, and preventing unfair competition when such resources participate in the electricity market. Energy storage is increasingly becoming an important part of the NEM; however, as an emerging technology, it still faces many challenges and barriers in its integration into the market. Australia is working on electricity market rule reforms to help energy storage enter the NEM and generate revenue by providing clear price signals, defined identities, effective incentives, and additional revenue streams. These rules include: the 5-minute settlement mechanism, the Integrated Resource Provider (IRP) market participant status, and the System Integrity Protection Scheme (SIPS).

(1) 5-Minute Settlement Mechanism

In July 2020, AEMC announced that a 5-minute settlement mechanism for NEM spot prices would be implemented from October, 2021. Australia implements zonal pricing, with each state serving as a pricing zone. During system clearing, a reference node is selected in each zone. The weighted average of the 5-minute clearing prices within each 30-minute settlement period at the reference node determines the regional price. Prices at other nodes within the zone are calculated by multiplying the reference node price by the corresponding loss factor for that location.

The 30-minute settlement interval being used, introduced in 1998, has become inadequate due to the increasing share of renewable generation and the retirement of fossil-fuel-fired plants, including coal-fired units. The system demands more flexible and fast-responding technologies. The 30-minute pricing mechanism fails to capture rapid price fluctuations and does not adequately incentivize fast-responding resources like battery storage, thereby limiting opportunities for energy arbitrage. The 5-minute settlement mechanism, on one hand, aligns better with the existing 5-minute dispatch interval, and on the other hand, increases the granularity of settlement periods. This allows for more accurate price signals, better compensation for fast-responding resources like energy storage during short-term charge/discharge cycles across multiple trading intervals, and ultimately improves their profitability.

This rule change facilitates the participation of fast and flexible resources such as energy storage systems and demand response services in the market, thereby encouraging investment in these technologies. Moreover, since this rule change increases the arbitrage opportunities for energy storage in both the NEM and the Frequency Control Ancillary Services (FCAS) market, it will also affect the payment mechanisms and cost allocations for both market-based and non-market-based ancillary service products.

(2) Integrated resource provider market

When the National Electricity Rules (NER) were first developed, there was limited deployment of energy storage in the market, so storage was not extensively considered in the rules. As more energy storage systems are connected to the power system, and without a clearly defined market identity, storage often registers and participates in the NEM under two different categories—generator and consumer. A series of issues related to this dual identity have gradually surfaced.

Firstly, the way energy storage shares non-energy costs differs from that of other market participants. Non-energy costs refer to technical costs incurred by AEMO in managing the power system through market-based ancillary services (e.g., frequency control), non-market-based services (e.g., black start), and regulatory mechanisms. Generally, AEMO recovers the costs of these services and mechanisms from market participants proportionally based on their energy consumption and generation during each trading interval. However, grid-scale battery storage operates under two registered market identities (as generator and consumer) during charging and discharging, meaning it must pay non-energy costs during both generation and consumption phases. Other market participants, including generators, users, and micro-generator service aggregators (MGSAs), register under a single identity. Their fees are mainly based on net metering data (i.e., the difference between consumption and generation). This results in an unequal cost burden for energy storage compared to other participants. Secondly, under the current identity framework, energy storage must participate in market bidding as either a load or a generation resource separately; it cannot be combined into a single bid. AEMO can only schedule them separately based on these two identities. In addition, during settlement, energy storage must calculate the marginal loss factor separately for both load and generation. The marginal loss factor is calculated by AEMO and published annually on 1 April. It reflects the losses incurred during transmission and distribution due to physical factors such as resistance. This factor is applied during settlements between AEMO and market participants, thereby affecting their revenues. Therefore, when considering the marginal loss factor twice (once for charging and once for discharging), the revenue of energy storage is significantly impacted. Finally, for hybrid systems—whether they include energy storage or not—the different technologies within the system must submit separate bids, undergo independent dispatch ranking, and be scheduled individually. For example, if a hybrid system includes both battery storage and a wind farm, the wind farm and the battery must participate in the market separately, which limits the flexibility of the entire hybrid system, or parts of it, in responding to dispatch instructions.

Based on the above issues, on 23 August 2019, AEMO submitted a request to AEMC to amend the market rules in order to better support energy storage participation in the NEM. AEMC launched a rule revision initiative titled *Integrating Energy Storage Systems into the NEM*, and after extensive consultation, finalized a draft rule determination in September 2021, in which AEMC proposed the following rule changes:

- Introduce a new market participant registration category called Integrated Resource Provider (IRP), allowing energy storage and hybrid systems to register under a single market identity instead of being classified under two separate categories.
- Clarify the dispatch obligations applicable to hybrid systems with different technology configurations, including DC-coupled systems (where multiple technologies are connected after a single inverter system), so that system operators can flexibly decide whether each component should be fully dispatched or partially dispatched.
- Allow hybrid systems to manage their internal energy flows beyond the point of connection, enabling overall dispatch consistency within the system's safety margins.
- Establish performance standards applicable to grid-scale storage units and individual technologies within hybrid systems, which can be used to measure the performance of those technologies at the point of connection.
- Move existing small generator aggregators into this new category and encourage aggregators of new small-scale generation and/or storage units to register under the IRP category (new aggregators may still register as market users). Units registered under the IRP category will be able to provide market ancillary services in both generation and load forms.
- The rule proposes that the new rules will recover non-energy costs based on a participant's consumption and generation, regardless of the market identity they register under. All market participants' consumption and generation will be measured separately, replacing the previous net metering provisions that allowed netting across a single connection point or multiple points of the same participant. The measured quantities do not include generation or consumption behind the point of connection, such as locally consumed rooftop PV generation.

This rule determination aims to simplify the registration process for energy storage in the electricity market, better integrate bidirectional resources like storage into the NEM, enhance clarity and transparency for stakeholders, create a fairer competitive environment for all participants, and ultimately support the transition toward a power system with higher shares of renewable energy and final version of the rule determination was released in June 2024.[217]

(3) System integrity protection scheme

Following the 2016 statewide blackout in South Australia, to prevent future large-scale blackouts caused by multiple generators tripping offline, ElectraNet, the transmission network service provider in South Australia, developed and implemented the System Integrity Protection Scheme (SIPS) in December 2017, supported by AEMO. The scheme consists of three progressive stages: i) Trigger fast response, where battery

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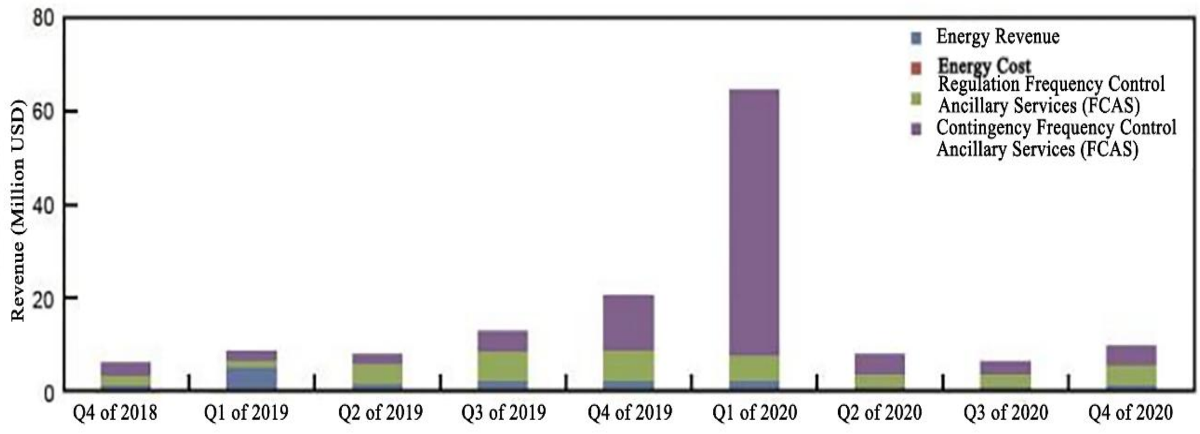
[217] AEMC. 2024. Implementing integrated energy storage systems.https://www.aemc.gov.au/rule-changes/implementing-integrated-energy-storage-systems.

storage systems inject energy into the grid; ii) Trigger load reduction, cutting 200–300MW of demand within South Australia; iii) Out-of-step tripping, disconnecting external interconnection points and causing South Australia to operate in island mode. Currently, Tesla's 100MW/129MWh battery at the Hornsdale Wind Farm in South Australia participates in SIPS and serves as a key player in the first stage of the scheme, protecting the Heywood Interconnector between South Australia and Victoria. Although SIPS reserves 70MW of capacity from this facility, the battery can respond within 250 milliseconds of receiving a signal from ElectraNet and provide 70–140MW of capacity support to the Heywood Interconnector.

While SIPS is a critical tool for the South Australian government to address increasing grid security challenges brought by growing renewable energy integration, the plan was not designed to address what actions should be taken if South Australia were to become isolated from the NEM. Therefore, on 5 November, 2018, AEMO submitted an application to AEMC requesting an upgrade to SIPS, including measures to limit the import capacity through the Heywood Interconnector when destructive wind events are forecasted.

The NEM transmission network has a long and low-density structure, with generation units and load centers distributed across wide areas. Therefore, Australia is seeking to enhance the connectivity between transmission networks through the deployment of new energy storage systems. Drawing on South Australia's SIPS experience, the Victorian government commissioned AEMO to implement a SIPS service procurement program aimed at reducing the risk of power outages during peak summer demand periods. Most of Victoria's thermal power plants are aging and pose supply security risks. Combined with increasingly frequent extreme heat events due to climate change, Victoria urgently needs additional capacity to ensure reliable and stable power supply. AEMO has selected Neoen to develop a 300MW 450MWh battery storage project and signed a SIPS service supply contract, reserving 250MW of its capacity to enhance the transfer capability of the Victoria–New South Wales interconnector. When a system emergency occurs, such as a transmission line trip, AEMO requires 15 minutes to secure system stability and avoid overloading the Victoria–New South Wales interconnector, thus preventing widespread blackouts. The battery can discharge continuously at 250MW for 30 minutes, providing system stability and giving AEMO time to adjust power flows or arrange alternative emergency measures. According to the contract, 250MW of energy storage capacity will provide SIPS services during the Australian summer period, while 50MW is be managed by the system operator and used for commercial purposes. Outside of the summer season, the entire capacity of the energy storage facility can be used for commercial purposes.

From 2018 to 2020, looking at the revenue sources of energy storage in the NEM, the Frequency Control Ancillary Services (FCAS) market remained the primary source of income for large-scale battery storage systems. According to Bloomberg New Energy Finance (BNEF) data, in 2020, energy storage participation in the FCAS market demonstrated strong profitability, accounting for 99% of total market revenues.



Source: Liu Guojing, Li Bingjie, Hu Xiaoyan, et al. Policies and Market Mechanisms of Energy Storage in Australia and Their Implications for China. Energy Storage Science and Technology, 2022

Figure 7-3 Revenue of Battery Storage in the Australian Electricity Market (2018–2020)

For residential energy storage, the main source of revenue comes from electricity bill savings achieved through self-consumption of rooftop solar PV, while additional revenues vary depending on state-level policies. Taking the South Australian VPP energy storage project as an example, in January 2020, after a storm damaged the state's transmission lines, the VPP energy storage project generated more than AUD1 million in revenue within less than two weeks. Related estimates show that the average Australian household consumes about 18kWh of electricity per year, and participating in the VPP program enables households to earn nearly AUD3,000 annually in the electricity market, meaning the payback period for their energy storage investment is approximately 6–8 years.

7.2.3 Korea

Korea's cumulative installed energy storage capacity from 2010 to 2020 reached 3.79GW. By applications, Korea's energy storage demand is concentrated in front-of-meter storage and behind-the-meter commercial & industrial applications, accounting for 56% and 31%, respectively, of total cumulative installations from 2010 to 2020; Energy-shifting installations have maintained high growth since 2013, with a CAGR of 104% from 2013 to 2020. However, the growth of commercial & industrial storage slowed after 2019 due to fire incidents and subsidy reductions.

All installation increases have been driven by policy, with energy storage showing stronger long-term sustainability. Industrial and commercial energy storage policies are focused on increasing revenue. Following the reduction of subsidies, there was a short-term decline in installed capacity. However, front-of-the-meter (FTM) energy storage installations benefit from long-term Renewable Portfolio Standard (RPS) targets and incentives provided by the Renewable Energy Certificate (REC) policy. Korea's industrial and commercial energy storage subsidy policies include electricity cost discounts and power-based subsidies.

Before 2017, the effectiveness of these subsidies was limited, but starting in 2017, both types of subsidies were significantly enhanced, greatly improving the IRR of industrial and commercial energy storage investments.

- Electricity cost subsidy: To encourage industrial and commercial users to install energy storage systems and participate in peak shaving, Korea introduced an electricity subsidy for industrial and commercial energy storage in 2015, offering a 10% discount on electricity costs when charging during off-peak hours. Starting in May 2017, the Korean government significantly increased the subsidy, raising the charging discount to 50%, and introducing a weighting mechanism based on system power capacity: for storage systems with contracted capacities less than 5%, between 5% and 10%, and greater than 10%, providing 0.8x, 1.0x, and 1.2x the base subsidy respectively.
- Power capacity subsidy: In April 2016, Korea announced that energy storage systems participating in peak load management during high-demand periods would receive subsidies based on their power capacity. In May 2017, the power compensation was increased to three times the original level. At the same time, the policy introduced a weighting mechanism based on the system power capacity: for storage systems with contracted capacities less than 5%, between 5% and 10%, and greater than 10%, providing 0.8x, 1.0x, and 1.2x the base subsidy respectively.

In addition, Korea implemented the RPS for electricity companies, making Renewable Energy Certificates (RECs) a key asset. In 2012, Korea implemented the RPS, mandating that a certain percentage of electricity sold by power companies come from renewable sources. According to the RPS plan, by 2022, after adjustments to REC weights, companies were required to ensure that at least 10% of their electricity generation came from renewable sources. Under the RPS, the assessment indicator imposed on enterprises is the REC—a tradable certificate that verifies a power generator's renewable energy output, making it a critical asset for power producers.

Wind and solar power paired with storage enjoy higher REC multipliers, improving the economics of energy storage investments and stimulating growth in energy-shifting storage installations. Korea's RPS mandates that power companies generate a certain percentage of their electricity from new and renewable sources. Compliance depends on actual renewable generation and REC multipliers, and excess RECs can be traded in the market. To encourage energy storage development, the Korean government grants higher REC multipliers to wind/solar + storage systems, enhancing the economic attractiveness of storage investments and driving rapid growth in the energy-shifting market.

7.4 Challenges faced for market participation

Despite the numerous benefits and increasing participation of BESS in electricity markets, several challenges and barriers still hinder their wider adoption. Navigating the complex and often evolving regulatory landscape poses a significant hurdle. These include: i) The lack of standardized regulations and consistent interconnection protocols across different jurisdictions can create uncertainty and impede the smooth deployment of BESS projects; ii) Obtaining the necessary permits can be a lengthy and challenging process, often exacerbated by local community concerns regarding the safety and potential environmental impact of BESS installations; iii) Policy changes, such as unexpected increases in tariffs on imported components or alterations to existing tax incentives, can also significantly impact the economic viability of BESS projects; iv) Limitations in current electricity market designs also present barriers to fully valuing the capabilities of BESS. Market rules, often initially developed for traditional power generation technologies, may not adequately recognize the unique characteristics and rapid response capabilities of BESS; (v) Existing market mechanisms may also undervalue the potential for BESS to provide multiple services simultaneously. Moreover, vi) limitations in grid infrastructure and the availability of interconnection capacity can restrict the participation of BESS in the market and limit their potential to generate revenue.[218] Table 7-6 main challenges and potential solutions for BESS market participation in the region.

Table 7-6 Main challenges and potential solutions for BESS market participation

Challenge	Potential solutions for market participation
Regulatory Hurdles	• Develop standardized regulations and interconnection protocols; • Streamline permitting processes; • Ensure consistent policy support and long-term visibility for incentives.
Market Design Limitations	• Reform market rules to fully value BESS capabilities, including fast response and multi-service provision; • Create market mechanisms that adequately compensate for the benefits of BESS; • Invest in grid infrastructure upgrades to improve interconnection capacity.
Economic Viability	• Implement revenue stacking strategies; • Provide continued government incentives and funding; • Develop innovative financing mechanisms to mitigate merchant risk; • Support research and development to further reduce capital costs and improve battery lifespan.
Technical Challenges	• Promote research and development in battery technology to improve performance, safety, and lifespan; • Establish and enforce robust safety standards and best practices for BESS deployment and operation; • Develop sophisticated energy management systems for optimized control and grid integration.

The economic viability of BESS deployment is another critical consideration. While the costs associated with battery technology have been decreasing, the upfront capital investment required for BESS projects remains substantial. Securing project financing can be challenging, particularly due to the reliance on

[218] American Clean Power Association. 2025. Market Reforms to Harness Energy Storage and Strengthen Regional Grid Reliability. The A merican Clean Power Association (ACP).

merchant revenue streams that are subject to market volatility. Therefore, the implementation of effective revenue stacking strategies is crucial for maximizing the financial returns of BESS projects. Additionally, the long-term economic analysis of BESS projects must account for battery degradation and the eventual costs associated with battery replacement.

Finally, several technical challenges need to be addressed to ensure the successful deployment and operation of BESS. Battery degradation over time can lead to a decline in system efficiency and increased maintenance requirements. Safety concerns, especially those related to the potential for thermal runaway and fires in lithium-ion batteries, necessitate the implementation of robust safety measures and proactive engagement with local communities. Operational complexities, including the effective management of the battery's state of charge, the optimization of dispatch strategies to maximize revenue, and ensuring seamless integration with the existing electricity grid, also require careful consideration.

7.5 Chapter summary

Battery energy storage systems are playing an increasingly vital role in the transformation of electricity markets. Their ability to enhance grid stability, facilitate renewable energy integration, improve market efficiency, and provide backup power offers significant benefits in the transition towards a more sustainable energy future. BESS is increasingly viewed as an essential technology for achieving net-zero emissions targets and enabling a successful energy transition. The ability to strategically stack revenues by participating in multiple markets will be crucial for maximizing the value of BESS assets. While challenges related to regulation, market design, economics, and technology persist, ongoing advancements and supportive policies are paving the way for wider and more effective BESS applications. To fully harness the potential of BESS, policymakers should focus on developing clear and consistent regulatory frameworks, reforming market designs to accurately value the diverse capabilities of BESS, and providing continued incentives for research, development, and deployment. Streamlining permitting processes, promoting industry collaboration on safety standards, investing in grid infrastructure upgrades, and supporting the advancement of long-duration energy storage technologies are also crucial steps in this endeavor.

Current market structures often fail to adequately compensate BESS for the multifaceted grid services they can provide, treating them merely as energy resources rather than flexible assets capable of rapid response. Optimizing BESS participation in electricity markets is important, and key policy recommendation revolves around refining electricity market designs to fully recognize and compensate the comprehensive value BESS offers. Policies should be enacted to create distinct market products and revenue streams for services without being unduly penalized such as fast frequency response, voltage regulation, black start capabilities, and inertia support, ensuring that BESS can stack these revenues. Policy recommendations to elevate BESS participation must begin with a fundamental redesign of market frameworks to properly value flexibility and speed. Across North America, Asia, and the Pacific, regulators should mandate that system operators implement "co-optimized" markets. This allows a single BESS asset to simultaneously bid into multiple value streams, such as the energy market for arbitrage, and a full suite of ancillary services like primary frequency response, voltage control, and spinning reserves. For example, a battery could be charging from the grid while also being paid to stand ready to instantly halt charging and discharge to correct a frequency deviation. Furthermore, markets must evolve to incorporate sophisticated locational and temporal price signals. This means a megawatt-hour of storage discharged in a transmission-congested area of a city during an evening peak is explicitly valued higher than one discharged in an uncongested area at midday. While operators like the California ISO (CAISO) are advancing these concepts, emerging markets in Asia should adopt these principles directly to avoid legacy inefficiencies and ensure BESS are dispatched based on their full, multi-faceted value to the grid.

For many nascent markets in the region, it is needed to establish explicit market mechanisms for BESS to participate, moving away from single-buyer models towards more competitive and transparent frameworks that incentivize the deployment of flexible resources to support increasing renewable penetration and greater grid flexibility. This requires a granular valuation of BESS attributes across different timescales and operational modes, moving beyond traditional energy arbitrage models to acknowledge their significant contributions to grid stability, reliability, and resilience. Also, by allowing BESS to participate in multiple markets simultaneously and optimizing their dispatch based on real-time needs, market operators can unlock greater value, incentivize private investment, and ensure that the economic benefits of BESS are fully realized by project developers. To obtain the necessary capital for a BESS build-out, policies should address investment risk by offering long-term revenue certainty. Energy-only markets, such as Texas's ERCOT, are subject to fluctuations that may discourage mainstream financial institutions. A key recommendation is therefore the implementation of robust capacity mechanisms. In these schemes, such as Australia's Capacity Investment Scheme or the auctions held in PJM territory in the United States, BESS providers receive a regular, fixed annual capacity payment in exchange for guaranteeing their availability during future periods of system stress. This reliable capacity payment acts as a foundational revenue layer, making projects more bankable and lowering the cost of capital. For regions yet to adopt full capacity markets, an alternative is promoting standardized, long-term government or utility-backed contracts for specific reliability services, which can provide a similar level of financial certainty needed to get projects built.

Finally, efficient deployment at scale requires a shift from reactive integration to proactive, strategic grid planning. A critical recommendation is for all jurisdictions to adopt a transparent, long-term planning process, modelled on AEMO's Integrated System Plan (ISP) in Australia. Such plans should holistically forecast the grid's needs over a 20+ year horizon, identifying the optimal locations and required durations (e.g., 2-hour, 8-hour, or seasonal storage) for BESS investment. This must be paired with aggressive reforms to streamline grid connection processes, which are a major bottleneck in many economies. Solutions include conducting "cluster studies" for multiple projects in a single area, creating fast-track approvals for projects at well-suited locations, and establishing clear communication standards for distributed resources. This latter point is crucial for unlocking the potential of Virtual Power Plants (VPPs), where policies must establish clear rules for aggregation, performance measurement, and compensation to allow thousands of household and commercial batteries to participate reliably in wholesale markets.

Chapter VIII Commercial Environment and Storage Project Development

8.1 Investment and project development

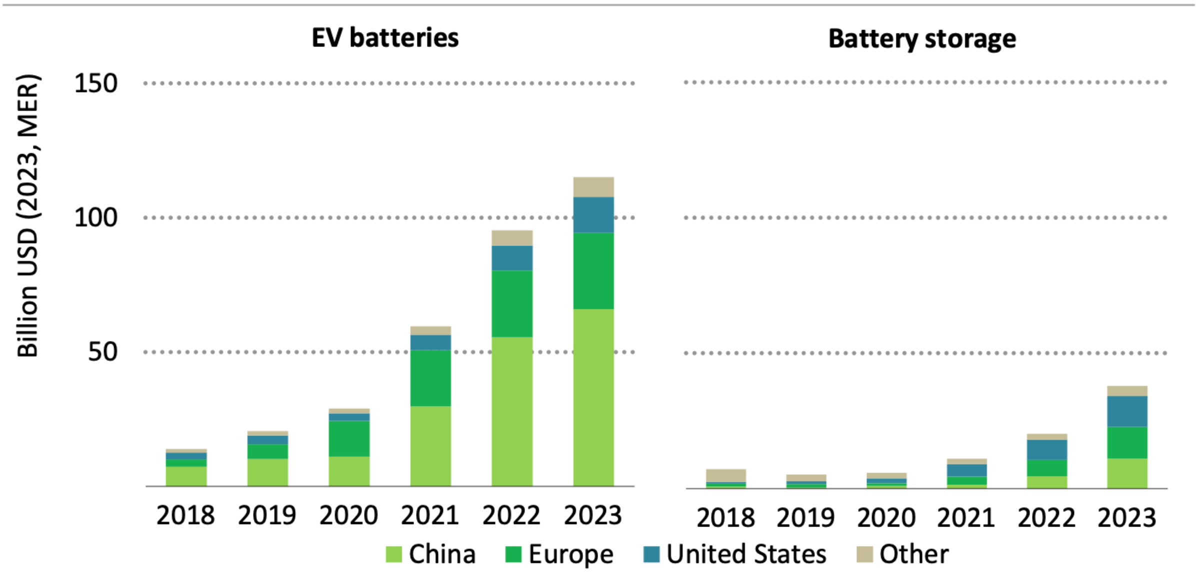
8.1.1 Investment in BESS

Globally, investment in EV batteries and battery storage increased rapidly to USD150 billion by 2023, with spending highly concentrated in China, Europe and the United States, in which storage counts for about 27% of total, USD40 billion. A fivefold increase of investment in BESS since 2018 is meet the demands of electrification and renewable integration. Technology investments have been driving innovation and sustainability, and investments are focusing on scaling and integration into existing energy.

Around 85% of the investment on utility-scale battery storage was in China and the United States. China has witnessed unparalleled growth in BESS investment and deployment over the last five years. Government policies and substantial manufacturing scale have driven down costs and accelerated deployment, making China the global leader. In 2024, China's investment in grid-connected batteries surged by 364% to CNY75 billion (USD11 billion).[219] The United States has seen a significant increase in BESS investment, becoming the second-largest market globally. The Inflation Reduction Act has provided substantial incentives for BESS deployment, further driving investment. Announced investment commitments in 2024 indicate strong continued growth, including a potential USD100 billion industry-wide pledge for domestic manufacturing and significant project-specific investments.[220]

[219] Energynews.pro. 2024. China steps up investment in energy storage. energynews.pro.

[220] Renewables Now. 2024) AIP buys stake in 300-MW solar, 200-MW battery project in Texas. http://renewablesnow.com.



Note: the survey data shows that the cost of capital for battery storage tends to converge to that of solar PV projects in hybrid projects.

Source: IEA

Figure 8-1 Global Investment in EV Batteries and Battery Storage

Other APEC economies like Australia and Korea are among the early adopt of energy storage. Government schemes like the Capacity Investment Scheme in Australia are designed to further stimulate investment in BESS. Australia's attractive energy market design, allowing for revenue stacking, has been a key factor in attracting BESS investment.[221] Korea aims to become a major player in the BESS market. Government mandates and incentives are supporting further growth in the BESS market. KEPCO's KRW830 billion (USD627.57 million) investment in 2024 in an 889MWh BESS portfolio highlights continued substantial investment. As mentioned previously, besides utility-scale storage, distributed BESS, including age for industrial and commercial storage, such as when combined with rooftop solar, has attracted most of the spending in economies like Australia and the United Stages.[222]

A major reason why capital flows to battery storage remain highly concentrated in advanced economies and China is the high cost of capital for clean energy projects in emerging market and developing economies. According to IEA, on average, cost of capital for battery storage projects in developing economies is at least twice as high as in advanced economies.[223] The macro factors like the rule of law and currency fluctuations are among main contributors to the higher cost of capital. Energy sector specific risks are also among the contributor such as unclear or unstable regulation, lack of reliability of revenues, and delays in obtaining grid connections. In APEC region, increasing battery storage investment in Southeast Asia suggest that some

[221] EY. 2024. Four factors to guide investment in battery storage. www.ey.com.
[222] Korea Herald. 2024. KEPCO unveils 889 MWh energy storage system. www.koreaherald.com.
[223] IEA. 2024. Reducing the Cost of Capital. Strategies to Unlock Clean Energy Investment in Emerging Market and Developing Econom. IEA/OECD.

economies are successfully addressing some of these risks, for example, through enacting policy reforms, enhancing the credit worthiness of off-takers, and issuing hybrid tenders that combine renewables with battery storage.

The conditions and approach to arrange and secure project revenue is among the key factors for the deployment of a BESS project. In general, the revenue models can be categorized into two groups, either contract-driven or merchant-driven, based on the operating strategy and risk tolerance of the project. Table 8-1 lists the main attributes of the BESS project investment and market participation, namely contract and merchant-driven revenue models, which shape the decision on a BESS project.

Table 8-1 Factors Affecting Investment Decision on BEES Project

Issues regarding investment and market participation	Category of BESS Projects	
	Contract-driven	Merchant-driven
Revenue stability	Predictable income: long-term agreements with fixed rates	Variable income: earning fluctuate based on market conditions
Level of market exposure	Limited exposure to price volatility in the market	Fully exposed to market dynamics
Risk level	Lower risk with guaranteed payments scheme	Higher risk due to market fluctuations
Profit potential	Consistent but relatively lower rates of returns	Potentially higher profits during favorable conditions
Main revenue streams	Tolling (fixed payments), capacity charge, energy hedge	Energy markets, capacity auctions, ancillary services
Investor profile	Risk-averse investors prioritizing stability	Investors with higher risk tolerance, seeking higher rates of returns

Most storage systems project developed in recent years in the region have applied or combination of these two models. In general, the choice of the model is influenced by the energy market where the BESS operates, as well as market conditions, financial goals, and the investor's risk appetite. Regardless of the model, as discussed, BESS systems normally offer the flexibility to provide multiple services simultaneously, which enables the operators to stack revenues from diverse sources and align revenue strategies with evolving market opportunities. This is particularly relevant in APEC region, given different structure of the power sector and the condition of electricity market development.[224] For the project deployment of BESS, the main commercial requirements include workmanship warranties, performance guarantees, corrective maintenance, insurance requirements and bankability, as specified Table 8-2.

[224] APEC EWG. 2020. Innovative Approaches for Scaling Up Renewable Energy Deployment in APEC Region. https://www.apec.org/publications/2022/07/innovative-approaches-for-scaling-up-renewable-energy-deployment-in-apec-region

Table 8-2 Commercial Considerations of BESS Projects

No.	Dimensions	Main issues and considerations
1	Workmanship warranties	Most BESS manufacturers, together with EPC contractors, offer a 'workmanship warranty' that covers a period following the system's reaching Commercial Operations Date (COD). Most commonly this warranty is valid for 1-3 years, covering initial defects and component failures (short-term).
2	Performance guarantees	Beyond COD, manufacturers typically offer performance guarantees for their systems under a separate Long Term Service Agreement (LTSA). These guarantees allow for a certain level of guaranteed degradation, verified by a capacity test, conducted annually. The most common terms for an LTSA include warranties: • 7,200 cycles over 20 years (equivalent to 1 cycle per day), although some manufacturers are offering warranties up to 10,000 cycles over 25 years • Typical degradation from 100% at COD to approximately 70% in year-20 • Typical round-trip efficiencies • Guaranteed Availability of 97% or more, outside of the system's scheduled maintenance hours
3	Corrective maintenance	Most LTSAs do not cover corrective maintenance, which is the result of an unexpected event in the system's operations, although some contracts offer a higher-priced 'Extended Warranty' which does include a larger payment to account for corrective maintenance work.
4	Insurance requirements	Insurance is typical at several tiers of the project: manufacturers insure their expected degradation levels, EPC contractors hold insurance policies to cover for unforeseeable issues in construction, and projects transition to operational project insurance once the project reached COD.
5	Bankability	All of the above policies, warranties, and guarantees have become more standardized in the industry, resulting in greater confidence for finance of utility-scale energy storage projects; collectively this is a sign of the industry maturing and becoming more bankable.

In addition, BESS project development deals with a range of regulatory issues and challenges tied to safety, environmental compliance, and grid integration. Permitting and zoning requirements often demand rigorous environmental assessments, adherence to technical code and standards and land-use restrictions, particularly for hybrid systems like solar-paired-storage. Safety regulations focus on mitigating risks such as thermal runaway, requiring emergency response plans and specialized fire suppression systems, and increasingly, environmental rules further mandate recycling and responsible end-of-life disposal of battery materials.

8.1.2 BESS project development

Developing BESS projects in urban environments presents a complex interplay of challenges and opportunities. Cities, by their very nature, demand reliable and resilient power, while also presenting significant hurdles such as high land costs, stringent safety regulations, and community concerns. However, the ability of BESS to support renewable energy integration, enhance grid stability, and provide localized energy solutions makes them indispensable for modern urban infrastructure. Examining leading markets like Australia; China; Korea; Japan; and the United States reveals common themes and unique approaches to navigating these urban complexities.

In China, the primary urban BESS development challenges revolve around land availability and cost, given its rapid urbanization and high population density. This leads to limited and expensive sites suitable for large-scale BESS, often necessitating creative solutions in design and siting. Furthermore, safety concerns are paramount, with rigorous regulatory stringency regarding fire risks and hazardous materials in densely populated urban settings, directly influencing public perception and obtaining necessary approvals. The complexity of permitting processes, involving multiple municipal, provincial, and economy’s authorities, can also lead to significant administrative burdens for project developers, requiring a deep understanding of the evolving regulatory landscape. To address these, China has been increasingly exploring vertical integration and co-location of BESS with existing infrastructure, such as substations, industrial parks, and even commercial buildings, to maximize space utilization. Innovations like TBEA's 6.25MWh containerized system, which boasts a 25% increase in energy density and cuts land usage by 30%, exemplify China's focus on space-saving urban solutions. Further implementing robust safety standards with transparent public engagement to build trust and educate communities on BESS benefits, alongside efforts to streamline permitting by developing fast-track processes create good condition energy storage projects in urban areas.

The United States faces considerable challenges related to zoning and permitting, as many municipalities lack clear classifications for BESS projects, leading to some uncertainty, project delays, and local opposition. For instance, in New York, local authorities have extended moratoriums on BESS development due to community concerns, with some officials even filing lawsuits to prevent projects near residential areas. Evolving fire codes (e.g., NFPA 855) and building codes specific to BESS necessitate detailed engineering and compliance, which can be time-consuming and costly for developers to meet stringent safety requirements. Community opposition ("Not-In-My-Backyard" - NIMBY) due to perceived fire risks, noise, and visual impact remains a significant hurdle, often requiring extensive public outreach and education campaigns to counter misinformation. Furthermore, utility interconnection processes can be lengthy and complex, with a significant backlog of projects seeking connection to the grid, delaying project energization and revenue realization.

Advocating for standardized zoning and permitting at municipal and state levels to create a more predictable development environment will help for BESS project development. Fostering proactive code adoption and early engagement with local fire departments is essential to ensure designs meet safety requirements and emergency response plans are in place. In addition, implementing robust community engagement strategies is crucial to build rapport, address concerns, and explain the benefits of BESS, and streamlining interconnection queues is vital for accelerating urban deployments[225].

Australia's urban BESS development is particularly impacted by planning policy gaps, where BESS are often not explicitly recognized as standalone land uses in local planning schemes, causing some uncertainty in zoning and approval processes and potentially requiring reclassifications. Specific concerns around bushfire risks and hazard management are critical, given the economy's climate, requiring detailed safety assessments, emergency response planning, and adherence to specific bushfire-related policies, especially in urban fringe areas.[226] The decommissioning and end-of-life management of batteries, including hazardous waste and recycling, also presents an emerging long-term challenge for sustainability, with regulations still evolving. Public perception regarding safety, noise (e.g., from cooling systems), and visual amenity often leads to opposition to the installations in urban or peri-urban areas. To overcome these, clear planning policy recognition for BESS is needed, along with early engagement with fire services for bespoke safety assessments and the development of comprehensive emergency plans. Developers are encouraged to proactively monitor battery recycling technologies and engage in transparent community consultation to address concerns and highlight the benefits of BESS in urban areas.[227]

In Korea and Japan, the most pronounced challenge is extreme land scarcity and high urban land costs, which makes finding suitable sites and achieving economic viability for large-scale BESS difficult in their densely populated cities. Korea, in particular, has faced historical BESS fire incidents, which led to heightened public scrutiny and the implementation of more stringent safety regulations. This has created a dynamic and sometimes uncertain regulatory environment, requiring developers to demonstrate exceptional safety compliance and often leading to delays as new standards are absorbed.[228] Both economies also operate under stringent building and seismic codes (especially Japan, due to frequent seismic activity), adding complexity and costs to construction in earthquake-prone regions, impacting everything from foundation design of storage station to structural integrity, and public acceptance is highly sensitive to safety and environmental impacts.[229]

For these highly urbanized economies, the solutions include focusing on small-scale and distributed BESS solutions within commercial, industrial, and residential sectors, or exploring innovative co-location opportunities to maximize limited space. Emphasizing advanced safety technologies (e.g., robust battery management systems, enhanced thermal management, and multi-layer fire suppression) and transparent communication about enhanced safety measures is crucial for rebuilding public trust. Both economies can

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[225] NREL. 2025. Renewable Energy System Interconnection Standards | State, Local, and Tribal Governments. https://www.nrel.gov/state-local-tribal/basics-interconnection-standards.html.

[226] Hamilton Locke. 2025. Navigating BESS planning approvals across Australia. https://hamiltonlocke.com.au/navigating-bess-planning-approvals-across-australia/. 16 May 2025.

[227] Alvarez & Marsal. 2025. Understanding the BESS market in Australia. https://www.alvarezandmarsal.com/insights/understanding_the_BESS_market_in-Australia.

[228] EPRI Storage Wiki. 2025. BESS Failure Incident Database. https://storagewiki.epri.com/index.php/BESS_Failure_Incident_Database.

[229] Japan Energy Hub. 2025. 27 grid-scale BESS projects secure 34.6B yen through METI's FY2024 storage subsidy program. https://japanenergyhub.com/news/fy2024-meti-grid-scale-storage-subsidy-results/. 27 January 2025.

leverage strong government incentives and subsidies (e.g., Japan's METI subsidies for grid-scale battery developers, which saw 27 projects secure JPY34.6 billion in FY2024) to offset high development costs and promote deployment. Additionally, for Korea, developing a clearer and more stable regulatory framework is essential to provide predictability and confidence for investors in the evolving BESS market, while Japan benefits from robust market mechanisms like balancing and capacity markets that provide revenue streams for BESS services. Table 8-3 list some main challenges faced for BESS project development in these APEC economies.

Table 8-3 Issues and Challenges for BESS Project Development in Selected APEC economies

Economy	Main challenges for Urban BESS development	Recommendations for urban BESS development
China	Land availability and costs: high population density and industrialization lead to limited and expensive urban land. • Safety concerns: public perception and regulatory stringency regarding fire risks and hazardous materials in urban settings. • Grid congestion: integrating new BESS into already constrained urban distribution networks can be complex. • Permitting complexity: navigating multiple municipal, provincial, and economy authority approvals.	• Vertical integration & co-location: utilize rooftops, basements, or integrate with existing infrastructure (e.g., substations, industrial parks). • Robust safety standards & public engagement: implement and visibly demonstrate adherence to international and local safety standards (e.g., fire suppression, thermal management) and conduct transparent public outreach. • Smart grid integration: leverage advanced control systems to manage grid congestion and optimize BESS dispatch. • Streamlined permitting: develop dedicated, fast-track permitting processes for urban energy storage.
The United States	• Zoning & permitting: varied and often unspecific zoning ordinances for BESS, leading to delays and uncertainty. Local opposition due to perceived safety risks. • Safety codes & standards: Evolving fire codes (e.g., NFPA 855) and building codes specific to BESS, requiring detailed engineering and compliance. • Siting constraints: setback requirements from residential areas, water sources, and environmentally sensitive zones. • Community opposition: Concerns about fire, noise, and visual impact. • Utility Interconnection: lengthy and complex interconnection queues and studies.	• Standardized zoning & permitting: develop clear municipal and state-level zoning classifications and streamlined permitting pathways for - Proactive code adoption & compliance: engage with local fire departments and authorities early to ensure design meets evolving safety codes (e.g., UL 9540, UL 9540A). • Strategic siting: identify industrial zones, former brownfield sites, or co-locate with existing substations. • Community engagement: implement robust public education campaigns to address safety concerns, highlight benefits, and involve local stakeholders. • Interconnection reform: advocate for faster, transparent, and more efficient interconnection processes from utilities and ISOs.

Economy	Main challenges for Urban BESS development	Recommendations for urban BESS development
Australia	• Planning policy gaps: BESS not explicitly recognized as standalone land uses in local planning schemes, causing uncertainty in zoning and approval. • Bushfire risks & hazard concerns: specific safety assessments and emergency response planning needed due to high bushfire risk areas. • Decommissioning & end-of-life management: uncertainty regarding hazardous waste, specialized recycling, and evolving regulatory expectations. • Public perception: concerns about safety, noise, and visual amenity in urban or peri-urban settings.	• Clear planning policy recognition: develop economy- and state-level guidance and policy recognition for BESS in planning schemes. • Early engagement with fire services: consult with relevant state/territory fire services early to integrate bespoke safety assessments and emergency response plans. • Proactive monitoring of recycling tech: developers to monitor legislative changes and technological advancements in battery recycling and ensure robust decommissioning strategies. • Community consultation: transparent communication on safety measures, benefits, and visual mitigation (e.g., landscaping).
Japan	• Land scarcity and cost: extremely high urban land values, making large-scale BESS economically challenging. • Stringent building & seismic codes: strict regulations for construction and seismic resilience for all infrastructure, including BESS. • Public acceptance: high sensitivity to safety and environmental impacts, particularly in densely populated areas. • Grid modernization pace: while advanced, the pace of integrating new flexible resources into a highly reliable, traditionally stable grid can be deliberate.	• Small-scale & distributed BESS: focus on residential, C&I BESS, or co-location with existing facilities. • Advanced safety technology: implement cutting-edge safety features and redundant systems to meet and exceed stringent safety standards. • Government incentives & subsidies: leverage existing and new subsidies from METI to offset high upfront costs. • Collaboration & research: foster collaboration between industry, government, and research institutions to develop optimized urban BESS solutions.
Korea	• Urban density & land use: high urban density makes finding suitable sites difficult and expensive. • Safety incidents & public trust: historical BESS fire incidents have led to increased public scrutiny and more stringent safety regulations. • Regulatory evolving: policy changes and evolving standards can create uncertainty for developers.	• Rebuilding public trust: implement and transparently communicate enhanced safety measures, robust fire suppression systems, and regular inspections. • Clearer and stable regulations: develop a consistent and predictable regulatory framework for BESS deployment, especially concerning safety and market participation. • Strategic siting and space optimization: explore underground installations, co-location with substations, or multi-story BESS designs.

Economy	Main challenges for Urban BESS development	Recommendations for urban BESS development
	• Interconnection grid capacity: ensuring sufficient grid capacity for BESS integration in dense urban areas.	• Community engagement: proactive outreach to address concerns and highlight benefits.

A common thread across the economies is the critical importance of robust safety standards and advanced safety technologies to mitigate public concerns and ensure secure operations. This includes comprehensive fire suppression systems (e.g., aerosol and water spray systems), sophisticated thermal management, arc fault detection, rapid shutdown functions, and strict adherence to international best practices. Streamlining and standardizing permitting and zoning regulations at local and economy levels are important to reduce project timelines and associated costs, fostering a more predictable investment climate. This could involve creating dedicated BESS permitting pathways or incorporating BESS into the cities' energy sector development policies.

Proactive and transparent community engagement strategies are essential to build public trust, address misconceptions, and secure social license to operate, particularly in areas with heightened community scrutiny. This involves open dialogue, clear communication about project benefits (e.g., grid reliability, support for renewables, economic advantages), and addressing concerns. Exploring innovative siting solutions such as co-location with existing infrastructure, vertical integration, and optimizing space in dense urban environments can help overcome land scarcity challenges. This also extends to considering behind-the-meter BESS within commercial and industrial buildings. Simultaneously, targeted financial incentives, such as tax breaks, grants, or favorable financing terms, can improve the economic viability of these crucial urban energy assets, accelerating their deployment in the energy transition and enhancing urban energy system resilience.

8.2 Creating market-oriented business conditions

A favorable business environment is essential to support the development of an energy storage project from initial feasibility studies to final implementation. The business environment refers to various external factors that influence a company's operations and commercial activities, including the policy environment, market conditions, legal framework, investment climate, and business models. Since policies, markets, and legal frameworks have been discussed in previous sections, this section will focus on the investment environment and business models.

8.2.1 Investment environment

Responding to the related policies, investment acts as the key driver for the advancement of energy storage, whereas the business model guarantees the optimization of value creation. Investment determines what and how much is installed, while the business model dictates how profits are made and how much they amount to. Among the three segments of energy storage applications, namely power generation-side, grid-side, and user-side, each presents distinct investment opportunities and, inevitably, associated potential risks. Furthermore, as technology progresses and new applications develop, new business models will emerge. The investment environment and business models for energy storage are closely interrelated. The profitability of a business model largely determines investors' willingness and ability to secure funding, while the investment environment can also drive innovation and development of business models. The following table lists selected APEC economies and cities that are actively promoting energy storage, creating necessary conditions and mobilizing investment for energy storage projects.

Table 8-4 Investment Conditions for Storage Projects[230,231,232]

Economy	Region/City	Investment conditions
United States	California, Texas, New York, Arizona, etc. San Francisco, Los Angeles, New York City, Houston, etc.	The US federal government's *Inflation Reduction Act of 2022* offers tax credits for standalone energy storage investments, significantly boosting the growth of the energy storage market. Additionally, some state governments mandate the installation of battery storage systems in new buildings, such as California. Furthermore, independent system operators in some states have facilitated the participation of battery storage systems in ancillary service markets, such as the New York Independent System Operator (NYISO), California Independent System Operator (CAISO), and ISO New England (ISO-NE).
China	Shandong, Inner Mongolia, Xinjiang, Gansu, Hunan, Ningxia, Guizhou, Guangdong, etc. Changsha, Ningbo, Guangzhou, Hangzhou, Xi'an, Hefei, Dongguan, Changzhou, etc.	Government subsidies and incentives are rapidly accelerating the development of energy storage, such as plans to reduce the cost of battery storage systems by 30% by 2025. Moreover, China's complete industrial chain and supply chain make it a dominant player, accounting for over 50% of global lithium-ion battery storage exports.
Australia	Victoria, New South Wales, South Australia, Queensland, Western Australia, etc.; Canberra, Melbourne, Sydney, Perth, etc.	Daily spot markets for electricity and system frequency control services provide diverse revenue streams. The storage capacities of battery, virtual power plants, and pumped hydro energy storage systems are expected to reach 61GW by 2050. The federal government has reached agreements with states to establish capacity investment programs, allowing bidding for battery storage systems to fill anticipated reliability gaps.

230 Top Five Energy Storage Projects in Japan， https://www.power-technology.com/data-insights/top-five-energy-storage-projects-in-japan/, 2024-09-10.

231 The 10 most attractive energy storage investment markets, https://tamarindo.global/articles/the-10-most-attractive-storage-investment-markets/, 2024-06-19.

232 SaiDi Consulting. https://m.bjx.com.cn/mnews/20230105/1281086.shtml, 2023-01-05.

Korea	North Gyeongsang, Gyeonggi, South Gyeongsang, etc.; Daegu, Ulsan, Ansan, Busan, Suwon, etc.	Major goals related to battery energy storage systems Significant goals related to battery storage systems: becoming the third-largest battery storage market after China and the United States. The Korean government mandates all new public buildings to install energy storage systems, with incentives including tax deductions for battery storage installations.
Japan	Hokkaido, Fukushima, Sendai City in Miyagi, Himeji City in Hyogo, Miyazaki City, etc.	Japan provides multiple revenue streams for battery storage systems, including rolling weekly and day-ahead markets. Battery storage systems can compete in capacity auctions for three-hour blocks, with winners receiving subsidies equivalent to the "fixed costs" of qualified projects, which will include standalone facilities for 20 years.

Enabling greater renewable energy penetration and supporting green energy transition, wide deployment of energy storage in energy systems is needed. However, it has been evidenced that there is an imbalance in energy storage investment, with funds favoring certain hotspot economies and cities, as well as projects that offer stable returns on investment with relatively mature technologies. Favorable government policies and stable profit prospects encourage investor enthusiasm. As discussed before, most of the investment hotspots in the APEC region not only have substantial market demand but also benefit from favorable energy storage incentives and subsidies, along with promising investment expectations.

The significant potential for growth and market demand drives investment increases. China, North America, and Europe are the primary markets for new energy storage globally, accounting for over 80% of the global market.[233] In APEC region, since 2020, the United States has seen rapid growth in energy storage installations, expected to exceed 30GW by the end of 2024, with California and Texas leading the growth.[234] China's operational installed capacity for new energy storage currently stands at 350GW, expected to reach 220GW by 2030. As one of the world's key energy storage markets, Australia's installed capacity is projected to grow from its current 500MW to over 12.8GW by 2030. From now until 2033, Korea's energy storage market is expected to grow at an annual rate exceeding 13.4%. By 2030, Japan's installed energy storage capacity will reach 10.074GW.

Since 2020, global energy storage investment has surged, primarily focused on grid and generation-side applications (accounting for over 65%), though investment priorities may vary across different economies and regions. In 2022, global energy storage investment exceeded USD20 billion reaching USD35 billion in 2023, with projections surpassing USD120 billion by 2030. Currently, the Chinese and the US markets focus mainly on front-of-meter storage, while Japanese and European markets emphasize behind-the-meter storage. The Australian market shows a trend of parallel growth in both behind-the-meter battery storage and large-

233 IRENA, The 360 Gigawatts Reason to Boost Finance for Energy Storage Now, https://www.irena.org/News/expertinsights/2024/Jan/The-360-Gigawatts-Reason-to-Boost-Finance-for-Energy-Storage-Now, 2024-01-14.

234 EIA. U.S. Battery Storage Capacity Expected to Nearly Double in 2024. https://www.eia.gov/todayinenergy/detail.php?id=61202, 2024-01-09.

scale storage.

8.2.2 Business models

As summarized in Figure 8-2, currently, the revenue sources for energy storage mainly come from peak-to-valley arbitrage, spot electricity trading, ancillary services, demand response, and capacity subsidies. The predominant business models include owner self-investment, leasing, energy performance contracting, and energy performance contracting combined with financial leasing.

Source: Sergey Syrvachev, the Big Book of BESS Revenue Models, https://www.linkedin.com/pulse/big-book-bess-revenue-models-examples-sergey-syrvachev-6usqc, 2024-04-10; Energy storage net. Business models of energy storage. http://mm.chinapower.com.cn/zx/hyfx/20231206/227067.html

Figure 8-2 Business Models of Energy Storage System Projects

Across the region, business models employed for energy storage project development are influenced by the maturity and openness of electricity markets, power supply-demand dynamics, laws and regulations, and government policies in different economies. Economies with more developed electricity markets tend to offer more diversified revenue sources and more mature business models for the storage projects, such as North

America; Australia; Japan; and Korea. In contrast, developing economies like those in South America and Southeast Asia, many economies' electricity markets are often in their infancy or early stages, typically have more limited revenue sources and simpler business models for energy storage.

International investment and cooperation impact the profitability and business models of energy storage projects, which reflects the benefits of international collaborations. In recent years, there has been a surge in demand for large and grid-scale energy storage in the United States, Europe, and Australia. Compared to the highly competitive domestic market in China, these regions offer higher prices and profit margins, making overseas operations particularly lucrative. The experience gained from international exerts influence on domestic energy storage industry and business models back home, for example the Chinese entities' efforts in overseas markets.

Box 4 Business Models of Energy Storage in APEC Economies

United States

The *Inflation Reduction Act of 2022* provides tax and financial support for energy storage, reducing its cost and enhancing the enthusiasm for building storage systems. States have established detailed rules for energy storage participation in electricity markets to support its development. **i) Front-the-Meter-Storage:** Large-scale grid-connected energy storage in the United States. generates revenue mainly from frequency regulation, price arbitrage, ramping or spinning reserve, reducing wind and solar curtailment, voltage or reactive power support, and system peak shaving. Among these, frequency regulation, price arbitrage, and ramping or spinning reserve are the primary sources of revenue. In recent years, the proportion of energy storage participating in energy market price arbitrage, as well as ramping or spinning reserve, has been steadily increasing. **ii) Behind-the-Meter (BTM) Storage**: This primarily includes residential and commercial-industrial energy storage, mostly in the form of distributed photovoltaic systems paired with storage. Its main revenue sources include: Revenue from reducing high-cost purchases from the grid, the value of backup power supply, and income from exporting excess electricity back to the grid.

Australia

Revising the APC (Average Power Cost) regulated price ceiling has introduced greater price volatility, creating favorable conditions for energy storage to engage in arbitrage within the electricity market. Providing financial support for energy storage projects reduces costs, improves economic viability, and enhances the motivation for construction**. i) Front-the-Meter-Storage:** Energy storage can participate in both the energy market and the frequency regulation ancillary service market. **ii) Behind-the-Meter (BTM) Storage:** The primary source of revenue comes from electricity bill savings generated by self-generation and self-consumption of the PV-storage system. Rising retail electricity prices and declining battery storage investment costs will encourage more users to install rooftop PV systems along with battery storage.

China

i) Renewable energy paired with storage: The main revenue sources include reducing renewable energy curtailment and lowering penalty fees. However, since most current renewable energy projects operate under flat-rate feed-in tariffs with relatively low electricity prices, the number of operations used to reduce curtailment is often below 300 times per year. As a result, the revenue from reducing curtailment is limited, making it difficult for storage to recover its costs; **ii) Coal-storage coordinated frequency regulation:** The main revenue sources include compensation for secondary frequency regulation and reduced penalty fees, with secondary frequency regulation being the dominant source; **iii) User-side energy storage:** In China, this model is primarily applied in commercial and industrial projects, generating revenue from price arbitrage, reduced capacity charges, reduced energy charges, demand response compensation, and participation in ancillary services. Among these, price arbitrage is the primary source of revenue; **iv) Standalone energy storage:** Revenue sources are more diversified. For energy-related revenue, there are two main approaches: provinces without spot markets generate value through peak shaving, while those with spot markets achieve value through nodal price arbitrage; Currently, the main way to generate revenue from ancillary services is through participation in Automatic Generation Control (AGC) frequency regulation; For capacity-related revenue, Shandong uses a "capacity tariff + capacity leasing compensation" model, Gansu employs a "peak-shaving capacity market + capacity leasing" model, and Hunan and Henan rely on capacity leasing alone. Although standalone energy storage has become economically viable in some provinces, it still faces challenges such as unstable revenue sources and immature market mechanisms.

8.2.3 Project development strategies

The project development strategies for energy storage include the following aspects. Firstly, the government should strengthen regulatory system and promote the healthy development of the energy storage market. Enterprises should establish strong management teams that understand both international developments and local markets, and conduct comprehensive assessments of the market prospects, technical risks, financial risks, and policy risks associated with investments. Investors need a comprehensive and in-depth understanding of global developments and the local investment environment. Through market research, they can obtain first-hand data and better assess market potential and investment risks; Conduct technical assessments and risk analyses of selected energy storage technologies to evaluate their maturity and reliability; Perform financial evaluations and analyses to understand key metrics such as payback period, cash flow, and financing costs, thereby better assessing the project's profitability and investment risks; Thoroughly understand the laws, regulations, and policies of the host economies and project locations to ensure compliance and mitigate investment risks.

Secondly, governments should rationally plan the layout of the new energy storage industry chain and supply chain, and promote the establishment complete industry standards. Enterprises should enhance innovation in energy storage technologies and use a systematic approach to optimize business directions and strategies. Governments must improve the policy framework for the energy storage industry, establish sound market entry and exit mechanisms for manufactures, and prevent the emergence of inefficient or ineffective production capacity. It is necessary to strengthen coordinated planning and investment guidance for key industries, guiding local governments and industry toward rational investment to avoid overcapacity and low-level duplication of manufacturing capacity. Enterprises should adjust production plans and product directions based on market demand to avoid irrational expansion, and product competitiveness should be enhanced through technological innovation, optimizing production structures, and increasing the capacity for high-tech, high-value-added products to align with the development trends of the energy storage. New tools such as artificial intelligence and digital technologies should be integrated into decision-making to help companies reduce investment risks and costs, respond effectively to regulatory changes, and better leverage opportunities arising from new market structures.

Lastly, actively explore various flexible and efficient market-oriented profit channels and business models for energy storage projects. The government should introduce policies and regulations to encourage and safeguard enterprises in generating legitimate revenues through proper profit channels and business models. As the international and domestic energy storage markets continue to develop, relevant policies are constantly improving, and the market environment is becoming more favorable, gradually opening-up new profit channels for energy storage projects. Project developers should explore new and more market-adaptive profit channels and business models through best domestic and international business practices, applying them in suitable contexts, such as shared leasing, and shared storage, virtual power plant models, and community energy storage. Governments should encourage such proactive exploration through policies and regulatory frameworks, while also recognizing and protecting the legitimacy of associated revenues.

Box 5 Business Models for Energy Storage Development

Shared storage mode

The shared energy storage model releases storage resources to the entire power system. Through large-scale investment, construction, and management, it effectively lowers both construction and operational costs, reducing the investment and management burden associated with self-owned storage. This model not only enables diversified service recipients but also diversifies investment entities, allowing for shared returns on investment. Compared to the approach of renewables pairing with self-owned storage, shared storage offers clear advantages in terms of safety, quality, and economic efficiency. Shared storage model has successfully used in the United States, Australia and some European economies for energy storage development.

Virtual power plant

By using control and communication technologies, relatively decentralized resources such as distributed renewable resources, loads, and storage are integrated to form a special type of virtual power plant (VPP) that participates in power system operations and electricity market management. Energy storage can play a critical role in the virtual power plant due to its fast response, flexibility, unique characteristics of bidirectional charging and discharging capability compensates for the unidirectional nature of loads and power sources. VPPs utilizing BESS are gaining significant traction globally, and several economies have successfully implemented and are actively expanding their VPP programs, including Australia; China; United States; Germany and others for increasing utilization of distributed energy resources and needs for grid flexibility and stability.

Community energy storage mode

Community energy storage refers to energy storage systems, typically batteries, that are strategically located within a community to serve the energy needs of multiple households or businesses in that area. Unlike large, centralized utility-scale storage or individual "behind-the-meter" residential batteries, community energy storage sits in between, often at the distribution feeder level of the grid, or even on a power pole. Instead of each home having its own battery, a single community battery can serve many homes. This can make battery storage more accessible and affordable for a wider range of residents. The trend for community energy storage is accelerating globally, driven by technological maturity, supportive policies, and the increasing recognition of its multifaceted benefits for energy security, sustainability, and community empowerment. Currently, Australia; New Zealand; Germany; and United States are among the APEC economies where the community energy storage model has successfully implemented.

8.3 Build resilient and sustainable supply chain for energy storage

8.3.1 Supply chain and industry chain

The supply chain and industry chain are two critically important chains in the deployment of energy storage. The *supply chain* is a concept from management science. It focuses on logistics supply, integrating various stages and resources in the production and distribution process into an efficient system capable of rapidly responding to customer demands. It forms a functional network structure connecting suppliers, manufacturers, distributors, and end-users into a unified whole.[235] Supply chain management (SCM) requires handling the flow of goods through distribution channels within the supply chain in the most effective way possible. The *industry chain* is an economic concept referring to the entire production and distribution process of a product, from raw materials to final consumers, focusing on inter-industry linkages and a macro-level perspective. The industry chain includes the supply chain, which is a part of it.[236]

Table 8-5 Scope and Coverage of Supply Chain and Industry Chain

	Supply chain	Industrial chain
Relationship	The supply chain is a part of the industry chain and serves as its foundation. Both reflect the interrelationships between different elements in the production and operation process, and both take the form of chain-like or network structures. At their core, both are extensions of the value chain.	
Differences	The supply chain takes enterprises as nodes and connections between enterprises as its form. By integrating diverse resources, it reduces logistics costs, improves logistics efficiency and overall product or service quality, providing competitive advantages to enterprises and enhancing customer value. From a micro perspective, it emphasizes the transformation and transmission of resources between enterprises, aiming primarily at reducing total production costs and improving supply efficiency.	The industry chain takes industries as nodes and inter-industry relationships as its form. It centers on products (tangible or intangible), with value addition as its guiding principle. Its research perspective is more macroscopic, focusing on industrial linkages, enterprise positioning, and division of labor and cooperation. Its primary goals include optimizing technological and economic linkages between industries, maximizing the benefits of the entire industry chain, and enhancing industrial efficiency and comprehensive competitiveness.

As shown in Figure 8-3, the upstream segment of the new energy storage industrial chain includes the supply of raw materials and core equipment such as energy storage batteries, power conversion systems (PCS), battery management systems (BMS), energy management systems (EMS), air compressors, heat exchangers, expanders, and hydrogen production equipment; The midstream segment involves the

[235] Analysis of the Supply Chain and Industrial Chain: Key Connections and Essential Differences [EB/OL]. https://www.iyunjing.com/post/1694.html, 2024-11-02.

[236] Duan Wei, Wang Bing. Theories and Paths to Enhance the Resilience of Industrial and Supply Chains. Chinese Social Sciences Network. https://www.cssn.cn/skgz/bwyc/202304/t20230412_5619345.shtml, April 12, 2023.

integration of energy storage systems. System integration is a critical component of the entire industrial chain, serving as a bridge linking upstream raw materials and equipment with downstream applications; The downstream segment consists of the application of energy storage systems. Based on their location within the power system, these applications are categorized into generation-side, grid-side, and user-side deployments.[237] This chapter focuses on the analysis of the supply chain for manufacturing of energy storage equipment.

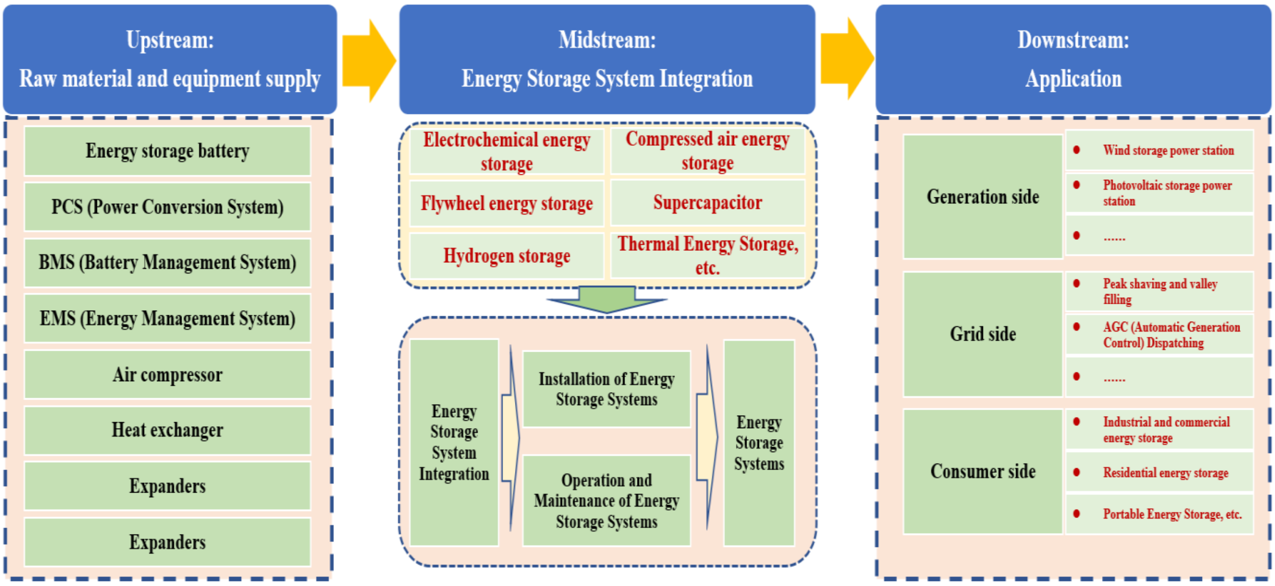
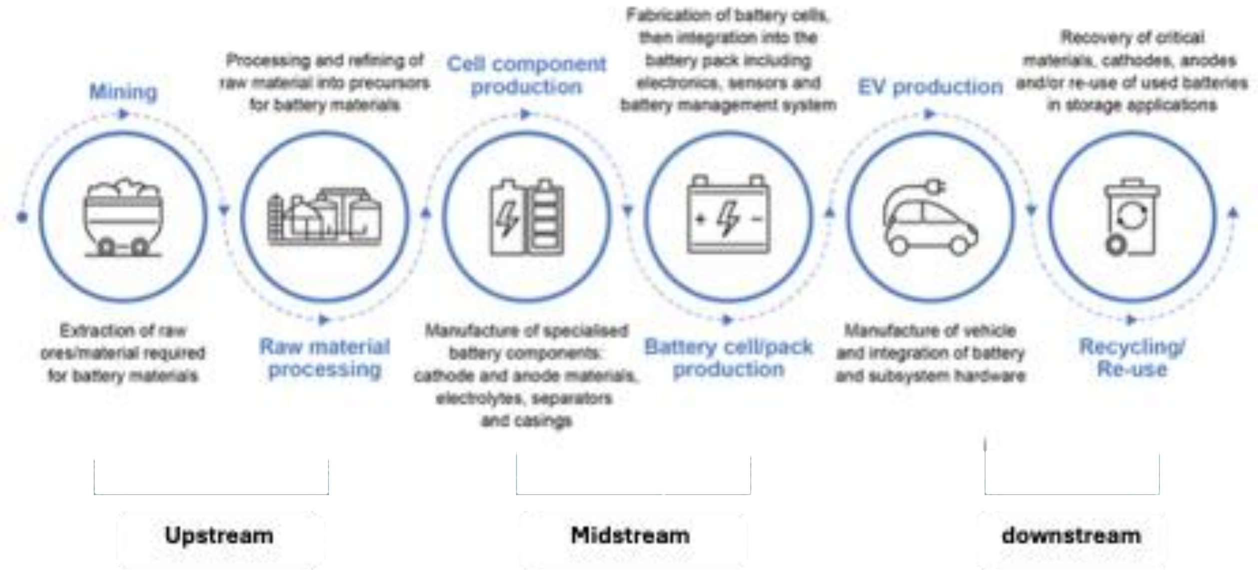


Figure 8-3 Industrial Chain of New Energy Storage Products

8.3.2 Supply chain of battery energy storage systems

The supply chain of BESS typically includes upstream raw material extraction and processing, midstream battery component manufacturing, and downstream system integration, recycling, and reuse. (see As shown in figure below, taking the supply chain of lithium-ion batteries for new energy vehicles as an example, the logistics and supply relationships among relevant enterprises usually consist of the following main steps, namely i)Mining: Extraction of metal materials required for batteries; ii) Raw material processing: Processing and refining raw materials to produce primary materials; iii) Battery component manufacturing and production: Such as anodes, cathodes, electrolytes, separators, and battery casings; iv) Cell/module production: Manufacturing battery cells and integrating individual cells into battery packs, including electronic sensors and battery management systems; v) System integration: Connecting battery hardware to energy systems such as new energy vehicles, photovoltaics, and wind power via software control devices like BMS; vi) Recycling/reuse: Recycling and reusing old or discarded battery equipment.

[237] 2024 China New Energy Storage Industry Chain Atlas Research and Analysis [EB/OL]. https://mp.weixin.qq.com/s/AGrpzgJWlp0bBadhFa36Ow. 2024-03-11.



Source: IEA. Global Supply Chains of EV Batteries. 2022

Figure 8-4 Lithium-Ion Battery Supply Chain for New Energy Vehicles

The supply chain for BESS should aim for resilience and security, while also promoting green development, and fulfilling corporate economic, social, and environmental responsibilities. Resilience and security refer to the internal stability, autonomy, and flexibility of the supply chain.[238] It should be able to quickly adapt to external shocks, maintain effective operations under blockades or pressure, and ensure basic functionality in extreme situations. Green development means that all participants across the supply chain should strive to reduce carbon footprint, water consumption, energy use, toxic waste generation, and air pollution. They should minimize impacts on biodiversity and natural resources, consider health and social issues related to mineral mining and battery materials from a life-cycle perspective, and promote the recyclability of hardware materials.[239] In practice, the green development of supply chains is often overlooked.

APEC economies dominate the global supply chain for energy storage equipment. The goal of each economy is to enhance the resilience and security of energy storage systems, and the concept of green supply chains is gradually becoming mainstream. According to the 2023 IRENA report *The Geopolitics of the Energy Transition: Critical Materials*[240] and Bloomberg New Energy Finance (BNEF) tracking analysis of

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238 Establishing and enhancing the institutional framework to improve the resilience and security of industrial and supply chains requires a focus on key priorities. https://www.gov.cn/zhengce/202408/content_6969460.htm,2024-08-20.

239 Energy storage: Total supply chain- Challenges and factors that influence investments[EB/OL]. https://www.deloitte.com/nl/en/Industries/energy/perspectives/energy-storage-total-supply-chain.html,2023-11-20.

240 IRENA，Geopolitics of the Energy Transition: Critical Materials [R]. 2023.

the global lithium-ion battery supply chain, the top 30 ranked economies occupy the upper echelons of the global lithium-ion battery supply chain. Among them, 12 are APEC members, including China; Canada; the United States; Korea; Japan; Australia; Chile; Viet Nam; Indonesia; Thailand; the Philippines; and Mexico.

In terms of raw materials, APEC economies such as China; Australia; Canada; Brazil; Indonesia; the United States; and Chile rank among the top. These economies possess abundant mineral resources required for the production of lithium-ion batteries. For example, during the raw material extraction phase, 91.5% of lithium is mined in the APEC region, with Australia accounting for 46.9%, Chile 30.0%, and China 14.6%; 77.8% of nickel is mined in the APEC region, with Indonesia at 48.8%, the Philippines 10.1%, Russia 6.7%, Australia 4.9%, Canada 4.0%, and China 3.3%; More than 64.6% of natural graphite is mined in China; Nine APEC economies — Chile; Peru; China; the United States; Russia; Indonesia; Australia; Mexico; and Canada — together account for 66.1% of global copper mining output; 70.0% of cobalt and 73.6% of platinum are mined in the Democratic Republic of the Congo and South Africa, respectively. The APEC region accounts for more than 60% of the global mining output of four critical raw materials: copper, graphite, lithium, and nickel. At the processing stage, China currently supplies 100% of refined natural graphite, 70% of cobalt, and nearly 60% of lithium and manganese.[241] In the battery manufacturing phase, China, Korea, and Japan rank in the top three. These economies have well-established battery manufacturing bases and supportive industrial policies. For instance, in 2022, Korea and Japan announced strategies for expanding domestic and international battery production capacity and securing critical material supply chains. Most of the world's operational GWh-scale battery manufacturing facilities are owned by companies from China, Japan, or Korea. the United States has seen strong growth in battery production capacity in recent years, rising to fourth place globally in 2022.

In terms of environmental, social, and governance (ESG) performance, Europe — particularly Northern and Western European economies — leads the way, with Norway, Finland, Sweden, Germany, and France at the forefront. Among APEC economies, only Canada; Japan; and Korea perform relatively well, while others generally rank lower. the United States and China ranked 16th and 17th respectively, while several Southeast Asian APEC economies, such as Viet Nam; Indonesia; Thailand; and the Philippines, ranked even lower, beyond 20th place. This is because Northern and Western European economies integrated ESG principles into laws, regulations, and industrial policies at an earlier stage, with unified standards, making ESG investment a common industry consensus. In contrast, ESG investment in China and Southeast Asian developing economies is still in its early stages, while the United States faces policy uncertainty due to its political system, which hinders ESG progress to certain degrees.

In the dimension of *Industrial Innovation and Infrastructure*, Nordic economies Finland, Sweden, and Norway ranked first through third, followed closely by APEC economies Canada and the United States.

[241] IEA, Share of top three producing countries in mining of selected minerals 2022, https://www.iea.org/data-and-statistics/charts/share-of-top-three-producing-countries-in-mining-of-selected-minerals-2022, 2023-07-11.

These economies lead in scientific and technological innovation, technology transfer, and R&D, making them traditional science and technology powerhouses. Notably, China ranks 9th, reflecting the Chinese government's emphasis and support, with China's innovations in the global lithium-ion battery supply chain increasingly recognized worldwide. In terms of *downstream demand*, economies such as China; the United States; Germany; the United Kingdom; Korea; and Japan demonstrate strong domestic markets and rank highly on the list.

Pioneer APEC cities are building comprehensive and efficient energy storage device supply chains, taking them as a key means to achieve renewable energy development goals, carbon neutrality targets, and ESG objectives. The accelerating energy transition in cities has significantly increased their demand for energy storage equipment. From the perspective of APEC economies, cities with high carbon emissions are often those with large populations, active economies, and developed industries. These cities hold great potential for emission reductions, and city governments are taking concrete actions to ensure the integrity and efficiency of energy storage equipment supply chains.

Table 8-6 Emission Targets and Energy Storage Supply Chains of APEC Cities

City	Carbon emissions ($MtCO_2$) 2021	Renewable energy target	Carbon neutrality timeline	Whether to prepare ESG report	Measures to ensure energy storage supply chain
Toronto, Canada[242]	16.16	By 2030, 50% of energy will be renewables. By 2050, 75% of energy will be renewables or low-carbon; 30% of total building area will be connected to low-carbon heating and cooling energy.	2050	Yes	Attracting energy storage equipment manufacturers and developers with preferential policies to invest locally; Establishing one of the largest battery recycling companies in North America; Ensuring stable output of cobalt and nickel; Promoting the development of electric vehicle assembly industries; Enhancing battery research and development.
Melbourne, Australia[243,244,245]	4.29	Without city target, Victoria Province target: By 2035, achieve 95% renewable energy share and at least 6.3GW of energy storage capacity.	2040	Yes	Government investment projects, collaborating with suppliers like Tesla and Samsung to establish Melbourne Renewable Energy Center; Ensuring suppliers adopt practices supporting biodiversity and climate resilience; Promoting circular economy through supplier partnerships to improve environmental management.

242 City of Toronto-Environmental, Social and Governance Performance Report, 2021, https://www.toronto.ca/legdocs/mmis/2021/ex/bgrd/backgroundfile-159902.pdf

243 Victorian renewable energy and storage targets. https://www.energy.vic.gov.au/renewable-energy/victorian-renewable-energy-and-storage-targets.2024-10-31.

244 City of Melbourne-Environmental, Social and Governance Procurement, https://www.melbourne.vic.gov.au/esg-procurement, 2024-10-18.

245 Australian state starts work on A$1 billion 600 MW BESS project in Melbourne, https://etn.news/buzz/victoria-600-mw-bess-melbourne-mreh, 2023-12-05.

City	Carbon emissions ($MtCO_2$) 2021	Renewable energy target	Carbon neutrality timeline	Whether to prepare ESG report	Measures to ensure energy storage supply chain
Santiago, Chile	15.36	Without city target, economy level target is: By 2030, renewables meet 70% of total energy consumption; Achieve 2GW of energy storage capacity by the end of 2026.	2050 Economy Objectives	No	Introducing optimal, cost-effective suppliers and technologies such as Huawei and Tesla; Developing regulatory frameworks for energy storage to increase profitability; Conducting market-based auctions for energy storage.
Mexico City[246]	28.21	Without city target, the economy target is: By 2030, achieve 45% renewable energy generation and reach 5501MW of battery storage capacity by 2027.	2050	No	Promoting energy storage investments, expanding electric vehicle (EV) development, upgrading old grid infrastructure; Fostering close cooperation among industry, academia, research institutions, and government in the supply chain domain; Encouraging participation from domestic and international capital.
Seoul, Korea[247][248]	44.07	Without city target, the economy target is: By 2038, increase electricity sources from carbon-free sources such as renewables and nuclear to 70%; Reach 36.454GW of energy storage capacity by 2030.	2050	Yes	Encouraging private sector-government collaboration in developing and mass-producing energy storage batteries and related products to enhance efficiency and reduce costs; Encouraging small and medium-sized enterprises (SMEs) to participate competitively and accumulate technological capabilities; Implementing policies to stimulate domestic demand for energy storage.
Tokyo, Japan[249]	56.97	By 2030, increase renewable energy usage to 30%, install 1.3GW of solar power facilities, and use renewable energy for all municipal facilities; Nationally, plan to increase domestic EV lithium-ion battery production to 100GWh.	2050	Yes	Revising the *Electricity Business Act* to grant energy storage devices equal status with traditional power generation, allowing them access to the grid, which benefits the development of energy storage enterprises; Using subsidies to incentivize R&D, pilot programs, and installation of large-scale battery storage systems or distributed storage systems.
New York City, the United States[250][251]	76.11	By 2030, ensure that 70% of New York's grid is powered by renewable energy, with energy storage capacity increasing to 6000MW.	2050	Yes	Government incentive policies; Financing loans provided by the New York Green Bank; Strengthening supply chain regulation; Close cooperation between city governments and investor-owned utilities. Unified standards.

[246] Mexico revises renewable energy capacity addition targets for 2024-2038, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/060624-mexico-revises-renewable-energy-capacity-addition-targets-for-2024-2038, 2024-06-06.

[247] Top five energy storage projects in South Korea, https://www.power-technology.com/data-insights/top-five-energy-storage-projects-in-south-korea/?cf-view, 2024-09-10.

[248] World Bank, Korea's Energy Storage System Development: the Synergy of Public Pull and Private Push, https://documents1.worldbank.org/curated/en/152501583149273660/pdf/Koreas-Energy-Storage-System-Development-The-Synergy-of-Public-Pull-and-Private-Push.pdf, 2020.

[249] Battery Storage In Japan – Policy Deep Dive, https://langleyesquire.com/battery-storage-in-japan/, 2024-01-30.

[250] ESG Compliance in New York City, https://www.cbiz.com/insights/articles/article-details/esg-compliance-in-new-york-city, 2023.

[251] New York City Government. Pathways to Carbon Neutral New York City, https://www.nyc.gov/assets/sustainability/downloads/pdf/publications/Carbon-Neutral-NYC.pdf.2021.

City	Carbon emissions ($MtCO_2$) 2021	Renewable energy target	Carbon neutrality timeline	Whether to prepare ESG report	Measures to ensure energy storage supply chain
Singapore[252][253]	45.16	Aim to achieve at least 2GWp of solar power generation by 2030, with a goal of reaching 200MW of energy storage deployment after 2025.	2050	Yes	Rewarding corporate R&D and technological advancements; Improving and expanding the supply chain through international and regional cooperation; Emphasizing green procurement and corporate ESG responsibilities.
Jakarta, Indonesia[254]	34.50	By 2030, renewable energy accounts for 30% of the energy mix, increasing to 42% by 2050.	2050	No	Building a complete electric vehicle supply chain including energy storage batteries based on domestic nickel industry; Fiscal and tax incentives; Attracting international capital investment from Hyundai, LG, BYD, CATL, Ford, etc., to fill gaps in the supply chain.
Shanghai, China[255][256]	200.00	By 2025, renewable energy accounts for 8% of the energy mix, aiming to reach 30 billion kWh of green power trading by 2030.	Before 2060	Yes	Introducing advanced companies such as Tesla and CATL to form industrial clusters; Implementing policies to promote multi-scenario applications of energy storage.

From the above table following observations can be made for the selected cities in APEC economies:

- The development and improvement of urban energy storage supply chains are closely related to their emission reduction targets. For example, New York City in the United States ties its renewable energy goals with energy storage development goals, advancing both simultaneously. Melbourne in Australia, Santiago in Chile, Mexico City in Mexico, Seoul in Korea, and Tokyo in Japan all have very clear renewable energy targets and energy storage development goals;
- Cities in relatively economically developed economies have stricter requirements for ESG and more widespread reporting. Apart from Santiago in Chile, Mexico City, and Jakarta in Indonesia, the other seven cities, including Shanghai in China, have clear and stringent disclosure requirements for ESG;
- Measures taken by cities to ensure the energy storage equipment supply chain can generally be categorized into fiscal and tax incentives, laws and regulations, technology research and development, government supervision, and market-oriented approaches.

Affected by the combined impacts of economic slowdown, climate change, and geopolitical conflicts, the energy storage equipment supply chains in APEC economies face five major challenges, namely i)

[252] Renewable Energy Target of Singapore, https://aseanenergy.org/policy/renewable-energy-target-of-singapore/, 2020.
[253] ESG Reporting in Singapore: A Strategic Guide for Businesses, https://www.aseanbriefing.com/doing-business-guide/singapore/company-establishment/esg-singapore-blueprint, 2024.
[254] Major Copper Discoveries, https://www.spglobal.com/marketintelligence/en/news-insights/blog/major-copper-discoveries, 2024-09-05.
[255] Shanghai leads way in China’s carbon transition, https://dialogue.earth/en/energy/shanghai-leads-way-in-chinas-carbon-transition/, 2021-06-23
[256] China Highlights Shanghai's Lead in Sustainable Development in First Local ESG Report, https://www.yicaiglobal.com/news/china-highlights-shanghais-lead-in-sustainable-development-in-first-local-esg-report, 2024-10-17.

overcapacity caused by overheated investment leads to price competition; ii) supply chain shortages due to geopolitical tensions and trade protectionism; iii) rapidly growing demand outstrips supply, causing price increases and creating supply chain bottlenecks; iv) companies along the supply chain need to disclose the environmental and social impacts of their products and take on more responsibility; and v) relevant laws and regulations are not sufficient, and safety standards urgently need to be improved and enhanced.

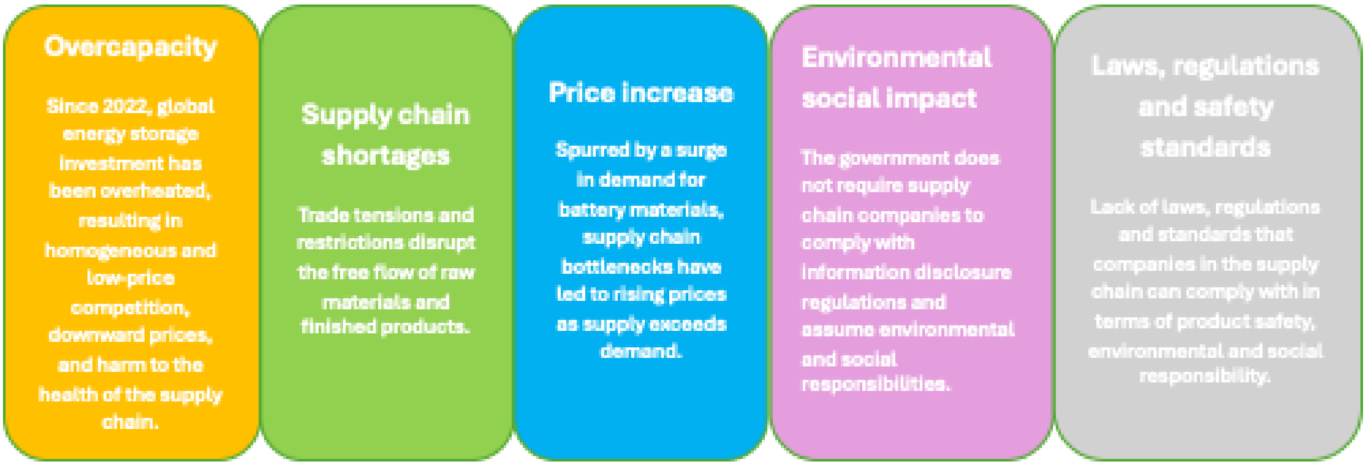

Figure 8-5 Main Challenges in Energy Storage Equipment Supply Chain

For developing resilient and sustainable supply chains for storage equipment, it is essential to implement effective strategies and policies.

Coordination among multiple chains — integrated planning and coordinated implementation. From government perspectives, the planning and design of the energy storage equipment supply chain should be synchronized and coordinated with the industrial chain, capital chain, innovation chain, and value chain. Comprehensive considerations should be given to logistics, industrial layout, investment and financing, scientific research and innovation, as well as value enhancement. Governments should optimize and upgrade the upstream, midstream, and downstream segments of each chain—strengthening weak links, filling gaps, and reinforcing capabilities—to stimulate market vitality and innovation; deeply integrate upstream and downstream resources to improve supply-demand transparency and guide investments into new production capacities, thereby ensuring a healthier and more stable supply chain operation. This approach can address the problems of overcapacity and cutthroat competition caused by overheated investment in energy storage equipment, helping to bring prices back to a rational level.

Strengthen domestic and international partnerships to promote regionalization and diversification of supply chains. A resilient and secure supply chain should be both regionalized and diversified. Regionalization means that demand can be met within a specific region (e.g., North America), while diversification refers to having multiple sources of supply, rather than relying on just one or a few suppliers. For example, a McKinsey report recommends that the EU set resilience targets for its supply chain:

meeting more than 90% of local battery demand and more than 60% of local refined material demand.[257] City governments, along with key domestic and foreign enterprises across the energy storage supply chain—including manufacturers, suppliers, and developers—should establish strategic partnerships by reaching public-private collaboration, establishing joint ventures and sharing resources to improve operational efficiency and streamline supply chain processes, while also enhancing the bargaining power. Enterprises should seek for long-term cooperation, co-financing, acquisition, and distribution arrangements with various raw material and equipment suppliers to ensure adequate supply. While enterprises with sufficient capabilities may expand internationally through cross-border operations, tapping into global markets and coordinating upstream and downstream supply chain entities within and across economies to bypass trade barriers, integrate R&D and technological innovation strength, and reduce costs and risks. By the above means, the problems of supply shortages and rising prices can be alleviated.

[257] McKinsey. Battery 2030: Resilient, sustainable, and circular, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular, 2023-01-16.

Box 6 Tesla's Energy Storage System Factory in Shanghai, China

In May 2024, the US-based EV manufacturer Tesla broke ground on a super factory in Shanghai. This is Tesla's first energy storage system factory outside the the United States, dedicated to producing its Megapack energy storage batteries. This project represents another major investment by Tesla in China following the completion of its Shanghai Gigafactory in 2019. It initially plans to produce tens of thousands of large-scale electrochemical commercial energy storage systems annually, with mass production expected to begin in the first quarter of 2025. Tesla's decision to build its second energy storage gigafactory in Shanghai was also driven by China's accelerated development pace and the global shortage of lithium iron phosphate batteries. Industry insiders point out that China is currently the only economy globally with large-scale production capacity for key raw materials used in energy storage batteries. Tesla's choice to build a factory in Shanghai is based on a favorable investment environment, a complete and stable supply chain, advanced energy storage technology, and broad market prospects.

This is another example of win-win cooperation between China and the the United States. For Tesla, it is an important strategy to ensure supply chain resilience and security through multinational operations. After Chinese Premier Li Qiang’s meeting with Elon Musk, CEO of Tesla, the Shanghai Lingang Economic Development Group signed China's first batch of contracts for electrochemical energy storage systems with Tesla. The contract negotiations and signing for the Shanghai energy storage super factory were completed in just one month, once again setting a new "Lingang Speed" record.

(Source: https://www.globaltimes.cn/page/202405/1312893.shtml)

Tesla's Gigafactory in Shanghai, China

Strengthen ESG management to create sustainable supply chains. ESG compliance along supply chains is a global trend and an inevitable direction of development. Stakeholders along the supply chain should enhance ESG management from the perspective of the full lifecycle of energy storage equipment. Firstly, cities and local governments should closely integrate ESG initiatives and goals into the formulation and implementation of regulations and policies related to energy storage, as well as in urban planning, budget allocation, service provision, and oversight. Sustainable indicators should be included in local agendas, with clear requirements regarding the social and environmental impacts of energy storage suppliers and their products. Performance management should also be emphasized, with restrictions and penalties imposed on actions harmful to society and the environment. Where conditions permit, local governments may consider compiling and publishing annual ESG reports (as practiced by cities such as Toronto, Canada). As for supply chain enterprises, the first step is to establish clear and achievable ESG objectives; secondly, these objectives should be broken down and integrated into daily operations and management policies, with sufficient communication maintained with upstream and downstream suppliers to implement them in delivery processes; Finally, scientific evaluation methods should be established to assess performance and update policies as needed based on changing circumstances. It is worth emphasizing that ESG management in supply chains should include the recycling and reuse of energy storage equipment.

Introduce policies, standards, and regulations to strengthen quality and safety management. Safe operation of energy storage systems has become a pain point in industry development. Comprehensive policies, safety standards, norms, and laws covering the entire lifecycle are needed to enhance quality control for companies across the upstream and downstream supply chain. Firstly, cities and local governments should incorporate sufficient fire safety distances and spatial arrangements for energy storage facilities into controlled detailed planning and specialized planning for land use; Secondly, drawing on international experience, establishing quality standards and safety technical specifications that cover all stages—including manufacturing, construction, installation, operation monitoring, and recycling—and applying them throughout the supply chain;[258] Thirdly, improving the early warning mechanisms before thermal runaway events in electrochemical energy storage battery systems along with protective measures during incidents and anti-diffusion strategies after accidents; Finally, encouraging supply chain enterprises' R&D and technological innovation to improve the quality and safety of energy storage products and services.

8.4 Chapter summary

Cities aiming to significantly accelerate BESS deployment must critically examine and streamline their local regulatory and permitting frameworks, which often represent the most significant hurdle. This necessitates a comprehensive review and updating of existing building codes, fire codes, and zoning ordinances to explicitly accommodate BESS installations of various scales, from small commercial

[258] The "Safety Rules" for Large-Scale Energy Storage Systems, https://m.bjx.com.cn/mnews/20220428/1221358.shtml, April 28, 2022.

applications to larger utility-scale deployments. Establishing clear, predictable, and expedited permitting pathways, potentially including dedicated BESS application processes or inter-departmental review teams, can greatly reduce project lead times and administrative burdens. Furthermore, proactively adaption of standardized safety protocols requires detailed hazard mitigation analyses, robust emergency response plans from developers, to ensure local fire and emergency services are well-trained and equipped to manage potential incidents. Finally, integrating BESS into broader energy planning and ensuring a flexible regulatory environment that adapts to technological advancements will be crucial for unlocking their full potential in supporting grid reliability and renewable energy integration.

A range of targeted financial incentives and innovative market mechanisms that effectively capture the unique value proposition of urban BESS projects can be implemented, which peak demand reduction, grid deferral benefits, and enhanced local resilience during outages. This could involve offering property tax abatements or reductions for BESS installations that provide significant community benefits like peak load shifting, energy management, power grid modernization. Establishing dedicated grant programs for behind-the-meter storage can provide focused supports. Exploring the integration of BESS into local clean energy programs, offering incentives for participation in VPP initiatives that aggregate distributed storage for grid services, and potentially facilitating access to low-interest financing options can further stimulate investment. Equally important, it needs to prioritize comprehensive and inclusive community engagement strategies, involving residents early in the planning process, clearly articulating the economic, environmental, and resilience benefits of BESS, and providing accessible platforms for feedback and addressing concerns, thereby fostering a strong social license for urban energy storage infrastructure. Furthermore, investing in R&D for advanced battery technologies, promoting domestic manufacturing to secure supply chains, and addressing community engagement and safety are vital to foster confidence and drive widespread BESS investment and deployment.

Supply chains and the business environment are essential prerequisites and safeguards for the development and deployment of energy storage projects. By summarizing the current development status and challenges faced by APEC economies and cities in this field, it is recommended to adopt corresponding strategies to build resilient, secure, and green supply chains, and foster a market-oriented, rule-based, and internationally integrated business environment. The supply chain is an important component of the industrial chain. Its current state of development is as follows: APEC economies dominate the global supply chain for energy storage equipment. The goal of member economies are to enhance the resilience and security of energy storage systems, and the concept of green supply chains is gradually becoming mainstream. Pioneer APEC cities are building comprehensive and efficient energy storage device supply chains, taking them as a key means to achieve renewable energy development goals, carbon neutrality targets, and ESG objectives. At the same time, the supply chain faces challenges such as overcapacity, supply shortages, rising prices, lack of environmental and social responsibility, and incomplete laws, regulations, and safety standards. It is recommended to take countermeasures from aspects including planning, cooperation, management, legislation, and standard formulation, and more specifically, i) Enhance coordination among multiple chains — supply chain, industrial chain, financial chain, innovation chain, and value chain — with integrated planning and coordinated implementation. ii) Strengthen domestic and international partnerships to promote regionalization and diversification of supply chains. iii) Strengthen ESG management across the supply chain to create green supply chains. iv) Introduce policies, safety standards, norms, and laws covering the entire lifecycle to strengthen quality management for enterprises along the upstream and downstream supply chain.

Investment and business models are key components of the commercial environment for energy storage projects. Currently, there is an imbalance in energy storage investment, with funds favoring certain hotspot economies and cities, as well as projects that offer stable returns on investment and have relatively mature technologies. The revenue sources for energy storage mainly come from peak-to-valley arbitrage, spot electricity trading, ancillary services, demand response, and capacity subsidies. The predominant business models include owner self-investment, leasing, energy performance contracting, and energy performance contracting combined with financial leasing. At the same time, the business environment faces challenges such as risk management of investments, guidance on investment directions, and limited diversity in business models.

To accelerate investment in BESS, policy recommendations should focus on creating stable revenue streams, reducing upfront costs, streamlining regulatory processes, and fostering market transparency. For the deployment of BESS in urban areas, cities should focus on targeted incentives for distributed energy resources, including rebates or low-interest loans for behind-the-meter batteries for households, small businesses, and apartment complexes. Policies should facilitate the deployment of community batteries in residential and commercial area, leveraging underutilized urban spaces and integrating with local renewable generation like rooftop solar. Streamlining local planning and permitting processes is crucial, specifically recognizing BESS as a permissible and valued urban infrastructure. Cities can also lead by example through municipal BESS initiatives and also foster VPP programs that aggregate urban distributed renewable energy and storage capacity, providing grid services and offering financial benefits to participants. The government and enterprises should seek solutions from aspects such as market rule and technological innovation. More specifically these include:

- The government should strengthen legal system construction and promote the healthy development of the energy storage market. Enterprises should establish strong management teams that understand both international developments and local markets, and conduct comprehensive assessments of the market prospects, technical risks, financial risks, and legal and policy risks associated with investments.
- Actively explore various flexible and efficient market-oriented profit channels and business models for project development. The government should introduce policies and legal regulations to encourage and safeguard enterprises in generating legitimate revenues through proper profit

channels and business models;

- Improve market condition and grant non-discriminatory access to electricity markets and provision of services, defining permissible use cases to facilitate planning by investors and operators and to make it easier to assess likely revenues. Where feasible, it would also mean reforming power markets to establish wholesale markets that help deliver cost-effective short- and medium-term flexibility, which could be a significant revenue driver for battery storage project developers, especially with increased variable renewables in the energy mix.
- Mitigate off-taker risk and lower the risk of delayed payments or failure to pay for services provided to transmission networks, which would help to provide a more secure investment environment, and it could be done by expanding off-taker guarantee and credit enhancement mechanisms.
- Lower the cost of capital and reduce perceived risks, enhancing investor confidence through stable and predictable revenue streams from diverse grid services, potentially facilitated by clear regulatory frameworks and long-term contracts. Government incentives, including tax credits, grants, and subsidies, directly lower the upfront capital required and improve project returns, making the storage projects more attractive to investors. Furthermore, the increasing availability of green financing options, such as green bonds, can offer favorable interest rates and attract environmentally conscious investors, lowering the costs of capitals.

Chapter IX Cases of Energy Storage Applications in China

Since 2013, the President Xi Jinping has attended or presided over every informal APEC Economic Leaders' Meeting and delivered important speeches. He proposed promoting Asia-Pacific cooperation through Chinese initiatives, advancing Asia-Pacific development through Chinese contributions, and building Asia-Pacific consensus through Chinese wisdom. He advocated for all parties to jointly build an Asia-Pacific community with a shared future that is open, inclusive, innovative, interconnected, and mutually beneficial. In China, the development of energy storage has been elevated to an economy-wide strategic level. On 15 March, 2021, the Chinese government proposed the construction of a new power system centered on new energy sources; In March 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration jointly issued the *Implementation Plan for the Development of New Energy Storage During the 14th Five-Year Period*, which pointed out that new energy storage is an essential technology and foundational equipment for building a new power system, and one of the key supports for achieving the goals of carbon peaking and carbon neutrality. China's practical experiences and innovations in new energy storage during the process of constructing a new power system are worth actively promoting to economies and regions around the world, including those within the APEC region.

This section analyzes representative cases of new energy storage in China through case study methods. Six typical cases targeting urban application scenarios were selected, including two cases of "distributed PV + storage", two cases of integrated "source-grid-load-storage" applications, and one case each of independent grid-side energy storage and energy storage-assisted frequency regulation in power systems; Each case was analyzed in detail from the perspectives of technical solutions, business models, and outcomes achieved. The planning, design, construction, and operational experiences were summarized, along with insights into their potential for broader promotion and application.

9.1 Integrated solar PV+energy storage+EV charging project in Nanning

9.1.1 Project overview

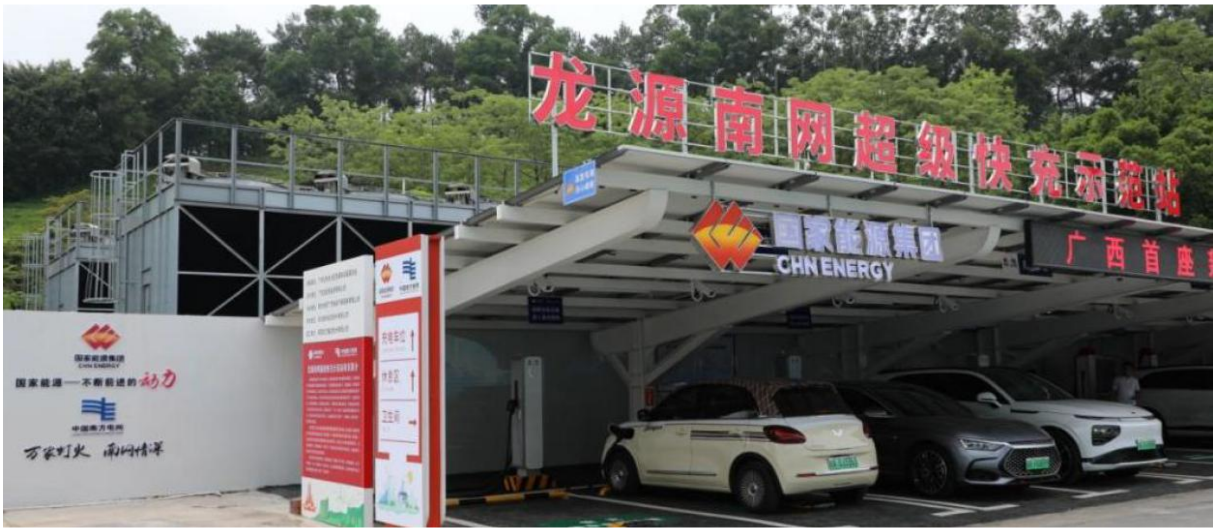

Figure 9-1 Demonstration of Solar PV+storage+EV charging at

Guangxi Longyuan Nanning International Convention and Exhibition Center

The Guangxi Longyuan Nanning International Convention and Exhibition Center Solar PV+Storage+Charge Demonstration Project implements President Xi Jinping's concept of new development, follows the group's requirements for new energy development, and meets Longyuan Power's strategy of science and technology leadership and digital transformation. Led by a central state-owned enterprise (SOE), the project demonstrates SOE responsibility and actively drives various business entities to participate in modern industrial system construction. It contributes to the trend of "new energy + storage", continuing to showcase new practices, stories, and patterns where SOEs play a leading role. The project was developed through a collaborative model involving both SOEs and private enterprises — a strong alliance between leading players. It was planned and developed by Guangxi Longyuan New Energy Co., Ltd., with participation from Minhai Energy, Tuorui Group, Huawei Digital Energy, and Guangxi Urban and Rural Planning Institute in construction. The project was implemented in collaboration with the Nanning International Convention and Exhibition Center and Kehan Group, creating Nanning's first commercial light-charge-storage demonstration project. The project covering a total area of 272 square meters. It includes the installation of 112 photovoltaic modules with a total capacity of 60.48kW, equipped with 60kWh lithium battery storage and three inverters. The development and operation of the project have established a new model for integrating new energy with urban green development, setting a new benchmark for city-enterprise promotion and publicity.

9.1.2 Project highlights

Centered on the theme of " new mechanisms, jointly infrastructure development, sharing the outcomes, creation of new ecosystems, and pursuit of new development goals", the project received approval as part of Longyuan Power's first batch of scientific and technological projects on 23 May 2023. Through the "new energy + storage" model, it opens up a new path for regional energy development in Nanning, Guangxi region.

(1) Technology empowerment: setting a new benchmark for brand promotion

The project is located at the Nanning International Convention and Exhibition Center, in Nanning city, it is the only designated venue for the ASEAN International Expo. Leveraging the unique regional advantages of the exhibition center, the project serves as an excellent international promotional platform for enhancing the group's brand visibility.

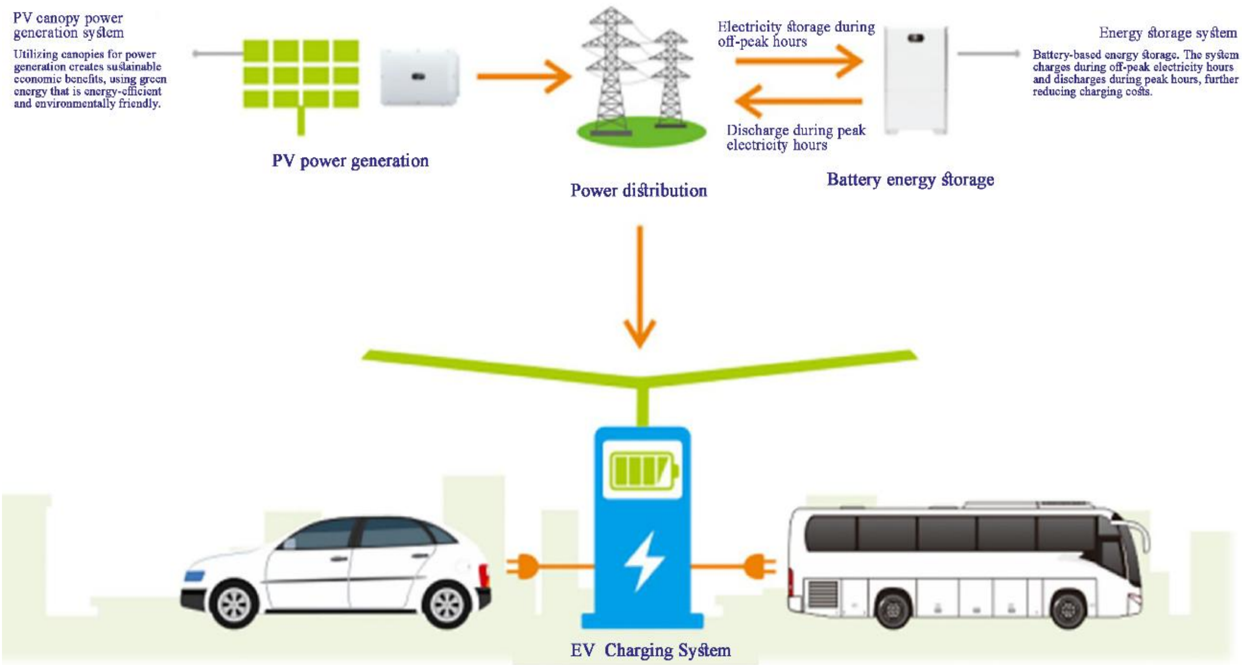

Figure 9-2 Demonstration of Solar PV-Storage-Charing at Guangxi Longyuan Nanning International Convention and Exhibition Center

In 2023, the Nanning International Convention and Exhibition Center Solar PV-Charge-Storage Demonstration Project was officially launched as the first commercial solar PV-charge-storage operation point and a pilot demonstration project for innovative new energy applications in Nanning, Guangxi. Longyuan Power fully demonstrated its role as a central enterprise by collaborating with local state-owned enterprises and multiple private companies to hold the project inauguration ceremony. It leveraged its strengths in infrastructure, operations management, cost control, and technological innovation in the new energy sector to advance Guangxi's "new energy + storage" development under the 14th Five-Year Plan and promote the implementation of the dual carbon goals.

In June of the same year, the project successfully completed its first commercial electricity fee collection from third-party users of new energy vehicle charging stations. Through a business demonstration model involving multi-party collaboration — including "new energy + storage" and "technology + revenue" applications — it established a new business operation model for future energy storage. This marked a significant shift from single investment in R&D to achieving economic returns through technological projects, opening a new chapter in diversified electricity sales operations for the company, and setting a new benchmark for Longyuan Power's integration of energy, storage, technology, marketing, and commerce.

Since the project's inception, institutions such as the Guangxi Development and Reform Commission and Energy Administration have conducted on-site visits and research. The project's unique commercial operation model and the innovative development concept combining industry, academia, and research have received high attention and strong support from the Guangxi regional government and relevant departments. It has also been reported by more than ten media outlets, including China Central Television (CCTV).

(2) Intelligent integration: application of advance technologies

The Guangxi Longyuan Nanning International Convention and Exhibition Center Solar PV-Charge-Storage Demonstration Project implements Guangxi's "14th Five-Year Plan" for new energy storage development. It aims to build data models for technological innovation and commercial operations that support the advancement of a new power system centered around new energy sources.

The project consists of three core components — photovoltaic modules, battery storage, and EV charging piles — forming a microgrid. It utilizes solar power generation, stores electricity in batteries, and supplies power to charging piles when needed. Through the solar PV-charge-storage system, solar energy is transferred into the traction batteries of electric vehicles. The project fully leverages the advantages of "new energy + storage" to enhance the regulation capability, overall efficiency, and safety assurance of the energy and power system. At the same time, the system can operate in either grid-connected or off-grid mode based on electricity demand. Moreover, it addresses the intermittency of photovoltaic power generation. In the event of a grid outage, the "new energy + storage" system can switch to off-grid operation to provide emergency charging for electric vehicles. Moreover, it addresses the intermittency of photovoltaic power generation. In the event of a grid outage, the "new energy + storage" system can switch to off-grid operation to provide emergency charging for electric vehicles.

Based on the development plan of the Nanning International Convention and Exhibition Center Light-Charge-Storage Demonstration Project, Guangxi Longyuan conducts in-depth research on the safety, stability, reliability, and commercial viability of the "new energy + storage" system. Firstly, the project applies arc-fault detection and cutoff technology to establish an experimental model for safe operation. To address safety issues caused by DC arc faults during the operation of the "solar PV + storage" system, the project uses current detection devices in inverters and adopts active protection measures through Arc Fault Circuit Interrupter (AFCI) technology to ensure the project's operational safety. Secondly, the project employs intelligent diagnostic technology to establish experimental models for stable and reliable operation. Using smart diagnosis methods in inverters, the system quickly identifies system faults and combines them with AI recognition algorithms to rapidly determine fault types. The management system includes built-in fault diagnosis and identification algorithms that automatically generate diagnostic reports. This enables efficient, timely, and accurate detection and resolution of operational faults, effectively addressing maintenance challenges. Thirdly, the project utilizes optimizer equipment to explore scalable paths for energy storage development and improve green electricity consumption rates. By using optimizers to monitor and regulate the current and voltage of PV modules in real time, the system enables automatic determination of optimal operating positions even under shaded or dirty conditions, significantly improving power utilization efficiency. Additionally, through tight integration between the equipment and monitoring systems, the system status can be monitored in real-time via software platforms, allowing for early detection of potential faults. This enhances operational efficiency and reduces manual inspection and maintenance costs.

(3) Contribute to renewable energy development

The Guangxi Longyuan Nanning International Convention and Exhibition Center Solar PV-Charge-Storage Demonstration, leveraging ASEAN as an international platform, demonstrates Guangxi's ability to construct higher-level, faster, and denser power grids centered around energy storage as a key hub in the new energy system. In August 2023, at the 20th China-ASEAN Expo, under the coordinated guidance of the Guangxi Development and Reform Commission, the project demonstrated how to comprehensively explore and promote innovative applications of "new energy +" and "storage +", which is Guangxi's first full-liquid-cooled ultra-fast charging station.

The project implements *the Science and Technology Innovation Plan* for the energy sector during the 14th Five-Year Period, advancing pilot engineering applications for renewable energy and new power systems. It establishes an integrated system model of "photovoltaics + storage + charging". In July 2024, the project obtained scientific and technological novelty certification from an institution affiliated with the Ministry of Science and Technology. Its intellectual property rights and combination of new technologies are uniquely applied economy-wide, marking a new phase where high-tech applications in "new energy + storage" systems enter a new era. This lays a solid foundation for Longyuan Power's diversified development, aligning new energy projects with urban construction, and establishing a new model of win-win cooperation.

9.1.3 Key accomplishments of the project

Intellectual property rights: Based on the project operation, comprehensive investigations into the safety, reliability, and stability of the "Solar PV + storage +" integrated power system model were conducted. Five research and analysis reports were completed: namely, i) Experimental Report on IV Diagnostic Technology for Key Technologies Research and Demonstration Project of Solar PV-Charge-Storage New Energy at Nanning International Convention and Exhibition Center; ii) Study on Commercial Feasibility of PV-Storage-Charging Mode and Economic Feasibility of Various Forms of New Energy Integration in the

Key Technologies Research and Demonstration Project of PV-Charge-Storage at Nanning International Convention and Exhibition Center; iii) Field Measurement and Power Generation Report of Optimizers in the Key Technologies Research and Demonstration Project of Solar PV-Charge-Storage New Energy at Nanning International Convention and Exhibition Center; iv) Analysis Report on Operating Load and Photovoltaic Power Generation Curves in the Key Technologies Research and Demonstration Project of Solar PV-Charge-Storage New Energy at Nanning International Convention and Exhibition Center; v) Field Measurement and Arc Fault Circuit Interrupter (AFCI) Experimental Report in the Key Technologies Research and Demonstration Project of Solar PV-Charge-Storage New Energy at Nanning International Convention and Exhibition Center.

Two invention patents were also applied for: i) Method, Apparatus, Storage Medium, and Photovoltaic Equipment for Determining Faults; ii) Control Method, Apparatus, Storage Medium, and Photovoltaic Equipment for Photovoltaic Devices. Through in-depth research on the commercial operation of the project, a paper titled Research on Business Operation Models for Urban Development and Innovative Solar PV-Charge-Storage New Energy Technologies was published.

Economic benefits: Since its commissioning, the project has consistently performed well. Based on data collected from October 2023 to April 2024, the average monthly power generation is approximately 2,118.53kWh, with an annual average of about 25,400kWh. By integrating photovoltaics, energy storage, and charging, real-time monitoring of power supply and demand can be achieved, allowing adjustments to power consumption strategies based on market demand, thereby generating significant economic benefits and profit margins. The optimal commercial operation model avoids large-scale use of expensive grid electricity, reducing operational costs for enterprises.

Social benefits: The Guangxi Longyuan Nanning International Convention and Exhibition Center Solar PV-Charge-Storage Demonstration Project has always adhered to the principle of "empowering society and boosting the economy". Since its inception, it has generated a cumulative total of 87,300kWh, saved 34.92 tons of standard coal, and reduced CO_2 emissions by 41.47 tons. The project supports the green development of "new energy + storage" in the Guangxi Autonomous Region, promoting the integration of "green electricity" with Nanning's "Green City" concept.

Through in-depth studies of the Guangxi Longyuan Nanning International Convention and Exhibition Center Solar PV-Charge-Storage Demonstration Project, data models are provided as references for constructing "PV + storage +" integrated power systems, offering decision-making bases for other similar systems. This significantly accelerates the scale-up construction of "PV + storage +" projects, contributing to building high-quality new energy storage systems.

9.1.4 Prospects for replication and application

The development of "new energy + storage" promotes high-quality development of renewable energy, achieves multi-energy complementarity, and reduces electricity costs, becoming an essential approach to achieving carbon neutrality goal. To enhance multi-scenario applications and fundamental data collection, this project focuses on microgrids featuring "Solar PV + storage +", addressing key issues such as power supply reliability, safety, and operational management under complex environments and dynamic load changes within integrated "PV + storage +" systems. Through the implementation of this project, models for operation and maintenance, efficiency, and safety of future "new energy + storage" systems are established, providing significant promotion for the applications and demonstration of the performance of the technologies.

9.2 Distributed solar PV+Zinc-iron flow battery energy storage project in Shanghai

9.2.1 Project overview

Project background: China has consistently promoted low-carbon energy transformation. Since the 14th Five-Year Plan, the addition of new energy storage installations has directly driven economic investments exceeding CNY100 billion, strongly supporting energy and power development, becoming a new driver of China's economic growth. According to statistics from CNESA, by the end of 2023, China had cumulatively installed 86.5GW of operational power storage projects, including 34.5GW of newly added new energy storage capacity. Both power capacity and energy capacity increased by over 150% year-on-year. According to the estimates by the China Photovoltaic Industry Association and the CWEA Wind Energy Committee, China's wind and solar installations are expected to reach at least 1,240GW by 2025. The long-duration energy storage market demand will reach 149GWh, with a market size exceeding CNY200 billion.

In March 2024, the Central Political Bureau proposed greater efforts to promote high-quality development of new energy, noting that the bottleneck in long-duration energy storage technology remains a significant "shortcoming" constraining new energy development. Energy is the lifeblood of urban development. As the proportion of new energy generation increases, the importance of energy storage technology becomes more prominent. Given the intermittency, randomness, and volatility of wind and photovoltaic energy, they cannot maintain stable output. New energy storage technologies act like a super battery, storing excess and unstable electricity generated by renewables for stable output.

Figure 9-3 The Zero-Carbon Smart Integrated Energy Center, Yangpu Riverside, Shanghai

Project overview: The Yangpu District Zinc-Iron Flow Battery Energy Storage Demonstration Project in Shanghai, also known as the Zero-Carbon Smart Integrated Energy Center at Yangpu Riverside Ash Silo, is a new energy storage demonstration project developed by WEVIEW Energy Storage Technology Co., Ltd., setting a green benchmark for urban areas.

The project involves the renovation of the former coal ash silo at the Yangshupu Power Plant. This site is situated near the Huangpu River and is surrounded by commercial districts and areas designated for industrial heritage conservation. The energy storage products must be non-flammable, non-explosive, pollution-free, and highly flexible in deployment with extended storage durations. WEVIEW's zinc-iron flow battery products utilize an alkaline aqueous electrolyte formula, ensuring non-flammability, non-explosivity, safety, and non-toxicity. They offer intrinsic safety, flexible site selection, easy deployment, long lifespan, and long-duration energy storage capabilities, fully meeting the requirements of megacities for new energy storage solutions. The project integrates photovoltaic technology, smart energy management, new energy storage, carbon footprint analysis, and a low-carbon concept café. By applying energy storage technology and integrating distributed solar PV, it utilizes the old Yangshupu Power Plant site to establish a smart microgrid along the Yangpu Riverside. This maximizes the utilization of local renewable energy resources, provides green electricity for the ash silo, surrounding cafes, shore power charging piles, and landscape lighting facilities. Using zinc-iron flow batteries, a centralized energy storage system of 100kW/400kWh was constructed, and a smart energy integrated management platform was set up to ensure the normal operation of the energy system. The zinc-iron flow batteries from WEVIEW Energy Storage support the integrated energy center in efficiently storing and discharging solar power, while also supplying high-quality green electricity to urban infrastructure. This enhances grid flexibility and achieves carbon neutrality through "multi-energy complementarity".

From construction and system debugging to control strategy validation and final grid connection, the entire project cycle was completed within just over three months. The project officially commenced operations in December 2023 and is currently providing stable green electricity to public facilities and service buildings such as cafes within the park.

Project innovation points: The project has achieved innovation from both technological and operational model perspectives.

- **Advanced technology:** By adopting zinc-iron flow battery technology, the project features intrinsic safety, long lifespan, and long-duration energy storage capabilities, filling a technical gap in China's flow battery industry;
- **Mode innovation:** Through the application of an integrated photovoltaic-storage-charging system, the project realizes multi-energy complementarity and efficient energy utilization, offering strong support for building a new power system.
- **Carbon-neutral demonstration:** The former coal ash silo of a thermal power plant has now become a green, carbon-neutral energy storage demonstration benchmark, offering a new path for the city's sustainable and high-quality development.

9.2.2 Project highlights

Overall technical plan: The Zero-Carbon Smart Integrated Energy Center repurposed the original coal ash silo of Yangshupu Power Plant, transforming it into three large cylindrical structures with photovoltaic panels installed on their rooftops. The zinc-iron flow batteries integrate, and store electricity generated by rooftop PV panels, ensuring efficient storage and discharge. They provide stable, high-quality green electricity to surrounding facilities such as cafes, charging piles, and landscape lighting, achieving multi-energy complementarity. The project includes a newly built solar PV-charge-storage energy station that provides clean power to riverside shore power charging piles, landscape lighting facilities, ash silos, and supporting service buildings through an integrated solar PV-storage-charging system. The project is located at No. 1 Tengyue Road, Yangpu District, Shanghai — within the site of the former Yangshupu Power Plant. The total area is 2,500 square meters, with approximately 80 square meters dedicated to the energy storage facility. The newly constructed solar PV-charge-storage energy station includes distribution systems, charging systems, solar photovoltaic systems, energy storage systems, and energy management systems, and more specifically:

- **Distribution system:** It is equipped with two 0.4kV switchgear units, with power supply lines drawn from the outgoing switches of the original ash silo distribution room;
- **Charging system: A 20kW shore power charging pile is configured, with one machine per**

charging point;

- **Photovoltaic system:** The roof of the ash silo is equipped with 75 solar PV modules rated at 540Wp each, totaling 40.5kWp. One 30kW string inverter is installed;
- **Energy storage system:** One set of 100kW/400kWh zinc-iron flow battery energy storage system is deployed;
- **Energy management system:** An Energy Management System (EMS) is configured to coordinate the operation of sources, grids, loads, and storage within the microgrid system, and to enable organic interaction between different microgrids or between microgrids and the main grid. This maximizes renewable energy utilization and improves the security, economic efficiency, and sustainability of the energy system.

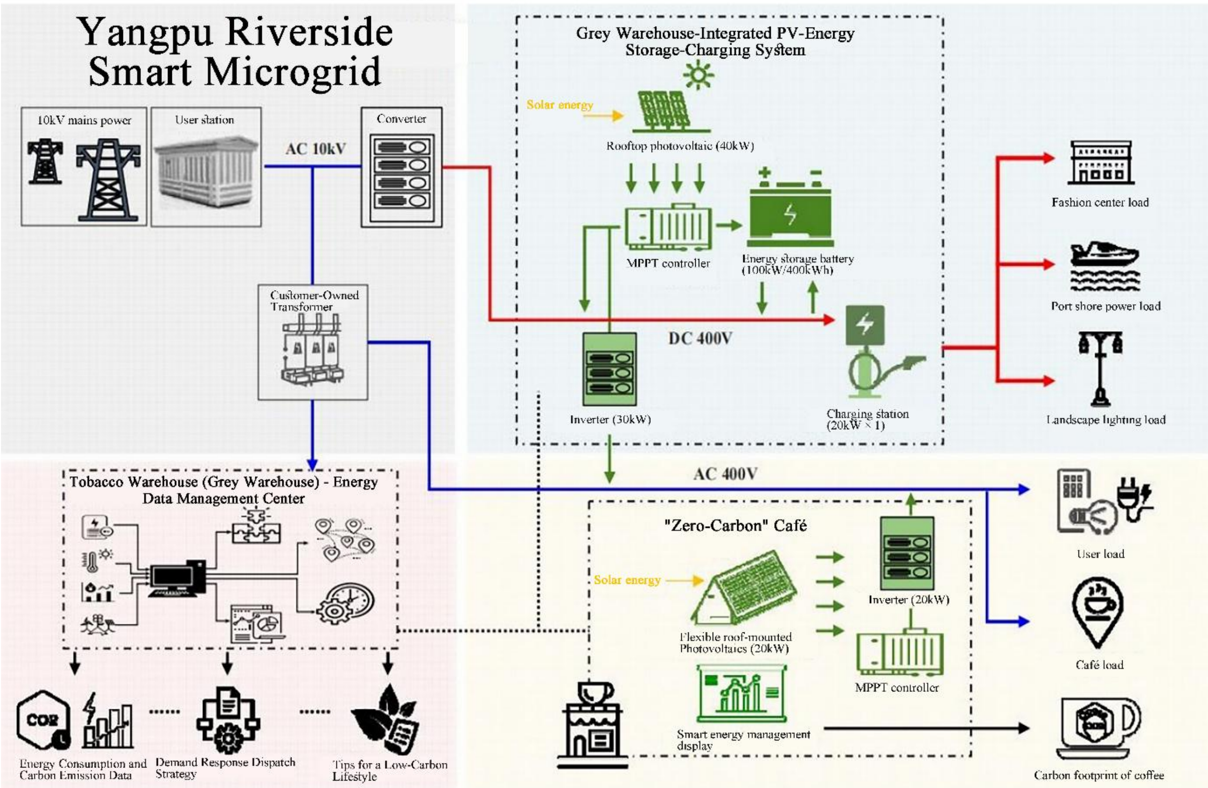

Figure 9-4 System configuration of the Zero-Carbon Smart Integrated Energy Center, Yangpu Riverside, Shanghai

Business model: The project adopts a business model that combines initial capital investment with long-term operational returns, ensuring its sustainable development. The total investment of the project is approximately CNY8 million, with the zinc-iron flow battery accounting for CNY1.24 million. After official operation, the project is expected to recover its investment in 8.42 years, with a full investment return rate of 11.12%. The project's revenue mainly comes from peak shaving and valley filling services of the energy storage system, electricity market trading income, and government policy subsidies. By optimizing the operation strategies of the energy storage system, the utilization rate and return on investment are enhanced, maximizing the project's economic benefits.

Key technical indicators: The project uses the next-generation zinc-iron flow battery product GP110, with key performance indicators as follows:

- Rated power: 100kW
- Rated capacity: 400kWh
- Response time: ms-level
- Energy conversion efficiency: 82% (DC side)
- Cycle life of 25 years (calendar life), with over 30,000 charge-discharge cycles
- Operational ambient temperature: From -20°C to 45°C.

9.2.3 Key accomplishments of the project

Project performance: Since its commissioning, the project has achieved significant economic and social benefits. At the same time, the project's operation validates the zinc-iron flow battery's ability to enhance regulation capacity, overall efficiency, and safety assurance in energy systems. It establishes a new power system featuring safe, long-duration, environmentally friendly, and flexible energy storage configurations.

Zinc-iron flow batteries use highly efficient and safe alkaline chemistries. Flexible modules can be interconnected to meet higher power and energy demands. It is estimated that the project can annually charge up to 306,890kWh and discharge 227,100kWh, with a comprehensive conversion efficiency of 74%. It can achieve annual CO_2 emission reductions of 83.26 tons. In addition, the peak-valley electricity price mechanism is fully utilized. The energy storage system charges batteries during off-peak hours when electricity prices are low and discharges them during peak hours via inverters, feeding power into the 0.4kV busbar inside the station. By employing peak shaving and valley filling strategies, the energy storage system effectively reduces electricity costs for surrounding facilities and improves energy utilization efficiency. The project's investment return rate is 11.12%.

Based on this project, Shanghai's first Industrial Zero-Carbon Smart Integrated Energy Center will be established. By constructing shared energy storage stations, upgrading the power system, it provides more cost-effective, intelligent, and low-carbon integrated energy services for Yangpu Riverside, showcasing a zero-carbon urban community. The application of *photovoltaics, energy storage, direct current, flexibility and charging* technologies improves building energy efficiency, reduces reliance on the external grid, and enables green and low-carbon building development. At the same time, the technology also enhances power supply reliability and stability, providing users with a better electricity experience.

Honors and awards: The project has received high recognition from the National Energy

Administration and the Shanghai Development and Reform Commission. In January 2024, the National Energy Administration listed WEVIEW Energy Storage's Zinc-Iron Flow Battery Energy Storage Demonstration Project in Yangpu District, Shanghai as a *New Energy Storage Pilot Demonstration Project*, making it the only new energy storage project in Shanghai to receive such designation. Additionally, the project has received widespread praise from experts and scholars in the industry. In July 2024, Vice Chairman Huang Zhen of the Shanghai Municipal Committee of the Chinese People's Political Consultative Committee led a special supervision session titled "Promoting Energy Structure Transformation and Advancing Shanghai's Dual Carbon Strategy". During a field visit to the Zero-Carbon Smart Integrated Energy Center demonstration project, he gave it strong endorsement to the project.

Strategic supporting role: The project actively responds to China's "dual carbon strategies" and the call for constructing new type power systems. Guided by the concept of "people-centered cities", it leads urban modernization in Yangpu Riverside — where General Secretary Xi Jinping proposed "cities built by the people". It has created Shanghai's first "Zero-Carbon Smart Integrated Energy Center", showcasing ecological civilization concepts and demonstrating firm commitment to the dual carbon strategy in Shanghai. As the only project in Shanghai recommended and designated by the National Energy Administration as a new energy storage demonstration project, its successful implementation offers a new path for the city's green and high-quality development, marking a transformative leap from an "industrial rust belt" to an "industrial showcase belt". It contributes to promoting the development of the new energy industry and the transformation and upgrading of the energy structure, helping realize the nation's dual carbon goals.

Taking this demonstration project in Shanghai as an opportunity and leveraging the intrinsic safety advantages of zinc-iron flow batteries, the integration of this technology with a PV-storage-charging system provides strong support for renewable energy integration and the secure, stable operation of the power grid. This project breaks through the challenges faced by megacities like Beijing, Shanghai, Guangzhou, and Shenzhen in deploying energy storage projects after the Dahongmen explosion incident. It acts as demonstrates project in setting examples, breaking through barriers, and driving the deployment of new energy storage systems in core urban areas, providing valuable reference for wide applications of new energy storage in China.

9.2.4 Prospects for replication and application

Key know-hows learnt from the project include:

Technology innovation is key: From both market demand and policy perspectives, clear requirements have been set for the safety, long-duration energy storage capability, and cost-effectiveness of medium-to-large-scale energy storage technologies. Zinc-iron flow batteries meet stringent policy requirements for energy storage safety due to their unique inherent safety characteristics. The battery uses non-toxic, non-flammable, and non-explosive alkaline electrolytes, fundamentally avoiding fire and explosion risks associated with traditional lithium-ion batteries. It meets the high-safety standards required for medium-to-large-scale energy storage systems by the state. This project fully validated the technical advantages, providing important safety design references for other energy storage projects.

Multi-energy complementarity is a trend: By constructing integrated photovoltaic-storage-charging systems and applying multi-energy complementarity, efficient energy utilization can be achieved, along with reduced electricity costs. The construction and application of an intelligent energy comprehensive management platform enables real-time monitoring, data analysis, and remote control of the energy storage system, offering strong support for optimized operation and decision-making.

Policy support is essential: Government policy guidance and support play a crucial role in promoting and implementing such projects. By formulating relevant policies and offering financial subsidies, the construction and operational costs of the project can be reduced, thereby enhancing its economic and social benefits.

There is a great potential for replication of the project and application of the technologies in other cities, considering the following points:

- With the advancement of the "dual carbon" goals and the implementation of policies such as the Guiding Opinions on Accelerating the Development of New Energy Storage, clear requirements have been set for the safety, long-duration energy storage capability, and cost-effectiveness of medium-to-large-scale energy storage technologies. It is estimated that China's long-duration energy storage market demand will reach 149GWh by 2025, with a total market scale exceeding CNY200 billion. The performance characteristics of zinc-iron flow batteries align closely with policy directions, providing a solid policy foundation for their economy-wide promotion.
- Flow batteries, with their inherent high safety, low cost per kWh, long storage duration, and extended cycle life, are highly aligned with the core needs of long-duration energy storage. They are poised to replace pumped hydro storage and become the primary new long-duration energy storage technology route. In addition, the raw materials used are abundant and inexpensive domestically, reducing reliance on imports and offering significant economic advantages for large-scale, long-duration energy storage.

9.3 Integrated generation, distribution, load management and storage: Zero-carbon demonstration at Dangan Island in Zhuhai

9.3.1 Project overview

Dangan Island lies amidst the azure waters southeast of Xiangzhou District, Zhuhai City, Guangdong Province. It is only 950 meters away from Erzhou Island and faces Kowloon, Hong Kong to the north at a distance of 30 kilometers. As the gem of the Dangan Islands, it spans an area of 13.2 square kilometers.

However, this beautiful island has long suffered from energy supply challenges. Currently, the entire island's power supply relies entirely on diesel generators, with an annual electricity consumption of up to 188,000kWh, growing at an average annual rate of 17%. Due to the costs of diesel generators, residential electricity prices remain high — reaching CNY3.28/kWh — placing a heavy burden on local residents' livelihoods. Moreover, the pollutant emissions and noise generated by diesel generator operations have significantly impacted the island's ecological environment and tourism image. Although laying a submarine cable from mainland Zhuhai was considered, the investment cost of up to CNY300 million makes this option economically unfeasible. Therefore, there is an urgent need to seek an innovative solution to break through Dangan Island's energy supply bottleneck and achieve green and sustainable development.

Advancing utilization of solar energy resources across Zhuhai is an important measure by the Zhuhai Municipal Party Committee and the government to implement the spirit of the 20th National Congress of the Communist Party of China, fulfill the "Dual Carbon Strategy", accelerate green energy transition, and promote high-quality development. Zhuhai Huafa New Energy Development Co., Ltd. and Aiko Solar are transforming Zhuhai's Dangan Island into China's first zero-carbon island and community, following instructions from the Zhuhai Municipal Party Committee and government. This project serves as a demonstration for the city, province, and beyond.

(1) Electricity demand and existing power supply infrastructure

Annual electricity consumption averages 188,000kWh, with an electricity price of CNY3.28/kWh. The island's grid operates at 0.4kV voltage level. Power supply entirely depends on diesel generators — two units of 200kW and one unit of 250kW, totaling 650kW capacity. The daily average load is 40kW. In 2021, the island consumed 150,000kWh of electricity; in 2022, it was 184,000kWh, representing a year-on-year growth rate of 13.52%; From 2021 to August 2023, the average annual electricity consumption growth rate was 17.07%. Based on existing 2023 data and annual growth projections, the island's total electricity consumption in 2024 is expected to reach approximately 198,000kWh, with monthly minimum usage at 12,000kWh and maximum at 24,000kWh. July to October are peak months, with the highest usage in August. November to April of the following year are off-peak months, with February having the lowest consumption. The island's average daily load is 40kW.

(2) Available resources

Most of Dangan Island consists of nature reserves and forested areas. The residential areas are divided into Dangan Head and Dangan Middle zones, covering about 332 mu (approximately 221,333 square meters), accounting for 1.6% of the island's total area. Among them, Dangan Head has a total rooftop area of about 5,000 square meters, relatively centralized in location; Dangan Middle has approximately 1,800 square meters of rooftop space, most of which already has installed photovoltaics. Field investigations indicate that currently, no barren hills or contiguous land suitable for PV station construction are available. The Dangan Head area has a high population density, with complete planning for power supply, administration, culture, healthcare, housing, and commerce. As the main administrative zone, it is recommended as the priority area for implementing the zero-carbon project.

(3) Carbon Emissions

The island currently emits about 108.45 tons of CO_2 annually, mainly from diesel generator power production, fuel vehicles, and kitchen gas usage. Of this, diesel power generation accounts for 99.28 tons, 91.54% of total emissions.

9.3.2 Project features

A dispatching and operation system based on microgrid scheduling and energy stations has been established, utilizing source-grid-load-storage coordinated interaction technology to ensure safe and reliable operation of the island's power system.

(1) Energy system

A multi-energy complementary microgrid system has been built to achieve full replacement of traditional energy sources with green alternatives on the island. Building upon the current diesel power supply, multiple new energy sources — including photovoltaics, wind power, and energy storage — have been added to meet the island's net-zero emission target. Firstly, for photovoltaics: Phase I includes a 208.03kW installation, with a planned installed capacity of 500kW. It adopts Aiko Solar's most advanced ABC modules, achieving a 10% improvement in PV efficiency compared to similar market products; Secondly, for wind power: A planned capacity of 25kW using landscape-integrated micro wind turbines utilizes the island's wind resources to create a diversified clean energy zero-carbon demonstration scenario, enhancing the scenic value of the tourist destination; Thirdly, for energy storage: Phase I includes a 430kWh storage installation, with a future plan of 1,000kWh. It uses Hi-PowerTech lithium iron phosphate electrochemical energy storage systems to provide stable power during periods of insufficient solar generation (such as nights and cloudy days), ensuring system security. This also supports EV charging piles (two units of 7kW), smart streetlights (15 units), intelligent microgrid management, and carbon emission monitoring systems. The completed project can generate 600,000kWh annually, enabling full green electricity supply across the island.

Implement smart energy management, collect real-time operational data from PV systems, energy storage, EV charging piles, diesel generators, and distribution networks for dynamic regulation; Establish a fault warning, maintenance log, and real-time monitoring system for the island's power distribution network to enhance intelligent operations and reduce maintenance costs.

Balancing tourism and cultural preservation, the new energy facilities are deeply integrated with the architectural style of Dangan Island's ancient villages. This enriches the project's connotation, creating the first-ever concept of a zero-carbon island and establishing a model for the "Bai Qian Wan" (hundreds, thousands, and ten-thousands) engineering initiative unique to Dangan Town.

(2) Project program

Without altering the island's existing power usage model, grid lines, electricity pricing, or billing management approach, a new microgrid system composed of photovoltaics, energy storage, charging infrastructure, and wind power is introduced to replace the original diesel-based energy supply. By building decentralized wind power, distributed solar PV, energy storage, charging piles, PV streetlights, and a smart energy management cloud platform, the project promotes new energy applications such as photovoltaic-storage-charging on the island. It constructs a multi-energy complementary microgrid platform to improve electrification levels, achieving five key objectives: net-zero emissions across the island, significantly reduced electricity bills for residents, secure and reliable power systems, digitally interconnected monitoring systems, and enhanced living safety for isolated islands — ultimately creating a zero-carbon island.

The overall implementation plan for the Dangan Island Zero-Carbon Demonstration Project is illustrated in Figure 10-5. Wind power (25kW), photovoltaics (208.03kWp), energy storage (430kWh), EV charging piles (two units of 7kW), smart streetlights (15 units), intelligent microgrid management, and carbon emission monitoring system. An average annual generation of 250,000kWh meets the island's full energy demand coverage.

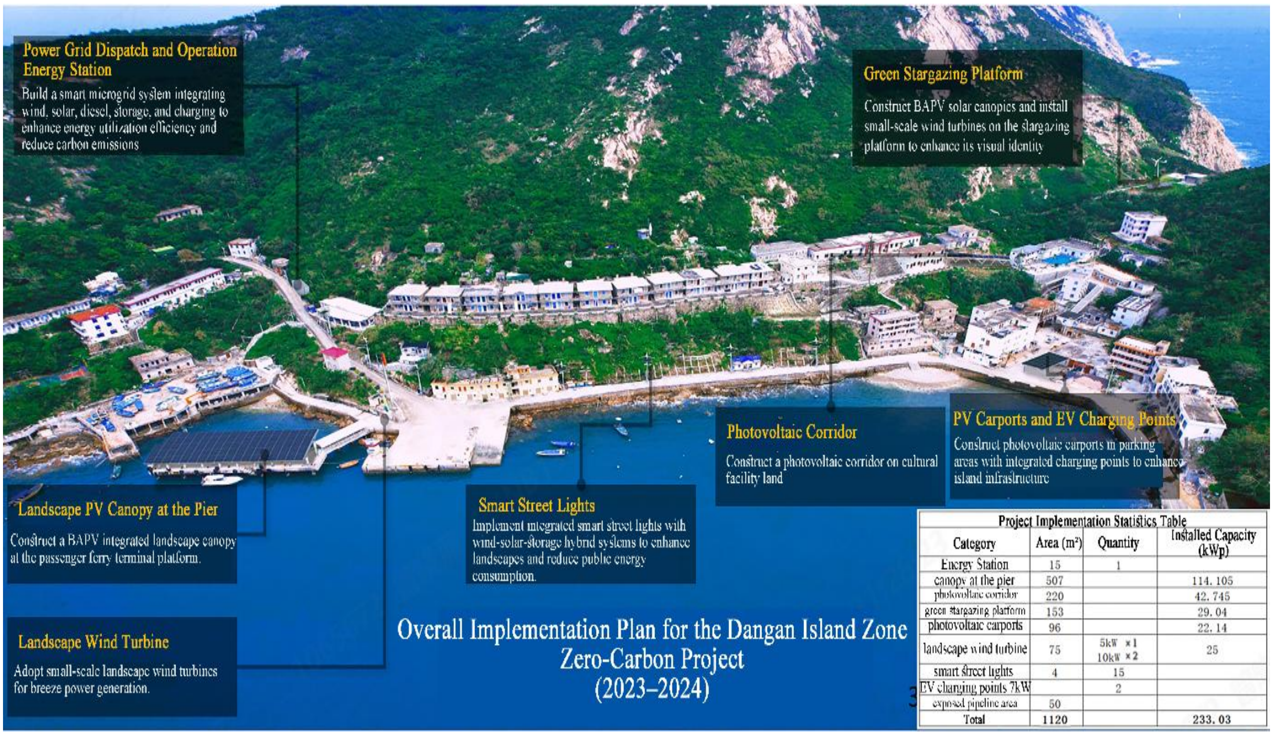

Figure 9-5 Implementation Plan for the Dangan Island Zero-Carbon Demonstration Project

Considering the actual conditions of buildings in Dangan Island and the protection requirements for ancient village architecture, photovoltaics are mainly arranged in scattered public areas — such as scenic piers, stargazing platforms, corridor-style PV installations — occupying approximately 1,120 square meters of fragmented land.

- **Photovoltaic system:** Integrated BIPV (Building-Integrated Photovoltaics) applications across multiple scenarios in the Dangan Head residential area, including corridors, piers, stargazing platforms, and PV carports. Combined with the characteristics of the village landscape, multi-scenario PV design integrates harmoniously with the environment. Approximately 1,000m2 of public land in Dangan Head is utilized for distributed PV installations, with a total installed capacity of 208.03kWp. Achieving a perfect integration of shading, rain protection, and aesthetic functions in areas such as piers, corridors, and stargazing platforms.
- **Micro wind power system:** Small-scale wind turbines are installed at the Dangan Head pier and stargazing platform to enhance the island's tourism appeal. One 5kW vertical-axis wind turbine is installed near the Dangan Head pier, with an overall height of 10–12m, a rotor diameter of 3.4m, and a footprint of approximately 8 m2; Two 10kW horizontal-axis wind turbines are installed at the Dangan Head scenic viewing platform, with an overall height of 12–16m and a footprint of approximately 33 m2 per unit.
- **New energy storage system:** Using electrochemical energy storage to store surplus electricity when photovoltaic and wind power generation exceeds load demand, enabling energy transfer across different time periods; Establish a "source-grid-load-storage" microgrid operation station. The system includes a 430kWh battery energy storage system, a 200kW PCS, AC/DC cabinets, network cabinets, and an O&M operation desk. Additional components will be added in later stages based on the island's operational load requirements; It adopts an intelligent prefabricated cabin design; It is deployed in available open space near the diesel station, occupying an area of 15 square meters.
- **Smart streetlights:** Public building service demonstration to build a full-scenario smart energy application. Ten hybrid solar-wind smart streetlights and five courtyard lights are installed along coastal roads and in the village committee area to improve the island's intelligent public lighting system, effectively reducing power consumption and maintenance labor costs.
- **Dispatching and operation system and carbon management:** Collect real-time operational data from PV systems, energy storage, EV charging piles, diesel generators, and distribution networks for dynamic regulation; Establishes a fault warning system, maintenance log, and real-time monitoring framework for the island's power supply and distribution system to enhance intelligent operations, reduce maintenance costs, and enable dynamic statistics, calculation, analysis, and management of carbon emissions.

Figure 9-6 Distributed Energy System Layout of Dangan Island Zero-Carbon Demonstration Project

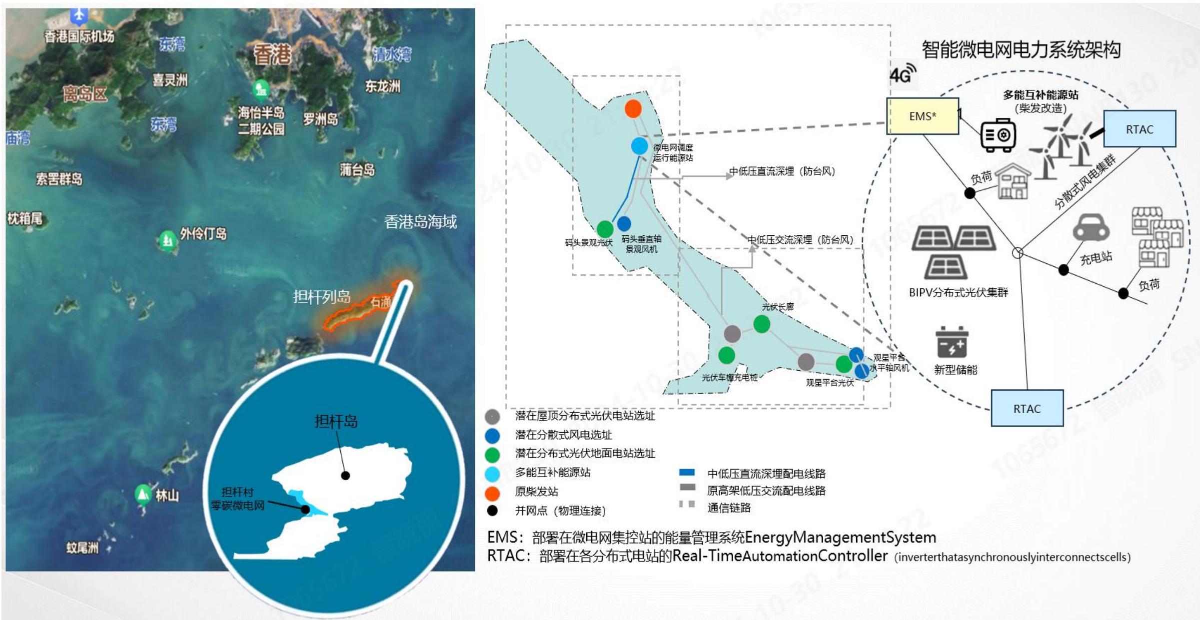

Figure 9-7 Energy System – Power System Architecture (Microgrid)

(3) Project business model

The project proposes a replicable and scalable zero-carbon island operation business model to ensure implementation, creating a cluster of zero-carbon microgrids across hundreds of islands and achieving mutual benefits for all stakeholders.

With government support and guidance, the project is invested in and constructed by enterprises, which are also responsible for the long-term operation of newly added energy infrastructure such as photovoltaics, wind power, energy storage, and EV charging stations. A 70% discount is offered on the existing island electricity rate to benefit residents, with reasonable investment returns achieved through green electricity sales and EV charging service fees. The project yields a return on investment (ROI) of 6%. Upon completion of the Dangan Island Zero-Carbon Microgrid Demonstration Project, it produces 600,000kWh of green electricity annually, reduces carbon emissions by 152.5 tons per year, lowers residents' electricity costs by nearly one-third, saves over CNY200,000 annually in energy expenses, and enhances power system safety, with a power supply reliability reaching 99.999%.

9.3.3 Key accomplishments of the project

(1) Social and economic benefits

The construction of the Dangan Zero-Carbon Island, based on integrated wind-solar-storage-charging and diesel backup systems, achieves net-zero energy emissions across the island, significantly reduces electricity bills for residents, ensures safe and reliable power systems, and strengthens life safety on remote islands, playing a key role in achieving carbon peaking targets. The social and economic benefits, as well as system efficiencies, achieved by the project are illustrated in the following figure.

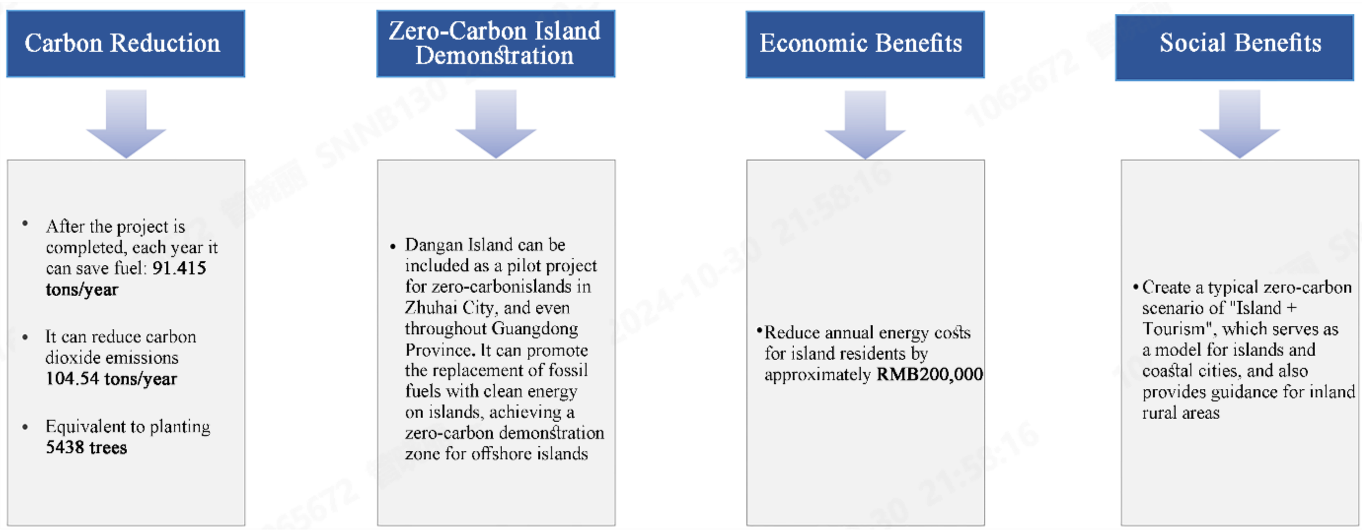

Figure 9-8 Social and Economic Benefits of the Dangan Island Zero-Carbon Demonstration Project

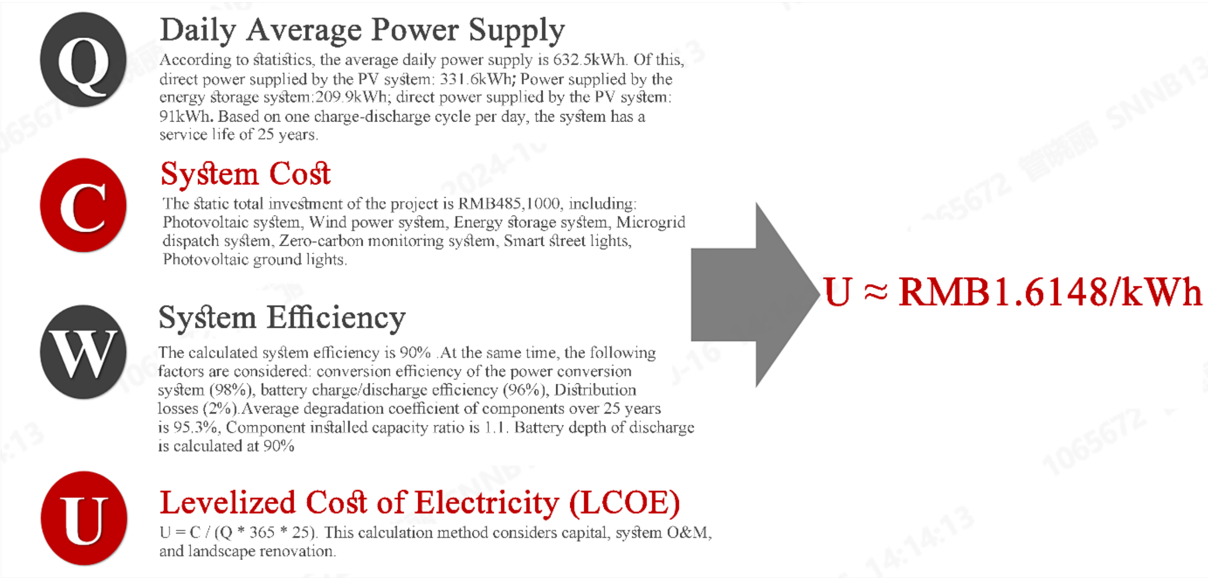

Figure 9-9 System Efficiency of the Dangan Island Zero-Carbon Demonstration Project

(2) Carbon emission

Five major carbon reduction strategies are employed to achieve carbon neutrality in this project, establishing a zero-carbon island demonstration, which include:

- Distributed PV: A 200kW distributed photovoltaic system generates 240,000kWh annually; full utilization equates to annual CO2 emission reductions of 126.7 tons and diesel fuel savings of 40.8 tons;
- Distributed wind power: A 25kW decentralized wind farm generates 10,000kWh annually; full utilization equates to annual CO2 emission reductions of 5.3 tons and diesel fuel savings of 1.7 tons;
- Energy storage: A 200kW / 430kWh energy storage system ensures stable power supply throughout the year for the island;
- Charger: Electric vehicle adoption reduces diesel usage by 32 tons annually, equivalent to 100 tons of CO2 emission reductions per year;
- Smart Management Cloud Platform: The intelligent cloud management platform improves energy efficiency by 5%, reducing annual carbon emissions by 5 tons.

9.3.4 Prospects for replication and application

The project establishes a government-enterprise collaboration mechanism. Lay the groundwork for broader implementation through technology demonstration projects, jointly launching zero-carbon island pilots, develops typical technology applications. Build new renewable energy microgrid systems, forming an integrated "source-grid-load-storage" system, promote practical implementation of project, adopt a "build-and-promote concurrently" zero-carbon island model, vigorously advancing the development of a hundred zero-carbon islands in Zhuhai, and explore an open and shared model. Achieve integrated investment, construction, and operation of zero-carbon islands.

Zhuhai, known as the "City of Hundred Islands", sees excellent comprehensive socio-economic benefits from the Dangan zero-carbon microgrid model. The energy system and model of the project can be further extended to other coastal islands in the Pearl River Estuary, such as Wailingding Island, to create a zero-carbon microgrid cluster across Zhuhai's hundred islands, promoting regional zero-carbon transformation with vast potential for replication.

9.4 Integrated source-grid-load-storage solution: PEDF intelligent DC-microgrid at office building in Qingdao

9.4.1 Project overview

In 2021, the State Council issued the *Action Plan for Carbon Peaking Before 2030*, clearly stating: "Enhance terminal electrification levels in buildings and construct PEDF buildings integrating photovoltaic power generation, energy storage, DC distribution, and flexible power consumption". Against this background, Qingdao Energy Thermal Power Group No.3 Thermal Co., Ltd. developed the Photovoltaic, Energy, DC, Flexible (PEDF) Intelligent DC Microgrid Demonstration Project, based on renovations to the interior decoration and air conditioning systems of existing office buildings. The project aims to achieve efficient and low-carbon building operations through the integrated application of photovoltaics, energy storage, DC distribution, and flexible power use, providing new technical pathways for the building sector to meet carbon peaking and carbon neutrality goals.

The project is located at No.12 Zhangpu Road, Shinan District, Qingdao City, Shandong Province. It was commenced construction in April 2022 and completed in July 2023, covering a construction land area of about 17,000 square meters. The project comprehensively renovated the office building, adopting PEDF technologies (solar power generation, battery energy storage, DC air conditioning units, DC water pumps), air-source heat pumps, water-coolant thermal storage, V2H/B technology, intelligent energy management, BIM technology, and more. It integrates multiple energy and ICT technologies to maximize intensive land use, constructing a PEDF "zero-carbon" building demonstration with high renewable energy penetration, high-efficiency power architecture, and high-quality service coordination.

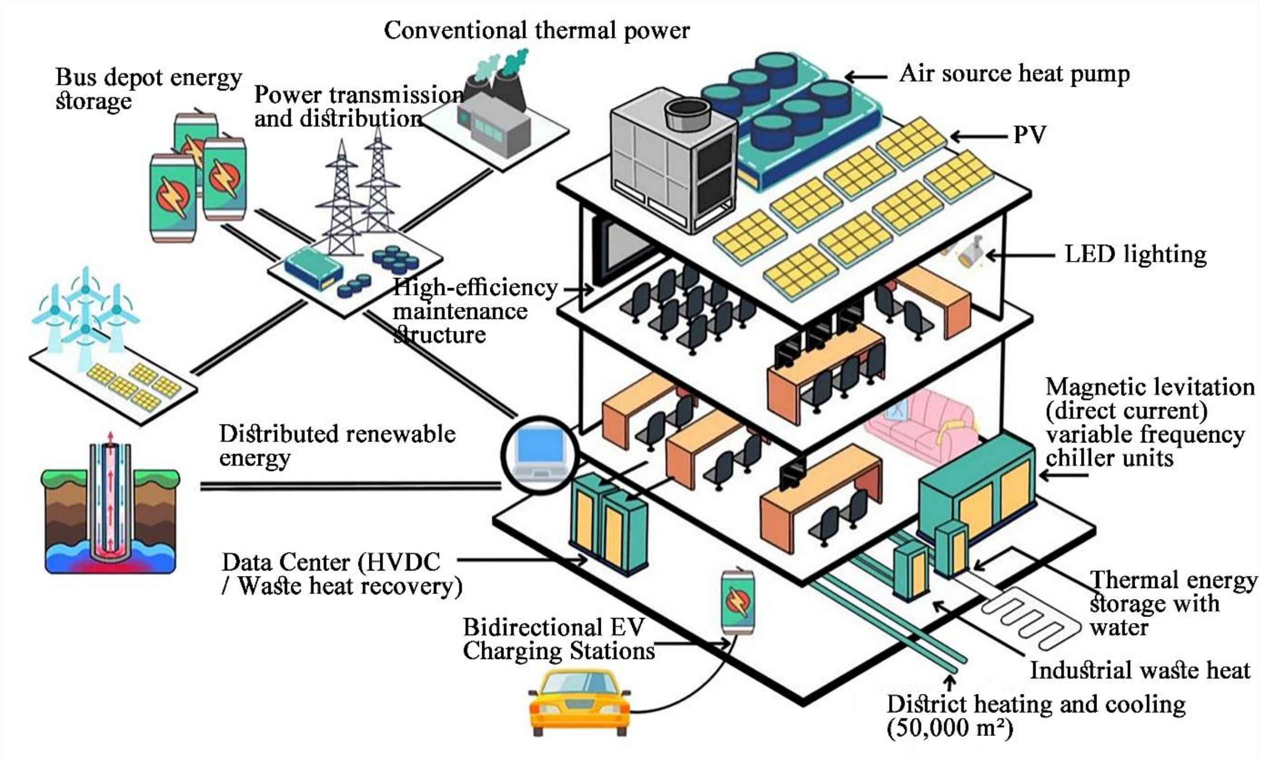

Figure 9-10 System layout of the project

9.4.2 Project features

The Qingdao Energy Thermal Power Office Building Photovoltaic-Storage-Direct-Flexible Smart DC Microgrid Demonstration Project is the first domestic project integrating PEDF technology with water-based cold storage and air-source energy. A distributed photovoltaic power generation system is installed on the vacant rooftop of the building (approximately 3,000m^2), and the existing water tank (approximately 810m^3) is retrofitted for cold storage. After the retrofit, during summer daylight hours, the project directly uses photovoltaic power to drive chillers for direct cooling. On cloudy or rainy days, grid AC power drives the chillers for direct cooling, while water-based cold storage provides auxiliary cooling. In extreme weather conditions, air-source heat pumps can be used as supplementary cooling sources; In winter, heating is provided through a combination of centralized heating and air-source heat pumps in a complementary manner.

(1) PEDF technology

This project integrates solar photovoltaic power generation, energy storage, DC distribution, and flexible interaction technologies into a unified system. It utilizes DC electricity generated by solar PV through a DC microgrid to directly power DC loads, achieving building cooling and heating, while using air conditioning thermal storage to realize "flexible energy use" in the building. The PEDF system in this project mainly consists of the following components:

- Photovoltaic power generation unit: The rooftop distributed PV system has an installed capacity of

150kWp;

- Energy storage unit: It is equipped with a 40kW energy storage converter and a 51.2kWh battery energy storage system;
- DC load unit: Major electrical loads include DC-powered equipment such as magnetic levitation chillers, variable frequency pumps, computers, projectors, and lighting;
- DC distribution system A DC power distribution system is built, equipped with DC microcomputer protection and insulation monitoring;
- Energy management system: An energy management unit and software are configured to monitor data, manage operating modes, and control power flow across the entire DC system, enabling flexible electricity usage;
- V2H/B bidirectional DC charging pile: New energy DC vehicles are used as mobile energy storage units to enable coordinated operation between electric vehicle batteries and the office building's power system.

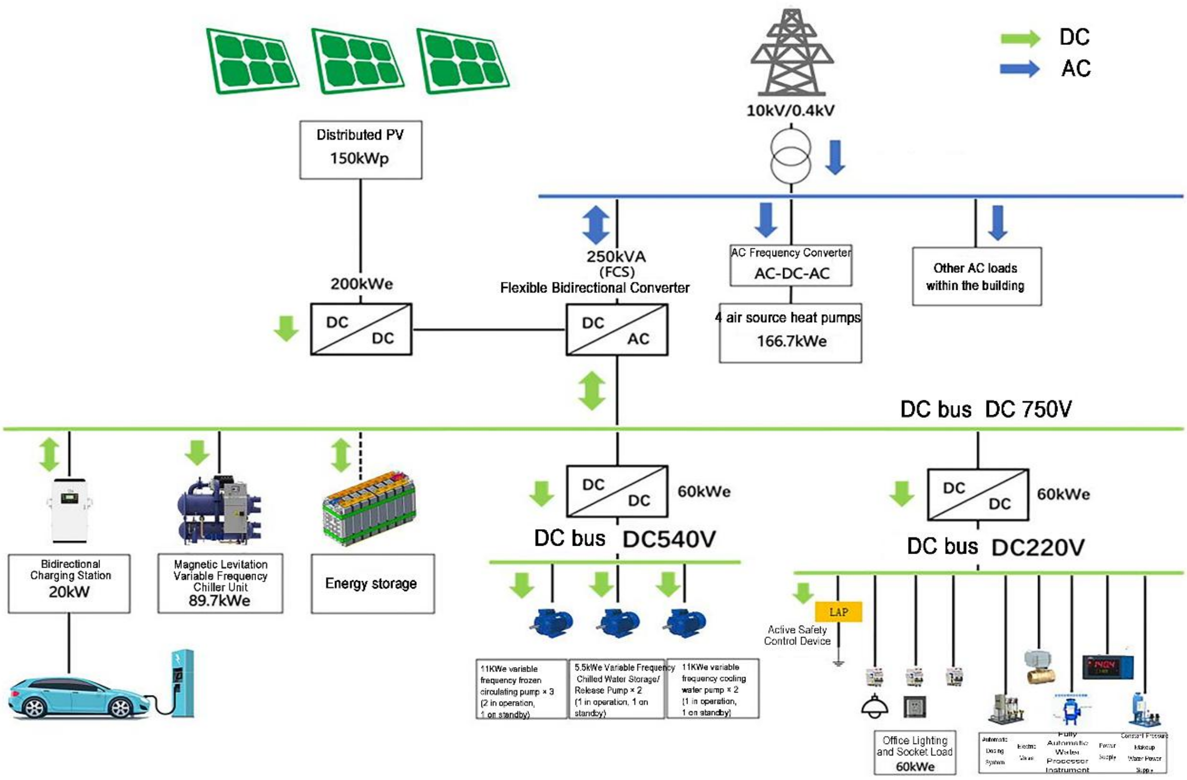

Figure 9-11 Schematic Diagram of the PEDF Power Distribution System in the Project

Rooftop distributed photovoltaic power is directly fed into a 750V DC distribution network, prioritizing supply to DC loads. The 750V DC directly powers magnetic levitation variable-frequency chillers, 540 VDC drives variable-frequency pumps and cooling tower fans, and 220V DC supplies power to certain end-use office lighting and outlets. Excess electricity is supplied to energy storage systems, where both battery storage and water-based cold storage are used for peak shaving in electricity and cooling load, respectively, enabling flexible electricity consumption. Photovoltaic power can also be converted via bidirectional smart inverters for AC loads. By controlling strategies such as bidirectional flow, unidirectional flow, grid connection, and off-grid operation, surplus power can be fed back to the grid or drawn from the grid when needed.

The project is equipped with V2H/B bidirectional DC charging piles that connect new energy DC electric vehicles as mobile energy storage units. During charging, they receive electricity from the grid or energy storage systems, and during peak grid load or building demand, they can reverse-discharge EV battery power back into the grid, enabling coordination between EV batteries and the office building's power system. This not only optimizes energy utilization efficiency but also enhances the flexibility and reliability of the power system, promoting integration among EVs, charging infrastructure, telecommunications networks, transportation systems, and power grids.

Figure 9-12 Project V2H/B EV Charging System Interface

(2) Water-based cold storage technology

The cooling solution adopts a magnetic levitation centrifugal chiller combined with water-based cold storage. One DC-driven magnetic levitation variable-speed centrifugal chiller is configured, and the original underground water tank (810m³) is retrofitted for cold storage. To efficiently utilize on-site photovoltaic power and assist in peak shaving for the grid, the cold storage-integrated cooling system must operate in both simultaneous supply-and-charging and simultaneous supply-and-discharging modes. That is, during periods of abundant photovoltaic power and off-peak grid tariffs, the chiller operates at full load to meet terminal cooling demands while storing excess cooling capacity; During high grid tariff periods, the chiller output can be reduced, and the chilled water tank can simultaneously provide cooling to end users.

The Office Building PEDF cooling system supports multiple operating modes: chiller cooling, tank cold storage, tank cold release, simultaneous supply-and-charging, and simultaneous supply-and-discharging. It can flexibly switch modes based on local power generation and consumption, external grid electricity prices, or dynamic carbon emission factors, enabling flexible energy storage and release for optimal energy supply and use.

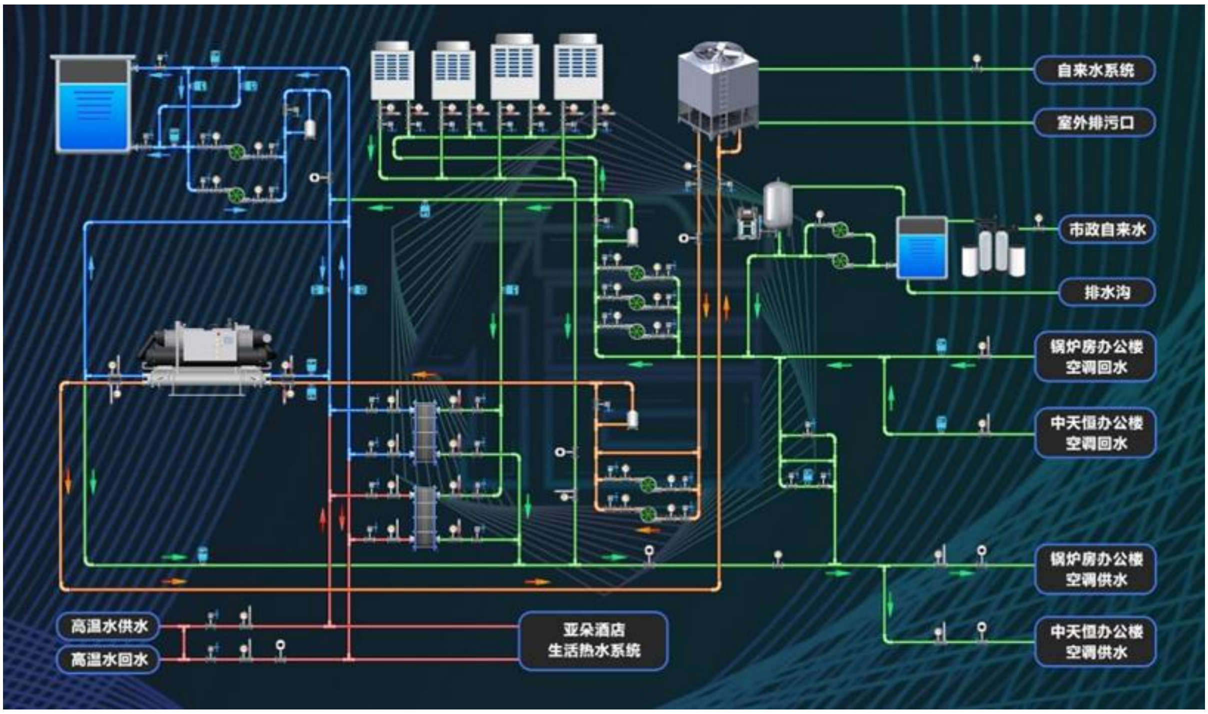

Figure 9-13 Schematic Diagram of the Water System

(3) Intelligent energy management platform

To achieve intelligent, multi-energy integrated operation and dual-control of energy and carbon emissions, the Thermal Power Group Office Building has developed an intelligent energy management platform capable of real-time big data analysis and visualization. By collecting, analyzing, and statistically processing energy consumption data from various monitoring points within the building, the platform optimizes energy use and reduces overall consumption, thereby achieving energy conservation and efficiency improvements. Additionally, the platform offers OPC-compliant software interfaces or BA interface boxes, ensuring openness, compatibility, and integration to meet users' needs for building automation management. Managers can access the intelligent energy management platform via PC clients or mobile mini-programs, achieving the goal of making energy consumption “visible, manageable, and precisely controllable”, providing convenient pathways for energy efficiency management, allowing real-time monitoring and control of energy use anytime, anywhere.

Figure 9-14 Interface of the Intelligent Energy Management System

(4) BIM technology applications

Given the comprehensive integration of multiple energy and power systems in this project, along with complex piping and numerous equipment in the mechanical room, the team built a web-based human-machine interactive display system using BIM technology to better visualize equipment layout, parameters, and performance. Through 3D dynamic visualization, the internal layout of the mechanical room, pipeline routing, and system operations become intuitively visible and accessible online, meeting the needs of remote access and providing a solid visual foundation for smart maintenance, demonstrations, promotion, and science education.

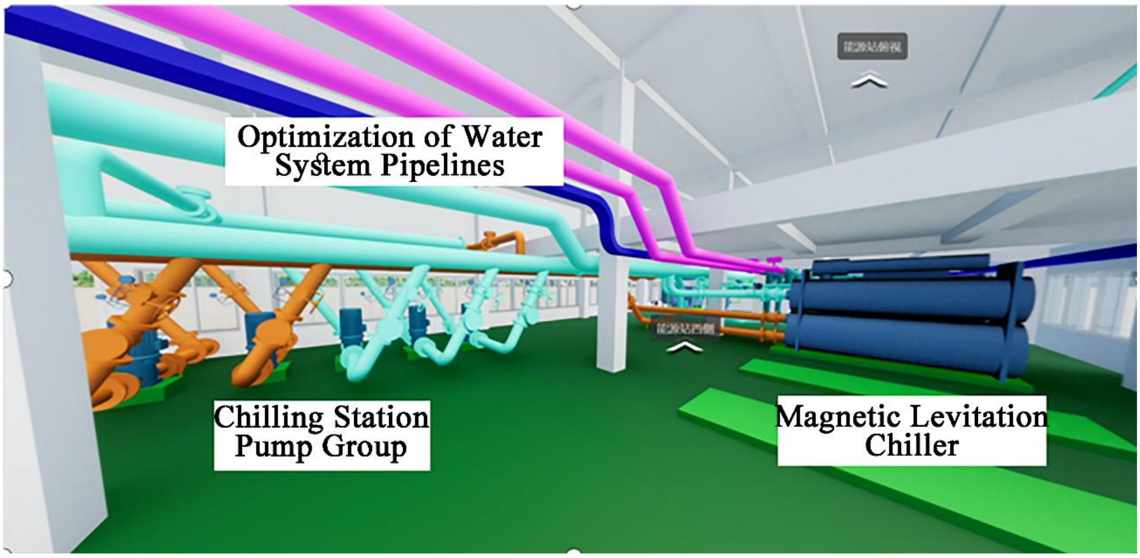

Figure 9-15 Interface of the Mechanical Room BIM System

9.4.3 Key accomplishments of the project

The Qingdao Energy Thermal Power Office Building "Photovoltaic-Storage-Direct-Flexible Smart DC Microgrid Demonstration Project" represents a major initiative in exploring energy transition. By combining photovoltaic power generation with energy storage technologies, it significantly reduces reliance on fossil fuels and consequently lowers greenhouse gas emissions such as CO_2. The annual photovoltaic power generation is approximately 136,000kWh, saving 55 tons of standard coal and reducing CO_2 emissions by 136 tons. The direct application system of photovoltaic power saves 5% to 14% more electricity compared to AC/DC conversion systems, significantly lowering building energy consumption. The project's energy-saving effect was verified by a third-party certification company, Shandong Gongxin Testing Co., Ltd. After renovation, the project saves 37,816kgce of energy annually, with an energy-saving rate of 23.17%.

The total investment in the energy-saving renovation of the project is CNY7.29 million. Compared to traditional renovation and upgrade solutions, this project adds components such as distributed PV, bidirectional charging piles, DC transformation of electromechanical equipment, and water-based cold storage system modifications, with an additional cost of CNY1,806,000. In terms of economic value generated, the annual income from selling excess power back to the grid at electricity rates is CNY274,600, with the additional costs expected to be recovered within about 6.5 years. After normal operation, the annual revenue of the project is CNY1.2 million, with an average annual net profit of CNY260,000, indicating good profitability.

The successful implementation of the project not only improves the efficiency of clean energy utilization but also reduces dependence on external grids, lowers overall power generation and consumption costs, promotes intelligent and flexible building power usage, and ensures safety in power consumption. In the efforts to achieve urban carbon reduction and carbon neutrality, Qingdao Energy Thermal Power Group Third Thermal Power Company leads industry development through technological innovation, further promoting the development of PEDF projects in existing buildings in Qingdao City, Shandong Province, and across China, providing new technical pathways for achieving peak carbon emissions and carbon neutrality goals.

As the first domestic project integrating PEDF technology with water-based cold storage and air-source energy, it has been selected as a model case for the "China Public Building Energy Efficiency Improvement Project" by the United Nations Development Programme (UNDP) and the Global Environment Facility (GEF), receiving research grant support from the foundation. This project serves as a demonstration application of PEDF technology under the Qingdao Science and Technology Benefit-for-People Project (Research and Demonstration of Ultra-Low Carbon Community Technology Integration System in Qingdao Olympic Sailing Center), receiving special fund support from the Qingdao Science and Technology Bureau. In 2023, this project won the title of a demonstration construction science and technology project in Shandong Province. CCTV conducted on-site investigations and produced a special report titled *Qingdao Energy Group— PEDF Renovation Makes Old Buildings More Energy-Efficient*.

9.4.4 Prospects for replication and application

Based on the development needs of Qingdao Energy Thermal Power Group Third Thermal Power Company, and with strong government support and policy guidance, the project successfully integrated PEDF technology with water-based cold storage, air-source heat pumps, V2H/B technology, intelligent energy management, and BIM technology, forming an efficient and intelligent energy solution. By constructing a smart DC microgrid, the DC electricity generated by photovoltaics directly powers loads like chillers and pumps, reducing energy conversion losses. Using energy storage devices and water-based cold storage systems achieves peak shaving for both electricity and cooling loads, ensuring stable system operation under various conditions. Additionally, the project established an intelligent energy management platform to flexibly schedule photovoltaic power, energy storage, and grid power, improving energy utilization efficiency and achieving flexible power usage.

The project maximizes the building's self-sufficiency in energy use, fully utilizing solar energy, energy storage (both electrical and thermal), and flexible load management. This approach benefits both the power system and building users economically while enhancing the security, stability, and reliability of the power system. Moreover, every 10,000kWh of electricity generated reduces CO_2 emissions by 8.3 tons, contributing to lower overall societal carbon emissions and yielding significant economic and environmental benefits. As the first domestic project combining PEDF technology with water-based cold storage and air-source energy, it has demonstrated significant exemplary effects, receiving strong support from economy authority and local governments. It achieved innovative breakthroughs in technology for addressing major carbon neutrality demands in the construction sector and provided referenceable technical solutions for retrofitting existing buildings and constructing new ones, showcasing broad prospects for promotion and substantial market potential.

9.5 Grid-side standalone storage: Jiangsu Sheyang 200MW/400MWh shared storage project

9.5.1 Project overview

The Longyuan Jiangsu Sheyang 200MW/400MWh shared energy storage station project is one of Jiangsu Province's key initiatives to ensure summer peak power supply in 2024. As part of the province's critical power supply assurance tasks, construction began on 15 March 2024, and full capacity grid connection was achieved on 10 July 2024. On one hand, this demonstrates the project's "high quality, high efficiency, low cost" construction speed and outstanding technical capabilities. On the other hand, it fulfills the company's commitment to timely participation in peak power supply assurance.

This energy storage station is located in Sheyang County, Yancheng City, Jiangsu Province. The main construction contents include the energy storage system and the boosting system. The energy storage system consists of 68 energy storage units. Each unit includes one PCS (Power Conversion System) integrated AC boosting cabin with a single-cabin capacity of 3.35MW and two DC battery cabins each with a capacity of 3.35MWh. In addition, the station is equipped with an EMS (Energy Management System). The boosting system mainly includes a 220kV transformer (220 MVA). The boosting system is connected to the 220kV side of the 500kV Hexi Substation. The total land area of the project is 55.4475 mu. The site is located on plain terrain, generally flat, and has convenient road transportation access.

According to Jiangsu Province's 14th Five-Year Plan for renewable energy development, with the combined impact of domestic growth and the introduction of external renewable power generation, large-scale renewable energy integration significantly affects system peak shaving, power flow distribution, and grid stability and security. Jiangsu Province plans and constructs a series of independent new energy storage projects in coastal areas, which can promote renewable energy consumption, fill power supply gaps, optimize the province's power structure, accelerate the construction of a new power system, and promote high-quality development in coastal regions.

Figure 9-16 Jiangsu Sheyang 200MW/400MWh Shared Energy Storage Station

On one hand, this energy storage project is strategically located in areas with concentrated renewable energy resources, effectively enhancing local renewable energy absorption capacity and alleviating grid congestion pressure; On the other hand, as an standalone energy storage station directly connected to the grid, it realizes functions such as peak load shifting, load tracking, frequency and voltage regulation, and power quality management according to system demand, thereby improving the grid's own regulatory capabilities. This energy storage station has a continuous regulation capability ranging from -100% to 100% of its rated power, effectively enhancing the system's peak-shaving capacity. By following the output behavior of renewable energy sources, it can smooth out power fluctuations, track dispatching plans, and improve the certainty and predictability of renewable energy generation; Combined with system actions, it can realize the functions of peak-load shifting, load tracking, frequency modulation and voltage regulation, power quality treatment, etc., and improve the adjustment ability of the system.

In addition, as a shared energy storage station, this project explores diversified operation and management experiences of energy storage systems within Jiangsu Power Grid. It made a special contribution to Jiangsu Province's 2024 summer peak power supply. Supported by various government departments, and in accordance with the requirements of document No. [2023] 1375 issued by Jiangsu Provincial Development and Reform Commission, the project demonstrates good operational efficiency and economic benefits in terms of charge-discharge cycles, electricity pricing, and peak support fees. Therefore, this project serves as a model reference for future energy storage projects.

9.5.2 Project features

(1) Site selection

From the perspective of site selection, the station site possesses the following characteristics:

- It meets the requirements of both the power system development plan and urban-rural planning;
- It follows the principle of land conservation, avoiding or minimizing occupation of basic farmland. The site is open and flat, without requiring demolition or extensive earthwork;
- After preliminary selection, geological assessments were conducted regarding regional and site stability;
- The site has access to a reliable water source;
- The incoming and outgoing lines at various voltage levels align with urban planning and final-phase corridor planning, with no cross-over issues. The distance to the opposite substation is only 1.5km;
- The site is close to existing highways, providing favorable conditions for transporting large equipment;
- The site avoids areas with severe atmospheric pollution, protected natural reserves, cultural heritage sites, mineral deposits, airports, communication stations, and flammable/explosive facilities;
- The site is near urban areas, offering convenient living conditions for staff, no need for relocation, and is environmentally friendly.

The station excels in safety, reliability, battery savings, energy efficiency, convenient power transmission line layout, and cost-effectiveness in site selection.

(2) Area planning

In terms of station area planning and layout, the overall layout of the station has the following characteristics:

- It fully considers and coordinates the arrangement of production areas, access roads, incoming/outgoing line corridors, water sources, water supply and drainage facilities, flood discharge and flood control facilities, resulting in a rational layout;
- The station is divided into four zones: energy storage equipment area, boosting system area, road system, and production and other auxiliary facilities. The energy storage equipment area is fully outdoors and separated from other areas by fencing;
- The station's perimeter walls, gates, and internal roads meet the requirements for equipment transportation, installation, operation, maintenance, and fire safety. The spacing between energy storage units meets the needs of equipment transportation and maintenance. The distance between long sides of prefabricated cabins is greater than 3 meters, short sides greater than 3 meters, and distance from internal roads (curb) greater than 1 meter;
- The energy storage equipment area is designed to be safe, reliable, and functional, facilitating handling, installation, commissioning, operation, and maintenance;
- The equipment is designed with anti-pollution, anti-salt spray, anti-dust, anti-humidity, waterproof, and cold-resistant properties suitable for local environmental conditions. The protection level of DC-

side battery cabin enclosures exceeds the technical standard *Degrees of Protection Provided by Enclosures (GB4208)*, reaching IP55. In addition, all equipment is treated against corrosion to suit the coastal environment;

- The battery layout fully meets fire prevention, explosion prevention, and ventilation requirements, with water-based fire protection systems installed in each energy storage unit.

(3) Energy storage system design

In terms of energy storage system design, the station has the following features:

- The battery type used in this station is lithium iron phosphate ($LiFePO_4$). The energy storage unit design integrates factors such as storage type, station capacity, DC-side grounding method, voltage levels, and battery pack connection methods. Protective devices are reasonably selected with sufficient battery margin considered;
- Each DC-side battery cabin is equipped with a liquid cooling system and industrial-grade air conditioning for thermal management, an explosion-proof switch and lighting system, a fire early warning system (including acoustic monitoring modules), a fire alarm system (including fire alarm controllers, combustible gas controllers, station control hosts, smoke detectors, temperature sensors, combustible gas detectors, cable layer temperature-sensing cables and accessories), a fire suppression system (each battery PACK is equipped with composite detectors and nozzle-based fire suppression using perfluorohexane, with at least 10 discharges and duration of no less than half an hour; a three-level control system allowing automatic, manual, and remote control), a ventilation system (with dehumidification function and IP65 protection rating), a video surveillance system (including infrared night vision temperature-measuring cameras), and a Battery Management System (BMS);
- Key components inside the DC-side battery cabin—including DC surge protectors, combiner disconnect switches, combiner fuses, UPS systems, containers, industrial air conditioners, liquid cooling units, fire suppression systems, terminals, and BMUs—are all sourced from well-known, high-quality brands. Each sub-component undergoes quality control in accordance with corresponding economy-wide and sectorial standards;
- The DC-side battery cabin offers high energy conversion efficiency, long cell lifespan, high charge/discharge efficiency, strong adaptability to operating environments, good high- and low-temperature tolerance, excellent cycle performance, and low self-consumption rate;
- The cabinet (rack)-type structure of the DC-side battery cabin is aesthetically pleasing, with consistent dimensions and color tones across cabinets (racks), ensuring overall coordination; Components inside the cabinets (racks) are neatly and reliably installed, with wiring arranged in a logical manner; Insulation between electrical components meets relevant standards, and input/output terminals from internationally renowned brands with proven reliability are selected; The busbar or terminal block design allows convenient operation, maintenance, and commissioning, offering excellent serviceability and replaceability for easy equipment maintenance and replacement; The exterior coating meets high standards, featuring a double-layer, sealed, corrosion-resistant, thermally insulated, and fireproof design with sufficient mechanical strength, along with a high-performance dustproof and explosion-proof environmental control ventilation system;

- The BMS enables active balancing of individual battery cells, real-time measurement of electrical and thermal parameters, and integration with Longyuan Power Group's digital production management system. It supports full data upload at the cell level, including parameters such as individual battery voltage, module temperature, module voltage, series circuit current, and insulation resistance;
- In terms of technological innovation, the project incorporates multiple patented technologies that represent the forefront of the industry. These technologies have significantly enhanced the technical level and market competitiveness of the energy storage station.

(4) Engineering and construction

In terms of engineering construction, the power station demonstrates the following features:

- The architectural design of the station is simple and practical, reflecting modern industrial architecture styles. All buildings within the station are harmoniously integrated, with reasonable structures that facilitate construction, operation, and maintenance;
- During survey and design, continuous optimization was carried out in accordance with the Design Code for Electrochemical Energy Storage Stations, resulting in advanced and reasonable project design. The structural design is independent, and the equipment system is complete;
- In terms of construction quality, after commencement, the project established excellence objectives, organizational support, and planning. Through optimized construction organization and schemes, standardized construction practices, and strict adherence to economy-wide and industry construction standards, the project achieved a high level of engineering quality. The main works have been fully completed. During acceptance inspections, no quality issues affecting structural safety or functional use were found. There are no phenomena such as concrete cracking or structural reinforcement. The construction process followed mandatory provisions of the building codes, and all engineering documentation is complete; Quality planning documents are also available, meeting structural safety and energy storage station charging/discharging functionality requirements. By comprehensively considering inter-process relationships, the design ensures convenient construction, economic rationality, and energy-saving and environmental protection. The foundation and substructure exhibit certain excellence features: The foundation and substructure are safe, reliable, and durable. The bearing capacity of the foundation and settlement of the base meet design and code requirements. Waterproofing is effective with no leakage observed, and settlement observation points are implemented according to high-standard practices;
- During construction, while ensuring quality and safety, the station actively promotes green construction through scientific management and technological advancement, implementing "four savings and one environmental protection" (energy saving, land saving, material saving, water saving, and environmental protection) measures. It complies with economy-wide and industry regulations on green, energy-efficient, and environmentally friendly construction, aligning with the national social and economic development principles of "innovation, coordination, green development, openness, and sharing";
- Throughout the construction period, no quality accidents, general or higher-level safety incidents, or environmental pollution or ecological damage events occurred that could cause adverse social

impacts. All subdivisional and item projects shall be fully completed with complete use functions. The equipment foundations are safe, reliable, and durable;

- The project actively promotes intelligent unattended construction. The equipment foundations are structurally sound and aesthetically pleasing, with clear nodes, straight edges, accurate geometric dimensions, square corners, and component cross-section sizes, axes, and elevations all conforming to design and code requirements, with no cracks, reinforcement, or leakage observed.

Figure 9-17 Energy Storage System Area of the Energy Storage Station

(5) Storage system operation and management

In terms of storage system operation and management, the station demonstrates the following features:

- The station actively engages in technological innovation, adopting new technologies, processes, materials, and equipment. Advanced energy storage technology is employed, providing the system with high efficiency and long life, ensuring reliable operation and efficient energy conversion;

- Since its commissioning, during the summer peak-shaving period (July and August), the station performs two rated-power charge-discharge cycles daily. Outside the peak season, it responds well to grid dispatch, fully demonstrating its high-frequency application and efficient operational capability;

- According to data from the Sheyang energy storage station's single-cycle charge-discharge reports, the total charge in August was 26,403.16MWh, and total discharge was 24,499.83MWh. The average number of daily charge-discharge cycles exceeded two, with peak daily charge-discharge volumes exceeding 1,000MWh. These figures fully demonstrate the project's high efficiency and stability in real-world applications. Additionally, the project received commendation documents from the Jiangsu Provincial Energy Administration and other departments for its peak shaving contributions. From July to August after grid connection, it participated in the "summer peak load management" program, generating cumulative revenue of nearly CNY30 million.

9.5.3 Prospects for replication and application

Due to frequent dispatch, the station conducts regular operations including daily management, fault elimination and maintenance, annual inspections and tests, performance evaluation, dispatch coordination, and auxiliary peak shaving activities, based on documents such as the *Operation Regulations for Energy Storage Stations, Maintenance Regulations for Electrochemical Energy Storage Stations,* and *Operational Indicators and Evaluation Criteria for Electrochemical Energy Storage Stations*. A comprehensive, accurate, timely, consistent, and complete energy storage station operation and maintenance system has been established; At the same time, by developing standardized documents such as the *Standardized Configuration Table for Energy Storage System Equipment* and *Acceptance Management Standards and Quality Control Points for Energy Storage System Equipment*, the station continuously refines sub-component-level quality control and craftsmanship standards, gradually establishing a comprehensive energy storage technology system and setting technical benchmarks for the industry; This station is integrated into Longyuan Power's digital operation and maintenance big data platform for energy storage. It applies early acoustic warning systems for thermal runaway detection, establishing a robust fire and thermal runaway management system for energy storage batteries. This plays a crucial role in enhancing the safety, reliability, and stable operation of energy storage stations.

Through the construction and excellence creation of this energy storage station project, typical designs for equipment foundations, standardized installation hoisting plans, standardized debugging outlines, and grid connection standardization processes for energy storage stations were compiled to improve the refined management level in terms of safety, quality, progress, and cost during the construction phase.

9.6 Lithium battery+supercapacitor hybrid energy storage for AGC auxiliary frequency regulation

9.6.1 Project overview

Under the "Dual Carbon" goals, the imbalance between supply and demand on both the generation and consumption sides of new power systems dominated by renewable energy is intensifying, posing significant challenges to system frequency stability. There is an urgent need for more flexible frequency regulation resources to enhance self-regulation capabilities. New energy storage technologies can play a role in short-term rapid adjustment and are expected to be the primary flexible regulation resource in the future. In the short term, they can effectively complement thermal power units.

Super capacitors, as a typical short-term high-frequency energy storage technology, offer significant advantages over traditional lithium iron phosphate batteries used for frequency regulation with thermal storage: high power density, fast charging/discharging speeds, long lifespan, superior performance in high/low temperatures, safety, and environmental friendliness, making them highly suitable for auxiliary frequency regulation applications. However, improvements in energy density and cost reduction are still needed to meet large-scale energy storage application requirements. This case focuses on domestication of key materials and large-scale system applications as breakthrough points, developing a new low-cost, high-energy-density hybrid supercapacitor system. It develops components and systems that meet the needs of short-term high-frequency energy storage scenarios, leveraging the high-power response characteristics of supercapacitors to explore matching application scenarios and business models.

Figure 9-18 Energy Storage Demonstration Project in Zhuhai

The project is located within Guangdong Zhuhai Jinwan Power Generation Co., Ltd. in Zhuhai City, Guangdong Province. It is invested by Guangdong Zhuhai Jinwan Power Generation Co., Ltd., EPC contracted by China Southern Power Grid Electric Power Technology Co., Ltd., and supported by Guangdong National New Energy Storage Research Institute Co., Ltd., Shanghai Institute of Ceramics, Chinese Academy of Sciences, and Nantong Jianghai Energy Storage Technology Co., Ltd. A 16MW/8MWh lithium iron phosphate + 4MW/0.67MWh supercapacitor hybrid energy storage system was installed next to the 3rd and 4th (2x600MW) coal-fired generating units, connected to the 6kV plant-use bus working section. The energy storage system uses a "one-to-two" configuration to participate in grid AGC frequency regulation in conjunction with the units. The project completed bidding in July 2022, officially started construction in April 2023, entered trial operation at the end of September, Unit 4 officially entered commercial trial operation in early November, and Unit 3 officially entered commercial trial operation in mid-December. Thanks to the significant improvement in K values after the energy storage system was put into operation, the probability of winning bids and frequency regulation revenue have both seen substantial increases compared to before the system's operation. As of July 2024, monthly average frequency regulation revenue exceeded CNY4.6 million, demonstrating significant economic benefits.

As a demonstration and validation for the results of the projects in China’s key research and development plan on "Fundamental Science and Prospective Technologies for High-Power, Low-Cost Large-

Scale Supercapacitors", this project innovatively adopted the "supercapacitor+" hybrid energy storage technology. During implementation, it tackled technical challenges such as megawatt-level supercapacitor system integration, coordinated control of "lithium iron phosphate battery + supercapacitor + unit", and on-site grid connection tests. It developed proprietary "supercapacitor+" hybrid energy storage solutions, promoting the comprehensive domestication of supercapacitor products and key materials and the promotion of "supercapacitor+" hybrid energy storage coordination control technology. This injects new momentum into the development of the hybrid energy storage and supercapacitor technology industries, thereby driving high-quality development in the supercapacitor industry chain.

The project is a collaboration of China Southern Power Grid Electric Power Technology Co., Ltd., Guangdong Zhuhai Jinwan Power Generation Co., Ltd., Guangdong National New Energy Storage Research Institute Co., Ltd., Shanghai Institute of Ceramics, Chinese Academy of Sciences, and Nantong Jianghai Energy Storage Technology Co., Ltd.

(1) Technical solution

The project is equipped with a 16MW/8MWh lithium iron phosphate + 4MW/0.67MWh supercapacitor hybrid energy storage system in containerized form, totaling 20 containers: 7 lithium battery containers, 1 supercapacitor container, 9 step-up containers, 1 high-voltage container, 1 station service transformer and high-voltage container, and 1 secondary monitoring container. The energy storage system uses a "one-to-two" configuration. Each of the three energy storage units (two 7.5MW/3.75MWh units and one 1MW/0.63MWh + 4MW/0.67MWh unit) is connected via two power cables to the 6kV plant-use bus sections 40BBA, 40BBB, 40BCA and 30BBA, 30BBB, 30BCA of the two generating units, integrating into the plant's own power system.

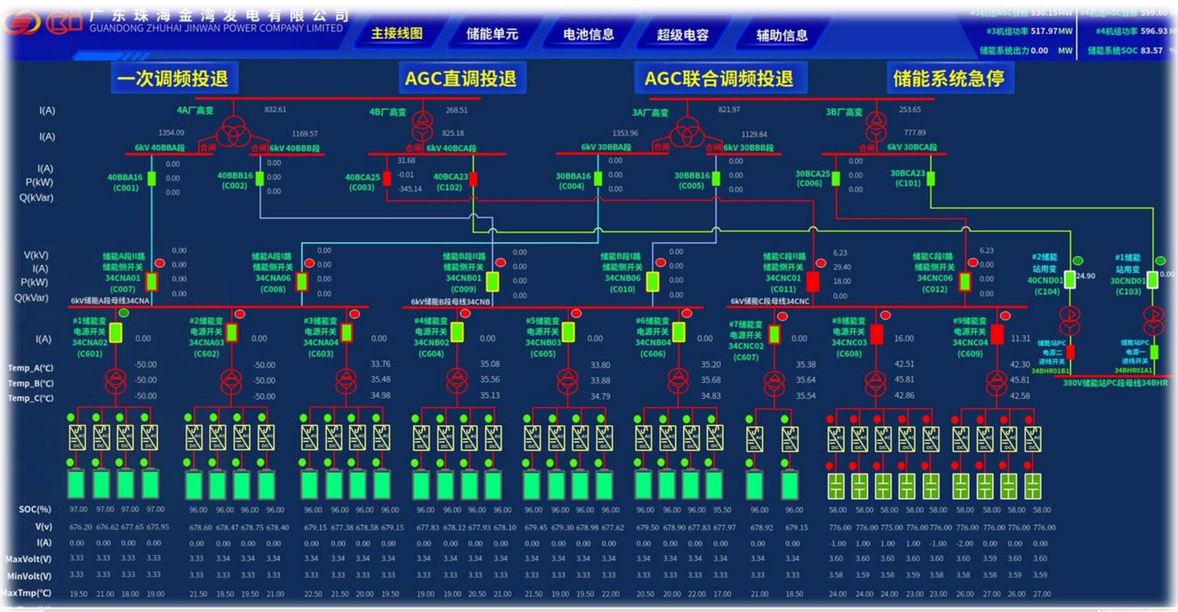

Figure 9-19 System Single-line Diagram of the Project

(2) Business Model

The main revenue model of this project is participation in the southern region's frequency regulation ancillary service market. Compared with similar lithium iron phosphate battery-based frequency regulation projects in other power plants: The comprehensive K value for conventional lithium iron phosphate battery-based frequency regulation typically ranges from 1.0 to 1.3, with average monthly revenue around CNY2.5 million. In contrast, the "lithium iron phosphate + supercapacitor" hybrid system can achieve a composite K value of 1.3 to 1.6, with average monthly revenue exceeding CNY4.5 million. As of 30 April 2024, the project has been operating well. After the commissioning of the energy storage project, the supercapacitors experienced approximately 7,200 equivalent charge-discharge cycles, while the lithium iron phosphate batteries had about 1,200 cycles. The average composite frequency regulation performance index (K value) was 1.381, with a maximum daily K value of 1.92 and an average monthly regulation mileage of 331GW (gigawatts). The total cumulative revenue of the project reached CNY30.69 million, with a maximum monthly income of CNY5.85 million, a minimum of CNY2.8 million, and an average monthly income of CNY4.38 million.

9.6.2 Features of the project

(1) High capacity energy supercapacitor integration technology

The project was among the first to apply low-cost hybrid supercapacitors developed under the National Key Research and Development Program, featuring energy density>80 Wh/kg, power density>10kW/kg, and a lifespan of over 50,000 cycles. An efficient thermal management method for supercapacitor energy storage units was proposed. To address the difficulty in designing heat dissipation for supercapacitors, a "fluid-thermal" coupling model was established for supercapacitor energy storage. Through temperature zone partitioning and spatial refrigerant balance control, a flow field-regulated thermal homogeneity design method was formed, ensuring that the maximum temperature difference between supercapacitor clusters remained within 5°C.

A cluster-level energy precision management architecture was established. To address the issue of low energy efficiency in supercapacitor systems, a zonal management strategy based on regional segmentation technology was proposed. This reduced the impact range of circulating currents and DC-side faults, forming a "one-cluster-one-management" energy management architecture and control method suitable for multi-scenario applications. It enabled suppression of state differences among supercapacitors and precise allocation of power, achieving an energy efficiency of 92%.

Figure 9-20 Supercapacitor Integration Technology and Large-Scale Equipment

(2) Intelligent Operation and Maintenance System

Accurate identification technology for the state of energy storage equipment was developed. To overcome the challenge of accurately identifying the state of lithium batteries and supercapacitors, a supercapacitor life prediction model based on aging characteristic curves was established. A data acquisition, storage, and analysis technology capable of processing massive amounts of data at the sub-second level was developed for the energy storage management system. A standardized database for health management and a condition monitoring platform were built, enabling precise identification of the operational states of both supercapacitors and lithium battery energy storage equipment. Within the AGC hybrid energy storage-assisted frequency regulation project at Jinwan Power Generation Company, an AGC hybrid energy storage power station data analysis system was built. This system enables real-time monitoring, analysis, and visualization of various states of lithium-ion batteries and supercapacitors in the energy storage station, including charging/discharging capability, charging/discharging status, extreme value analysis, voltage consistency, temperature equilibrium, real-time trends, alarm analysis, fault diagnosis, and cell quality warnings. In particular, the project also conducted statistical analyses on various AGC response data from the hybrid energy storage system, including AGC duration, command magnitude, frequency regulation mileage, and charge/discharge quantities of lithium batteries and supercapacitors. These analyses provided valuable data support for optimizing the EMS control strategy and intelligent operation and maintenance of the energy storage station.

Figure 9-21 Interface of the Intelligent Operation and Maintenance System

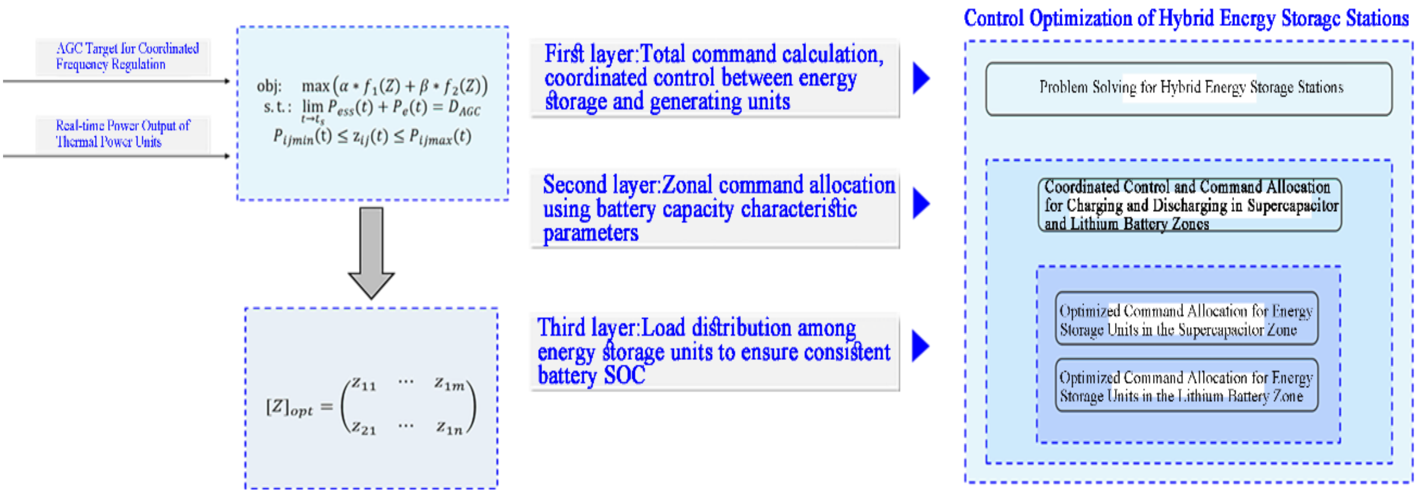

Figure 9-22 Hybrid Energy Storage Coordinated Control Strategy

(3) Coordinated hybrid energy storage control strategy

The project developed a coupled frequency regulation technology combining supercapacitor energy storage systems with thermal power units. To address the difficulty in coordinating supercapacitors with generating units, a deep-coupling coordinated frequency regulation control strategy was proposed based on "supercapacitor priority", integrating the supercapacitor hybrid energy storage system with thermal power units. The supercapacitor and energy storage system operate asynchronously. When the power command is less than or equal to the rated power of the supercapacitor, it handles the entire load. If the command exceeds the supercapacitor's rated capacity, the excess is handled by the energy storage system. The basic logic of this design is that the supercapacitor handles small and frequent power commands, while the energy storage system serves as a backup power source when the power demand is large or when the supercapacitor cannot act (fully charged/empty). This design leverages the high-rate characteristics of supercapacitors and the large-capacity features of the energy storage system, allowing the energy storage station to maintain full-power operation for longer periods, thereby improving overall operational efficiency. The unit's frequency regulation performance improved by more than two times, forming a supercapacitor energy storage coupled thermal power unit frequency regulation technology, as well as an independent hybrid frequency regulation technology combining supercapacitors and lithium-ion batteries.

(4) Large-scale supercapacitor application

A megawatt-level long-life, low-cost energy storage frequency regulation system based on hybrid supercapacitors was developed. To address the short lifespan of conventional energy storage-based frequency regulation systems, an optimal capacity configuration method for supercapacitor-based frequency regulation systems was established to meet diverse scenario application requirements; The world's largest MW-level supercapacitor hybrid energy storage frequency regulation system was developed first, establishing an economically viable technical route for supercapacitor-based frequency regulation.

9.6.3 Main accomplishments of the project

The project outcomes have been evaluated by academician experts including Academician Rao Hong, Academician Yan Deyue, Academician Dou Shixue, and Academician Liu Huakun, among others have been confirmed to have reached an internationally leading level. The project has pioneered a technical pathway for supercapacitor energy storage in frequency regulation, along with a replicable and scalable business model. The project outcomes have been fully applied in MW-level supercapacitor energy storage frequency regulation projects such as the Jinwan Power Plant, achieving independent control over the entire supercapacitor industrial chain. This advancement contributes significantly to enhancing the stability of China's new power system and improving the R&D and manufacturing capabilities of energy storage equipment, delivering notable economic and social benefits.

(1) Economic benefits

In terms of application in hybrid energy storage AGC frequency regulation at coal-fired power plants, the system K value has been significantly enhanced through the adoption of hybrid energy storage technology. At Zhuhai Jinwan Power Plant, the performance improvement rate of the thermal-storage combined frequency regulation reached as high as 190%. As of July 2024, the average monthly frequency regulation revenue exceeded CNY4.6 million, demonstrating significant economic benefits.

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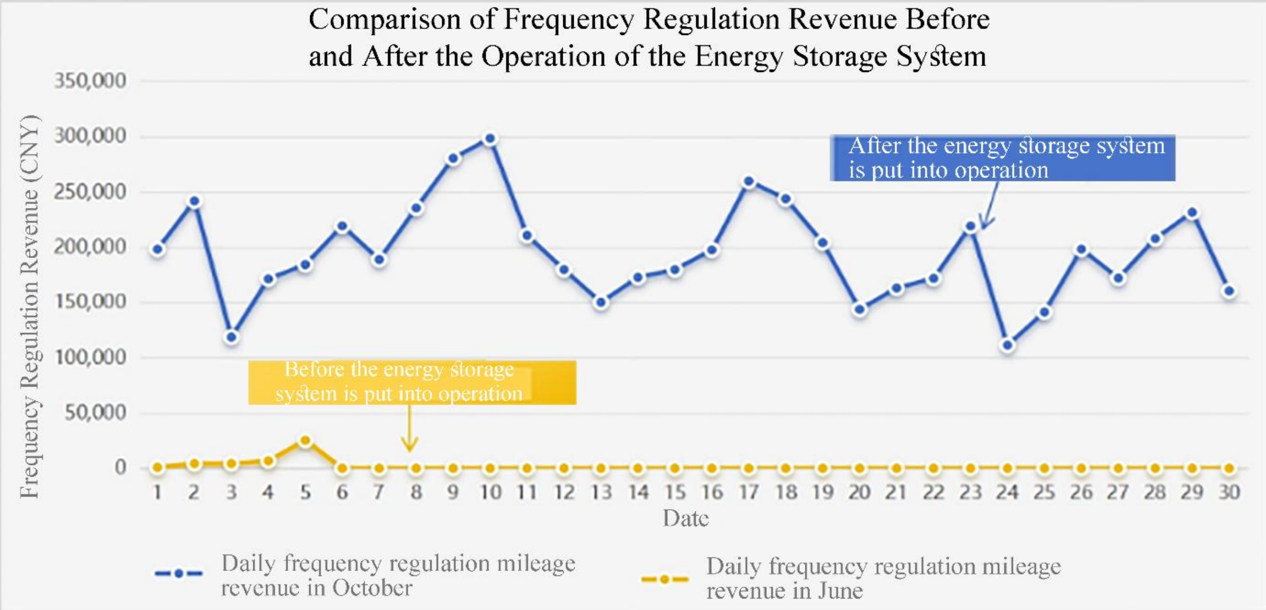

Figure 9-23 Revenue from Frequency Regulation Revenue After Project Commissioning

(2) Social Benefits

Promoted the development of supercapacitor technology with high power and energy characteristics. Through technological innovations in key materials, core processes, and structural design, the team significantly increased the energy density of supercapacitors, greatly enhancing the performance of individual components. This created a new application model for supercapacitors in power frequency regulation, playing a crucial role in developing highly secure smart grids, transforming traditional power generation and energy storage methods, and meeting the nation's strategic demand for short-term energy storage technologies.

Helps promote comprehensive transformation and upgrading of the supercapacitor industry chain. The case study has developed hybrid capacitors and modules with high specific power and energy characteristics, which have demonstrated significant application potential in areas such as DC backup power supply for power grids and thermal-storage combined ACG frequency regulation. The researched supercapacitor industry chain involves strategic emerging products like new materials, new energy sources, new energy vehicles, and energy-saving and environmental protection technologies. This helps enhance China's innovation capabilities in the supercapacitor-related industries and plays a vital role in upgrading the economy's supercapacitor industrial structure, yielding notable social benefits.

Enhanced the operational safety and stability of the power system. The promotion and application of related technologies have advanced the use of supercapacitors in both auxiliary frequency regulation and independent frequency regulation modes in thermal power plants. It fully verified the safety, reliability, and economic viability of large-capacity supercapacitor energy storage technology, filling a critical technological gap in China's supercapacitor energy storage field. Further improved the flexibility of the power system, which is of great significance for promoting renewable energy integration and ensuring the safe and economical operation of the power grid.

9.6.4 Prospects for replication and application

The research outcomes of this project have broad prospects for application and promotion. Supercapacitor-based frequency regulation has already gained recognition within the industry. The demonstration effect at Jinwan Power Plant has been remarkable, and supercapacitor frequency regulation projects are now being launched across the economy, driving the development of the supercapacitor industry chain.

High-power, high-energy supercapacitor integrated devices are suitable for many advanced scenarios such as short-term high-frequency frequency regulation, smoothing renewable energy output, instantaneous power support, power quality management, and STATCOM applications. Under the background of future dual-carbon goals, they will also be widely applied in various scenarios such as smart grids, electric vehicles, wind and solar power generation, rail transit, combined thermal power frequency regulation, combined hydropower frequency regulation, new energy paired with energy storage, and standalone energy storage stations.

Chapter X Summary and Policy Recommendations

Energy systems are increasingly confronted with challenges stemming from the growing penetration of variable renewable energy sources and the rising demands for power consumption. To address these issues effectively, energy storage technologies, particularly electrochemical solutions, have emerged as critical tools in fortifying system resilience, enhancing operational flexibility, and ensuring stability and efficiency in power grids. The research and application of these innovative storage technologies have played a transformative role in driving industry advancements and improving the security and reliability of electricity supply. Within this context, the APEC region has established itself as a pivotal market for emerging energy storage solutions, fostering innovation in areas such as battery energy storage systems and contributing to the global transition towards low-carbon energy systems. These developments significantly support the achievement of carbon neutrality goals and sustainable energy futures.

10.1 Summary

(1) Urban areas serve as central venues and critical junctures for achieving carbon neutrality goals. The APEC region plays a pivotal role in advancing global green low-carbon energy transitions and attaining carbon neutrality.

Cities function as hubs of human social and geoeconomic activities, using the majority of global resources and energy. According to data from UN-Habitat, as of 2022, over 55% of the global population resided in urban areas, consuming more than two-thirds of the world's energy. Urban carbon emissions make up approximately 50–60% of total global emissions. It is projected that by 2040, cities will account for about 80% of global energy consumption. Therefore, cities play a crucial role in the efforts towards green energy transition and achieving carbon neutrality.

Currently, 147 economies globally have set proposed carbon neutrality or net-zero emission targets, addressing 88% of global carbon emissions, 93% of GDP, and 89% of the population. Carbon neutrality is a significant point for development cooperation among economies worldwide. The 21 economies in the APEC region account for approximately 67% of global CO_2 emissions, 62% of GDP, and 38% of the population, making it the most critical region for achieving global carbon neutrality goals. As of November 2024, except for Brunei Darussalam and the Philippines, all other 19 APEC economies have explicitly committed to carbon neutrality through legislation, policy, or declaration, covering 99.3% of carbon emissions, 99.3% of GDP, and 96.1% of the population in the APEC region. The APEC region is the largest consumer of energy globally and has the fastest growth rate. The 21 member economies constitute about 60% of global energy and electricity demand. Transitioning to clean energy and pursuing inclusive and sustainable development are common objectives among all APEC economies.

(2) Urban energy systems encounter several significant challenges, including guaranteeing a stable energy supply, facilitating large-scale high-proportion renewable energy development and utilization, improving energy efficiency, and enhancing the resilience of the energy system. Energy storage technology is essential in overcoming these challenges.

The stability of urban energy supply directly affects economic activities and residents' quality of life. However, cities—especially large and megacities—often lack sufficient local energy resources and rely heavily on external resources; This imbalance makes urban areas highly sensitive to fluctuations in global energy markets. In recent years, geopolitical uncertainties and climate-induced supply disruptions have increasingly affected energy security. Urban centers are pivotal in the transition to green energy, with municipal authorities globally implementing measures to expedite the adoption of renewable energy sources. The rapid growth in the scale of renewable energy installations brings significant stability and flexibility challenges to the energy system due to their volatility and intermittent nature of renewables such as solar and wind. Improving end-use energy management and energy efficiency is not only one of the key measures for reducing carbon emissions, addressing climate change, preventing environmental pollution, and achieving carbon neutrality—it is also a core requirement and a major driving force for promoting economic efficiency and building sustainable development models.

Currently, many urban energy governance systems remain largely centralized and top-down in structure, lacking sufficient flexibility and resilience to meet today's complex and dynamic energy demands. Particularly when facing sudden crises and extreme conditions, traditional centralized energy systems often demonstrate limited adaptability with high recovery costs. With the rapid development of emerging technologies such as artificial intelligence (AI), advanced telecommunication and information technologies, energy governance is gradually transitioning from a centralized model to a more decentralized structure. Future effective urban energy governance will place greater emphasis on flexibility and system resilience.

Energy storage performs multiple functions, delivering a range of services to the energy system within the evolving landscape of the energy sector. Novel energy storage solutions, particularly electrochemical energy storage, embody disruptive technologies that tackle the challenges related to energy supply and demand across temporal, spatial, intensity and flexibility dimensions. Energy storage is one of the five pillars of the Third Industrial Revolution and a significant support for the global green and low-carbon energy transition. Energy storage serves as an ideal complement to variable renewable energy sources such as wind and solar. It enables and facilitates the extensive development and consumption of renewable energy within urban environments.

Energy storage, as a highly representative flexible energy resource, plays a crucial role in enhancing resilience, flexibility, reliability, cost-effectiveness, and efficiency within urban energy systems. Energy storage is becoming a crucial element in driving urban energy transitions. Integrating energy storage solutions has emerged as a fundamental strategy for cities to effectively manage high levels of renewable energy and fluctuating power demands in the future. The advancement of the energy storage industry, especially in areas such as battery manufacturing and installation, significantly drive economic development.

(3) Various energy storage technologies are continuously developing, with new types of energy storage such as electrochemical energy storage experiencing rapid growth. The APEC region has become a significant application market for new energy storage worldwide, contributing to research and development, manufacturing and supply of batteries and associated systems, as well as mining and processing of key raw materials.

Energy storage has the potential to accelerate decarbonization process of energy system, and it is essential for building a net-zero emission energy system. Given their technological maturity and the status of industrial development, both pumped hydro storage and lithium-ion battery energy storage have established industries and supply chains. They have also reached the stage of commercial application. Compressed air energy storage and flow battery energy storage have progressed to the development of initial prototype products and are currently in the demonstration and application phase. Flywheel energy storage is utilized mainly in power-oriented applications and has developed mature technologies and products. Gravity energy storage and sodium-ion batteries have established technical foundations and are actively being prepared for demonstration projects. Metal-air batteries, aqueous batteries, and liquid air energy storage technologies remain in the research and development stages, seeking significant breakthroughs. Research and development efforts have increasingly concentrated on long-duration energy storage systems capable of meeting demands over extended periods, including several days, weeks, or even entire seasons.

At present, pumped hydro storage and lithium-ion battery energy storage dominate the energy storage applications in power systems. By the end of 2023, the cumulative installed capacity of energy storage projects in power systems reached 289.2GW, with an average annual growth rate of 21.9%. Pumped hydro storage is currently recognized globally as the most mature large-scale energy storage technology. Among existing energy storage technologies, it offers the best overall performance and serves as a critical method for economies worldwide to ensure the safe and stable operation of power systems. With the rapid development of new energy storage projects in recent years, the share in cumulative installed capacity of pumped hydro storage has been declining annually, falling below 70% for the first time in 2023. In 2023, the newly commissioned installed capacity of global energy storage projects reached 52.0GW — with a rise of 69.5% from the previous year; Among these, new energy storage represented by electrochemical energy storage accounted for 87%. The newly commissioned of new energy storage reached a record high of 45.6GW.

As of the end of 2022, six out of the top ten economies globally in terms of cumulative installed capacity of new energy storage projects were APEC economies, namely, China; the United States; Korea; Australia; Japan; and the Philippines, with a total installed capacity accounting approximately 70% of the global total; In 2022, five out of the top ten economies globally in terms of installed capacity of energy storage projects newly put into operation were from APEC economies, namely China; the United States; Australia; Japan; and the Philippines, whose newly added capacity in 2022 collectively accounting 69% of the global total. About 70% of both the world's total cumulative installed capacity and new installed capacity were attributed to the APEC region. The APEC region also contributes 91.5% of global lithium extraction, 77.8% of nickel, 66.1% of copper, and 64.6% of natural graphite—all critical raw materials for battery manufacturing; China holds an absolutely dominant position in the processing of these critical raw materials for battery energy storage, supplying 100% of the world's refined natural graphite, over 90% of manganese, 70% of cobalt, nearly 60% of lithium, and around 40% of copper. The APEC region is not only the most important application market for battery storage globally but also leads in manufacturing and supply of batteries for storage systems in the global market, as well as in the upstream of the battery industry regarding mining and processing of key minerals materials.

(4) The policy framework, incentive mechanisms, and business models facilitating the extensive development of energy storage projects are progressively enhancing. This advancement positions energy storage as significant catalyst for accelerating urban green energy transitions.

In the context of global low-carbon energy transition, the growing importance of energy storage has led to sustained growth in industry interest. With continuously increasing policy support, government policies have become the most powerful driving force behind the development of energy storage. Major APEC economies have introduced favorable policies related to the energy storage industry, promoting its entry into a fast development phase. Taking China and the United States, the two largest economies in terms of new energy storage applications, as examples, the United States government and state governments have successively introduced various policies to promote the development of energy storage. At the federal level, the *Inflation Reduction Act of 2022* is the most important policy concerning energy storage, introducing investment tax credits (ITC) for standalone energy storage for the first time, paving the way for faster deployment of energy storage in the United States; At the state level, Michigan became the 10th state of the United States to establish a clear energy storage development target.

In China, the development of energy storage has been elevated to a strategic level of the economy. Over 600 relevant policies at the economy and local levels have been released, directly facilitating the implementation of large-scale energy storage projects across various regions. As power market reforms gradually advance into deeper stages, the focus of energy storage policies has begun to shift toward market mechanisms and dispatching mechanisms. Under the current policy and market mechanisms, energy storage still lacks a stable and sustainable profit mechanism, which remains the main constraint on its commercial development. Regarding the allocation of energy storage with renewable energy: Policies should follow the principle of adapting measures to local conditions, coordinating the planning of energy storage integration with renewable energy sources to avoid inefficient investments; Accelerate the pace of full participation of new energy sources in various markets; Explore business models combining renewable energy with shared energy storage in joint operations. Regarding standalone energy storage: Further clarification is needed on the definitions and dispatching mechanisms of independent and non-standalone energy storage. The joint or independent operation mechanisms of shared standalone energy storage with renewable energy stations need further refinement. For the shared leasing market, corresponding operational rules or guidance schemes should be introduced, and a credible regional capacity leasing platform should be established to ensure transparent and fair transactions and protect the rights and responsibilities of both lessors and users. At the same time, it is recommended to introduce preferential fiscal and tax policies to support the development of new energy storage, reduce storage costs, and further intensify policy support for energy storage technologies, equipment, and manufacturing to enhance the competitiveness of the energy storage supply chain. In addition, safety policies should take into account technological advancements and the needs of large-scale development, further standardizing the construction and operation management of energy storage projects. Since 2024, China's energy storage industry continues to maintain a rapid growth trend. In the context of fierce international market competition, China holds an absolute leading advantage globally in new energy storage technologies represented by lithium-ion batteries. At the same time, other major energy storage technologies are also at the forefront internationally in terms of R&D and manufacturing. Sustained policy support for the new energy storage industry requires, on one hand, precision and depth to break through market access barriers. On the other hand, policies across sectors including industry, academia, research, application, finance, taxation, and finance should work in synergy to form a systematic framework. This will create a healthy market environment for the development of new energy storage, promote its healthy and sustainable growth, and help China maintain and expand its hard-earned international competitive advantage in this field.

Australia; Canada; Japan; and Korea are all actively pursuing energy storage development, primarily driven by the need to integrate growing renewable energy sources, enhance grid stability, and achieve decarbonization targets, though their approaches vary. Australia is experiencing a "big battery boom" with supportive government policies like the Capacity Investment Scheme (CIS) and the Cheaper Home Batteries Program, offering long-term underwriting contracts and discounts to accelerate the deployment of utility-scale and small-scale battery systems, aiming for significant renewable energy penetration by 2030. Canada incentivizes energy storage through refundable investment tax credits for clean technology manufacturing and clean electricity, including for grid-scale energy storage equipment, alongside a Clean Electricity Strategy and funding for smart renewables and electrification pathways to modernize its grid and achieve net-zero by 2050. Japan's energy storage market is rapidly expanding, supported by its "Green Transformation" policy strategy, which includes a subsidy scheme offering capital expenditure support for projects and market opportunities in balancing, wholesale, and capacity markets, with a focus on diversifying beyond lithium-ion to include sodium-sulfur batteries for enhanced grid stability and resilience. Korea's "Energy Storage System Industry Development Strategy" aims for a 35% global market share by 2036, emphasizing a flexible power system with diverse energy storage technologies (including lithium-ion, redox flow, and sodium-sulfur batteries), supported by the 11th Basic Plan for Long-Term Electricity Supply and

Demand to significantly increase renewable energy capacity and stimulate domestic investment while addressing safety standards.

Southeast Asian economies, facing rapidly growing energy demand and ambitious decarbonization targets, are increasingly turning to energy storage solutions to integrate burgeoning renewable energy capacity and enhance grid stability. While specific policies vary, common themes include feed-in tariffs (FITs) that incentivize renewable energy coupled with storage, the development of economies' national power development plans (PDPs) that explicitly set energy storage targets (e.g., Viet Nam's PDP8 targeting 2.7GW by 2030), and efforts to reduce red tape for distributed solar PV and storage projects (as seen in Thailand). There's also a growing recognition of the need for advanced grid infrastructure and market mechanisms to facilitate the integration of intermittent renewables. Notably, economies like the Philippines are leveraging privatization and free competition to unlock energy storage potential, while Indonesia is pursuing investment plans like the Just Energy Transition Partnership (JETP) to accelerate its energy transition, including dispatchable renewable energy. Pumped hydro storage is also gaining attention in the region due to its geographical advantages.

Chile stands out as a leader in energy storage development within Latin America, largely driven by its rapid build-out of solar and wind power and the consequent need to address grid constraints and ensure system stability, especially during periods of low solar electricity yields. The economy has implemented a carbon tax and emissions standards for coal-fired facilities, alongside the recently enacted Energy Transition Law, which aims to accelerate investments in the power grid and battery storage infrastructure. Chile has set an ambitious economy's target of 2GW of energy storage by 2030, with significant operational and under-construction capacity already in place. Its regulatory framework is considered progressive, with ongoing efforts to refine wholesale power market mechanisms and rules for remunerating ancillary services provided by energy storage systems. The focus is on integrating large-scale BESS, often co-located with solar PV projects, to mitigate renewable energy curtailment and enhance grid flexibility, making Chile a pioneering example in the South America for energy storage regulations and deployment.

(5) Enhancing urban energy resilience and stability, boosting energy supply security and reliability, and increasing operational efficiency are advancing with rapid progress in energy storage deployment.

A favorable business environment is essential to support the development of an energy storage project from initial feasibility studies to final implementation. Most of the investment hotspots in the APEC region not only have substantial market demand but also benefit from favorable energy storage incentives and subsidies, along with promising investment expectations. Currently, the revenue sources for energy storage mostly come from peak-to-valley arbitrage, spot electricity trading, ancillary services, demand response, and capacity subsidies. The predominant business models include owner self-investment, leasing, energy performance contracting, and energy performance contracting combined with financial leasing. Favorable government policies and stable profit prospects encourage investor enthusiasm on energy storage project. International Energy Agency (IEA) suggested that that 1.5TW of storage capacity will be needed to facilitate energy transition and enable global renewable energy targets globally. The 29th United Nations Climate Change Conference (COP29), took place in Baku, Azerbaijan, in November 2024 paid particular attention on the development and integration of storage into the power grid and the reinforcement of the power grid supporting green energy transition and achieving net-zero emissions by 2050. At COP29, the world leaders signed a pledge to collectively increase global energy storage capacity to 1,500GW by 2030. According to BloombergNEF (BNEF), the Asia-Pacific remains the leader in installed energy storage capacity, expected to account for nearly half (47%) of new installations by 2030. The development and deployment of energy storage projects serve as accelerators for energy transitions in the region.

With a focus on battery energy storage system (BESS) of the present study, the overall trend observed clearly indicates a significant increase in BESS deployment, recognizing its critical role in enabling the energy transition. Technological advancements in battery chemistries, coupled with decreasing costs and supportive regulatory frameworks, are expected to further accelerate this trend in the coming years. As renewable energy penetration continues to rise and the need for grid flexibility and resilience becomes more pronounced, BESS will undoubtedly play an increasingly pivotal role in shaping the future of the global energy system. The diverse approaches and growth trajectories observed across these key markets highlight the varied priorities and challenges each economy faces in integrating energy storage into their unique energy landscapes.

In urban environments, BESS are becoming increasingly vital, serving as crucial infrastructure for modernizing power grids and facilitating the transition to cleaner energy sources. The BESS projects play a multifaceted role, enhancing grid stability by providing rapid response capabilities to balance supply and demand fluctuations, particularly with the growing integration of intermittent renewable energy like solar PV. Furthermore, BESS can improve the reliability of electricity supply in cities, supporting distribution network, reducing the frequency and duration of power outages. They also enable more efficient use of existing grid infrastructure by storing energy during periods of low demand and releasing it during peak times, potentially deferring the need for costly upgrades. The cities across the region are actively pursuing and implementing BESS projects to address their specific energy challenges and sustainability goals. In Australia, cities like Sydney, Melbourne, and Brisbane are witnessing significant investments in large-scale battery storage to support renewable energy integration and grid resilience. Similarly, in Japan, the Tokyo Metropolitan Government is heavily subsidizing grid-scale BESS projects, while other urban centers in the region are exploring innovative solutions like repurposing EV batteries for energy storage. Korea demonstrates a strong commitment to BESS deployment in the economy, evidenced by the completion of massive grid-stabilization projects that benefit urban centers by ensuring a more reliable power supply at the economy level.

According to studies by IRENA, out of 671 sampled cities worldwide, 551 cities have set renewable energy development goals (accounting for 82%), many of which have explicitly outlined plans for energy storage development. In urban environments, BESS are becoming increasingly vital, serving as crucial infrastructure for modernizing power grids and facilitating the transition to cleaner energy sources. The BESS projects play a multifaceted role, enhancing grid stability by providing rapid response capabilities to balance supply and demand fluctuations, particularly with the growing integration of intermittent renewable energy like solar PV. Furthermore, BESS can improve the reliability of electricity supply in cities, reducing the frequency and duration of power outages. They also enable more efficient use of existing grid infrastructure by storing energy during periods of low demand and releasing it during peak times, potentially deferring the need for costly upgrades.

The cities across the region are actively pursuing and implementing BESS projects to address their specific energy challenges and sustainability goals. In Australia, cities like Sydney, Melbourne, and Brisbane are witnessing significant investments in large-scale battery storage to support renewable energy integration and grid resilience. Similarly, in Japan, the Tokyo Metropolitan Government is heavily subsidizing grid-scale BESS projects, while other urban centers are exploring innovative solutions like repurposing EV batteries for energy storage. Korea demonstrates a strong commitment to BESS deployment, evidenced by the completion of massive grid-stabilization projects that benefit urban centers by ensuring a more reliable power supply in the economy. These highlight a trend towards recognizing the indispensable role of BESS in shaping the future of urban energy systems. By providing essential energy storage capabilities, cities are better equipped to manage the complexities of modern power grids, integrate higher penetrations of renewable energy, and ensure a secure and sustainable energy future for their residents and economies. The continued innovation and deployment of BESS technologies in urban areas will be critical in achieving ambitious climate goals and building more resilient and efficient energy infrastructures worldwide.

(6) With the increase in global energy storage system deployments, ensuring the safety of installed energy storage systems has become a priority for maintaining the stability of the entire energy system and user safety.

Global energy storage accident data show that fire incidents caused by lithium-ion battery thermal runaway occur frequently, making them a key focus of safety concerns. BESS face primary safety concerns related to thermal runaway, which can lead to fires and explosions, particularly with lithium-ion batteries. Other issues include chemical hazards from electrolyte leaks and the potential for toxic gas emissions during a fire. Manufacturing defects, especially at the system integration level (including fire detection and suppression, auxiliary circuit panels, and thermal management systems), and improper installation are significant contributors to these risks. While fire incidents can be alarming and lead to localized environmental concerns like air quality and firefighting runoff, studies indicate that toxic gas emissions dissipate quickly, and contamination risks are often minimal compared to other industrial fires.

Despite these concerns, the safety of BESS has significantly improved in recent years, with incident rates decreasing dramatically from 2018 to 2024. This improvement is largely due to advancements in battery management systems, the use of fire-resistant materials, enhanced thermal management, and sophisticated early detection systems. The industry is increasingly adopting a "let it burn" approach in controlled environments to prevent explosions and reignition. Robust safety standards and codes, such as UL 9540, NFPA 855, and IEC 62619, are being widely implemented and continually updated, providing comprehensive guidelines for design, installation, operation, and emergency response. Ongoing efforts focus on strengthening coordination with fire departments, providing specialized training and ensuring compliance with the latest safety protocols to further mitigate risks as BESS deployment accelerates globally.

10.2 Policy recommendations supporting energy storage development

(1) Refining and enhancing regulatory frameworks and policy guidelines is of utmost importance to provide comprehensive direction for the progress, widespread adoption, and seamless integration of energy storage systems into modern energy infrastructures, ensuring their effective operation and contribution to energy transition goals.

Achieving the goals for energy storage development requires improvement of operating practices or regulatory frameworks for the deployment of the technologies and project development. Policymakers should implement and consistently update clear, streamlined permit processes that account for the unique characteristics of BESS, avoiding outdated regulations designed for traditional generation or loads. Market mechanisms and financial incentives are crucial, which include establishing clear valuation and allowing for the multiple services that BESS provide and offering direct subsidies, tax credits, or performance-based incentives to de-risk investments and improve project economics. In addition, robust and adaptable safety codes and technical standards must be uniformly adopted and rigorously enforced, coupled with ongoing training for first responders and public awareness campaigns to ensure community acceptance for the battery storage projects. With rapid advancement of battery technologies, policymakers and regulators can encourage familiarization with storage through the development of more pilot projects. These projects allow stakeholders to experiment with various technical, operational, and regulatory options to incorporate energy storage in urban energy systems. Such pilot projects could be significantly important when determining how to use distribution-level storage facilities to meet the needs of both distribution and the transmission systems. The pilots will also help regulators determine the better ownership models to provide the most benefits to the grid at least cost, and can help utilities familiarize themselves with providing electricity services with the storage facility that they own or procure from the third parties. The pilot projects are also pivotal in disseminating best practices and identifying optimal strategies for technology deployment, enabling stakeholders to refine operational models and updating relevant technical standards.

(2) It is essential to enhance innovation in the development of new energy storage technologies while facilitating the transformation of research outcomes into practical applications. Additionally, efforts should focus on expanding use cases and establishing diverse business models to maximize the

potential of energy storage solutions.

Innovation is the key driver of technological and industrial advancement. As a multidisciplinary field, new energy storage technologies are currently advancing toward large capacity, high density, long cycle life, enhanced safety, and intelligent operation, which requires collaborative efforts among governments, enterprises, research institutions, and other stakeholders to actively pursue breakthroughs in new materials, technologies, and equipment for energy storage. For battery technologies, these includes significant and sustained government investment in fundamental and applied R&D to explore novel battery chemistries (e.g., solid-state, sodium-ion, flow batteries) and long duration energy storage. Alongside R&D, policies should implement targeted manufacturing incentives, such as production tax credits, investment tax credits, and grants for domestic gigafactories and supply chain development, to scale up efficient and cost-effective production of advanced battery cells and components.

Effective collaboration among the stakeholders is critical to promote information sharing and technical exchange, thereby driving coordinated development across the entire energy storage industry chain; Strengthen close cooperation with universities and energy storage enterprises, combine academic knowledge with industry demands, and accelerate the incubation and transformation of new technologies. Concurrently, the energy storage industry should leverage demonstration projects as innovation drivers to accelerate technology commercialization and spearhead sector-wide advancement; Efforts should be made to explore the new application cases such as grid integration, integrated services of solar PV-energy storage-EV charging, and virtual power plants, demonstrating the actual benefits and potential of advanced energy storage technologies in actual applications across various sectors—such as industrial, transportation, residential and commercial buildings.

(3) It is essential to enhance technical regulations and establish comprehensive standard systems that encompass the entire lifecycle of energy storage solutions, thereby providing a solid foundation for their efficient deployment.

The standardization supports the commercial and large-scale application of energy storage technologies, ultimately accelerating the global transition toward low-carbon energy systems. To promote the deployment of new energy storage, priority should be given to enhance technical regulations and standard norms, covering the entire life cycle of the BESS. Technical guidance and standards for energy storage play a core role in promoting the safe and efficient operation of energy storage systems and their compatibility with existing and future energy systems.

Integrating energy storage into the power system and accessing its full value require technical regulations that ensure reliable, predictable behavior from the asset during both normal operations and in response to contingency events. Such regulations could cover myriad topics from communication capabilities, level of observability over the storage system for system operators, and various operational characteristics such as minimum response times to signals from a system operator. Although existing technical codes standards may adequately cover most of the technical requirements, energy storage systems that provide power to both the distribution and transmission system may need additional review and capabilities. To support the safe and effective integration of BESS into the power grid, focused areas include: i) Technical rules should ensure BESS are installed and operated safely, addressing risks like fires or chemical leaks. Standards should also require batteries to communicate smoothly with the grid, helping to stabilize voltage and frequency during outages or sudden changes in energy supply; ii) From a grid operator's perspective, regulations and standards for BESS should prioritize reliability, simplicity, and fairness. Connection rules shall ensure batteries can respond quickly and safely to grid needs. Standards must address safety risks like fires or overheating by mandating proven designs, emergency shutdown features, and regular inspections. Grid operators need straightforward protocols for how batteries connect to the grid, reducing delays and technical conflicts; iii) Policies should be prepared helping batteries compete fairly in energy markets while supporting grid stability. Remove outdated rules that penalize batteries for charging from the grid or limit how they can earn revenue. Grid operators need flexibility to use batteries for multiple purposes, like easing congestion on overloaded power lines or delaying costly grid upgrades.

(4) To ensure the safety and reliability of energy storage systems, it is essential to enhance quality control across the supply chain, optimize operation and management practices, and address public concerns effectively.

Improving safety of energy storage systems requires great efforts from multiple aspects including design, operation, and management. During the design phase, modular structures and thermal management systems can be used to control battery temperature and prevent thermal runaway risks; During operation, enhanced maintenance and real-time monitoring systems should be implemented to detect and address potential issues promptly; At the same time, AI-based safety maintenance and system optimization management are among effective methods. Safety education and emergency training are essential for ensuring operational safety; virtual training and case analysis can enhance emergency response capabilities. With increased attentions and greater efforts from the authorities and technology advancement, safety records of energy storage systems have improved greatly in recent years. Improved safety directly impacts market confidence of energy storage products. Implementing high safety standards significantly reduces investment risks, increases consumer acceptance of energy storage technologies, and thus drives research, development, and commercialization of energy storage system. These not only ensure the deployment of energy storage systems but also provide safe and reliable supports for energy system stability and large-scale applications of renewable energy.

The safe operation of energy storage systems has become a critical challenge, requiring strengthened quality control across the supply chain. Firstly, cities and local governments should incorporate sufficient fire safety distances and spatial arrangements for energy storage facilities into controlled detailed planning and specialized planning for land use; Secondly, drawing on international experience, establishing quality standards and safety technical specifications that cover all stages—including manufacturing, construction, installation, operation monitoring, and recycling—and applying them throughout the industry chain; Thirdly, improving the early warning mechanisms before thermal runaway events in electrochemical energy storage battery systems along with protective measures during incidents and anti-diffusion strategies after accidents; Finally, encouraging enterprises research efforts, through technological innovation to improve the quality and safety of energy storage products and services. In addition, grid operator and power dispatching agencies should develop detailed grid connection rules and guidelines, clearly defining grid connection procedures, relevant technical standards, and requirements for grid-related testing, laying a solid foundation for the safe and efficient operation of energy storage systems.

(5) To enhance the strategic planning and operational efficiency of power networks, it is imperative to establish a systematic approach to the development of energy storage solutions, ensuring the effective utilization of the diverse services provided by storage systems, thereby contributing to the overall optimization and reliability of the power infrastructure.

Long-term energy storage targets and integrated resource planning can provide critical policy certainty, signaling a stable market for developers and investors while accelerating the integration of BESS into urban energy system. Alongside renewables development, utilities need to fully include energy storage in long-term grid planning of urban energy system, ensuring integrated considerations of batteries for various power system services. Such requirements can help make sure more novel approaches to power system needs are considered on an even playing ground with more traditional investments.

The ability of batteries to provide both network services and market services means that both networks and other parties can lead the roll-out of energy storage infrastructure. Distribution network service providers in cities could effectively support scaling up BESS deployment by: i) fully embedding BESS into the planning and design of networks, for example, due to network operator's intimate knowledge of evolving electricity demand and future infrastructure augmentation requirement, as well as related replacement and operational needs of the network; ii) taking the advantage to use existing land assets of the urban network operators, such as land adjacent to zone substations, to host batteries, lowering the cost of delivery. This also avoids the social license cost of procuring new land within communities and effectively navigating change of its use; iii) partnering with market facing third parties, including BESS developers and integrators, which can reduce the barriers for those parties to manage wholesale electricity market risks and sustain the BESS project development; iv) leveraging existing processes and workforce for the operation and maintenance of energy storage assets to maximize the values and benefits of BESS.

(6) Initiatives should center on streamlining procedures, ensuring the seamless integration of energy storage systems with the power grid, and facilitating the advancement of energy storage projects.

To accelerate the grid integration of BESS project, policy recommendations should prioritize streamlining and standardizing interconnection procedures. This involves developing clear, efficient, and transparent processes for connecting BESS to both transmission and distribution networks, which are often characterized by significant delays and uncertainties. Key policy actions include establishing firm deadlines for grid operators to complete interconnection studies and approvals, implementing "cluster study" approaches instead of serial processing to manage backlogs, and requiring higher readiness requirements for projects entering the queue to ensure only mature proposals proceed. Furthermore, policies should promote the provision of granular and accessible grid data, such as hosting capacity maps and circuit strength information, enabling developers to identify optimal interconnection points and design more effective projects, thereby reducing speculative applications and subsequent withdrawals.

Additionally, policies should address the technical and financial aspects of interconnection to facilitate BESS deployment. This includes updating technical standards to specifically accommodate the unique operational characteristics of BESS, such as their fast response times and ability to provide grid-forming services, rather than treating them solely as traditional generators. Policies should also clarify cost allocation mechanisms for necessary grid upgrades associated with BESS interconnections, ensuring that these costs are allocated fairly and do not disproportionately burden BESS developers. Finally, encouraging innovative connection models, such as co-location with existing renewable generation or shared connection points, can further optimize grid infrastructure utilization and reduce the need for extensive new transmission or distribution investments, thereby accelerating project timelines and reducing overall costs for BESS integration.

(7) Effectively advocate for distributed storage systems to deliver cost-effective and reliable energy services to consumers.

Supporting the widespread adoption of distributed BESS, including community battery programs, industrial and commercial storage, and virtual energy storage, requires a multi-faceted approach. Governments and regulators should prioritize targeted financial incentives such as grants, low-interest loans, and performance-based payments that specifically encourage the deployment of these systems at various scales. Concurrently, regulatory frameworks need to be updated to fairly value the diverse grid services offered by distributed BESS, including peak shaving, demand response, and frequency regulation, ensuring they can fully participate and monetize their benefits in electricity markets. Cities can streamline local planning and permitting processes for these installations, reducing administrative burdens and accelerating deployment. Clear guidelines for community engagement and benefit-sharing, such as discounted electricity rates for participants, will also foster public acceptance and drive widespread adoption. Clear and streamlined interconnection rules are also essential to reduce project development times and costs, facilitating faster deployment.

In cities in developing economies, where industrialization and energy demand are soaring, policies can encourage I&C BESS through demand charge reduction incentives, preferential grid access for BESS-integrated renewable energy, and support for microgrids in industrial parks. These in industrialized economies cities should continue to leverage existing tax credits and relevant mandates for storage projects. Fostering the growth of virtual energy storage and I&C BESS necessitates regulatory innovation. This involves developing sophisticated market mechanisms that allow aggregated smaller storage units to participate in wholesale energy markets and provide ancillary services, effectively creating VPPs. These VPPs can optimize distributed BESS assets across a city, enhancing grid stability and efficiency, allowing them to provide demand response and grid services to the local network. For industrial and commercial users, policies should incentivize the integration of BESS with on-site renewable generation through tax credits or specific tariffs that reward self-consumption and grid support. continued investment in research and development, alongside public education on technology advancement and safety of distributed BESS.

(8) In order to ensure the successful development and implementation of energy storage projects, it is essential to devise effective fiscal and tax policies while simultaneously establishing a robust mechanism that allows comprehensive participation of energy storage systems in electricity markets.

Effective fiscal and tax support policies play a significant role in accelerating the early-stage development of energy storage and facilitating its transition from commercialization to large-scale deployment. Governments should study and develop appropriate subsidy policies for energy storage, while actively exploring financial models that support the development of new energy storage technologies. For the standalone energy storage model, on one hand, governments can reduce upfront investment costs through industrial policies, enabling more energy storage companies to participate in spot market competition and thus help reduce peak-to-valley load differences; On the other hand, governments can also increase the charging and discharging revenue of standalone energy storage systems to reduce operators' incentives to withhold capacity from the market. For the renewable energy-integrated storage model, governments may promote shared energy storage business models to realize society-wide allocation of storage resources, thereby maximizing the ability of energy storage to flatten peak and valley loads. For the user-side storage model, on one hand, governments can provide subsidies for the installation costs of energy storage systems to enhance users' self-regulation capabilities; On the other hand, governments can also implement time-of-use (TOU) pricing policies to widen the price gap between peak and off-peak hours, thus strengthening users' willingness to adopt energy storage solutions. Governments should streamline cost transmission mechanisms for energy storage and establish a comprehensive mechanism for energy storage participation in the electricity market. Governments should relax the access conditions for energy storage participating in the electricity market, and continue to refine the rules governing participation in spot trading, improve the auxiliary service market mechanisms and trading products, establish and improve cost recovery mechanisms for energy storage capacity, so as to eliminate barriers preventing new types of energy storage from participating in the electricity market. Furthermore, governments should encourage enterprises to explore innovative profit channels and business models that better align with market development through policy measures and legal frameworks—such as shared leasing, arbitrage in the spot market, virtual power plant models, and community energy storage models, and recognize and protect the legality of enterprise revenues.

(9) The establishment of a supportive and strategically structured business environment is of paramount importance to fostering the growth and driving the innovation required for the advancement of sophisticated energy storage solutions. This approach ensures that entry barriers are minimized while simultaneously maximizing opportunities for sustainable development and expansion within the energy storage sector.

To accelerate investment in BESS, policy recommendations should focus on creating stable revenue streams, reducing upfront costs, streamlining regulatory processes, and fostering market transparency. For the deployment of BESS in urban areas, cities should focus on targeted incentives for distributed energy resources, including rebates or low-interest loans for behind-the-meter batteries for households, small businesses, and apartment complexes. Policies should facilitate the deployment of community batteries in residential and commercial area, leveraging underutilized urban spaces and integrating with local renewable generation like rooftop solar. Streamlining local planning and permitting processes is crucial, specifically recognizing BESS as a permissible and valued urban infrastructure. Cities can also lead by example through municipal BESS initiatives and also foster VPP programs that aggregate urban distributed storage capacity, providing grid services and offering financial benefits to participants. Related recommendations include: i) Actively explore various flexible and efficient market-oriented profit channels and business models. The government should introduce policies and legal regulations to encourage and safeguard enterprises in generating legitimate revenues through proper profit channels and business models. ii) Improve market condition: granting non-discriminatory access to electricity markets and provision of services, and defining permissible use cases to facilitate planning by investors and operators and to make it easier to assess likely revenues. Where feasible, it would also mean reforming power markets to establish wholesale markets that help deliver cost-effective short- and medium-term flexibility, and can be a significant revenue driver for battery storage projects, especially with increased variable renewables in energy mix; iii) Mitigate off-taker risk: Lowering the risk of delayed payments or failure to pay for services provided to transmission networks would help to provide a more secure investment environment, which could be done by expanding off-taker guarantee and credit enhancement mechanisms; and iv) Lower the cost of capital: reducing perceived risks and enhancing investor confidence through stable and predictable revenue streams from diverse grid services, potentially facilitated by clear regulatory frameworks and long-term contracts. Government incentives, including tax credits, grants, and subsidies, directly lower the upfront capital required and improve project returns, making them more attractive to investors. Furthermore, the increasing availability of green financing options, such as green bonds, can offer favorable interest rates and attract environmentally conscious investors, lowering the cost of capital.

(10) To ensure a comprehensive approach to enhancing the energy storage industry, it is essential to strengthen coordination across various dimensions of battery manufacturing processes. This includes implementing robust Environmental, Social, and Governance (ESG) management practices that aim to foster diversification and promote environmentally sustainable practices throughout the

energy storage industry's supply chain. Such measures are vital for ensuring the long-term viability and growth of the sector while aligning with global sustainability trends.

From a government perspective, the planning and design of the energy storage equipment supply chain should be synchronized and coordinated with the industrial chain, capital chain, innovation chain, and value chain. Comprehensive considerations should be given to logistics, industrial layout, investment and financing, scientific research and innovation, as well as value enhancement. Governments should optimize and upgrade the upstream, midstream, and downstream segments of each chain—strengthening weak links, filling gaps, and reinforcing capabilities—to stimulate market vitality and innovation; deeply integrate upstream and downstream resources to improve supply-demand transparency and guide investments into new production capacities, thereby ensuring a healthier and more stable supply chain operation. A resilient and secure supply chain should be both regionalized and diversified. City governments, along with key domestic and foreign enterprises across the energy storage supply chain—including manufacturers, suppliers, and developers—should establish strategic partnerships by reaching public-private collaboration, establishing joint ventures and sharing resources to improve operational efficiency and streamline supply chain processes, while also enhancing the bargaining power. Enterprises should seek for long-term cooperation, co-financing, acquisition, and distribution arrangements with various raw material and equipment suppliers to ensure adequate supply. While enterprises with sufficient capabilities may expand internationally through cross-border operations, tapping into global markets and coordinating upstream and downstream supply chain entities within and across economies to bypass trade barriers, integrate R&D and technological innovation strength, and reduce costs and risks. Moreover, ESG (Environmental, Social, and Governance) compliance in the supply chain is an inevitable global trend. Stakeholders along the supply chain should enhance ESG management from a full life-cycle perspective of energy storage equipment, aiming to build a green supply chain.

(11) To foster the development of Battery Energy Storage Systems (BESS), it is essential to establish robust mechanisms for information and knowledge sharing that allow stakeholders across various domains to exchange data, practical insights, and lessons learned. Additionally, sharing experiences derived from demonstration projects and pilot initiatives implemented across different economies can provide valuable guidance for the design and execution of similar endeavors on a broader scale.

Effective policy for BESS development hinges on robust information and knowledge sharing mechanisms. This includes establishing international platforms and forums where diverse stakeholders – including governments, regulators, industry players, researchers, and fire services – can regularly exchange data, best practices, and lessons learned from BESS deployment. Key areas for sharing encompass safety protocols, technical standards (e.g., harmonizing UL, IEC, and domestic standards), operational guidelines, and insights into new battery chemistries and their associated risks and benefits. Furthermore, transparent reporting of BESS incidents, including near-misses and root cause analyses, is crucial to identifying systemic vulnerabilities and refining safety measures. Policies should incentivize the development of open-access databases and analytical tools that synthesize this information, enabling a proactive and data-driven approach to BESS regulation and innovation.

To accelerate BESS adoption and ensure its safe integration into energy systems, it is vital to share experiences from demonstration and pilot projects across different economies. This involves documenting and disseminating detailed case studies that highlight successful project implementations, innovative financing models, regulatory frameworks that foster investment, and the performance of BESS in various grid applications (e.g., frequency regulation, peak shaving, renewable energy integration, off-grid solutions). Particular attention should be paid to lessons learned regarding project complexity, integration challenges, and the evolution of operational and maintenance procedures. By analyzing these real-world examples, policymakers can identify effective strategies for de-risking BESS investments, tailoring policies to local contexts, and fostering public-private partnerships that are essential for scaling up BESS deployment globally.

(12) Facilitating and advancing international collaboration in the field of innovative energy storage technologies is of great importance for addressing the multifaceted challenges inherent in transitioning towards energy systems that incorporate a significantly higher proportion of renewable energy resources while ensuring stability and sustainability.

As a core technology in the energy revolution and a strategically critical area of competition, energy storage has been elevated to energy transition strategies in APEC economies including Australia; China; Japan; Korea; and the United States. It is recommended that the APEC region, guided by the principles of complementary strengths and mutual benefit, draw on the experience of mature markets regarding energy storage development. To foster and promote international cooperation in the APEC region for energy storage development, policies should prioritize the harmonization of standards and regulatory frameworks. Given the diverse economic and energy landscapes within APEC economies, a "one-size-fits-all" approach is impractical. Instead, policies should encourage the development of common technical standards, safety codes (such as those for BESS), and interoperability guidelines. This would facilitate cross-border trade of energy storage technologies, components, and expertise, while reducing market fragmentation and investment risks. Furthermore, policies should support joint research and development initiatives, potentially through APEC's existing expert groups, to accelerate technological advancements in areas like long-duration storage, grid integration, and sustainable supply chains for critical minerals. This includes fostering public-private partnerships to co-fund innovative projects and facilitate technology transfer.

Beyond technical cooperation, policies should focus on building robust capacity and promoting inclusive policy dialogues across APEC member economies. This involves creating platforms for policymakers, regulators, and industry leaders to share best practices on market design, financial incentives, and regulatory mechanisms that successfully attract investment in energy storage. Targeted capacity-building programs, workshops, and peer reviews, particularly for developing economies within APEC, can help bridge knowledge gaps and accelerate the adoption of effective energy storage policies. Ultimately, a strong emphasis on consistent, transparent policy signals and a commitment to collaborative learning will be critical for unlocking the full potential of energy storage in supporting APEC's ambitious goals of enhancing energy security, integrating renewables, and achieving carbon neutrality.

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