Long-duration energy-storage technologies: A stabilizer for new power systems

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Against the backdrop of realizing the target of "carbon peak and carbon neutrality", renewable energy sources such as wind and solar power have developed rapidly. However, the inherent randomness, fluctuation, and intermittency of these energy sources pose challenges to the power system stability and supply-demand balance. Long-duration energy-storage (LDES) technologies, with long-cycle and large-capacity characteristics, offer a critical solution to mitigate the fluctuations caused by new energy generation over a long period. These systems enable reliable power supply across seasonal variations and extreme weather conditions. LDES technologies have garnered significant attention globally and would unlock investment opportunities valued up to $4 trillion by 2040. This paper emphasizes the importance, future market size, and technological landscape of LDES in the large-scale utilization of new energy generation, among which it is proposed that flow batteries are the most promising LDES technology in the future.

To control global warming to approximately 1.5 °C above pre-industrial levels, the Intergovernmental Panel on Climate Change indicates that renewable energy must constitute 70-85% of global electricity generation by 2050, with solar and wind power playing a dominant role. For China to achieve the carbon neutrality target by 2060, it is estimated that solar and wind power will need to supply 60-70% of the nation's electricity mix, necessitating a total installed capacity of over 5,000 gigawatts (GW) for wind and photovoltaic power generations. However, the inherent randomness, fluctuation, and intermittency of wind and photovoltaic power pose significant challenges to the power systems stability and supply–demand balance.[1] Energy-storage systems can effectively mitigate these characteristics of photovoltaic and wind power,[2] supporting their large-scale integration into the grid, which has been widely applied in Generation, Grid, and Load (Figure 1). Assuming a 20-50% energy-storage deployment ratio, China alone would require an installed energy-storage capacity of 1-2.5 TW by 2060, with the industry's annual output value potentially exceeding $trillion, positioning energy storage as a key component in the global transition to sustainable energy systems.

Compared to short- and medium-duration energy storage technologies, long-duration energy storage (LDES) systems demonstrate superior capability at mitigating the intermittent power output of solar and wind power. Specifically, LDES technologies exhibit extended energy storage capabilities with discharge durations ranging from a few hours or days to several months. This LDES capability enables the release of electricity from the energy-storage system in the event of insufficient wind or solar power generation, ensuring a stable power supply. The integration of LDES with smart grid technologies enables optimized energy management real-time demand response. During periods of renewable energy surplus, excess electricity is stored and then strategically released during peak demand periods to maintain supply-demand balance. LDES technology can provide rapid response capabilities to help the power grid adjust quickly during sudden demand fluctuations or generation drops. This flexibility enables the power grid to better cope with natural wind and solar energy fluctuations. The global energy sector has yet to establish a unified standard definition for LDES systems. Still, it is operationally defined as energy storage systems capable of continuous discharge at rated power for durations over 4 hours, even several days or months, and it also possesses low costs, large scale, and a cycle life over 20 years. In 2024, the global newly installed LDES capacity exceeded 1 GW/4.6 GWh. The installed capacity of global LDES reserve projects has surged to 76 GW/357 GWh, more than doubling from last year. On November 14, 2024, the LDES Council emphasized the necessity and urgency of developing LDES technologies. It estimated that LDES capacity over 1 TW would need to be deployed by 2030, with a target of 8 TW by 2040 to ensure the achievement of net-zero CO_2 emissions, which would unlock investment opportunities worth up to $4 trillion (Figure 1).

In 2024, a series of supportive policies and regulatory frameworks were published to facilitate the high-quality development of LDES. On September 5, 2024, the Clean Energy Demonstrations Office of the U.S. Department of Energy (DOE) announced $100 million in federal funding applications to support pilot-scale energy storage demonstration projects, prioritizing non-lithium battery technologies, systems with discharge durations exceeding 10 hours, and stationary storage applications. Subsequently, on November 6, 2024, China's Ministry of Industry and Information Technology issued the draft Action Plan for the High-Quality Development of the New Energy Storage Manufacturing Industry, which emphasized the need to develop LDES technologies and proactively plan for ultra-long-duration energy-storage systems. Two days later, on November 8, 2024, the Standing Committee of the 14th National People's Congress of China formally adopted the Energy Law of the People's Republic of China, explicitly highlighting the importance of leveraging various energy

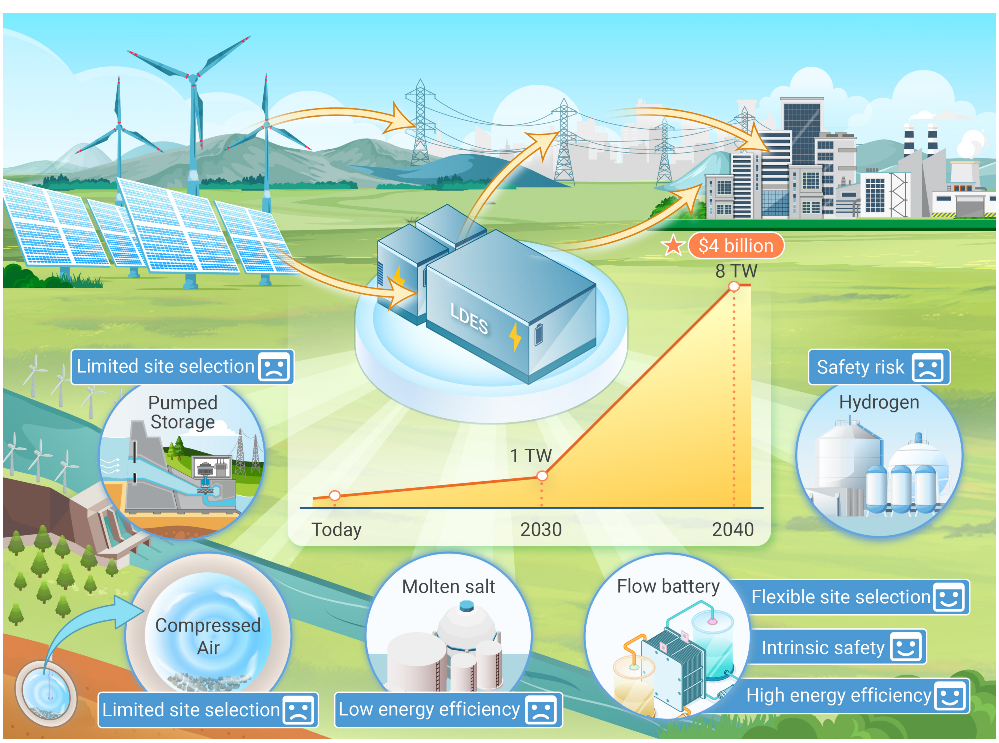

Figure 1. Application scenarios and classifications of LDES systems, as well as prediction of their market size and industry value.

storage systems, particularly LDES, in grid regulation and stability. On December 20, 2024, the U.S. DOE released the draft Energy Storage Strategy and Roadmap, which identified LDES as a strategic breakthrough area in U.S. energy strategy and a crucial solution against the challenges of integrating renewable energy into the grid.

In 2020, Paul Albertus et al. highlighted that increasing the penetration rate of solar and wind power exhibits a direct positive correlation with energy-storage duration.[2] To achieve the carbon neutrality target, the share of solar and wind power must rise to 50-80%, which requires energy-storage systems with durations of at least 10 hours. For scenarios approaching 100% penetration of solar and wind power, energy-storage durations extending to several hundred hours would be necessary. Energy-storage duration is directly linked to energy-storage capacity, with greater capacity enabling longer durations. Whether capacity can be scaled without limitation depends on the type of energy carrier and whether it is flowable. Flow-based energy carriers allow decoupling of energy capacity from power rating, enabling scalable and flexible energy-storage durations. In contrast, non-flow energy carriers exhibit strong interdependence between energy capacity and power rating, leading to escalating costs and safety risks as capacity scales. For instance, the energy carriers of lithium-ion batteries (LIBs) are non-flowable, which significantly limits their energy-storage duration. Current LIBs are primarily deployed for 2-hour energy storage, with some applications extending to 3-4 hours, but once achieving durations beyond 6 hours, LIBs would face challenges in terms of economic viability and safety management. Consequently, the decoupling of capacity and power of energy carriers is a prerequisite for achieving LDES.

LDES technologies of intrinsic safety should be prioritized to mitigate the explosion risk during long-term operation. Besides, comprehensive evaluation criteria should also include economic feasibility, energy efficiency, cycle life, power rating, construction period, and geographical adaptability (terrain and climate compatibility). LDES technologies mainly include pumped storage, compressed air energy storage, hydrogen energy storage, thermal energy storage, and flow batteries. Different LDES technologies exhibits distinct duration capabilities aligned with specific grid applications: flow batteries are particularly effective for diurnal load shifting, while compressed air, pumped storage, and thermal storage technologies demonstrate superior performance in seasonal and multi-day energy storage applications. Hydrogen energy storage has a longer duration compared with other technologies. The key LDES technologies portfolio varies according to specific duration requirements across different grid application scenarios, necessitating distinct development strategies and deployment approaches. Each LDES technology has its respective advantages and disadvantages (Figure 1). Pumped storage is technologically mature, with low cost per kWh but a long construction period and limited site selection, restricting its implementation to Generation and Grid. Compressed air energy storage offers a short construction period but limited site selection, high construction cost, and safety risks associated with its characteristics of high pressure, high temperature, and high speed of compressed air, which limits its application in Generation and Grid. Hydrogen energy storage system provides a long energy-storage duration but high safety risks due to hydrogen's flammable and explosive properties, currently confining its application to Generation and Grid. Thermal energy storage system, while has complex technology and high operation and maintenance costs, but offers substantial capacity and high safety, enabling broader applications across Generation, Grid, and Load. Flow batteries demonstrate distinctive advantages of intrinsic safety, modular design flexibility, flexible siting, minimal land footprint, and short construction period that can meet the increasing demand for wind and solar installation capacity. Besides, flow batteries offer high energy efficiency, and competitive cost structures, making them a promising alternative to conventional pumped storage. Flow batteries with adjustable energy storage durations ranging from 4 to 24 hours, even longer, sufficient to support renewable energy penetration rates of 50-80%, establishing their critical role in achieving carbon neutrality target. The above advantages of flow batteries make them widely applied in Generation, Grid, and Load.

Flow batteries are primarily categorized into four types: vanadium-based, iron-based, zinc-based, and organic systems, among which all-vanadium redox flow batteries (AVRFBs) currently represent the most technologically mature and commercially advanced solution.[1] China has been a global leader in this field. The development trajectory began in 2008 with the establishment of Dalian Rongke Energy Storage Technology Development Co., Ltd, China's first AVRFB company. In 2009, the Dalian Institute of Chemical Physics (ICPs) established a 5 kW/50 kWh AVRFBs project in Xizang. In 2011, Dalian Rongke deployed a 10 kW/200 kWh AVRFBs system in Dalian. In 2012, the company installed the world's largest 5 MW/10 MWh AVRFBs system at that time in Liaoning Woniushi Wind Farm. In 2022, Dalian Rongke constructed the world's largest AVRFB station with a 100 MW/400 MWh capacity. In 2024 alone, the newly initiated energy-storage capacity for flow batteries in China exceeded the GWh level, with AVRFBs accounting for approximately 85%. The scale of station construction and energy-storage duration are showing an increasing trend, as well as a more comprehensive station construction environment, such as Zhejiang's 500 kW/5 MWh station, Gansu's 1 GW/4 GWh project, and Jilin's 100 MW/400 MWh station, which represents the first large-scale deployment in a cold climate region.

Despite the rapid development of flow batteries, it represented only approximately 1% of the global total battery energy-storage capacity in 2024. Their high cost remains a significant barrier to their large-scale deployment. Besides, the large occupation space caused by low energy density also greatly limits its large-scale application on the user side. The high-power and high integration technologies of battery stacks and systems are the key to breaking through the cost bottleneck, which needs performance breakthroughs of key components such as electrodes, membranes, and bipolar plates.[3,4] E-Fuel Energy Technology (Guangdong) Co., Ltd. is a leader in this domain, having developed AVRFB stacks that have achieved an energy efficiency of over 80% at a rated current density of 400 mA cm^{-2}, representing the highest level in the industry. Taking a 16 KW stack as an example, when the rated current density increases from 180 to 400 mA cm^{-2}, the size of the stack can be reduced from 1026 * 650 * 450 mm to 640 * 560 * 510 mm, which can greatly decrease the construction cost of flow batteries. The cost of electrolytes, accounting for ~60% of AVRFB costs calculated based on a 4-hour energy-storage duration,[1] is another opportunity for cost reduction through technology innovations in reducing vanadium costs, electrolytes utilization enhancement, concentrations improvement, and vanadium ions valence state restoration.[5] Additionally, increasing energy-storage durations can also reduce the cost-sharing per KWh, further improving cost competitiveness. For example, initial investment costs for 4-hour energy-storage systems were ~$0.34/Wh, and extending energy-storage durations beyond 8 hours could reduce costs to $0.27/Wh or less. Additional cost reduction strategies include extending cycle life to decrease lifecycle costs, optimizing design and production processes to minimize material waste, and improving manufacturing efficiency.

Currently, large-scale AVRFB energy-storage stations predominantly operate with energy-storage durations of 4-5 hours, while stations with durations exceeding 10 hours remain limited in both scale and quantity, primarily consisting of pilot projects in the KW or several MW range. To achieve the carbon neutrality target, it is imperative to enhance energy density and extend energy-storage durations, particularly through the development of 100 MW or larger power stations with a duration exceeding 10 hours. Realizing these advancements will require sustained and coordinated efforts among scientists, engineers, and cross-industry stakeholders.

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DECLARATION OF INTERESTS

The authors declare no competing interests.