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# Application of Energy Storage Systems in Renewable Energy

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**Abstract:**
The global energy transition is accelerating, with renewable energy becoming the primary driver of power capacity expansion. However, the intermittent and volatile nature of solar and wind energy poses challenges to grid stability. Energy storage systems are key to addressing these challenges. This paper systematically examines the application of energy storage systems in renewable energy, covering their mechanisms, technical classifications, typical application cases, and future development directions. Combining these with photovoltaic, wind, and hydropower applications, it analyzes their value in smoothing power output, increasing renewable energy consumption, and enhancing grid peak and frequency regulation and reliability. The study finds that energy storage systems can control photovoltaic output fluctuations to ±5%, achieve 100% compliance for wind power primary frequency regulation, and increase renewable energy consumption by 15%–35%. Case studies demonstrate the economic viability and feasibility of energy storage in various scenarios. While current challenges remain, such as high costs, efficiency limitations, and inadequate recycling systems, future development directions include innovations in solid-state and flow batteries, hybrid energy storage integration, digital twins and intelligent operations and maintenance, and improved market and policy mechanisms. The paper argues that energy storage systems will become a core supportive force in promoting high-proportion renewable energy integration and achieving the "dual carbon" goals.

**Keywords:** Energy storage system, renewable energy, electrochemical energy storage, pumped storage, photovoltaic and wind power applications

## 1. Introduction

The global energy transition is advancing at an unprecedented speed, and renewable energy has become the dominant force in the expansion of power sys-

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tems. According to data released by IRENA in 2025, the world's new renewable energy power generation capacity will be 585GW in 2024, with a growth rate of 15.1%, accounting for 92.5% of the global power expansion that year, and the installed capacity share will increase from 43% in 2023 to 46.4%. Among them, solar photovoltaic will add 452GW, with a total installed capacity exceeding 1865GW; wind power will add 118GW, with a total installed capacity of 1200GW, with offshore wind power accounting for 28% [1]. Asia contributed 72% of the global new capacity, with China accounting for the highest share, while the penetration rate in Africa and Latin America is still less than 20% [2]. However, the intermittent and volatile nature of renewable energy poses a challenge to the stability of the power system. Solar energy is affected by day and night and weather, and its output can fluctuate by 80%–100%. Wind energy often fluctuates by more than 30% at the hourly level, resulting in a global average absorption rate of only 82% in 2024, and in some regions, the wind and solar power curtailment rate still exceeds 10% [3].

In this context, the importance of energy storage systems as the "regulator" of the power system has become increasingly prominent. Energy storage can smooth fluctuations, transfer loads, enhance grid flexibility, and provide support for the access of a high proportion of renewable energy. In particular, pumped storage and lithium battery energy storage are developing rapidly. In 2024, global energy storage will add 38GW, with a total installed capacity of 230GW. Among them, electrochemical energy storage will account for 52% for the first time, exceeding pumped storage [3]. Energy storage systems have become an important means to ensure the absorption of new energy and promote the goal of "carbon neutrality" [4].

This paper systematically examines the role, classification, typical applications and future development trends of energy storage systems in renewable energy. The research highlights the key value of energy storage in mitigating new energy fluctuations and facilitating grid integration, providing technical and strategic references for achieving global energy transformation and "dual carbon" goals.

## 2. Overview of Energy Storage Systems

Energy storage systems achieve dynamic balance of the power system through the storage and release of energy. Their core role threefold. First, it smoothes out fluctuations in renewable energy output and increases the absorption rate of new energy. Second, it participates in grid peak and frequency regulation to maintain system frequency and voltage stability. Third, it serves as a backup power source to ensure the continuity of power supply to critical loads [3-5]. In systems with a high proportion of new energy, energy storage can also undertake energy time and space transfer and black start support, and is an important link for achieving coordinated operation of source, grid, load and storage [4]. According to the energy storage form and conversion principle, energy storage technology are categorized into five types: mechanical energy storage, electrochemical energy storage, thermal storage, electromagnetic energy storage and chemical energy storage [6].

Mechanical energy storage is the most widely used form. Pumped storage accounts for 48% of the world's installed energy storage capacity. It relies on the water level difference between the upper and lower reservoirs to achieve energy conversion. It has the characteristics of large scale (single station capacity can reach GW level), long life (>50 years) and low cost (about US$0.05/kWh). In 2024, the world will add 6GW of pumped hydropower storage, with a total installed capacity of 110GW [7]. Flywheel energy storage stores electrical energy through rotational kinetic energy, with a response speed of milliseconds and a cycle life of more than one million times. In 2024, 120MW of new installed capacity will be added, mainly for primary frequency regulation of wind farms [5]. Compressed air energy storage uses compressed air during low electricity price periods and releases it during peak periods, which is suitable for long-term energy storage. The 100MW/400MWh project in Ulanqab, Inner Mongolia, achieves cross-period transfer of wind energy with a conversion efficiency of 65% [8]. Electrochemical energy storage includes lithium-ion batteries, lead-acid batteries, flow batteries, and sodium-sulfur batteries [4]. Among them, lithium-ion batteries have the fastest development, with an energy density of 200–300Wh/kg and a charge and discharge efficiency of 85%–95%. In 2024, the world will add 32GW, accounting for 84% of the total new energy storage [3]. Liquid flow batteries have an independently adjustable capacity and a lifespan of over 10,000 cycles. All-vanadium liquid flow batteries are the most mature, with China adding 1.2GW of new projects in 2024[9].

Sodium sulfur batteries are suitable for long-term energy storage, with an efficiency of 75%–90%. Thermal storage technology uses molten salts, phase change materials, or sensible heat media to store energy, with low costs (approximately \$20/kWh), and is commonly used in solar thermal power stations and industrial waste heat recovery. In 2024, 2.5GW of new capacity was added globally, mainly in Spain and China [10]. Electromagnetic energy storage includes supercapacitors and superconducting magnetic energy storage. Supercapacitors have the characteristics of fast charging and discharging speed (microseconds) and high power density (>10kW/kg). They are often used in regenerative braking of new energy vehicles and grid voltage support, with a 35% increase in application in 2024 [11]. Superconducting magnetic energy storage has high efficiency (nearly 95%), but is relatively expensive. Chemical energy storage mainly includes hydrogen energy and synthetic fuels. Hydrogen energy storage has a high energy density (120MJ/kg) and is suitable for long-term regulation. In 2024, global investment in green hydrogen energy storage projects reached US\$8 billion, 2.3 times that of 2023 [12]. As the efficiency of electrolyzers and fuel cells increases, hydrogen energy storage is becoming an important direction for large-scale energy storage.

# 3. Application of Energy Storage Systems in Different Renewable Energy Sources

## 3.1 Application of Energy Storage in Solar Energy

Solar energy is intermittent, and energy storage systems are crucial for its grid connection. In 2024, the global "photovoltaic + energy storage" project will add 120GW, accounting for 26% of the total new photovoltaic power [1].

In the distributed field, the Yuzhong County project in Gansu Province uses 20kW photovoltaic modules and 120kWh lithium iron phosphate batteries, supporting both on-grid and off-grid modes. On sunny days, the system generates electricity for self-use, stores the surplus electricity, and supplies electricity to the energy storage on rainy days. The system achieves 100% clean energy supply for village public facilities, reduces carbon dioxide emissions by about 32 tons annually, and reduces residents' electricity bills by 20%–30% [13]. Operational data shows that the photovoltaic absorption rate has increased from 65% to 98%. In industrial parks, photovoltaic energy storage systems are combined with peak and valley electricity price differences for energy management. For example, a park in Jiangsu Province has obtained an annual income of 200,000 yuan/MWh through the "photovoltaic + energy storage" project, and the investment recovery period has been shortened to 6 years [14]. In large-scale power stations, energy storage plays the role of smoothing output and participating in peak regulation. The 500MW photovoltaic power station in Horsham, Australia is equipped with a 125MW/250MWh energy storage system. Through the MPC control algorithm, the output fluctuation is controlled within ±2%/15min, and the grid connection qualification rate is increased from 82% to 99.5% [10].

## 3.2 Energy Storage Application in Wind Energy

Wind power is highly volatile, making energy storage system particularly critical for stabilizing its output. Flywheel energy storage compensates for wind power fluctuations with a millisecond response speed. The 5MW/175kWh flywheel energy storage project in Pingdingshan, Henan uses magnetic levitation technology, with a frequency regulation response of <50ms, an accuracy of ±0.02Hz, a frequency regulation qualification rate of 100%, and an operation and maintenance cost of only 1.2% of the investment [5]. During the trial operation, the wind power output fluctuation was reduced from ±30% to ±5%. In high wind speed areas, compressed air energy storage is used for wind energy transfer. The Ulanqab project in Inner Mongolia uses compressed air to store energy during off-peak electricity prices (0.25 yuan/kWh) and releases electricity during peak electricity prices (0.75 yuan/kWh), absorbing 120 million kWh of abandoned wind power annually [8]. In addition, wind-storage combined systems have gained traction. For example, the Huolin River project in Inner Mongolia uses a combination of 1MW/2MWh lithium batteries and 1MW/0.2MWh flywheels. The flywheel is used for high-frequency peak regulation, and the lithium battery is used for long-term frequency regulation and peak regulation. The wind curtailment rate has been reduced from 12% to 3% [3].

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### 3.3 Energy Storage Applications in Hydropower

Hydropower is the most mature renewable energy source, and pumped storage plays a key role in it. In 2024, the world's pumped storage capacity will increase by 6GW, reaching a total installed capacity of 110GW, of which China will add 3.5GW, accounting for 58%. The Anhui Jixi Power Station, equipped with 4×300MW variable-speed units, has achieved a 15% reduction in operating vibration amplitude, extended service life by 5 years, and shortened power regulation response by 20% [7]. Intelligent operation and maintenance methods have achieved a fault identification accuracy of 99.66%, improving safety. Internationally, the Kinmen Pumped Storage Project in the United States has invested US$2 billion and uses a closed circulating water system. The unit scale is 2.4GW and is expected to store 560 million kWh of wind and solar power annually, increasing the regional new energy consumption rate by 15% [8].

## 4. Current Challenges and Future Development Directions of Energy Storage Systems

### 4.1 Main Challenges

Despite rapid development, energy storage still faces multiple challenges in terms of cost, lifespan, environment, and grid integration.

In terms of cost, the cost of lithium battery energy storage will drop to $150/kWh in 2024, but the initial investment for a GW-scale project is about $6 billion, with a payback period of 8–10 years [3]. Pumped hydropower storage is expensive and subject to geographical constraints, with an investment of about $5,000 per kilowatt and a construction period of 5–8 years [7]. Regarding lifespan, the energy density of ternary lithium batteries reaches 300Wh/kg, but the cycle life is only 3,000 times; the lifespan of lithium iron phosphate batteries is 6,000 times, but the energy density is only 200Wh/kg [6]. Thermal storage systems have a daily loss of 2%–3%, and their efficiency across seasons is less than 60% [10]. From an environmental perspective, less than 20% of waste batteries are recycled. In 2024, the amount of retired lithium-ion batteries for energy storage reached 20GWh, and it is expected to reach 200GWh in 2030 [9]. 0.8kg of lithium and 10kg of cobalt can be recycled per ton of waste ternary batteries, but the recycling cost is higher than the benefits, resulting in insufficient recycling enthusiasm [9].

In terms of grid integration, the coordinated control of different energy storage types still needs to be improved. In 2024, a frequency deviation of ±0.5Hz caused by energy storage control errors in Europe led to a power outage [11]. At the same time, energy storage safety issues are prominent. The fire risk of lithium-ion battery energy storage is 0.1 times/GWh. In 2024, 12 accidents occurred, with economic losses exceeding US$100 million [3].

### 4.2 Future Development Direction

Energy storage development will focus on new materials, new structures and intelligent directions. Solid-state batteries can reach an energy density of 400–500Wh/kg and a cycle life of more than 10,000 times. Mass production is expected in 2027[11]. Hydrogen energy storage is expected to achieve large-scale, long-term applications as the cost of electrolyzers drops to $300/kW and the efficiency of fuel cells increases to 60% [12]. Iron-chromium flow batteries are only 1/10 of the cost of vanadium and have a cycle life of 15,000 times, making them an emerging direction [12]. Hybrid energy storage systems, combining flywheels (fast response) with lithium batteries (large capacity), can significantly improve regulation performance by 30%–50%[4]. In terms of operation control, energy management algorithms based on reinforcement learning can increase system benefits by 15% and have been piloted in Australian photovoltaic storage projects [10]. Intelligence is a future focus. The tensor feature extraction method proposed by Wuhan University has increased the fault identification rate of pumped storage units to 99.66% [7]. Digital twin systems have been applied in CATL's 1GWh energy storage power station, reducing operation and maintenance costs by 30% and extending life by 3 years [11]. In terms of application models, the integration of "source-grid-load-storage-use" and zero-carbon communities are worth promoting. Anji Zero Carbon Town in Zhejiang Province has achieved 100% clean energy supply for the community through a 20kW photovoltaic + 120kWh lithium battery solution, reducing carbon dioxide emissions by 500 tons annually [13]. In terms of policy mechanisms, China issued the "Management Measures for

Energy Storage Participation in Power Ancillary Services" in 2024, which clearly stipulates "payment based on performance" and shortens the investment payback period by 2-3 years [3]. The EU carbon price has reached 90 euros/ton, and energy storage projects can increase annual profits by 10%-15% through carbon emission reduction benefits [12]. In terms of international cooperation, the IEA launched the "Global Energy Storage Standards Initiative" in 2024 to promote the unification of efficiency and safety standards, and 30 countries have responded [2].

## 5. Conclusion

This paper reviews the current status of energy storage applications in renewable energy, its technical classifications, practical cases, and future development directions. Research demonstrates that energy storage, as the core of new power systems, plays an irreplaceable role in smoothing fluctuations, ensuring grid stability, and improving energy efficiency. For example, photovoltaic output fluctuations can be controlled to ±5%, wind power primary frequency regulation response time is less than 100ms, and the renewable energy absorption rate has increased by 15%–35%. With global renewable energy capacity expected to reach 585 GW by 2024 (97% of which will come from solar and wind), demand for energy storage is increasing significantly. By 2024, 38 GW of new energy storage capacity will be added, bringing the total installed capacity to 230 GW. For the first time, electrochemical energy storage will surpass pumped hydroelectric storage in terms of share, reaching 52%. Different energy storage technologies demonstrate distinct paths: pumped hydropower storage is developing towards variable-speed regulation and intelligent operations and maintenance, reaching a total installed capacity of 110 GW; lithium batteries are rapidly expanding in grid and distributed applications due to falling costs (US$150/kWh), accounting for 52%; and flywheel storage excels in rapid power regulation, with an additional 120 MW expected in 2024. Case studies demonstrate their feasibility, such as the use of photovoltaic (PV) and lithium-ion battery microgrids for clean energy supply, flywheel storage for improved wind power grid integration, and variable-speed pumped hydropower storage for enhanced regulation capabilities.

However, this study still has certain limitations. First, the case studies focus on Asia, North America, and Australia, with insufficient coverage of energy storage applications in Europe, Africa, and Latin America, failing to fully reflect global disparities. Second, the discussion of cutting-edge technologies such as supercapacitor storage, gravity storage, and nuclear energy storage is limited, failing to fully reflect the latest developments. Future research should strengthen the systematic analysis of regional diversity and cutting-edge technologies to propose more targeted energy storage application solutions.

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