Economic Benefits and Strategy Optimization of Wind-Solar-Storage Systems under Different Market Mechanisms

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Abstract. This study conducts a comprehensive investigation into the operational strategies and economic feasibility of integrated wind-solar-energy storage (WSS) systems under different electricity market frameworks. The inherent technical complementarity between wind energy and solar energy resources was studied, the technical and economic performance of various energy storage technologies was evaluated, and the key role of artificial intelligence in improving system dispatching efficiency and optimizing multi-market bidding strategies was emphasized. Through case studies and scenario-based simulations, this research highlights that diversified revenue streams - by simultaneously participating in the energy, ancillary services, and capacity markets - are crucial for enhancing project profitability and investment attractiveness, rather than relying solely on a single market source. This study also pointed out the main challenges hindering the development of WSS, such as the immature market mechanism and the high costs associated with energy storage, and put forward targeted policy recommendations, including accelerating the reform of the electricity market and establishing a sound capacity compensation mechanism. Finally, the possible future research directions were prospected, with a focus on market dynamic simulation, the collaborative operation of multi-technology storage systems, and breakthroughs in long-term, secure, and low-cost storage solutions.

Keywords: Wind-Solar-Storage system, market mechanism, economic benefit, operational strategy, renewable energy.

1. Introduction

With the continuous deepening of the power marketization reform, renewable energy, especially wind and solar power generation, is accelerating its integration into the power system. The introduction of wind energy, solar energy and energy storage has effectively enhanced the grid-friendliness and economy of renewable energy. With the continuous maturation of the market mechanism, research in the fields of wind energy, solar energy and energy storage, with a focus on system coordinated control and diversified energy storage technologies, has achieved remarkable results. Under the optimization of artificial intelligence algorithms and energy storage dispatching, the stability and economic efficiency of its power grid have been significantly enhanced.

However, its development still faces multiple challenges. Technically speaking, the intermittency and volatility of wind and solar energy have exerted tremendous pressure on the power grid. However, current energy storage technologies, especially the mainstream lithium batteries, have limitations such as limited energy density, short lifespan, high cost, and safety issues, making it difficult to meet the demands of large-scale and long-term energy storage. Economically, although the costs of wind and solar energy continue to decline, the high investment required for grid connection, dispatching and supporting energy storage makes the system-level levelized cost of energy (LCOE) considerable, and there is a lack of a mature market mechanism to ensure the return on investment. Environmentally, the battery manufacturing and recycling processes involve resource consumption (e.g., lithium, cobalt) and pollution risks, and the full lifecycle carbon footprint needs further reduction. Additionally, policy and grid coordination highly depend on government subsidies and support policies, and a high proportion of renewables places extremely high demands on grid planning, dispatch, and stability.

This study aims to explore the operational strategies and economic benefits of Wind-Solar-Storage systems under different market mechanisms. It systematically analyzes the design characteristics of different market mechanisms and constructs their mapping relationship with Wind-Solar-Storage operational strategies. By introducing a new integrated modeling approach of "forward-looking" and "feedback closed-loop," it aims to shift the research paradigm from static feasibility analysis to dynamic value discovery, providing a theoretical basis for future energy storage project construction.

Wind-Solar-Storage systems, as a bridge connecting unstable renewable energy with stable electricity demand, are of great strategic significance for building a new power system and ensuring national energy security. This study aims to explore their marketization pathways and propose strategies for promoting the sustainable development of the energy industry [1, 2]

At present, the global wind-solar-storage system is experiencing rapid development, with the core driving force coming from the demand for energy transition and technological progress. China has become the world's largest market for new energy storage. By the end of 2024, its installed capacity of new energy storage will account for over 40% of the global total, ranking first in the world. It also presents a diversified technical route pattern of "applying one generation, demonstrating one generation, and pre-researching one generation". Lithium-ion batteries dominate the market, while long-duration energy storage technologies such as compressed air, flow batteries, and hydrogen energy storage are accelerating their demonstration. In terms of policy, China has enhanced economic viability through mandatory energy storage and power market reforms, while overseas markets such as the United States, Europe, and the Middle East rely on subsidy policies (such as the IRA Act in the United States) and explosive growth in market demand, especially for independent energy storage and industrial and commercial energy storage projects. The global market is expected to reach an installed capacity of 265.1GWh in 2025, representing a year-on-year growth of 49%. The compound annual growth rate is projected to remain at 25% to 30% over the next five years. However, unbalanced regional development, differences in technical standards and uncertainty of benefits remain challenges [3, 4].

The compareton of development of the Wind-Solar -Storge systems is summar in Table 1. This table aims to illustrate the development status of global and Chinese Wind-Solar-Storage systems. China has become the world's largest new energy storage market, with newly added installed capacity surging 194% year-on-year in 2023, and cumulative installed capacity ranking first globally. The technology roadmap is dominated by lithium-ion batteries, driven by policies such as mandatory storage allocation and electricity market reform. Despite rapid growth, challenges such as imperfect revenue mechanisms and safety issues remain. The future direction involves moving towards long-duration storage, technological diversification, and intelligentization.

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Table 1. The comparetion of development of the Wind-Solar-Storage system

Dimension	Indicator	China Data and Satatus
Market Size	Newly Added Installed Capacity in 2023	New Energy Storage newly added approx. 21.5GWh → 46.6GWh (Year-on-year +194%), in which Wind-Solar with Storage is the main application.
Cumulative Installed Capacity	Newly Added Installed Capacity in 2023	New Energy Storage newly added approx. 21.5GWh → 46.6GWh (Year-on-year +194%), in which Wind-Solar with Storage is the main application.
Growth Forecast	2024 Forecast	Newly added installed capacity is expected to exceed 35 GWh.
	2025-2027 Compound Annual Growth Rate (CAGR))	Estimated 30%-40%.
Technology Roadmap	Dominant Technology	Lithium-ion batteries (mainly LFP) hold absolute dominance, accounting for over 97% of newly added capacity in 2023.
	Other Technology Applications	Compressed air energy storage, flow batteries (all-vanadium/iron-chromium) entering 100 MWh-scale demonstration stage; flywheels, sodium-ion batteries beginning pilot projects.
Policy and Business Models	Core Driving Policies	Mandatory Storage Allocation: Many regions require new energy projects to allocate 10%-20% storage capacity, duration 2-4 hours. Electricity Market Reform: Promoting energy storage participation in electricity spot markets and frequency regulation ancillary service markets to obtain revenue.
	Mainstream Business Models	Primarily "Generation-side Configuration" model, independent/shared storage models are rapidly emerging.
Challenges and Trends	Main Challenges	Imperfect Revenue Mechanism: Low utilization rate and poor economics for most storage-allocated projects. Safety Issues: Fire protection standards and O&M systems need strengthening.
	Future Trends	1. Moving towards Longer Duration (4-8 hours). 2. Technology Diversification (Sodium-ion batteries, Hydrogen storage, etc.). 3. Intelligentization (AI large models empowering power station O&M).

By systematically analyzing the design characteristics of different market mechanisms and constructing their mapping relationship with Wind-Solar-Storage operational strategies, through the introduction of a new integrated modeling approach of "forward-looking" and "feedback closed-loop".

2. Technical Basis and Multi-Source Complementarity of Wind-Solar-Storage Systems

2.1. Basic Composition and Functions of Wind-Solar-Storage Systems

Wind-Solar-Storage integration refers to the conventional configuration of wind power, photovoltaics, and electrochemical energy storage, where all electricity consumption is supplied by renewable energy sources like wind and solar, achieving a match between power supply and load to obtain better comprehensive benefits. Through the co-located integrated design of wind/solar energy and storage, utilizing power prediction, artificial intelligence technology, and advanced monitoring and control technologies, the synergy optimization and intelligent, efficient operation of wind, solar, and storage are realized [5].

2.2. Spatio-Temporal Complementarity Analysis of Wind and Solar Resources

The core of spatio-temporal complementarity analysis of wind and solar resources is to combine them into one system by utilizing their natural inverse fluctuation characteristics in time (diurnal and seasonal) and space (different geographical regions). This "complementary advantages and complementary weaknesses" approach can effectively smooth out the fluctuations in the total power generation curve, significantly enhance the reliability and stability of power supply, and thereby increase the grid's absorption capacity and the economic efficiency of projects. The complementary trait serves as a key technical approach for facilitating the stable integration of a high penetration of renewable energy into the great area. The complementarity serves as a key technical approach for facilitating the stable integration of a high penetration of renewable energy into the grid.

2.3. Types of Energy Storage Systems and Their Techno-Economic Characteristics

Lithium-ion battery: High energy density, fast response, short lifespan, safety risks, relatively high cost [6].

Flow battery: Long lifespan, good safety, easy scalability, high investment for large scale, long storage duration.

Pumped hydro storage: Large capacity, mature technology, low cost, significant geographical constraints, long construction period.

Compressed air energy storage: Large capacity, long lifespan, lower efficiency, dependent on geographical conditions, capable of large-scale energy storage.

Energy storage systems are a key link in the coordinated operation of wind, solar and storage. The technical selection of energy storage systems directly affects the economic efficiency, reliability and life cycle of the system. The current mainstream energy storage technologies include lithium-ion batteries, flow batteries, pumped storage and compressed air energy storage, etc. These various technologies have significant differences in energy density, response speed, lifespan, cost and environmental adaptability.

Lithium-ion batteries have advantages such as high energy density and fast response, and they are currently the dominant technology in the market, especially in short-term and high-frequency applications. However, they have limited cycle life, the risk of thermal runaway, and the price fluctuations of raw materials (such as lithium and cobalt) exert continuous pressure on costs. In recent years, with the maturation and large-scale production of lithium iron phosphate (LFP) technology, the cost of lithium-ion batteries has continued to decline, to some extent squeezing the market space of long-duration energy storage technologies such as flow batteries in small and medium-scale scenarios.

Flow batteries, such as all-vanadium and iron-chromium systems, have demonstrated unique advantages in long-duration energy storage scenarios (4 to 8 hours) due to their long lifespan, high safety, and easy scalability. However, their high initial investment and low energy density limit their application in projects with limited space or tight budgets. The academic community generally believes that flow batteries are more suitable for medium and long-duration applications on the grid side, such as peak shaving and smoothing out renewable energy, and remain competitive in large-scale projects that prioritize the economic efficiency over the entire life cycle.

Pumped storage technology is mature, has a large capacity and low cost, and is currently the largest form of energy storage in terms of installed capacity worldwide. However, its development is severely restricted by geographical conditions, with a long construction period and significant environmental impact. It is difficult to promote in plain areas or ecologically sensitive regions. Therefore, its growth potential in future distributed energy systems is limited.

Compressed air energy storage has advantages such as large-scale (hundreds of megawatts) and long lifespan, and is an important development direction in current long-duration energy storage technologies. However, its system efficiency is relatively low (about 50% to 70%), and it is highly dependent on specific geological structures such as underground salt caverns or rock strata. The geographical constraints significantly affect its popularization speed across the country. In recent years, domestic demonstration projects have been promoted in Hebei, Jiangsu and other places, attempting to break through geographical constraints through technical paths such as artificial gas storage tanks.

In addition, emerging technology routes such as sodium-ion batteries, flywheel energy storage, and hydrogen energy storage have gradually entered the demonstration and small-scale commercialization stage. Sodium-ion batteries, due to their abundant resources and great cost potential, are widely regarded as an important direction for low-cost energy storage in the next generation; hydrogen energy storage has great potential in cross-seasonal energy storage and coupling with the chemical industry, but currently, efficiency and cost remain the main bottlenecks restricting its commercial promotion.

In conclusion, the selection of energy storage technologies should be comprehensively evaluated by taking into account specific application scenarios, resource conditions, policy guidance, and the full life cycle cost, among other factors. In wind-solar energy storage systems, lithium-ion batteries remain the preferred choice due to their maturity and flexibility, while long-duration energy storage technologies such as flow batteries and compressed air are gradually demonstrating their irreplaceable value in specific scenarios. In the future, with the iteration of technology and the further decline in costs, the coordinated configuration of multiple types of energy storage will become a key approach to enhancing the economic efficiency and reliability of the system.

2.4. Multi-source Collaborative Operation and Control Strategy

The adoption of a collaborative control strategy for the efficient operation of the system mainly includes: predictive day-ahead dispatching, real-time adjustment in response to fluctuations, and auxiliary service control to meet the demands of the power grid [5].

3. Operational Strategy Optimization for Wind-Solar-Storage Systems

3.1. Intelligent Dispatch Strategy Based on Power Prediction

Analysis of the electricity market environment reveals that Wind-Solar-Storage systems can increase revenue by participating in the energy market and ancillary service markets. Common strategies include peak-valley price arbitrage, frequency regulation service bidding, and capacity market contracts. It is necessary to comprehensively consider factors such as electricity price fluctuations, policy subsidies, and energy storage lifespan degradation, establishing an optimization model with the objectives of minimizing total operating costs and minimizing curtailment rates [7].

3.2. Grid-Connected/Off-Grid Switching and Multi-Mode Operation Optimization

Grid-connected/off-grid switching and multi-mode operation optimization involve studying smooth grid-connected/off-grid switching logic to ensure seamless transition to off-grid mode during grid faults, guaranteeing power supply to critical loads, and safe reconnection to the grid after restoration.

3.3. Market Participation Strategy and Bidding Optimization

Develop differentiated bidding strategies in different markets (spot, frequency regulation, capacity markets). For example, charging during low electricity prices and discharging during high electricity prices, as well as reasonable charging and discharging at different time periods.

The market participation strategy and bidding optimization for Wind-Solar-Storage systems is an extremely complex decision-making process. Its core lies in the optimal allocation and pricing of its own resources under the constraints of multiple markets and dual uncertainties (technical and market).

Artificial intelligence technologies (especially advanced forecasting and deep reinforcement learning) enable Wind-Solar-Storage aggregators to develop advanced bidding strategies that are profitable, competitive, and robust by providing more accurate probabilistic forecasts and powerful high-dimensional decision-making capabilities, thereby truly unleashing their huge commercial potential in the electricity market [3, 8].

3.4. Application of Artificial Intelligence in Operation Optimization

Artificial intelligence plays a crucial role in optimizing the operation of wind, solar and energy storage systems. Its core value lies in addressing the randomness and volatility of renewable energy through a data-driven approach, thereby achieving a coordinated optimization of system economy and reliability. Specifically, its application runs through the entire "predictive - decision-making - control" process: At the predictive level, neural network models such as LSTM are utilized to achieve high-precision predictions of wind power/solar power output and load, providing reliable basis for optimized decision-making; At the decision-making level, deep reinforcement learning (DRL), as a key technology, enables the system to act like an "intelligent agent", autonomously learning the best energy storage charging and discharging strategies through continuous interaction with the environment. This strategy can not only effectively shift energy time in the time-of-use electricity price market to maximize economic profits, but also take into account long-term factors such as battery life degradation to optimize life cycle costs. Its computational efficiency far exceeds that of traditional mathematical programming methods. Finally, at the control level, AI can also make adaptive real-time adjustments to ensure the safe and stable operation of the system. Therefore, artificial intelligence has become an indispensable core technology for enhancing the intelligence level and overall performance of wind, solar and energy storage systems [9]. Overall, the advantage of AI lies in that, after being trained with a large number of algorithms, it can independently learn and make the best decisions in complex and ever-changing market environments and system conditions, achieving maximum profits.

4. Case Analysis and Empirical Research

4.1. Introduction to Typical Regional Wind-Solar-Storage Projects

This section takes the "Power Supply Configuration Project of Ultra-High Voltage Outbound Base in Qinghai Province and Hainan Province (Wind Energy - Solar Energy - Energy Storage Integration)" as an example for introduction. With a total installed capacity exceeding 10 gigawatts, it is one of the important green energy bases in the country's "West-to-East Power Transmission" strategy. The core challenge it addresses is the inherent intermittency and volatility of wind and solar power generation, which seriously affects the stability and power quality of the ultra-high voltage (UHV) power grid.

The project configuration includes the power generation side and the energy storage side, which are optimized through coordinated operation. In terms of power generation, it is characterized by large-scale photovoltaic power stations using bifacial modules and single-axis tracking systems to maximize efficiency, as well as large-scale onshore wind farms equipped with turbines suitable for high-altitude conditions. In terms of energy storage, this project adopts electrochemical energy storage, mainly lithium iron phosphate batteries. The configured storage capacity is generally 10% to 20% of the installed capacity of new energy, and the duration is 2 to 4 hours. For instance, a 1-gigawatt wind and solar energy project might be equipped with a storage system of 100 to 200 megawatts. These storage units are distributed in multiple photovoltaic power stations and wind farm step-up substations, but they are under centralized monitoring and dispatching.

The coordinated operation is managed by the Energy Management System (EMS), which intelligently controls the charging and discharging of the energy storage system based on grid dispatching commands and wind and solar power generation predictions. This integration has multiple key functions: filling the gap by immediately discharging or charging or absorbing excess power when the wind or solar irradiance changes suddenly, thereby smoothing power fluctuations and stabilizing the power curve fed into the grid; Peak shaving and valley filling are carried out. Excess solar energy is stored during the midday peak period and released during the evening peak demand period to enhance the value of transmitted electricity. And it provides rapid frequency regulation services to support grid stability.

This project is highly innovative and has achieved remarkable benefits. Its gigawatt-level integration of wind, solar and energy storage has set a global benchmark, and also provides a technical demonstration for large-scale energy storage applications, safety standards and operation and maintenance in high-altitude areas. The economic and social benefits are remarkable. The transmission of green electricity from Qinghai to the load centers in the central and eastern parts of China through the ultra-high voltage power grid has significantly promoted the absorption of renewable energy in the western regions, reduced the consumption of fossil fuels and carbon emissions in the receiving areas, and achieved a "win-win situation for green electricity". A detailed benefit analysis indicates that the project generates revenue from electricity sales. Although energy storage increases the initial investment, it generates additional income by reducing wind and solar power curtailment, providing auxiliary services (such as frequency regulation), and avoiding grid fines due to power fluctuations, thereby comprehensively enhancing the economic efficiency of the project. In terms of the environment, it can provide hundreds of billions of kilowatt-hours of clean electricity every year, which is equivalent to saving over 10 million tons of standard coal and reducing tens of millions of tons of carbon dioxide emissions. For the power grid, it has greatly enhanced the utilization efficiency and stability of ultra-high voltage transmission channels, proving that the combination of large-scale variable renewable energy and energy storage can become a reliable primary power source.

4.2. Operational Simulation under Different Market Mechanisms

Scenario 1: Participation only in the energy market (spot market). In this basic scenario, the system mainly adopts a "store low, discharge high" peak-valley arbitrage strategy and prioritizes the consumption of renewable energy to reduce curtailment.

Scenario 2: Energy market + Frequency Regulation Ancillary Service Market. In this scenario, while participating in the spot market, the system allocates part of its storage capacity to provide frequency regulation services (e.g., primary frequency regulation, Automatic Generation Control AGC). The model needs to balance the profit from energy arbitrage and frequency regulation services.

4.3. Economic Benefit and Stability Assessment

Economic benefits: The single energy market model (Scenario 1) can achieve basic profitability, but the project's economic benefit (IRR=5.8%) is only close to the break-even point, and its investment appeal is limited. Simultaneously participating in the frequency modulation market (Scenario 2) can significantly increase project profits, with an IRR reaching 7.5%, indicating that the diversification of market revenue channels is crucial for enhancing the economic viability of the project. The introduction of the capacity compensation mechanism (Scenario 3) further provided a stable source of income, enhanced the project's risk resistance capacity, raised the IRR to 8.3%, and significantly improved the feasibility of investment [10].

System stability: In Scenarios 2 and 3, when the energy storage system provides frequency regulation services, its charging and discharging behaviors become more frequent. However, the battery life degradation caused by this needs to be controlled within a reasonable range through optimization algorithms. Meanwhile, through intelligent dispatching, the wind and solar power curtailment rates in various scenarios have been effectively controlled at a relatively low level (<5.5%), which is significantly better than the situation without energy storage configuration (about 15%), demonstrating the crucial role of the wind-solar-energy storage system in enhancing the absorption of renewable energy. The comparison of the yields in the three scenarios is summarized in Table 2.

Table 2. The comparison of the yields in the three scenarios

Evaluation Dimension	Scenario 1 (Energy Market)	Scenario 2 (Energy + Frequency Regulation Market)	Scenario 3 (Introducing Capacity Compensation)
Economic Benefit	IRR: 5.8% (Near break-even point) Limited investment attractiveness	IRR: 7.5% - Diversified revenue channels significantly improve economics	IRR: 8.3% - Stable income source enhances risk resistance, significantly improves investment feasibility
System Stability	Curtailment Rate < 5.5% Significantly better than no storage (~15%)	More frequent charge/discharge, requires optimal algorithm to control battery degradation. Curtailment Rate < 5.5%	More frequent charge/discharge, requires optimal algorithm to control battery degradation. Curtailment Rate < 5.5%

Evaluation Dimension Scenario 1 (Energy Market) Scenario 2 (Energy + Frequency Regulation Market) Scenario 3 (Introducing Capacity Compensation).

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4.4. Policy Recommendations and Optimization Paths

Accelerate the construction of the electricity market: Speed up the coordinated construction and improvement of the spot market, ancillary service market and capacity market, clarify the identity of energy storage as an independent market entity, and provide it with diversified channels for value realization.

Design a reasonable capacity compensation mechanism: In the early stage of market construction, it is advisable to consider introducing performance-based capacity compensation or capacity electricity price mechanisms to ensure the basic returns of energy storage projects and encourage investment [11].

Encourage technological innovation and cost reduction: Support the research and development and demonstration of new technologies such as long-duration energy storage and sodium-ion batteries, and continuously reduce the cost of energy storage systems through technological progress.

Optimize operation strategies: Project investors should rely on technologies such as artificial intelligence and big data to develop more intelligent joint optimization bidding strategies, dynamically balance the energy market, ancillary service market and battery life loss, and achieve the maximization of full life cycle returns [12].

5. Conclusion

The economic benefits of wind-solar energy storage systems are highly dependent on the types of markets they can participate in. A single market is not sufficient to support its good economic performance. Diversified revenue channels - including energy, ancillary services and production capacity - are the key to the success of the project.

Adopting intelligent operation strategies such as multi-market joint bidding and optimized dispatching based on closed-loop predictive feedback can effectively increase system revenue, smooth the output of renewable energy, reduce wind curtailment rates, and enhance the stability of the power grid.

At present, the imperfect policy mechanism and technical and economic challenges remain the main obstacles to the large-scale development of such systems. Specific issues include the lack of stable capacity revenue and ancillary service pricing mechanisms, as well as the high cost of energy storage itself.

Future research should focus on the following aspects: conducting dynamic evolution simulations of market mechanisms and exploring the commercial value of energy storage under the high penetration rate of renewable energy; Research the coordinated configuration and operation of multiple types of energy storage (such as hydrogen storage, compressed air, and electrochemical energy storage); Explore innovative models of distributed wind and solar energy storage systems and participate in the market through aggregated technologies such as blockchain and cloud-edge collaboration. In terms of technological trends, it should move towards longer energy storage times (80 hours), intrinsically safe batteries, low-cost solutions (such as sodium-ion batteries), and end-to-end processes that support artificial intelligence.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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