

Article

Comparative Lifecycle Economic Assessment of Shared Energy Storage Under Multi-Service Revenue Scenarios

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Abstract

This study develops a lifecycle economic comparison framework for shared energy storage, in which multiple users share a common storage asset through capacity leasing. A multi-service revenue structure, including capacity leasing, spot-market arbitrage, auxiliary frequency regulation, peak shaving, and capacity compensation, is established for comparative evaluation. Case studies are conducted for lithium iron phosphate (LFP) and vanadium redox flow (VRF) batteries across six representative Chinese electricity markets and six standardized revenue-combination scenarios. The results show that, among the scenarios that more closely reflect current operating practices, P3 (capacity compensation + spot market + auxiliary frequency regulation) delivers the highest net present value (NPV). P6 combines all five revenue streams without explicitly modeling service-coupling dispatch constraints, and is therefore treated as a theoretical benchmark rather than an immediately deployable operating mode. Under this benchmark assumption, its calculated NPV is 21.1% and 41.7% higher than that of P3 for the two battery types, respectively. The study also shows that power-related services are more sensitive to rated power, while spot-market and peak-shaving revenues are more dependent on rated capacity.

Keywords: shared energy storage; revenue scenario; net present value

1. Introduction

Climate change has become a critical global challenge. The Intergovernmental Panel on Climate Change has emphasized the need to limit global warming to 1.5 °C to ensure sustainable development [1]. With the continuous rise in global demand for clean energy and the increasingly severe structural difficulties of the traditional energy system, the installed capacity and power supply proportion of renewable energy sources such as solar energy and wind energy in the power system are showing a rapid upward trend. Statistics show that China's installed photovoltaic capacity exceeded 890 gigawatts, marking a year-on-year increase of 45.2%, while its wind power installed capacity reached approximately 520 gigawatts, with an annual increase of 18.0% by the end of 2024. However, the high penetration of renewable energy entering the grid has caused significant uncertainty on both the generation and demand sides [2], posing a major challenge to the secure and stable operation of the grid [3,4]. In this context, energy storage, as a flexible resource with strong regulation capability, has attracted increasing attention because of its strategic role and



Academic Editor: Marco Merlo

Received: 13 March 2026

Revised: 27 April 2026

Accepted: 27 April 2026

Published: 30 April 2026

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supporting value in power systems. It enhances grid stability and the utilization rate of renewables while reducing costs and improving transaction flexibility [5–7].

Nonetheless, there are still many obstacles to the large-scale promotion of China's energy storage industry, including the lack of long-term mechanisms and considerable uncertainty in revenue streams [8]. Standalone energy storage projects often suffer from low utilization rates and limited revenue, and shared energy storage emerged as a viable solution [9]. Relying on intelligent dispatching, flexible sharing can be achieved among renewable generators, grid operators, and end users, which not only improves efficiency but also reduces costs [10]. With the help of favorable policies and a mature power market, shared energy storage obtains diversified benefits through auxiliary services, spot markets, capacity compensation and other methods [11]. Therefore, it is the key to the new power system and the development of sustainable energy [12], and at the same time, the role it plays in the process of reconstructing the global energy landscape is also becoming increasingly crucial.

Previous studies have examined shared energy storage from multiple perspectives, primarily focusing on business modes, investment strategies, and market mechanisms. Regarding business operation modes, studies [13–17] have summarized diverse pathways such as the ancillary service market mode, virtual power plant mode, and energy performance contracting mode, aiming to integrate dispersed storage resources for peak shaving and frequency regulation. These modes address the limitations of the traditional “exclusive” mode, which suffers from high initial investment and low utilization rates, by promoting resource sharing among generation, grid, and user sides. In terms of investment and economic viability, research [8,18,19] distinguishes between independent investment and joint investment modes. It is noted that while independent investment suits large enterprises with strong capital, joint investment facilitates multi-party cooperation by leveraging technical and financial advantages. However, recent analyses [20,21] highlight that the profitability of shared storage remains a challenge, often heavily reliant on capacity leasing revenue and constrained by immature market mechanisms. Furthermore, concerning market mechanisms and pricing, scholars [22] have proposed pricing strategies based on capacity, flow, and packages to optimize revenue distribution and facilitate market transactions.

However, notable limitations persist in the aforementioned research. Studies on business modes often remain conceptual, lacking a quantitative evaluation framework. Meanwhile, operational optimization research is typically confined to single or limited revenue streams, failing to systematically assess the combined impact of multi-service coupling on the lifecycle economics of projects. Furthermore, comparative studies on different storage technologies (e.g., LFP vs. VRF batteries) under identical market rules are scarce.

To address these gaps, this study establishes a unified lifecycle economic comparison framework for shared energy storage under multiple revenue combinations, including capacity leasing, spot arbitrage, capacity compensation, peak shaving, and frequency regulation ancillary services. Rather than proposing a real-time dispatch optimization strategy, this study focuses on comparative economic assessment across representative market settings and battery technologies. Specifically, this work: (1) characterizes region-specific revenue environments in six typical provincial electricity markets in China; (2) compares the lifecycle economic performance of two representative battery technologies under six standardized revenue-combination scenarios; and (3) identifies key revenue-driving parameters through sensitivity analysis. The main contribution of this paper therefore lies in offering a structured comparative framework for assessing economic potential, rather than demonstrating the operational feasibility of fully stacked multi-service dispatch.

2. Energy Storage Business Modes

To better support the economic analysis in this study, Figure 1 illustrates the relationships among the major revenue services of shared energy storage. The figure shows that some services may be combined in a relatively compatible manner, whereas others are more closely related in terms of their use of storage power, capacity, and dispatch time. Therefore, the economic performance of shared energy storage is influenced not only by the availability of multiple revenue channels but also by the relationships among different services. In the commercialization process of China's energy storage industry, differentiated business modes have emerged in diverse application scenarios [23,24]. This study applies the SWOT [25] (Strengths, Weaknesses, Opportunities, Threats) analysis method to comprehensively analyze six energy storage business operation modes, aiming to systematically sort out the core competitiveness and potential problems of each mode: the two-part tariff mode, the negotiated leasing mode, the ancillary services market mode, the energy performance contracting mode, the independent energy storage mode, and the shared energy storage mode [26], as shown in Table 1.

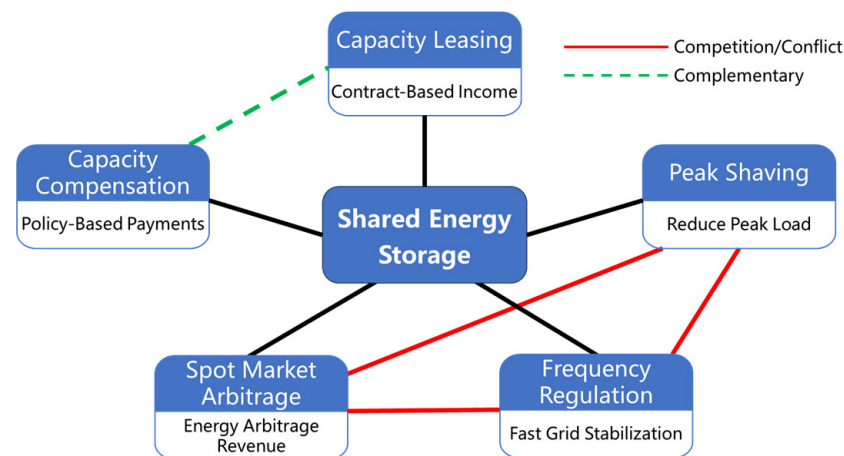


Figure 1. Relationships among major revenue services of shared energy storage.

The two-part tariff mode can accurately reflect the fixed operating costs and variable production expenditures of the power system. Setting the capacity tariff makes large industrial users bear more fixed costs and prevents residential users from being overburdened. Capacity pricing prompts users to adjust their electricity consumption, for example, transferring production to off-peak hours, reducing the peak–valley difference, and optimizing resource allocation. However, its current application scope remains limited, and the proportion of the capacity tariff in the overall electricity price is relatively low.

Under the ancillary services market model, competitive bidding and dynamic compensation incentivize resources such as energy storage to respond rapidly to grid requirements. This technical means can effectively stabilize the fluctuation range at the load end, and at the same time promote the large-scale grid connection and efficient integration of renewable energy. The current policy framework prominently places the strategic position of energy storage technology in the market development, and at the same time, also reserves policy space for energy dispatch and transaction between regions. However, competition rules and regulatory standards vary substantially across regions, and coupled with changes in policies or changes in market supply and demand, the returns will fluctuate.

The negotiated leasing model offers flexible revenue arrangements. Users can rely on lease amortization to share costs and do not need to make large upfront investments in equipment. This point is particularly crucial for small and medium-sized enterprises, and it can also inject new impetus into the vigorous development of the leasing industry.

However, with more people participating and market competition becoming intense, the profit margin may decrease.

Table 1. SWOT analysis of energy storage business modes.

Business Mode	Advantages (S)	Disadvantages (W)	Opportunities (O)	Threats (T)
Two-part Tariff Mode	Strong cost fairness; Promotes resource optimization	Limited user coverage; Low proportion of basic electricity price	Policy extended to small and medium—sized users; Driven by the demand for new energy consumption	User resistance to electricity price adjustment; Market—oriented reform impacts traditional structure
Negotiated Leasing Mode	High flexibility; Low threshold to meet the needs of small and medium—sized users	Contract risks and unregulated market restrict development	The sharing economy trend drives demand growth; Technological progress reduces leasing costs	Imperfect legal system; Intensified market competition leads to profit dilution
Ancillary Service Market Mode	Flexible market—based compensation mechanism; Policy support	Large regional differences in compensation standards; Insufficient revenue stability	New space provided by new energy consumption and thermal power transformation	Coexistence of market mechanism defects and technology substitution risks
Energy Performance Mode	Low initial investment by users; Technology—driven energy conservation	Long contract cycle; Service providers bear technology and market risks	High demand for energy efficiency management; Technological innovation expands application scenarios	Coexistence of technology attenuation and policy change risks
Independent Energy Storage Mode	Diversified revenue; Policy support	High initial investment; Imperfect spot market mechanism	Demand driven by the mandatory energy storage policy for new energy	Coexistence of policy risks, subsidy reduction, and technology substitution risks
Shared Energy Storage Mode	Diversified revenue; Low cost; Policy support	High coordination difficulty; Imperfect revenue distribution mechanism	Policy dividends and business mode innovation	Intensified market competition leads to profit dilution

In the energy performance contract, the service provider pays first, and the user pays according to usage. However, situations such as too long contract period, reduced technical performance, and changed user behavior will affect the energy-saving effect, and the service provider bears the risks of technical degradation and revenue decline.

Independent energy storage operation mode can obtain operating revenues by participating in multi-dimensional energy services and has relatively high operating autonomy. There are drawbacks, such as high initial investment costs, long payback periods, and often relying on policy subsidies in some regions. Policies that require renewable energy projects to install energy storage have created market opportunities for this mode.

Shared energy storage belongs to a collaborative mode, that is, one energy storage asset provides services for multiple interested parties. Different from traditional dedicated energy storage (one entity owns and operates it), aggregating users' capacities to achieve economies of scale can be flexibly leased and coordinated, and can also obtain benefits from

multiple markets (such as the spot market, frequency regulation market, and peak shaving market). It reduces the burden of personal investment and improves the utilization rate of assets. However, there are also difficulties, such as coordinating stakeholders' interests, meeting users' needs, resolving conflicts in profit distribution, and dealing with imperfect profit-sharing mechanisms.

The core features of shared energy storage are multi-user participation, capacity leasing, and intelligent regulation. The subsequent part will evaluate the economic benefits of the mode according to this.

3. Shared Energy Storage Benefit Evaluation Model

3.1. Energy Storage Technology Cost Model

This paper adopts the full lifecycle theory to analyze the costs of modern energy storage technologies. Over the full lifecycle of an energy storage technology, its costs cover multiple aspects, including investment, operation and maintenance, equipment replacement, and recycling. Analyzing modern energy storage technologies from a full lifecycle perspective allows the entire project cycle to be divided into three stages in chronological order: construction, operation, and decommissioning. The construction stage corresponds to the initial investment cost, primarily considering the unit capacity cost and unit power cost of the energy storage technology. The operation stage covers operation and maintenance costs, replacement costs, and charging costs. In the decommissioning or end-of-life stage, the main consideration is the residual value after deducting disposal costs once the energy storage technology has completed its service life. This residual value is typically negative.

The construction-phase cost, denoted as the initial investment cost C_{in} , is the total expenditure when building the energy storage technology, covering design, software or hardware, equipment procurement, installation engineering, and civil engineering, including coordination cost and power cost:

$$C_{in} = P_c \cdot P + E_c \cdot E, \quad (1)$$

where P_c is the power cost of the energy storage technology ($\text{CNY} \cdot \text{MW}^{-1}$), P is the power rating of the energy storage technology (MW), E_c is the capacity cost of the energy storage technology ($\text{CNY} \cdot (\text{MW} \cdot \text{h})^{-1}$); E is the capacity of the energy storage technology ($\text{MW} \cdot \text{h}$).

The Operation and Maintenance Cost (C_{om}) refers to the expenses incurred to ensure the normal operation of energy storage technology throughout its entire lifecycle. These expenses include labor costs, regular inspections, replacement of aging components, and fault repair costs, among others. It is typically calculated using an operation and maintenance cost coefficient:

$$C_{om} = \sum_{i=1 \dots N} \mu \cdot C_{in} / (1 + r)^i, \quad (2)$$

where μ is the operation and maintenance cost coefficient (%), r is the discount rate (%), taken as 5% in this study, and N is the station lifetime (years).

Replacement Cost (C_{rep}) refers to the expense incurred when components of an energy storage system, whose lifespan is significantly shorter than that of the overall storage station, need to be replaced after failure to allow the station to continue operating. For the system considered in this study, a lithium iron phosphate battery station with a design life of 25 years, one replacement is required in peak-shaving scenarios. In frequency regulation scenarios, due to the higher number of cycles and consequently shorter battery life, replacements are needed five times. The replacement cost is calculated as follows:

$$C_{rep} = C_r \cdot E \cdot (1 - \tau)^j / (1 + r)^j, \quad (3)$$

where C_r is the unit replacement cost ($\text{CNY} \cdot (\text{MW} \cdot \text{h})^{-1}$), which is $660 \text{ CNY} \cdot (\text{MW} \cdot \text{h})^{-1}$ for lithium iron phosphate batteries, τ is the cost reduction rate (%), taken as 7.78% in this study [27], j is the year in which replacement occurs.

In this study, battery aging is represented through periodic replacement rather than a year-by-year degradation trajectory. Therefore, the revenue calculation is based on a stepwise replacement assumption, under which battery performance is treated as constant between replacement events.

The cost in the decommissioning stage primarily (C_{fix}) consists of the residual value, which refers to the remaining value after deducting disposal costs from the revenue generated by recycling parts of the equipment for secondary use when the energy storage technology reaches the end of its service life. This value is typically a negative cost. The calculation formula for the decommissioning stage cost of an energy storage power station is as follows:

$$C_{fix} = \gamma \cdot C_{in} / (1 + r)^N, \quad (4)$$

where γ is the residual value (%), taken as 5% in this study.

Life Cycle Cost Calculation for Energy Storage Technologies:

$$C = C_{in} + C_{om} + C_{rep} + C_{fix}, \quad (5)$$

3.2. Shared Energy Storage Revenue Model Based on Multiple Types of Services

3.2.1. Capacity Leasing Revenue Model

The capacity leasing of shared energy storage generates income by flexibly leasing storage capacity to grid operators, industrial and commercial users, or renewable energy power plants [28,29]. The revenue from capacity leasing is influenced by the leasing price, which varies according to regional policies. Notably, the leasing ratio typically decreases by 5% every three years (or every five years in Guangdong Province). The revenue is calculated as follows:

$$R_{LEA} = \sum_{i=1 \dots N} \psi \cdot P \cdot k_{lea} / (1 + r)^i, \quad (6)$$

where ψ represents the leasing ratio (%), P denotes the power rating of energy storage technology (MW), r is the discount rate (%), and k_{lea} refers to the leasing price ($\text{CNY} \cdot (\text{kW} \cdot \text{year})^{-1}$).

3.2.2. Ancillary Services Revenue Model

Energy storage systems can provide ancillary services such as peak shaving, valley filling, and frequency regulation [30]. The main revenue mechanism for peak regulation is arbitrage based on price differences between peak and off-peak periods. The income level is also comprehensively affected by multiple factors, such as the peak-shaving subsidy standard, the energy conversion efficiency within the discharge cycle, and the frequency of participating in dispatching annually. The revenue is calculated as follows:

$$R_{PS} = \sum_{i=1 \dots N} E \cdot DOD \cdot B_{ps} \cdot n_{yr} / (1 + r)^i, \quad (7)$$

where DOD is the Depth of Discharge (%) corresponding to the energy storage method, n_{yr} is the annual number of dispatches, and E is the peak shaving compensation capacity ($\text{MW} \cdot \text{h}$).

Revenue from ancillary frequency regulation primarily stems from mileage-based subsidies. As capacity-based subsidy policies in typical cities have not yet been well-established, they are not considered in this study. The revenue from ancillary frequency regulation is calculated as follows:

$$R_M = \sum_{i=1 \dots N} n_d \cdot t_y \cdot P \cdot B_{mil} \cdot K / (1 + r)^i, \quad (8)$$

where n_d is the number of equivalent full mileage cycles per day. In this study, a 15 min dispatch period is assumed to equate to one full mileage cycle, where t_y is the number of operating days per year, B_{mil} is the mileage compensation for frequency regulation (CNY·MW⁻¹), and K is the comprehensive regulation performance metric.

3.2.3. Electricity Spot Market Revenue Model

The primary revenue source for energy storage participation in spot electricity markets is arbitrage between peak and valley prices. The cost loss incurred due to system efficiency reduction must be accounted for, along with its constraints, such as transmission and distribution tariffs and governmental funds. The income accounting process for participating in the electric power spot market is as follows [31]:

$$R_M = \sum_{i=1 \dots N} P \cdot t \cdot [k_m \cdot \eta - (1 - \eta) \cdot (k_1 + k_2)] / (1 + r)^i, \quad (9)$$

where k_m is the peak–valley price differential (CNY·(kW·h)⁻¹), η is the round-trip efficiency of the energy storage technology (%), k_1 is the transmission and distribution tariff (CNY·(kW·h)⁻¹), and k_2 represents governmental funds and surcharges (CNY·(kW·h)⁻¹).

3.2.4. Capacity Compensation Revenue Model

For the shared energy storage system, some provincial administrative regions in China (such as Shandong Province and Inner Mongolia Autonomous Region) have introduced capacity subsidy policies. The relevant revenue accounting rules are as follows:

$$R_C = \sum_{i=1 \dots N} P \cdot k_r / (1 + r)^i. \quad (10)$$

where k_r is the annual compensation rate (CNY·(kW·year)⁻¹).

3.3. Shared Energy Storage Economic Benefit Evaluation Framework

Within the framework of the shared energy storage revenue model based on multi-service participation [32], this paper systematically investigates the differences in revenue structures and policy environments among six typical electricity markets in China, which collectively cover five revenue models and the current policy environment of the country: Shandong Province, Shanxi Province, Inner Mongolia, Ningxia Province, Guangdong Province, and Henan Province. This study constructs an economic benefit evaluation framework [33], as illustrated in Figure 2. For each typical market under its respective revenue scenario, key economic indicators of the shared energy storage technology—including cost, Net Present Value (NPV), payback period, and Internal Rate of Return (IRR)—were calculated to assess its economic viability. Furthermore, a case study was conducted, in which the combined revenue potential of shared energy storage was examined under a scenario where it concurrently obtains multiple revenue streams, such as capacity leasing, capacity compensation, the spot market, and ancillary services.

It should be noted that two analytical layers are distinguished in this study. The regional analysis in Section 3.4 reflects revenue combinations that are currently permitted or commonly observed under provincial market rules, whereas the P1–P6 framework in Section 4 is a standardized comparative scenario framework under unified assumptions. Therefore, the P1–P6 scenarios should not be interpreted as province-specific real-time dispatch portfolios. In particular, P6 is used as an upper-bound benchmark under additive revenue stacking rather than as a physically and institutionally feasible operating strategy under current market conditions.

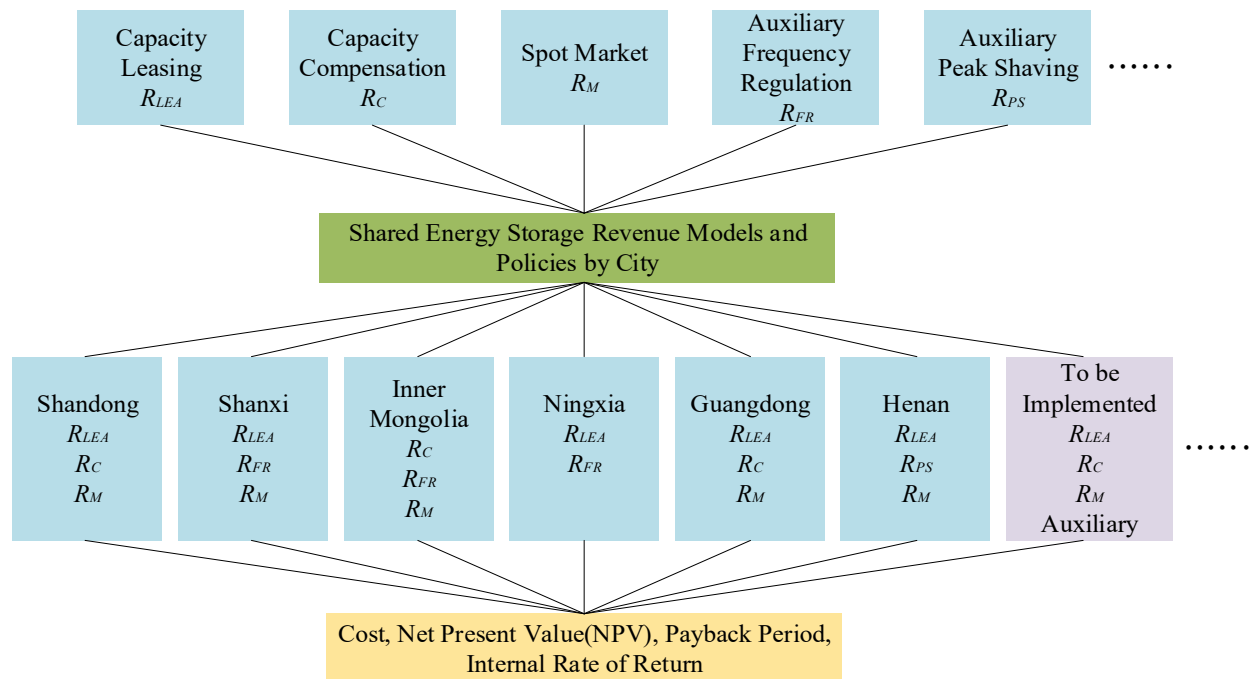


Figure 2. Shared energy storage technology and economic benefit evaluation framework.

3.4. Economic Benefit Analysis of Shared Energy Storage in Typical Regions

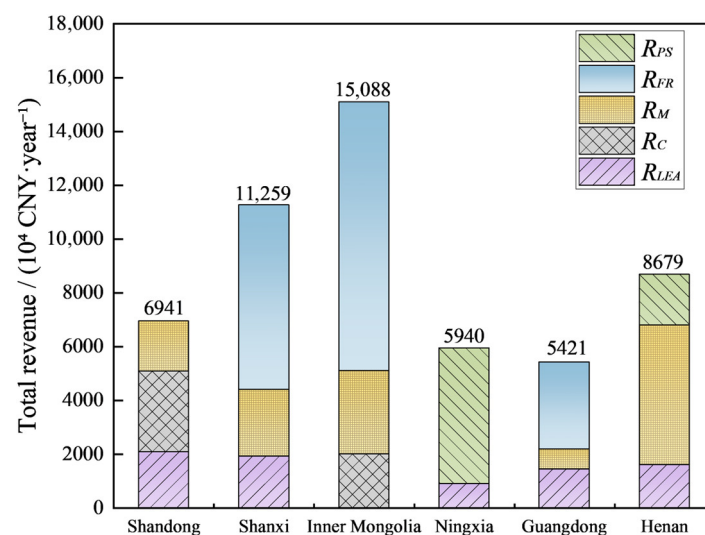
Policy designs vary substantially across regions. In Shandong Province, the revenue structure of shared energy storage is “capacity leasing + capacity compensation + spot market/ancillary services”. Energy storage technology cannot participate in the spot market and ancillary services market simultaneously; therefore, this study focuses on the case in which the energy storage system participates in the spot market. For Shanxi Province, the revenue structure of energy storage technology is “capacity leasing + spot market + frequency regulation”. The revenue structure in the Inner Mongolia electricity market is “capacity compensation + spot market + frequency regulation”. Ningxia Province has relatively fewer revenue types, primarily relying on capacity leasing and peak shaving. The revenue structure in Guangdong Province is “capacity leasing + spot market + ancillary services”. The revenue structure in Henan Province is “capacity leasing + spot market + peak shaving”. The parameter settings for the economic revenue calculation of shared energy storage technology in typical regions are shown in Table 2. All regional revenue calculations are based on lithium iron phosphate batteries.

This paper conducts an economic revenue calculation for a 100 MW/200 MW·h shared energy storage project using lithium iron phosphate batteries. The annual revenue of energy storage projects in typical regions is shown in Figure 3. Among them, Inner Mongolia ranks first with an annual revenue of 150.88 million CNY, with its core revenue derived from frequency regulation services (accounting for 66.2%). Compared with Shanxi and Guangdong, Inner Mongolia has formed a significant advantage in frequency regulation revenue by virtue of its higher comprehensive regulation performance index and frequency regulation mileage compensation standards. Shanxi ranks second, relying on frequency regulation compensation, participation in the spot market, and capacity leasing. Shandong maintains a moderate revenue level through peak shaving and other services. Ningxia and Guangdong yield relatively lower revenues due to factors such as policy compensation.

Table 2. Parameters for revenue calculation of shared energy storage technology in typical regions.

Parameter	Unit	Shandong	Shanxi	Inner Mongolia	Ningxia	Guangdong	Henan
Capacity Lease Price	yuan·(kW·year) ^{−1}	200–300	240	/	150	180	200
Rental Proportion	%	80	80	/	60	80	80
Annual Compensation Cost	yuan·kW ^{−1}	300	/	200	/	/	/
Cycling Efficiency	%	85	85	85	92	80	93
Annual Operating Days	day	300	260	260	/	260	300
Peak—Valley Electricity Price Difference	yuan·(kW·h) ^{−1}	0.4	0.56	0.75	/	0.18	0.93
Transmission and Distribution Price	yuan·(kW·h) ^{−1}	0.17	0	0.05	/	0	0
Governmental Funds and Surcharges	yuan·(kW·h) ^{−1}	0.03	0	0.22	/	0	0
Frequency Regulation Mileage Compensation	yuan·MW ^{−1}	/	5	10	/	10	/
Comprehensive Regulation Performance Index	/	/	5.5	4		1.3	/
Depth of Discharge	%	/	/	/	90	/	90
Peak Shaving Compensation	yuan·(kW·h) ^{−1}	/	/	/	0.8	/	0.3
Annual Call—on Times	time	/	/	/	350	/	350

The parameters in Table 2 are compiled from representative provincial policy documents, market rules, and public information, and are used to characterize region-specific revenue environments for comparative regional analysis.

**Figure 3.** Annual revenue of shared energy storage projects in typical regions.

The revenue structure of shared energy storage technology in typical provinces of China exhibits significant differentiation characteristics. The analysis of various revenue sources for shared energy storage technology in each region. Shandong Province, relying on the highest national capacity subsidy standard of 300 CNY/kW, has formed a dual-pillar revenue structure of “capacity compensation + capacity leasing,” with capacity compensation accounting for 43.2% and capacity leasing accounting for 30%, reflecting revenue stability driven by policy. In contrast, Shanxi, Inner Mongolia, and Guangdong provinces

see their frequency regulation revenue reach 61%, 66.2%, and 59.9%, respectively, which primarily stems from the high demand for frequency regulation services in the electricity markets of these three provinces. As a major thermal power province, Shanxi requires frequent output adjustments when thermal power units operate in deep peak shaving (especially during valley load periods), necessitating reliance on frequency regulation ancillary services to maintain frequency stability. As the largest new energy base in China, Inner Mongolia has seen the installed capacity of wind and photovoltaic power exceed 40%; the randomness of new energy output intensifies grid frequency fluctuations, requiring reliance on frequency regulation services to maintain grid frequency stability. Guangdong Province, as a major economic province, has a peak–valley load difference exceeding 30 million kilowatts, urgently requiring fast-responding resources. The Ningxia Hui Autonomous Region, due to prominent demand for thermal power flexibility retrofitting, sees its peak shaving revenue account for as high as 84.8%, highlighting the value of peak shaving in Ningxia’s role as a hub for West-to-East Power Transmission.” Henan Province represents a special case with spot market revenue accounting for 59.8%, which is closely related to the high volatility characteristics during the trial operation phase of its electricity spot market, enabling energy storage technology to maximize revenue through intraday price arbitrage. In summary, the revenue structure of each province exhibits a strong correlation with the local power generation structure, grid characteristics, and policy orientation, highlighting the regional adaptability characteristics of the shared energy storage business mode.

A full life cycle economic benefit analysis is conducted for a 100 MW/200 MW·h lithium iron phosphate battery shared energy storage project with a project cycle of 15 years. The full life cycle cost of the lithium iron phosphate battery is 339 million CNY, and the calculation results of the life-cycle net present value (NPV) for energy storage projects in typical regions are shown in Figure 4. The full life cycle NPV of the shared energy storage project in Inner Mongolia ranks first, primarily supported by the high revenue from the frequency regulation market. Relying on outstanding comprehensive regulation performance indices and combined with local high-frequency regulation mileage compensation standards, its shared energy storage obtains considerable revenue from frequency regulation, with an NPV reaching nearly 6 times that of Guangdong Province. Shanxi Province ranks second with 808 million CNY through the combination of frequency regulation, capacity leasing, and the spot market, with an NPV approximately 4 times that of Guangdong Province. Henan Province achieves an NPV of 545 million CNY relying on the synergistic participation in the spot market and the ancillary services market. Shandong Province obtains higher capacity revenue due to the capacity subsidy of 300 CNY/kW, accounting for 43.2%. In contrast, Guangdong Province, constrained by factors such as market mechanisms and revenue structure, has one of the lowest NPVs among the typical regions, fully reflecting the profound impact of different regional market environments and revenue source differences on the full life cycle economic benefits of shared energy storage projects.

Furthermore, the dynamic payback period and internal rate of return of the shared energy storage projects were analyzed, as shown in Figure 5. Relying on the efficient revenue mechanism of the frequency regulation market, Inner Mongolia has a dynamic payback period of only 2.22 years and an internal rate of return of 48.65%; the higher comprehensive regulation performance index and high compensation standards promote rapid cost recovery, leading to the revenue level. Shanxi Province has a dynamic payback period of 3.06 years and an internal rate of return of 35.42%, where the synergistic effect of the diversified revenue structure accelerates the return on investment. Henan Province achieves a dynamic payback period of 4.14 years and an internal rate of return of 26.35% through two-way participation in the spot market and ancillary services, realizing the

optimal balance between revenue and cost with flexible market strategies. Shandong Province has a dynamic payback period of 5.44 years and an internal rate of return of 19.85%, with balanced revenue from various sources. Ningxia has a dynamic payback period of 6.61 years and an internal rate of return of 16.20%, where the maturity of the peak shaving market and the scale of revenue constrain its return on investment cycle. Guangdong Province has the longest dynamic payback period of 7.49 years and an internal rate of return of 14.05%, where intensified market competition compresses revenue space, directly affecting the efficiency of return on investment.

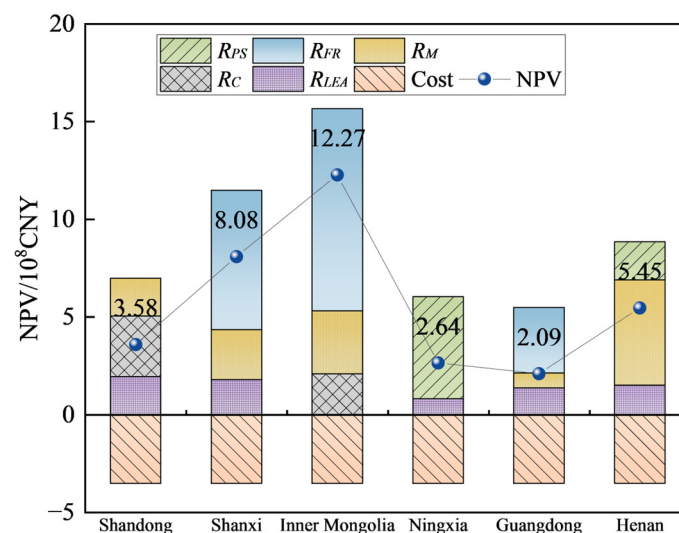


Figure 4. NPV of shared energy storage projects in typical regions.

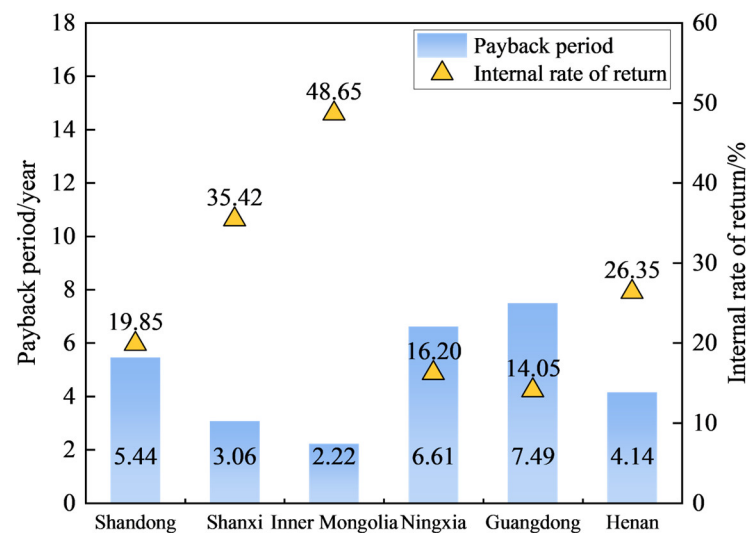


Figure 5. Rate of return and payback period of shared energy storage projects in typical regions.

The economic viability of shared energy storage projects is significantly influenced by regional market mechanisms and differences in revenue structure. High compensation in the frequency regulation market, the synergy of diversified revenues, and flexible market strategies can substantially shorten the dynamic payback period and enhance the internal rate of return, whereas low maturity of the peak shaving market or intensified competition constrains return efficiency. The revenue level of projects is positively correlated with regional policy support, market openness, and business mode innovation; therefore, perfecting market mechanism design is a critical pathway for optimizing return on investment.

Accordingly, the regional results in Section 3.4 are intended to reflect region-specific feasible policy environments, while the scenario analysis in Section 4 serves a different purpose, namely standardized cross-scenario comparison under a common parameter set. The two parts are therefore complementary rather than numerically identical.

4. Results and Discussion

4.1. Parameter Specification and Baseline Values

In the current practical implementation of shared energy storage projects in China, lithium iron phosphate (LFP) batteries dominate the market, whereas vanadium redox flow batteries have been deployed in only a limited number of projects [34]. To reflect this reality, case analyses were conducted based on two representative battery technologies: lithium iron phosphate batteries and vanadium redox flow batteries, as detailed in Table 3 [35]. In the LFP battery case study, the system was configured with a capacity of 100 MW/200 MWh. In the case study of the vanadium flow battery, a configuration of 100 MW/400 MWh was adopted, and the residual recovery value was incorporated into the cost assessment framework. For clarity, the replacement assumption used in the lifecycle cost calculation is restated here: for LFP batteries, one replacement is assumed for peak-shaving-dominated operation, whereas five replacements are assumed for frequency-regulation-dominated operation because of the higher cycling intensity. In scenarios involving frequency regulation, the higher-cycle replacement assumption is adopted in the cost calculation.

Table 3. Shared energy storage technical and economic parameters.

Parameter	Unit	Lithium Iron Phosphate Battery	Vanadium Redox Flow Battery
Cycle Efficiency	%	90	80
Power Cost	CNY·kW ^{−1}	400	223
Capacity Cost	CNY·(kW·h) ^{−1}	1300	1875
Station Lifetime	year		15
O&M Cost Coefficient	%		1.5
Residual Value	%	5	0
Capacity Leasing Price	CNY·(kW·year) ^{−1}		225
Leasing Ratio	%	80 (decrease by 5% every 3 years)	
Annual Compensation Fee	CNY·kW ^{−1}		250
Annual Operating Days	day		280
Peak–Valley Electricity Price Difference	CNY·(kW·h) ^{−1}		0.555
Transmission and Distribution Price	CNY·(kW·h) ^{−1}		0.11
Government Fund and Surcharge	CNY·(kW·h) ^{−1}		0.125
Frequency Regulation Mileage Compensation	CNY·MW ^{−1}		7
Comprehensive Regulation Performance Index	/		4.5
Depth of Discharge	%		90
Peak Shaving Compensation	CNY·(kW·h) ^{−1}		0.55

The baseline parameters in Table 3 were used for standardized comparison. The lifecycle cost treatment of LFP batteries was referenced to Hemmati et al. [36], the comparison of vanadium redox flow batteries was informed by da Silva Lima et al. [37], and the overall parameter setting was further supported by prior lifecycle studies, especially Li et al. [35]. The LFP capacity cost of 1300 CNY·(kWh)^{−1} is used as a conservative baseline for standardized lifecycle comparison. Although recent market prices of LFP batteries have declined in recent years, this conservative assumption avoids overstating the economic performance of shared energy storage projects.

Based on representative revenue structures observed in current shared energy storage practice [38], this study defines six standardized revenue-combination scenarios (P1–P6) for comparative economic evaluation, as summarized in Table 4. These scenarios are designed to support structured comparison under unified assumptions rather than to represent dispatch-feasible operating portfolios in a specific province.

Table 4. Standardized revenue-combination scenarios for comparative evaluation.

Scenario	Revenue Combination
P1	Capacity Leasing (R_{LEA}) + Spot Market (R_M) + Capacity Subsidy (R_C)
P2	Capacity Leasing (R_{LEA}) + Spot Market (R_M) + Auxiliary Frequency Regulation (R_{FR})
P3	Capacity Subsidy (R_C) + Spot Market (R_M) + Auxiliary Frequency Regulation (R_{FR})
P4	Capacity Leasing (R_{LEA}) + Auxiliary Peak Shaving (R_{PS})
P5	Capacity Leasing (R_{LEA}) + Spot Market (R_M) + Auxiliary Peak Shaving (R_{PS})
P6	Capacity Leasing (R_{LEA}) + Spot Market (R_M) + Capacity Subsidy (R_C) + Auxiliary Peak Shaving (R_{PS}) + Auxiliary Frequency Regulation (R_{FR})

P1–P6 are comparative scenarios defined under a unified parameter set. Among them, P6 represents an additive-revenue benchmark scenario and does not imply the current operational feasibility of simultaneous multi-service dispatch.

4.2. Economic Analysis of Shared Energy Storage Technology

First, the life-cycle costs, revenues, and NPVs of shared energy storage under the six standardized revenue-combination scenarios were calculated and compared [39], as shown in Figure 6. Among the scenarios more consistent with currently observed operational frameworks (P1–P5), P3 yielded the highest NPV, reaching CNY 2.738 billion for LFP batteries and CNY 2.242 billion for vanadium redox flow (VRF) batteries. By contrast, P6 is treated in this study as a benchmark scenario that aggregates all five revenue streams without explicitly modeling service-coupling dispatch constraints. In practical operation, the attainable revenue of P6 would likely be lower than this benchmark value because different services compete for the same storage power, energy capacity, and dispatch time. For example, frequency regulation usually requires reserved fast-response power and state-of-charge headroom, whereas spot-market arbitrage and peak shaving consume storage capacity during specific time periods. Therefore, mutual exclusivity between frequency regulation and spot-market arbitrage may reduce the actual P6 revenue, and the magnitude of this reduction depends on how storage resources are allocated among services over time. Under this additive-revenue assumption, the calculated NPV of P6 is 21.1% and 41.7% higher than that of P3 for LFP and VRF batteries, respectively. The full-lifecycle cost of the LFP battery system was CNY 339 million, while that of the VRF battery system was CNY 893 million. Due to its higher cost, the NPV of the VRF battery remained lower than that of the LFP battery across all scenarios.

Taking LFP batteries as an example, the proportion of revenue from various sources under the six revenue scenarios was analyzed, as shown in Figure 7a. In P1, capacity subsidies accounted for 50.4% of the shared energy storage project's revenue, representing a significant subsidy contribution. In P2, P3, and P6, revenue from ancillary frequency regulation constituted 89.9%, 87.3%, and 73.6% of total revenue, respectively. In P4 and P5, revenue from providing ancillary peak-shaving services accounted for 62.4% and 54.4%, respectively. The data shows that the auxiliary service revenue of shared energy storage is much higher than that of other service types.

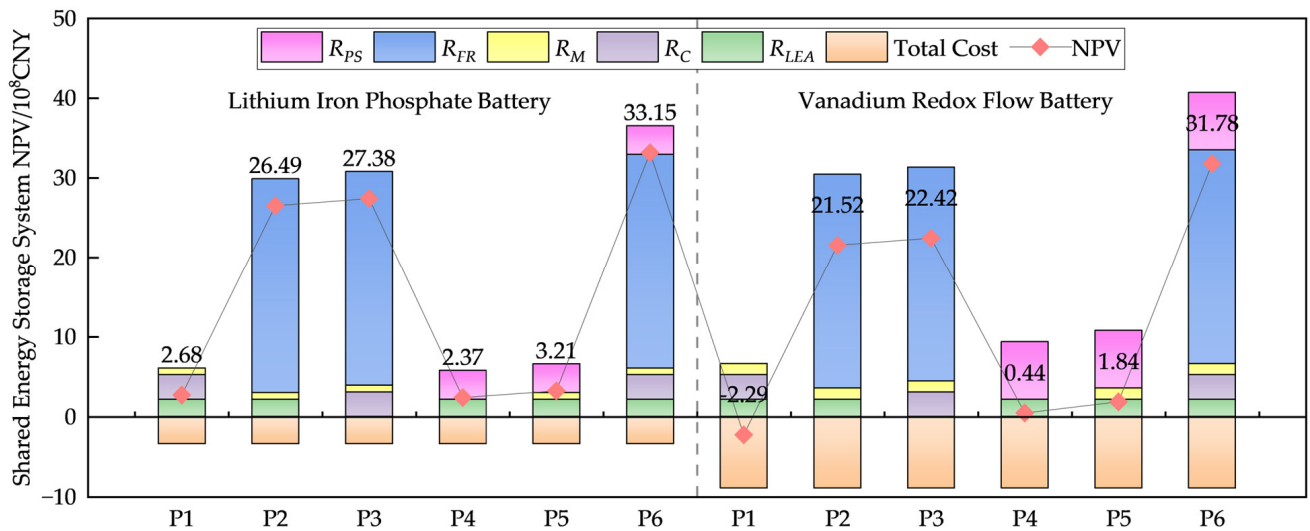


Figure 6. Shared energy storage project net present value.

For completeness, the revenue-share distributions of VRF batteries under P1–P6 are additionally provided in Figure 7b. Compared with LFP batteries, VRF batteries show a relatively larger contribution from peak-shaving revenue in scenarios involving longer discharge duration, although their overall NPV remains constrained by higher lifecycle cost.

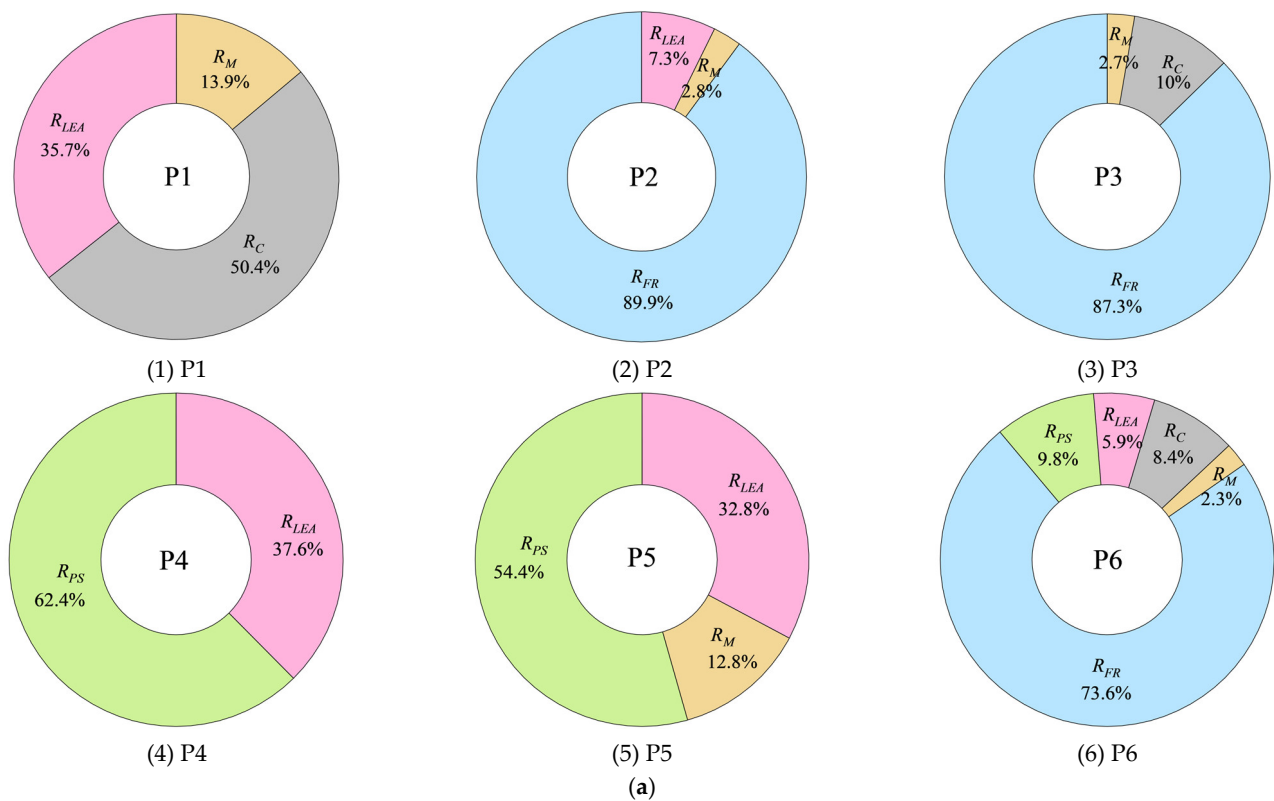


Figure 7. Cont.

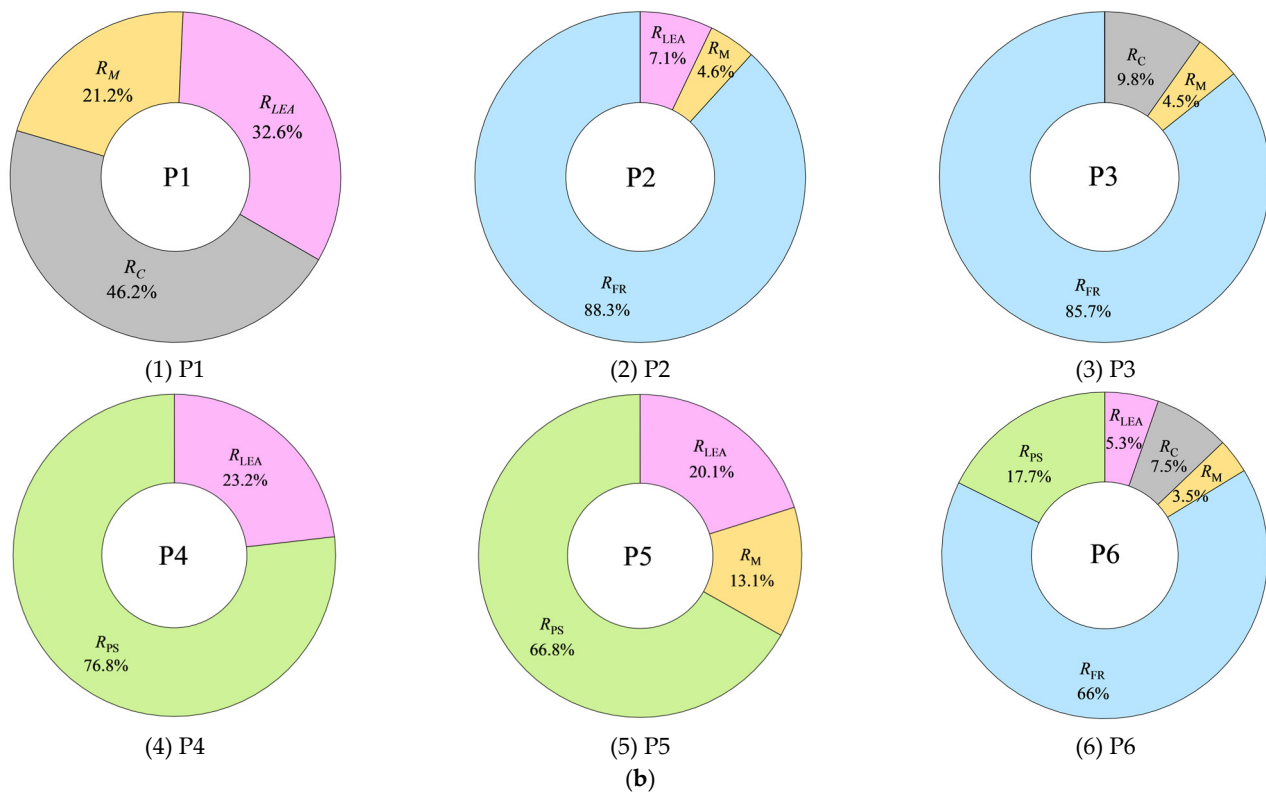


Figure 7. Proportion of revenue in P1-P6 scenarios. (a) LFP (b) VRF.

To further interpret the role of the 4 h VRF configuration across different revenue-combination scenarios, it should be noted that its longer discharge duration provides only limited benefit in P2 and P3, where the dominant revenue is ancillary frequency regulation and is more closely related to rated power than to storage duration. By contrast, the longer duration of VRF is more relevant in P4 and P5, because these scenarios include peak-shaving revenue, which is more energy-oriented. In P1, the longer duration can moderately improve spot-market arbitrage potential, but the gain remains insufficient to offset the much higher lifecycle cost. In P6, although the longer duration contributes to peak-shaving-related revenue, the overall economic result is still constrained by the cost premium of VRF and by the fact that the largest revenue share is not exclusively determined by storage duration.

In summary, cost remains a key constraint on the NPV of VRF batteries. Although some revenue streams are more favorable to long-duration storage, higher lifecycle cost still weakens overall economic competitiveness. The higher NPV obtained in P6 should be understood as the theoretical value space associated with broader multi-service participation under additive revenue stacking, rather than as evidence of a currently achievable operating improvement.

4.3. Comparative Analysis of Net Present Value Under Different Energy Storage Capacities

Using the LFP battery as an example and holding the technical parameters constant, the rated energy storage capacity is, respectively, set to 100 to 400 MWh, and the rated power is adjusted to 50 to 150 MW. Then, a comparative study on the system performance under different combinations of capacity and power is carried out. Using the economic value evaluation framework of collaborative energy storage, the NPV of collaborative energy storage projects under six revenue-combination scenarios is calculated. This research process needs to explore the mechanism by which the configuration selection of capacity and power parameters affects the NPV of the project.

Figure 8 presents the effect of different energy storage capacity and power parameters on the NPV of energy storage projects under scenarios P1–P6. In P1, when the installed capacity was constant, each 25 MW increase in rated power resulted in an NPV increase of CNY 120 million. Conversely, with rated power held constant, each 50 MWh increase in rated capacity led to an NPV decrease of CNY 52 million. Since the main sources of income for P1, namely capacity subsidies and leasing, are positively correlated with power, increasing the capacity has a relatively limited improvement in the spot market income and also incurs higher costs.

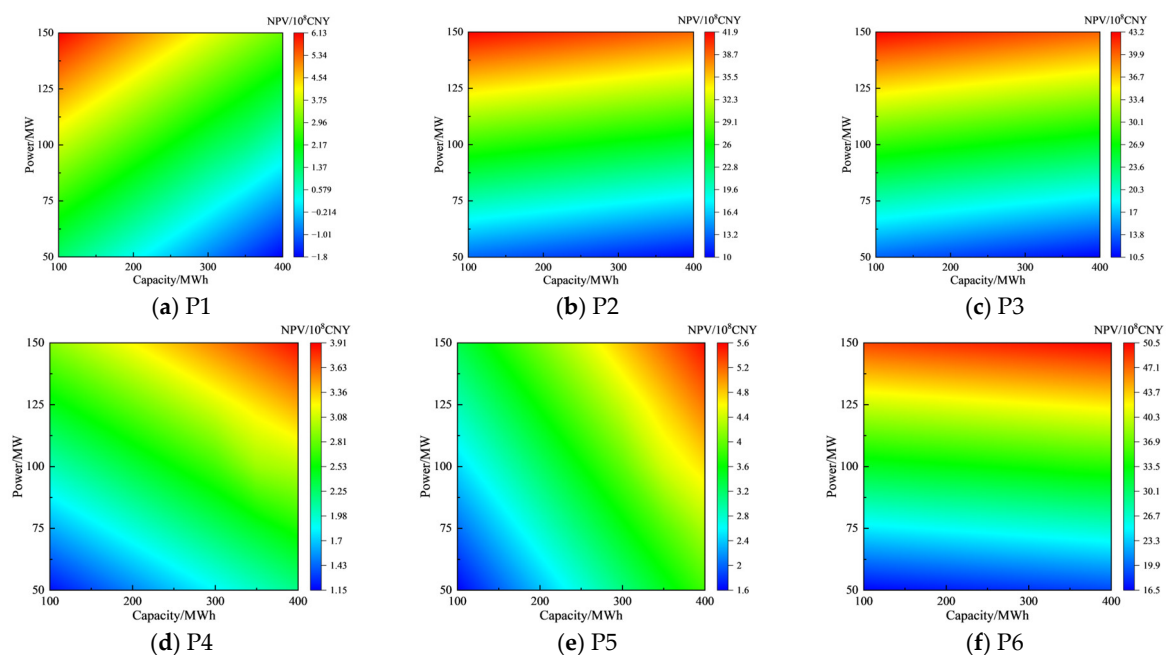


Figure 8. The influence of different energy storage capacities on the net present value.

In P2, with the installed capacity being constant, each 25 MW increase in rated power resulted in a linear NPV increase of CNY 715 million. Conversely, when the rated power was constant, each 50 MWh increase in rated capacity led to a linear NPV decrease of CNY 52 million. This is because revenue in P2 primarily came from ancillary frequency regulation, which was positively correlated with power, while increased capacity only marginally improved spot market revenue at a disproportionately higher cost.

In P3, with the constant installed capacity, increasing the rated power from 50 MW to 150 MW yielded a linear NPV growth of CNY 2.948 billion. With the rated power being constant, increasing the storage capacity from 100 MWh to 400 MWh resulted in a linear NPV decrease of CNY 315 million. This pattern is similar to that observed in P2 and P3, because ancillary frequency regulation accounts for up to 87.3% of total revenue. Therefore, the influence of capacity configuration on project NPV in P3 and P2 followed the same pattern.

In P4, when the installed capacity was constant, each 25 MW increase in rated power led to an NPV increase of CNY 43 million. With rated power held constant, each 50 MWh increase in rated capacity resulted in an NPV increase of CNY 16 million. The main revenue sources in P4, namely auxiliary peak regulation (positively correlated with capacity) and capacity leasing, both contribute significantly to the increase in returns.

In P5, with the installed capacity being constant, each 25 MW increase in rated power yielded a linear NPV growth of CNY 42 million. When the rated power was constant, each 50 MWh increase in rated capacity produced a linear NPV increase of CNY 37 million. P5 was built on the basis of P4 by incorporating additional revenue from the spot market.

However, ancillary peak shaving was the dominant revenue component (constituting 54.4% of the total) and positively correlated with capacity.

In P6, with the constant installed capacity, increasing the rated power from 50 MW to 150 MW resulted in a linear NPV increase of CNY 3.165 billion. With the rated power being constant, increasing the storage capacity from 100 MWh to 400 MWh led to a linear NPV growth of CNY 354 million. This is because the revenue in P6 was primarily derived from ancillary frequency regulation (accounting for 73.6% of the total), while the diversified revenue streams consisted of the enhanced ancillary peak shaving and spot market earnings that were obtained through increasing capacity.

For Figures 8–12, the three-dimensional bar charts are retained to provide an intuitive comparison of the overall trends under different parameter combinations. The exact numerical values corresponding to these figures are provided in the Supplementary Materials to facilitate quantitative comparison and reproduction.

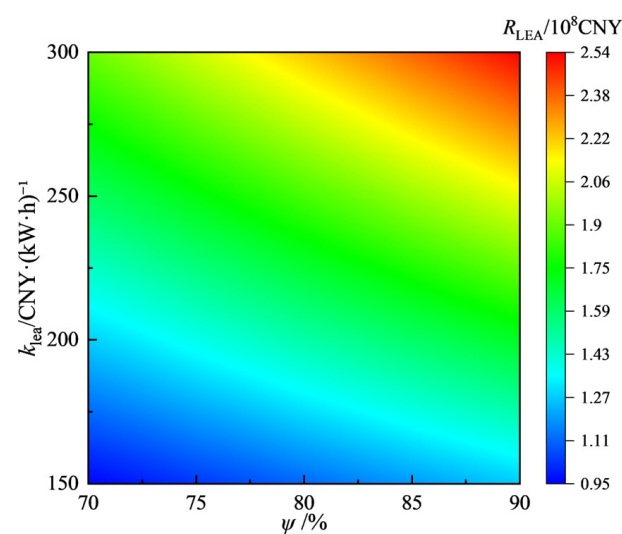


Figure 9. The impact of rental ratio and rental price on rental income.

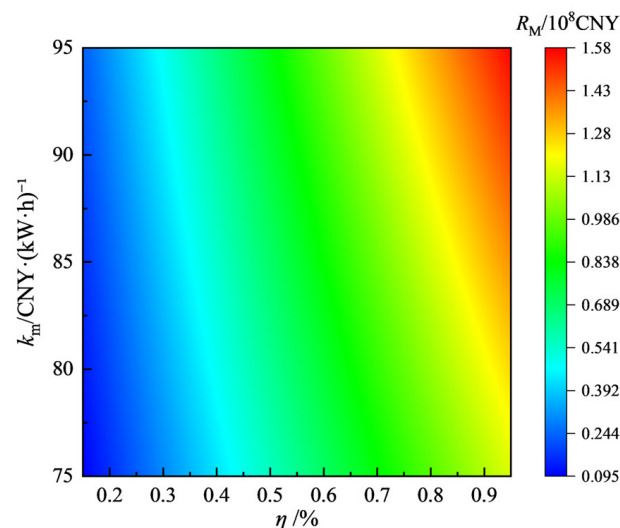


Figure 10. The impact of peak–valley price differential and energy storage efficiency on spot market revenue.

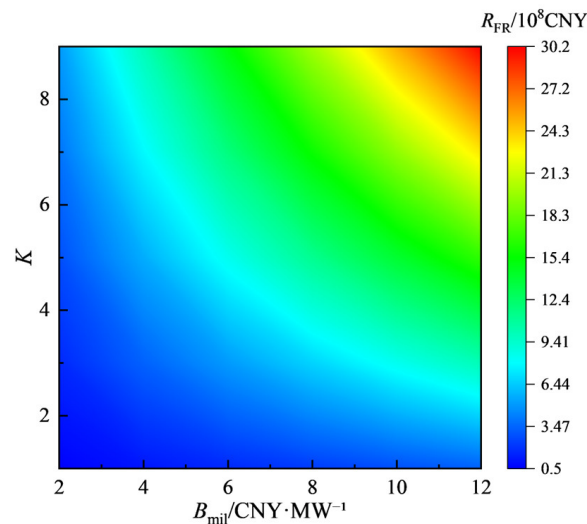


Figure 11. The impact of mileage compensation and comprehensive adjustment performance indicators on auxiliary frequency modulation revenue.

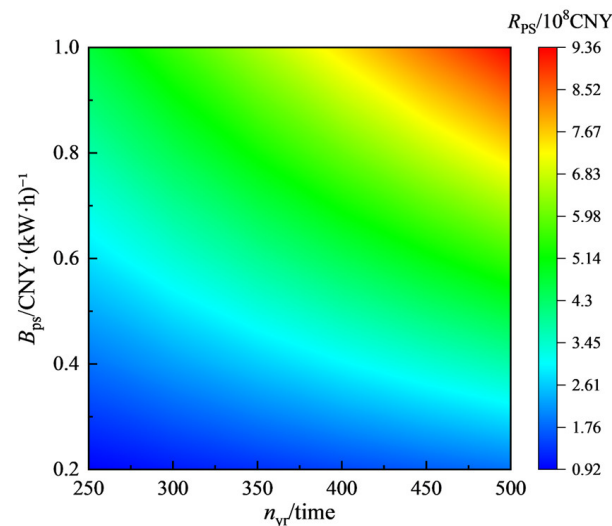


Figure 12. The impact of annual dispatch count and peak shaving compensation on auxiliary peak shaving revenue.

This also helps explain the comparative performance of the 4 h VRF configuration: longer-duration storage is more advantageous in energy-oriented services, whereas several of the more profitable scenarios in this study are dominated by power-oriented revenues. Therefore, extending storage duration alone does not necessarily improve overall lifecycle economic performance.

In conclusion, there is a significant correlation between the NPV level of the shared energy storage project and its installed capacity configuration. Revenue from ancillary frequency regulation, capacity subsidies, and capacity leasing increases with higher rated power, whereas earnings from participation in the electricity spot market and ancillary peak shaving rise with increased rated capacity. Although revenue is important, cost impacts must also be considered. Maximizing economic benefits requires balancing capacity configuration optimization and effective cost control.

4.4. Analysis of Parameters Affecting Shared Energy Storage Revenue

To examine the sensitivity of different revenue components to key market and operational variables, this study uses the P6 benchmark scenario as the basis for sensitivity

analysis. This choice is made because P6 contains all five revenue components within one unified scenario, which facilitates parameter-wise sensitivity analysis. It does not imply that the full combination is currently dispatch-feasible under existing market constraints.

4.4.1. Impact of Leasing Ratio and Leasing Price on Leasing Revenue

The impact of the leasing ratio and leasing price on leasing revenue is shown in Figure 9. Leasing revenue increased significantly with a higher leasing ratio and leasing price. Analysis reveals that within the range of the 70–90% leasing ratio and the price of 150–300 CNY·(kW·year)^{−1}, when the price was fixed, each 5% increase in the ratio raised revenue from CNY 80 to 160 million. When the ratio was fixed, each increase in price of 30 CNY·(kW·year)^{−1} could lead to revenue increment between CNY 190 and 250 million. Therefore, reasonably increasing the leasing ratio and optimizing the leasing price are key strategies for enhancing project leasing income, which could provide important strategic guidance for practical project operation.

4.4.2. Impact of Peak–Valley Price Differential and Energy Storage Efficiency on Spot Market Revenue

Figure 10 illustrates the impacts of the peak–valley electricity price difference and the conversion efficiency of energy storage systems on the profits in the spot market. The analysis indicates that spot market revenue was positively correlated with both of them. Within the examined ranges of the 0.15–0.95 CNY·(kW·h)^{−1} price differential and 75–95% efficiency, when the price differential was fixed, each 5% increase in efficiency yielded a revenue increment from CNY 27 to 34 million. When efficiency was fixed, as the price differential increased from 0.15 to 0.95 CNY·(kW·h)^{−1}, the revenue increment varied from CNY 3 to 10 million with each increase in efficiency of 5%. In project operation, leveraging policy advantages related to the peak–valley price differential and improving storage efficiency are the key pathways for enhancing spot market revenue.

4.4.3. Impact of Mileage Compensation and Comprehensive Regulation Performance Metric on Ancillary Frequency Regulation Revenue

The impact of mileage compensation and the comprehensive regulation performance metric on ancillary frequency regulation revenue is shown in Figure 11. The revenue was positively correlated with both the mileage compensation price (ranging from 2 to 12 CNY·MW^{−1}) and the comprehensive regulation performance metric (ranging from 1 to 9). Analysis shows that when the metric increased from 1 to 9, the revenue increment ranging from CNY 56 to 502 million was achieved with each 2 CNY·MW^{−1} increase in mileage compensation. As mileage compensation increased from 2 to 12 CNY·MW^{−1}, each 2-unit increase in the performance metric contributed to a revenue increment between CNY 112 and 670 million. In the daily operation process of shared energy storage projects, it is essential to closely monitor policy developments to optimize mileage compensation strategies on the one hand, and improve the comprehensive regulation performance metric on the other hand. Maximizing ancillary frequency regulation revenue requires the coordinated optimization of these two variables.

4.4.4. Impact of Annual Dispatch Count and Peak-Shaving Compensation on Ancillary Peak-Shaving Revenue

The impact of the annual dispatch count and peak-shaving compensation on ancillary peak-shaving revenue is shown in Figure 12. The revenue was positively correlated with both the annual dispatch count (ranging from 250 to 500 times) and the peak-shaving compensation (ranging from 0.2 to 1.0 CNY·(kW·h)^{−1}). Analysis indicates that as the compensation increased from 0.2 to 1.0 CNY·(kW·h)^{−1}, each increase in the annual dispatch

count of 50 times led to a revenue increment from CNY 18 to 93 million. When the annual dispatch count rose from 250 to 500, a revenue increment ranging from CNY 93 million to CNY 187 million was obtained for each increase of $0.2 \text{ CNY} \cdot (\text{kW} \cdot \text{h})^{-1}$ in compensation. In summary, in the operation of shared energy storage projects, maximizing ancillary peak-shaving revenue requires simultaneous policy alignment and operational optimization. On the one hand, it is necessary to closely monitor policy developments to obtain higher compensation standards. On the other hand, strengthening equipment operation and maintenance management is crucial for increasing the annual dispatch count.

4.5. Limitations

This study has several limitations. First, the P1–P6 comparison is not a time-series dispatch optimization model; rather, it provides standardized revenue-combination scenarios for comparative lifecycle economic evaluation. In particular, P6 is an upper-bound benchmark based on additive revenue stacking and does not explicitly enforce service exclusivity, time-coupled dispatch, or shared-capacity allocation constraints across markets. Second, battery aging is represented through replacement-cost treatment rather than a year-by-year performance degradation trajectory, and revenues are therefore evaluated under a stepwise replacement assumption. Third, the unified parameter set used in Section 4 is intended for cross-scenario comparison and does not reproduce the full heterogeneity of provincial market rules discussed in Section 3.4. These limitations do not affect the comparative purpose of the present study, but they should be considered when interpreting P6 as a theoretical benchmark rather than a directly deployable operating mode.

Although this study establishes a lifecycle revenue assessment framework for shared energy storage, it still simplifies the allocation logic of storage power and energy and does not include a discrete time-step dispatch model. Future work will focus on developing a dispatch framework that can explicitly represent SOC evolution, energy balance, and service interaction during multi-service operation, thereby improving the engineering applicability of the analysis.

5. Conclusions

This study establishes a comparative lifecycle economic framework for evaluating shared energy storage under multiple revenue combinations. Based on regional case analysis, technology comparison, and parameter sensitivity analysis, the main findings can be summarized as follows:

1. Among the revenue-combination scenarios that are more consistent with currently observed operational frameworks, P3 yields the highest NPV for both LFP and VRF batteries. By contrast, P6 should be interpreted as a theoretical upper-bound benchmark under additive revenue stacking rather than as an immediately realizable operating strategy. Therefore, the role of P6 in this study is to reveal the potential economic headroom associated with broader multi-service participation, not to demonstrate a currently achievable enhancement pathway. Realizing such value in practice would require future dispatch optimization models that explicitly incorporate service exclusivity, temporal coupling, and capacity-sharing constraints.
2. Auxiliary frequency regulation, capacity reserve and rent will increase with higher rated power. Spot-market and ancillary peak-shaving revenues increase with higher rated energy capacity. When evaluating energy storage projects, revenue should exceed relevant costs. Therefore, to achieve the maximum economic benefit of the project, a balance needs to be sought between optimizing capacity configuration and cost control.

3. The parameter analysis indicates that revenue streams are highly sensitive to market and policy variables, such as peak–valley price differences for spot trading and mileage compensation for frequency regulation. Consequently, adopting a collaborative strategy that combines policy adaptation with operational optimization is crucial. This approach systematically improves economic feasibility by leveraging multi-resource synergy and diversified service participation, providing a viable path for maximizing life-cycle returns.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en19092177/s1>.

Author Contributions: Conceptualization, Y.L.; Investigation, W.T.; Methodology, Q.X.; Validation, F.Z.; Writing—original draft, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Science and Technology Project of State Grid Henan Electric Power Company, “Research on Grid-Connection Characteristics Analysis and Cooperative Regulation Technology for 100MW-Class Compressed Air Energy Storage Power Station” (Project No. 521770250002, Contract No. SGHAXY00XTJS2500487).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Authors Yang Liu and Weijun Teng were employed by the company, State Grid Henan Electric Power Research Institute. Qishan Xu and Feng Zhang were employed by State Grid Henan Xinyang Power Supply Company. Jinggang Wang was employed by the company, State Grid Henan Electric Power Company. The authors declare that this study received funding from State Grid Henan Electric Power Company. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

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