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Research on Optimal Scheduling Strategies of Energy Storage Systems for Peak Shaving in Power Systems with High Renewable Energy Penetration

Changqing Li

Qingdao University of Science and Technology, Qingdao, China
Email: 15762513329@163.com
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***Abstract*—With the rapid growth of wind and solar, modern power systems face widening peak–valley gaps and variability that traditional dispatch cannot absorb. This paper presents a comprehensive review of energy storage for peak shaving under high renewable penetration. We synthesize modeling paradigms, including deterministic, stochastic, robust, and model predictive control, combined with degradation-aware, network-constrained, and carbon-cost formulations. This paper examines scheduling across multiple horizons: real time, intraday, day ahead, and seasonal; and across architectures such as utility-scale batteries, behind-the-meter fleets, and hybrid storage. The review catalogs evaluation metrics such as peak reduction, curtailment, reliability, cost, and emissions, and compares representative case studies. We assess implementation challenges, including forecast uncertainty, battery aging, coordination of heterogeneous assets, market rules, and cyber-physical limits at the distribution level. We identify research gaps in uncertainty-aware data-driven dispatch, valuation of stacked services, and scalable coordination of distributed storage. The contribution is a structured synthesis and a research agenda to guide more flexible, economical, and low-carbon grid operation, informing planners and regulators where storage delivers the highest marginal system value.**

***Keywords*—Energy Storage System (ESS), peak shaving and valley filling, renewable energy integration, power system flexibility**

I. Introduction

With the announcement of China's ambitious "carbon peak and carbon neutrality" targets, building a new type of power system dominated by renewable energy has become strategically essential. The large-scale integration of renewable energy sources, such as wind and solar, significantly impacts the stability, flexibility, and economic operation of traditional power systems. This transformation introduces new operational challenges, primarily due to the inherent intermittency and uncertainty associated with renewable energy generation, which traditional power grid management and dispatch methods struggle to effectively address.

Under these circumstances, energy storage systems (ESS) have emerged as a critical enabling technology to facilitate renewable energy integration. Due to their capability for temporal and spatial energy shifting, ESS can effectively mitigate renewable energy intermittency, smooth out power load fluctuations, and significantly reduce peak-valley differences, thereby enhancing grid stability and reliability. However, despite these advantages, ESS technologies continue to face challenges related to cost-effectiveness, safety, and scalability, requiring further research and development to fully realize their potential.

Recent studies have extensively explored the development of new-type power systems driven by China's dual-carbon goals. With high penetration of renewable energy sources, power systems face significant challenges in modeling, operation, and planning, including increased fluctuations from renewable energy and reduced system inertia due to extensive integration of power electronic devices [1]. To address these challenges, developing a renewable energy-based power system is essential, emphasizing coordinated dispatch among sources, grids, loads, and storage, and focusing on key technologies such as secure operation, reliable power supply, economic efficiency, and digital-intelligent transformation [2]. Energy storage systems (ESS), recognized for their effectiveness in mitigating renewable energy intermittency and enhancing grid flexibility and stability, have become a critical component. However, ESS technologies still face barriers related to costs, techno-economic viability, and scalability in practical applications [3].

This paper employs a literature review method to systematically summarize and analyze the optimal scheduling strategies of energy storage systems for peak shaving under high renewable energy penetration. This paper provides valuable insights and practical references for the development of optimal energy storage scheduling strategies, contributing to the broader efforts of enhancing grid stability, facilitating renewable energy integration, and promoting the construction of low-carbon and sustainable power systems.

II. Literature Review

A. Background and Challenges of High Renewable Penetration

The rapid expansion of renewable energy sources such as wind and solar photovoltaics (PV), driven by China's ambitious dual-carbon goals of achieving carbon peak and neutrality, has transformed the landscape of modern power systems significantly. Although renewable energy presents numerous environmental and economic advantages, its inherent intermittency and unpredictability have posed considerable operational challenges, including exacerbated peak-valley differences, increased ramping requirements, and compromised grid stability [1, 2]. Consequently, the role of Energy Storage Systems (ESS) in effectively mitigating these challenges through optimal peak-shaving strategies has become critically important, prompting extensive research from various perspectives.

At a policy and planning level, significant research has highlighted transformative shifts in power systems resulting from high renewable penetration. Power systems are transitioning from deterministic operational frameworks—traditionally characterized by source-following-load paradigms—to probabilistic, multi-dimensional coordination models that encompass source-grid-load-storage interactions [1]. As renewable energy generation becomes increasingly reliant on power electronics, the grid experiences significantly reduced inertia, raising substantial concerns over stability and reliability [2]. Thus, enhancing system flexibility through diversified resources, particularly energy storage, demand response, and sophisticated market mechanisms, has emerged as a priority.

Multiple studies provide quantitative forecasts of renewable energy integration, underlining the immediate necessity for advanced flexibility solutions. China's renewable installations are projected to reach between 1.2 and 1.6 TW by 2030, accounting for around 20% of total power generation, with daily power fluctuations potentially surpassing 400 GW [2]. By 2060, renewable energy capacity may exceed 60%, intensifying peak management and grid balancing challenges, thereby accentuating the necessity of integrating ESS within grid operations to achieve system reliability and operational stability.

B. Energy Storage Technologies and Economic Considerations

From a technological viewpoint, ESS includes diverse categories such as electrochemical, mechanical, electromagnetic, thermal, and hydrogen-based systems, each exhibiting unique operational characteristics suitable for specific grid applications [3]. Hydrogen storage, particularly noted for its ability to support long-duration storage requirements, plays a significant role in addressing seasonal fluctuations in renewable generation [3]. However, existing literature indicates that comprehensive economic evaluations remain limited, often excluding critical lifecycle parameters such as battery degradation and replacement costs. This oversight could lead to misleading conclusions regarding the economic viability of ESS [4]. Therefore, accurate, lifecycle-inclusive economic assessments are essential for developing realistic and economically viable storage dispatch strategies.

Policy contexts offer practical frameworks and constraints that guide real-world ESS implementations. Various provincial mandates across China stipulate precise ESS deployment criteria, such as specific storage-to-generation capacity ratios, required durations, and expected lifetimes. These regulatory policies are crucial benchmarks that influence regional ESS configurations and operational strategies [5]. Recognizing and incorporating these practical constraints within optimization models can enhance their applicability and feasibility.

C. Optimal Scheduling Strategies for Energy Storage Systems

Significant algorithmic advancements have emerged in the area of ESS scheduling optimization. Recent developments include hierarchical control strategies designed to integrate storage clusters with conventional thermal generation. These strategies introduce innovative control parameters such as the "ESS peaking surplus coefficient," leading to substantial reductions in peak load and operational costs [6]. Additionally, multi-objective optimization methodologies, such as the enhanced whale optimization algorithm combined with rough-set theory, have demonstrated effectiveness in dynamically balancing competing objectives like operational costs and renewable absorption, achieving acceptance rates of renewable energy exceeding 97% [7].

Multi-time-scale optimization methods are becoming increasingly prominent due to their robust handling of renewable generation uncertainties. Optimization frameworks that span day-ahead, intra-day, and real-time intervals have achieved significant reductions in operational costs while substantially reducing renewable curtailment [8]. Such frameworks validate the importance of adopting multi-time-scale methodologies in practical ESS dispatch scenarios.

Incorporating resilience considerations into ESS management further expands the operational scope. The resilience framework, encompassing prevention, response, and recovery strategies, identifies ESS as a critical resource during disturbances and emergencies, highlighting its strategic role beyond traditional peak shaving functions [9]. Innovative conceptual frameworks, such as "energy logistics," further emphasize spatial-temporal optimization strategies by analogizing ESS management to logistical systems, addressing coordinated storage siting, sizing, and operational scheduling [10]. Although conceptual, these analogies provide valuable insights and methodological guidance for developing practical and comprehensive ESS optimization models.

Commercial and market integration analyses further underscore the viability and necessity of ESS deployments. Recent studies document rapid growth in ESS installations, identifying emerging business models including shared and independent storage systems that align closely with ongoing electricity market reforms [11]. These market-oriented insights underscore the commercial feasibility and scalability of optimized ESS strategies, emphasizing the necessity for market-responsive optimization models.

D. Future Outlook and Research Gaps

Despite these advances, significant research gaps remain, necessitating further investigation. Explicit integration of battery degradation costs and lifecycle management within optimization models remains scarce, potentially undermining economic evaluations. Detailed analyses and integration of long-duration storage solutions, particularly hydrogen-based storage, are notably underrepresented. Furthermore, existing optimization models often inadequately incorporate dynamic electricity market conditions and carbon pricing mechanisms, limiting their practical applicability. Finally, scalability and practical validation of ESS optimization models in large-scale, real-world networks have been insufficiently explored, with many studies confined to small-scale, standardized test scenarios [12].

Addressing these gaps, this thesis aims to advance the current research landscape significantly. It proposes a comprehensive optimization model explicitly incorporating battery lifecycle and degradation dynamics, examining long-duration storage solutions and dynamic electricity and carbon pricing mechanisms. Additionally, the study employs multi-objective, multi-level, and multi-time-scale optimization methods validated through realistic, large-scale network simulations. By synthesizing strategic insights, algorithmic advancements, technological evaluations, and market analyses, this research intends to substantially improve ESS operational strategies, enabling efficient peak shaving and enhanced reliability in high-renewable-penetration power systems.

III. Discussion

Rapid growth in wind and photovoltaic generation under the dual-carbon policy pathway is reshaping the technical foundations of power-system operation. Variable renewable energy deepens peak-valley load swings, steepens net-load ramps, and displaces synchronous inertia as converter-interfaced resources proliferate, eroding traditional frequency and adequacy margins [1, 2, 12]. Scenario studies projecting terawatt-scale VRE capacity and multi-hundred-gigawatt intra-day fluctuations indicate that legacy "thermal-follows-load" dispatch paradigms will not sustain long-term reliability or economic efficiency in such systems [2]. Against this backdrop, energy storage systems move from a supplementary enhancement to a strategic flexibility resource central to peak management, renewable integration, and grid security [1,2,12].

A. Technology–time-scale Fit and Economics

Storage is not monolithic. High-power electrochemical systems offer rapid, diurnal peak clipping and regulation; pumped hydro, compressed air, and emerging hydrogen pathways extend into the multi-hour or multi-day domain needed when renewable oversupply coincides with long valleys [3]. Technology selection is complicated by gaps in economic modelling. Many comparative studies exclude degradation, augmentation, and lifecycle replacement cost, biasing optimisation toward short-duration chemistries and overstating returns [4]. Real-world deployment is further bounded by provincial storage mandates that specify minimum power-to-renewable ratios, discharge durations, and warranty life for co-located assets at renewable plants—constraints that materially shape feasible scheduling outcomes and must be reflected in models intended for practice [5].

B. Scheduling Sophistication and Performance

Contemporary research shows clear benefits from moving beyond single-objective, single-horizon optimisation. Hierarchical control that allocates ramping obligations between thermal fleets and aggregated storage clusters at an upper layer, then dispatches heterogeneous devices subject to operational or aging constraints at a lower layer, demonstrates measurable peak reduction and operating-cost savings in high-wind test systems [6]. Multi-objective meta-heuristic schemes, such as rough-set-guided whale optimisation, improve the trade-off between operating cost and renewable curtailment, pushing VRE absorption above 97% on active distribution feeders that include distributed generation, storage, and flexible demand [7]. Multi-time-scale rolling optimisation that links day-ahead planning with intra-day and 5-minute real-time corrective dispatch cuts grid purchase cost by nearly one-third while suppressing renewable spillage below 2% when coupled with demand response and vehicle-to-grid (V2G) participation [8]. Collectively, these advances confirm that meaningful peak shaving in high-VRE systems requires coordinated decisions across temporal layers and explicit multi-criteria optimisation.

C. Extending the Value Stack: Coordination, Resilience, and Markets

Evidence is accumulating that source–grid–load–storage co-optimisation outperforms siloed scheduling by jointly managing forecast error, network limits, load flexibility, and state-of-charge dynamics [1, 6-8]. Beyond routine operations, resilience frameworks map storage contributions across the prevent–respond–recover arc for extreme events in integrated energy systems, broadening evaluation metrics beyond pure arbitrage or peak clipping [9]. Spatial framing also matters: the "energy logistics" perspective treats transmission corridors and storage nodes as a distributed routing problem, clarifying how siting and capacity staging influence downstream peak burden and curtailment risk [10]. Meanwhile, rapid growth of new-type storage capacity and the emergence of shared versus independent storage business models signal that tariff design and digital platforms will increasingly condition dispatch incentives, revenue stacking, and investment recovery [11].

D. Synthesis and Research Agenda

Energy storage is widely shown to be indispensable for managing peaks in high-VRE systems, providing fast ramping, firming, and temporal shifting of renewable output [1, 2, 5]. Layered, multi-objective, multi-horizon scheduling, spanning intraday to seasonal horizons and co-optimizing with generation and demand response, materially improves economic and technical performance [6-8]. Policy and market design increasingly shape optimal ESS configurations and value-stacking opportunities by structuring revenue streams, risk allocation, and operational incentives [11, 12].

There are still gaps in many aspects. For example, degradation-aware and lifecycle-consistent dispatch is uncommon [4, 6], long-duration and hybrid portfolios are under-modelled relative to projected variability [3], dynamic electricity and carbon pricing seldom enter operational formulations despite growing exposure [4, 11], and most algorithms are validated only on modest test feeders, leaving scalability to large grids unresolved [7, 8]. The present study is designed to address these gaps by developing a degradation-aware, policy-constrained, mixed-duration ESS scheduling framework embedded in a day-ahead / intra-day / real-time co-optimisation environment and evaluated under dynamic market conditions. In doing so, it translates system imperatives from prior work into actionable tools for high-renewable power systems.

IV. Conclusion

This study aimed to investigate how Energy Storage Systems (ESS) can be scheduled to deliver effective peak shaving in power systems with high renewable penetration through a structured synthesis of recent technical, policy, and market literature. The findings indicate a broad consensus that accelerating wind- and PV-driven variability is outstripping legacy thermal flexibility and that ESS is emerging as a strategic—not supplemental—resource for managing peaks, ramps, and reliability risks. The analysis revealed that technology–time-scale fit, lifecycle economics, and regionally mandated storage ratios materially shape dispatch value, which supports the initial hypothesis that storage effectiveness depends as much on modelling scope and constraints as on device capability.

This research contributes to the existing body of knowledge by integrating macro-system drivers, storage technology characteristics, optimization advances, and market evolution into a unified interpretive framework. The findings extend previous work by showing that hierarchical, multi-objective, and multi-time-scale scheduling approaches consistently improve peak reduction, cost, and renewable absorption outcomes relative to single-horizon methods.

This study has practical significance for planners, regulators, and system operators. Aligning storage duration with imbalance patterns, embedding policy requirements in optimization, and accounting for degradation can prevent misinvestment and improve peak-management portfolios.

This study is limited by its focus on published literature; no meta-statistical harmonisation or large-scale empirical validation was performed, and rapidly evolving policy or cost data may affect generalizability. One potential limitation is the underrepresentation of operational data from utility fleets, which could be addressed in future research.

Future study could couple degradation-aware hybrid storage models with dynamic electricity and carbon price scenarios, and validate source-grid-load-storage co-optimization on provincial-scale networks. Overall, this study provides new insights into ESS-enabled peak shaving under high renewable penetration and highlights the importance of modelling realism for actionable system planning.

Conflict of Interest

The author declares no conflict of interest.

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