Energy Storage Integration in Market-Based Energy Systems: Advanced Technologies and Decision-Making Models

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Bulk, or large-scale, energy storage systems are indispensable for future energy networks with very high shares of intermittent renewable generation. The increasing penetration of wind and solar resources requires substantial flexible capacity that can shift energy over many hours or days, hedge against forecast errors, and provide multi-market services. In this context, long-duration energy storage technologies, such as advanced compressed air and liquid air systems, are attracting growing attention and moving toward large-scale demonstration worldwide. Yet, bulk storage investments remain difficult to justify because of high upfront costs and uncertain, market-driven revenue streams, even in net-zero carbon roadmaps for the coming decades. This thesis therefore asks a central question: how can we design operational and market-integration models that enable bulk and long-duration storage assets to make informed, profit seeking decisions while supporting secure and cost-efficient operation of future low-carbon power systems?

To address this question, the thesis first establishes physical and methodological foundations for bulk storage operation in market environments. It clarifies the roles and applications of storage across different timescales, presents a technology-oriented view of bulk storage and its interfaces with wholesale electricity markets, and identifies the main products and services relevant for long duration flexibility. On this basis, the work develops a common mathematical framework based on deterministic and scenario-based stochastic programming, multi-level models, optimality conditions, and mathematical programs with equilibrium constraints. The interaction between optimization and data-driven methods is also examined, laying the foundation for learning-assisted solution approaches that accelerate decision making.

Within this framework, the thesis first develops a risk-aware market dispatch model for a grid-scale lithium-ion battery that participates in day-ahead and intraday electricity markets from a non-strategic, price-taking perspective. A risk-neutral bidding formulation serves as a reference and is extended to an operational model with second-order stochastic dominance constraints that control the downside risk of revenues relative to a data-driven benchmark portfolio. Numerical studies based on realistic price scenarios show that suit able risk constraints can substantially reduce regret and improve the reliability of battery revenues, at the cost of moderate reductions in expected profit.

Motivated by the need for long-duration flexibility and for exploiting cross vector synergies, the thesis then turns to emerging bulk storage concepts that either couple electricity and gas systems or combine different storage media. Within this context, it first develops a two-stage stochastic dispatch model for an integrated liquid air energy storage and liquefied natural gas system that co-optimizes electricity generation, liquefaction, regasification, and cold exergy usage across power and gas markets. A probabilistic payback period metric is introduced to assess economic feasibility under joint price and demand un certainty. Second, the thesis studies the strategic look-ahead operation of a hybrid above-ground compressed air and liquid air storage plant that offers energy in a day-ahead market with network constraints. A bi-level market model is cast as a mixed-integer mathematical program with equilibrium constraints, and a learning-assisted solution approach is proposed to warm-start integer decisions. Case studies on systems of increasing size show how hybridization, forecast horizon, and strategic behavior affect profitability, market prices, and dispatch patterns, and illustrate the value of combining advanced optimization with data-driven techniques for bulk storage operation.

Taken together, the developments and case studies in this thesis demonstrate that risk-aware, multi-market, and learning-assisted models enable bulk and long-duration storage assets to convert their physical flexibility into more predictable and robust revenue streams, while aligning their operation with prevailing market rules and network constraints. Overall, the proposed methodologies provide a coherent toolbox for operators, planners, and investors who seek to integrate large-scale storage into liberalized energy markets, and they contribute to the broader transition toward data-driven, market-aware operation of flexible resources in future net-zero power systems.