Techno-Economic Assessment of Grid-Scale Energy Storage Technologies Under Evolving Market and Decarbonization Scenarios: Liquid Air and Lithium-ion Systems

by

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The transition to a low-carbon energy system has amplified the demand for grid-scale energy storage, which plays a critical role in enabling deep decarbonization by balancing intermittent renewable generation with variable electricity demand. To date, pumped hydro energy storage and compressed air energy storage account for over 95% of global grid-scale storage capacity. However, both technologies are location-constrained and offer limited potential for expansion, motivating the need to explore and deploy more flexible alternatives capable of delivering multi-hour to multi-day storage. Among emerging options, liquid air energy storage (LAES) systems and lithium-ion battery energy storage systems (Li-ion BESS) have gained significant attention due to their scalability and siting flexibility, with LAES particularly suited for long-duration applications and Li-ion BESS increasingly considered for mid-duration storage needs.

This thesis investigates both the technical modeling of LAES and the economic optimization of LAES and Li-ion BESS. The first part focuses on efforts to rigorously model LAES systems using nonsmooth modeling approaches. This work includes an exploratory study applying nonsmooth formulations to key LAES process components with the objective of improving simulation efficiency and enabling more robust technical optimization. The study demonstrates that nonsmooth models can be implemented successfully in certain configurations. However, challenges involving bifurcations were identified when implementing a three-equation nonsmooth multistream heat exchange model, revealing numerical issues that limited the practicality of this approach for broader process optimization. These findings informed the broader modeling strategy adopted in subsequent phases of the research.

Building on these insights, the thesis next adopts a higher-level modeling approach to assess the economic performance of LAES systems under realistic market conditions. In this phase, the design and operation of standalone LAES installations were optimized to maximize net present value (NPV) over the project lifespan across 73 load zones spanning six U.S. and 27 European electricity markets. The analysis assumed that 2023 levels of renewable generation would persist over time, providing a baseline assessment of economic viability. A mixed-integer linear programming framework was developed to optimize system design and hourly operation under detailed technical constraints and conservative cost assumptions. This study revealed that under current renewable penetration, LAES was only economically viable in a single Texas load zone and not in any other U.S. or European markets. Significant variation in NPV across load zones within the same market also demonstrated the value of this approach as a site-selection tool. The results showed that storage economics cannot be captured by a single viability determination or levelized cost of storage (LCOS) value per technology, emphasizing the importance of detailed, location-specific analyses to identify viable deployment opportunities.

In the final part of the thesis, which will be the focus of the thesis defense, the assumption of static renewable penetration was relaxed to evaluate both LAES and Li-ion BESS using projected future electricity prices. Two analogous economic optimization studies were conducted in which each technology was assessed across 18 U.S. electricity markets using price projections from the National Renewable Energy Laboratory's Cambium 2023 dataset. Eight distinct decarbonization scenarios were modeled to capture a range of potential policy and market trajectories. This approach enabled a consistent, side-by-side comparison of the relative economic viability of LAES and Li-ion BESS under identical assumptions, addressing a critical gap in the literature where differing modeling frameworks and assumptions have often hindered direct comparison. To reflect realistic deployment considerations and avoid overstating profitability, the analysis excludes ancillary service and capacity market revenues and relies exclusively on arbitrage in the day-ahead wholesale energy market, where storage systems purchase electricity during low-price periods and sell during high-price periods.

A key finding is that although the Cambium scenarios assume widespread storage deployment over time, the projected price signals did not, in most cases, generate sufficient arbitrage opportunities to yield positive NPVs. This disconnect suggests that without targeted policy support or further market reforms, the economic incentives required to drive large-scale storage adoption may not materialize spontaneously. Under more aggressive decarbonization scenarios—characterized by higher renewable penetration and greater price volatility—LAES showed improved profitability and achieved positive NPVs in some regions. The Texas and Florida markets consistently stood out as particularly favorable for LAES deployment. The analysis also established LCOS ranges for both LAES and Li-ion BESS, providing a consistent basis for comparing their relative cost-effectiveness. In contrast, Li-ion BESS did not produce positive NPVs in any market or scenario, highlighting its economic infeasibility under an arbitrage-only revenue model. Sensitivity analyses identified the most influential drivers of economic performance and informed recommendations for policy interventions to improve the economic outlook for these technologies. Collectively, these results underscore the importance of aligning policy, market design, and investment incentives to support the conditions necessary for widespread energy storage adoption.

Overall, this work establishes a generalizable framework for rigorously assessing the economic feasibility of emerging energy storage technologies under both current and projected future market conditions. By integrating mathematical optimization with consistent, comparative techno-economic analysis, the thesis presents a transparent approach that can be readily applied to evaluate other storage technologies and policy scenarios as the energy landscape continues to evolve. Together, these contributions provide practical tools to support investment decisions and strategic planning for a reliable, low-carbon electricity system.

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