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Doctoral Dissertation
Doctoral Program in Energy Engineering (37th Cycle)

Battery Energy Storage Systems Optimal Energy Management and Techno- Economic Analysis in Power System Applications

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Abstract

The integration of utility-scale battery energy storage systems (BESS) with renewable energy sources (RES) is pivotal for advancing the energy transition. These systems mitigate renewable intermittency, enhance grid stability, and unlock economic opportunities through participation in electricity markets. This dissertation investigates the optimal energy management of BESS integrated with photovoltaic (PV) and wind power plants, emphasizing long-term techno-economic analyses to evaluate profitability under varying market conditions and system constraints. Through comprehensive optimization frameworks based on deterministic mathematical programming, the works proposed in this dissertation evaluate optimal energy dispatch strategies, BESS sizing and profitability, as well as the effects of critical factors such as battery degradation and dynamic efficiency, aiming to maximize net profit while ensuring operational feasibility over the system's lifetime.

Firstly, a data-driven modeling approach and a semi-empirical degradation model are developed based on an experimental campaign conducted on a real-world BESS. These contributions provide an accurate representation of battery ageing dynamics and their impact on operational performance. Secondly, the research introduces computationally efficient optimization frameworks, primarily employing mixed-integer linear programming (MILP) and mixed-integer non-linear programming (MINLP) approaches. These models account for key factors, including battery degradation, dynamic efficiency, and curtailment costs, to simulate realistic operational scenarios throughout the system's lifecycle. Real-world data from the Italian electricity market and the California Independent System Operator (CAISO) market were used to conduct empirical case studies, providing practical insights and validating the model's applicability. Key findings reveal that the economic viability of PV-BESS and wind-BESS systems is highly sensitive to battery costs, market price volatility, and energy management strategies. For instance, in the Italian market, integrating a BESS with a wind farm reduced curtailment and enhanced net revenues, achieving a net present value of

152 k€ for a 4 MW / 4 MWh configuration. Sensitivity analysis underscores the importance of reducing battery costs below 325 €/kWh to ensure financial viability. Similarly, the analysis of PV-BESS systems in California electricity market highlighted that optimized scheduling mitigated degradation impacts, with annual profits decreasing by 13-24 % due to battery ageing. The presented case studies further explore key design, energy, and economic indicators, comparing systems with and without storage to highlight the added value of integrating BESS with renewable power plants. Sensitivity analyses across multiple scenarios evaluate the influence of critical factors such as battery cost, efficiency, and curtailed energy. Long-term profitability analyses reveal that reducing battery cycling and incorporating penalty costs in the optimization objective function can extend the BESS calendar lifetime, improving overall economic returns.

This dissertation provides actionable insights for researchers, power plant owners, and grid operators, highlighting the economic viability and technical feasibility of integrating BESSs with RESs. It underscores the importance of designing systems that account for battery degradation and market dynamics to achieve optimal performance. By extending the BESS lifetime and refining operational strategies, this research advances the development of sustainable and cost-effective power systems, effectively bridging the gap between technical innovation and real-world market adoption.