STORAGE IN FUTURE ENERGY SYSTEMS – COMPUTING STOCHASTIC MARKET EQUILIBRIA WITH A SYSTEM-ORIENTED LEAST-SQUARES MONTE CARLO APPROACH

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Overview

Energy storage systems (ESS) are essential for integrating renewable energy and stabilizing electricity markets, offering flexibility through energy arbitrage and supply stabilization [1] [2]. However, most existing models for stochastic ESS operation assume price-taking behavior, failing to account for the market influence of large-scale ESS [3]. This study presents a novel hybrid model that integrates the Least-Squares Monte Carlo (LSMC) approach [4] with a fundamental equilibrium electricity price model [5]. This combination enables the analysis of price effects caused by ESS operations in a stylized market setting, addressing a significant gap in existing methodologies [6].

Methods

The hybrid framework models the dynamic control of a joint cost-minimizing ESS, combining LSMC simulations [4] with a system-oriented equilibrium price model [5] [3]. This integration captures the interactions between ESS operations and market price dynamics, allowing for detailed evaluations of ESS-induced price effects [6]. The methodology incorporates high-dimensional uncertainties [7] [8], hourly granularity, and rolling heuristics [6] to simulate and optimize ESS behavior over long-term scenarios. The stylized example models the market impacts of an aggregated ESS in a national electricity market, utilizing synthetic data and Monte Carlo simulations to reflect realistic system dynamics [2] [5].

Results

The hybrid model highlights the critical role of energy storage systems (ESS) in influencing electricity market dynamics, addressing a key gap in traditional approaches. By incorporating price effects, the model reveals how ESS operations impact market prices—charging during low-price periods tends to increase prices slightly, while discharging during peak demand hours reduces extreme price spikes. This interaction underscores the potential of ESS to stabilize market prices and contribute to overall system reliability.

The novel approach effectively captures the dynamic relationship between ESS operations and market conditions, demonstrating its ability to reduce price volatility and enhance system efficiency. Unlike traditional models, which assume price-taking behavior, this framework allows for the evaluation of ESS as active market participants, providing valuable insights into their role in mitigating supply scarcity and optimizing energy use.

The results also highlight significant temporal variations in the marginal value of ESS, reflecting the need for flexible and adaptive operational strategies to capitalize on market opportunities. The stylized example illustrates the broader system benefits of integrating ESS, such as improved market stability and more efficient allocation of energy resources. This underscores the importance of considering price effects in the design and operation of future energy systems with high renewable penetration.

Conclusions

The hybrid LSMC approach offers a robust, computationally efficient tool for analyzing the price effects of ESS in electricity markets. By explicitly incorporating these dynamics into the stochastic control problem, the model provides valuable insights into ESS operations from a system perspective. The stylized example highlights the potential of ESS to stabilize markets, optimize energy use, and enhance system efficiency. Future work could expand this framework to incorporate cross-border interactions and diversified ESS technologies, further enriching its applicability in complex energy systems.

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