Data-Driven Inverse Optimization Approaches for the Participation of Price-Responsive Demand in Short-Term Electricity Markets

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The rapid growth of variable renewable energy sources is increasing short-term flexibility needs in European power systems, raising challenges for maintaining system balance and reducing reliance on fossil-fueled flexibility. Demand side flexibility from small-scale consumers offers a promising solution, yet its integration into operational decision-making is hindered by the difficulty of accurately modeling consumer price-response behavior and the uncertainty associated with their reactions to dynamic price signals. This thesis develops scalable, data-driven frameworks that infer and integrate price-response models of small-scale demand response resources (DRRs) into an aggregator's real-time participation in Belgium's single-price imbalance settlement mechanism.

First, a bilevel optimization framework is proposed that embeds inverse optimization (IO)-based estimates of DRR price-response parameters into the aggregator's real-time control problem. The model captures the hierarchical interactions among the aggregator, consumers, and balancing market while accounting for market price feedback and uncertainty in DRR behavior. Second, recognizing that forecast accuracy does not necessarily translate into operational value, the thesis introduces a Value-Oriented Inverse Optimization (VOIO) framework. VOIO selects IO models based on the ex-post profit they yield in the aggregator's decision problem rather than on statistical forecast accuracy. This approach provides a computationally efficient alternative to fully integrated decision-focused learning. Third, a Scenario-Based VOIO (SBVOIO) framework is developed to generate multiple sets of price-response parameters representing different quantiles of historical consumer behavior. These scenario-based models enable aggregators to hedge against uncertainty by incorporating multiple behavioral realizations into operational decision-making.

A proof-of-concept study grounded in the Belgian balancing market demonstrates the effectiveness of the proposed methods. Results show that VOIO improves aggregator profitability compared to forecast-oriented IO (FOIO) approaches, while SBVOIO enhances robustness against consumer response uncertainty. Collectively, the contributions of this thesis provide scalable, integrable, and decision-aware methods for modeling and leveraging small-scale demand response in short-term electricity markets, enabling aggregators to more effectively provide flexibility services in renewable-dominated power systems.