Model development for the market clearing mechanism in the Japan Electric Power Exchange (JEPX), considering the role of the virtual power plant

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Title : Model development for the market clearing mechanism in the Japan Electric Power Exchange (JEPX), considering the role of the virtual power plant（仮想発電所の役割を考慮した日本卸電力取引所（JEPX）の市場清算メカニズムのモデル開発）

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論 文 内 容 の 要 旨

Thesis Summary

The progress achieved in clean energy production technologies is poised to eventually replace conventional fossil fuel energy sources. Conversely, this transition is challenged by a rapidly escalating energy demand and rising global warming indicators. The implementation of electricity market liberalization serves as a mechanism to foster a competitive landscape for energy supply and demand. This approach not only aids in broadening the spectrum of energy resources but also plays a pivotal role in curbing carbon emissions and bolstering investments in energy infrastructure through the investor's competition in the dynamic electricity prices. However, liberalizing electricity markets is a complex- and long-term process, requiring extensive national legal and economic reforms. For instance, Japan's journey towards electricity sector liberalization spaned approximately sixty years. Therefore, this dissertation investigates the concept of aggregating and controlling the complete sets of energy resources in a determined region, which can transform the pricing mechanisms from oligopoly to liberal pricing. This bridges the gap between the realms of electricity market liberalization and the transformative potential of virtual power plants (VPPs).

To this end, although the current active liberalization process in Japan's electric power exchange market (JEPX) makes it one of the rapidly evolving global electric power exchange markets, it is still lacking in the literature and needs further investigation. This dissertation offers one of the core contributions is a detailed quantitative analysis of the energy policy regulations in the JEPX market, quantitative estimation of the merit order effect (MOE) on market clearing price (MCP) based on all existing energy production technologies, and considering the fragmented spot market prices, and determining the interdependency of the regional spot prices on the national MCP. Moreover, this dissertation introduces a novel modeling structure to synthesize the microeconomic equilibrium of the market clearing mechanism (MCM) based on correlating the energy supply and demand at the national electricity grid with the wholesale MCP. The developed modeling framework in this dissertation employs comprehensive price-driving parameters of supply and demand quantities to synthesize the MCM based on the marginal price of each energy production technology extracted from the MOE and the hourly price elasticity of demand (PED) of each region in JEPX, including the energy traded over other electricity markets with the wholesale MCPs. Furthermore, the hourly PED is estimated nationwide considering the impact of variable renewable energy (VRE), while the MCPs are forecasted using the Long-Short Term Memory (LSTM) model by limiting the predictors to comprehensive price-driving parameters of supply and demand quantities. Eventually, based on the investigation conducted on JEPX, the dissertation

proposed the concept of aggregating and controlling a regional VPP as a solo price-making entity that produces dynamic liberalized electricity prices by formulating a regional VPP considering the JEPX at the three stages of day-ahead, intra-day, and balancing markets. The data-driven modeling structure is formulated by hybridizing the conventional unit commitment models, market clearing models, LSTM forecasting models, and econometric models.

The results revealed that adding one gigawatt-hour of hydroelectric power reduces the MCP by 769 ¥/MWh, while the same amount of biomass electric power decreases MCP by 295 ¥/MWh. The nuclear energy contributed to MCP reduction by 43.7 ¥/MWh. The slight MCP reduction from nuclear energy production was expected to continue due to gradual resumption post the Great East Japan Earthquake, aiming for a planned capacity of 20% to 22% by 2023. Conversely, additional GWh from thermal power, hydroelectric storage, or regional interconnections increases the MCP by 27.4, 606, and 103 ¥/MWh, respectively. The significant price drop to near zero and spikes to 250 ¥/kWh across many regions in 2020 are linked to increased hydroelectric storage adoption. On the other hand, regional correlation analysis highlighted significant direct relations in spot prices among Kansai, Shikoku, Chugoku, and Hokuriku. Tokyo and Tohoku spot prices exhibited a high direct correlation, slightly differing from other regions. Furthermore, Kyushu and Tohoku effectively controlled MCP due to high VRE penetration and a positive supply-demand balance. The price elasticity of demand variations across the JEPX regions exhibit elasticities between -0.1 to -0.25. At the regional market level, the synthesized MCM model for hours 12 and 18 of February 24, 2022, revealed that Kyushu's near-zero price drop was justified due to the 93.5% contribution of clean energy to regional demand. Additionally, its regional interconnections ranked second lowest according to MOE, suggesting that Kyushu's local suppliers bid for other regions with higher demand. This reflects the distinction feature of the MCM model, correlating MCM with marginal prices of each energy supply per technology and spatiotemporal PED using nationwide equilibrium, aids market participants, system operators, and policymakers in assessing pricing mechanisms, handling price fluctuations, and policymaking. Sequentially, the developed data-driven modeling structure revealed a seasonal RMSE ranging from 3.24 to 7.63 ¥/kWh between actual JEPX prices and VPP prices. This indicates that aggregating the energy resources of a single region in a single VPP control can produce dynamic liberalized prices. Furthermore, a comparison was made between the flat electricity pricing of oligopoly markets and liberalized VPP prices, highlighting the superior profitability of liberalized VPPs by approximately 49 percent, factoring in the fuel price escalation throughout the fiscal year 2021.

Overall, this dissertation presents an innovative interdisciplinary approach that addresses technical and economic diffusion barriers encountered in the electricity sector liberalization process of global electricity markets, thus offering a comprehensive analysis of the current electricity sector in Japan and then aiding in the liberalization of global markets.