Model development for the comprehensive analysis of demand response programs in the Japan Electric Power Exchange (JEPX) day-ahead wholesale market

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論 文 名　: Model development for the comprehensive analysis of demand response programs in the Japan Electric Power Exchange (JEPX) day-ahead wholesale market（日本卸電力取引所（JEPX）前日比卸売市場におけるデマンドレスポンスプログラムの包括的分析に向けたモデル開発）
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論 文 内 容 の 要 旨
Thesis Summary

Among all countermeasures recommended by the Japanese government, Demand Response Programs (DRPs) is a voluntary program that allows end-user customers (CUs) to reduce their electricity usage during higher electricity prices and achieve specific outcomes on the electrical grid at varying levels. However, there has been little success in adopting DPRs in the smart electricity market due to insufficient integration between major market players, which is affected not only by technical and financial issues, but also by the social acceptance of DPRs. The purpose of this study is to investigate the main drivers of the successful application of DRPs in the Japan Electric Power Exchange (JEPX) wholesale market, through the development of a robust mathematical modeling framework that can be used to formulate both Price-Based Demand Response Programs (PBDRPs) and Incentive-Based Demand Response Programs (IBDRPs). The modeling approach is founded on the concept of social welfare maximization of market actors, considering both service providers (SPs) and CUs profitabilities from trading electricity, while addressing the aversion of the CUs to the risk of choosing PBDRPs and their satisfaction with participation in IBDRPs.

The modeling framework developed in this research is divided into three main models. The **first model** focuses on developing an analytical approach grounded in customer theory in microeconomics, using the concept of the expected utility function to model the behavior of the risk-averse CUs in response to different PBDRPs. An hourly-based model for short-term price elasticity of demand is introduced, considering the day-ahead price mechanism in the Japan Electric Power Exchange (JEPX) market. The estimated price elasticities are utilized in a price elasticity matrix of demand (PEMD) to accurately reflect various response strategies such as flexible, in-flexible forward-shifting, backward shifting, and optimizing responses. Accurate day-ahead hourly load forecasting using the Seasonal Autoregressive Integrated Moving Average (SARIMA) model is performed. The developed model is then employed to analyze the behavior of CUs with different response strategies in the JEPX market. The results indicate that, applying the Time-of-Use (TOU) and Real-Time-Pricing (RTP) programs suggests a peak reduction potential of 10.7% and 7.3%, respectively, for the flexible CUs. Applying the RTP program to the curtailable loads can achieve a 7.7%

reduction in daily peak demand and a 1.6% reduction in daily electricity consumption.

The **second model** is developed to investigate the potential of Real-Time Pricing Demand Response Programs (RTP-DRPs) in adjusting the microeconomic equilibrium of the wholesale electricity market. A region-wise analytical approach is proposed to maximize end-users' social welfare by considering regions with varying supply-demand dynamics, including excess supply, high demand burden, and inter-regional connections. The results reveal that, the RTP-DRPs could potentially reduce the peak demand of the residential sector in Chubu, Chugoku, Kansai, Kyushu, Tokyo, and Tohoku by 1.91% to 7.81%. Meanwhile, in Hokkaido, Hokuriku, and Shikoku by 16.13% to 22.9%. The avoided greenhouse emission (GHG) in Tokyo is estimated to be 82.6 and 192.2 tons in summer and winter, respectively.

The **third model** focuses on IBDRPs, which aim to encourage customers to reduce electricity consumption during peak periods in exchange for incentives. A multi-objective modeling approach is employed to maximize the social welfare of both SPs and CUs participating in IBDRPs. The Long–Short Term Memory (LSTM) artificial neural networks approach is used to forecast an accurate day-ahead hourly load on four years of Tokyo Electric Power Company (TEPCO) hourly power demand data from 2016 to 2020. The Kano model for customer satisfaction is utilized to assess CUs' satisfaction with participation, considering attributes such as comfort, flexibility, energy security, and environmental protection. A questionnaire survey is carried out to collect 349 responses to a pair of functional and dysfunctional questions on the four attributes mentioned above, which helps identify the explicit formulation of the CUs' satisfaction function. The analysis of the proposed IBDRP in the JEPX market using real-time wholesale electricity prices and demand loads in Tokyo's residential areas reveals that the environmental protection attribute positively impacts CUs' satisfaction and welfare, leading to greater reductions in electricity consumption and increased incentive incomes. The model is used to estimate the optimal demand load, peak reduction, optimal incentive rates, and welfare of CU and SP for two scenarios, including with and without CU's satisfaction. Based on the two scenarios considered in this study, the optimal load reduction of a dissatisfied customer is estimated at 186,103,70 and 64 MWh with environmental protection, comfort, flexibility, and energy security attributes, respectively. Despite that, the daily electricity reduction after implementing the proposed IBDRP is estimated at 277 MWh with all IBDRP attributes for a satisfied CU.

Overall, this research contributes to the development of mathematical models for evaluating demand response programs in Japan's wholesale electricity market. The findings demonstrate the potential of different strategies to maximize welfare, reduce peak demand, mitigate greenhouse gas emissions, and enhance customer satisfaction, ultimately leading to a more sustainable and efficient electricity system.