IMPACT OF RAPID EXPANSION OF RENEWABLE ENERGY ON ELECTRICITY MARKET PRICES

Mizue Shimomura, Kyushu University, +81-(0)92-802-3405, shimomura.mizue.443@s.kyushu-u.ac.jp
Alexander Ryota Keeley, Kyushu University, +81-(0)92-802-3405, keeley.ryota.alexander.416@m.kyushu-u.ac.jp
Ken'ichi Matsumoto, Toyo University, +81-(0)3-3945-7337, matsumoto1005@toyo.jp
Kenta Tanaka, Musashi University, +81-(0)3-5984-4662, k-tanaka@cc.musashi.ac.jp
Shunsuke Managi, Kyushu University, +81-(0)92-802-3405, managi.s@gmail.com

Overview

Introduction of renewable energy (RE) is progressing owing to global decarbonization. The merit order effect (MOE) is known for the effect of expanding RE in the electricity market. A drop in the electricity market price owing to the introduction of RE with low marginal costs has been identified in prior studies (e.g., Cludius et al. (2014)). However, diffusion of variable RE (VRE), such as solar and wind power, not only decreases the market price but also leads to other things, such as the need for adjustability to handle a sudden fluctuation (ramp-up), a backup power supply to deal with the so-called windless period when VRE output disappears, and the lack of supply capability owing to "missing money," resulting from the drop in market price in the mid to long term. This study aims to estimate the multidirectional effects of VRE in the Japanese electricity market, where the rapid introduction of REs has advanced by using machine learning and a technique of explainable artificial intelligence (XAI). In Japan, the Fukushima Daiichi nuclear power plant accident occurred in 2011. As expectations about RE heightened with the decline in the perceived reliability of nuclear energy and the introduction of the feed-in-tariff scheme in Japan in 2012, the amount of RE introduced, mainly from solar power systems, suddenly increased. Such dynamic structural change of electricity supply causes unstable electricity market price. The average spot price in Japan in FY2019 decreased to JPY 7.93/kWh, but it was hit by an unprecedented price surge during the winter in 2020–2021, with a maximum price of JPY 251/kWh. The effects of the rapid expansion of solar power on the electricity market in Japan have important implications for other regions and countries.

Methods

The electricity market fluctuates and it is non-linear because of multiple factors (e.g., Bushnell & Novan (2021)). Therefore, a machine learning model that can handle non-linear fluctuations was applied to analyze the price trends in the electricity market. We use the extreme gradient boosting decision tree method by Python XGBoost package for machine learning analysis. To prevent overfitting, the sample data are divided into training and validation data—from April 2016 to March 2020 are the training, and from April 2020 to March 2021 are the validation data. In addition, we use the partial dependence plot (PDP) and Shapley additive explanation (SHAP) as XAI to investigate factors that influence the VRE market. PDP visualizes the average relationship between variables and can determine whether an appropriate form function is either monotonic, linear, polynomial or more complicated. The SHAP value shows how individual data and variable influences are different from the baseline. A positive SHAP value indicates an increasing effect of the predicted price, and a negative value indicates a reducing effect. Using these approaches, we show that VRE has different effects on electricity market price depending on the time of day or season and the lapse of time.

In this study, we used the following variables: electricity demand, power generation with RE, fuel price, and operable power facility capacity (operation capacity). Operation capacity is defined as the capacity of operable power generation facilities that are derived from the capacities of authorized power stations minus the capacities of inactive power stations. We analyze the spot market (day-ahead market) in the Japan Electric Power Exchange (JEPX) from April 2016 to March 2021. The analysis was performed using hourly data. The data of the market price is collected from JEPX and the hourly demand and the generation with VRE (solar and wind) data are also collected from ordinary transmission system operators in each area. The data about operation capacity is from the power generation information disclosure system (HJKS) released by the JEPX. HJKS reports the data about the shutdown of power stations with a capacity of 100 MW or more lasting for 24 hours or longer. The operation capacity had seasonal variation, decreasing in spring and fall when demand is low and increasing in summer and winter when demand is high, but the annual average consistently decreased from FY2016 to FY2020. The fuel prices used are monthly import prices (CIF price) of coal, LNG, and oil in Japan and are taken from customs statistics.

Results

The results of the XGBoost fitted very well during the training period, i.e., until March 2020. The accuracy during the verification period from April to November 2020 was also comparatively well, and the performance of the model was secured. However, the magnitude of the price surge from December 2020 was not able to be reproduced. The result of feature importance with SHAP shows the variable with the largest degree of contribution to market price is demand, followed by solar generation, operation capacity, and fuel price. The results reveal that the degree of contribution of wind generation to price is small; this may be because of its small generation.

The analyses based on the year, time of day, and season by SHAP showed that the reducing effect of solar generation on the daytime market price increased with time; the reducing effects of solar generation were greatly different depending on the time of day and season, and summer evenings experienced raising effects of the price. The MOE due to solar generation varied depending on the demand (Figure 1). Its reducing effect was approximately 0.11 Yen/kWh in the 90th percentile demand, and approximately 0.20 Yen/kWh at the upper 10% demand, implying that MOE also increased when demand increased. However, when demand was high and solar generation was small, the raising effects on the market price were observed. This may be because energy sources with high marginal costs, such as natural gas, which were able to deal with the start-up or sudden fluctuation for evening ramp-up fluctuation, were used at that time, which is consistent with the findings of Bushnell and Novan (2021). The effect of operation capacity has recently been an increasing effect on market price. This reflects the downward trend in operation capacity. The PDP results showed that the effects of solar, wind generation and operation capacity on the market price are all highly non-linear. Furthermore, the effects on the price were not by each factor alone but are largely different depending on the interaction with the demand.

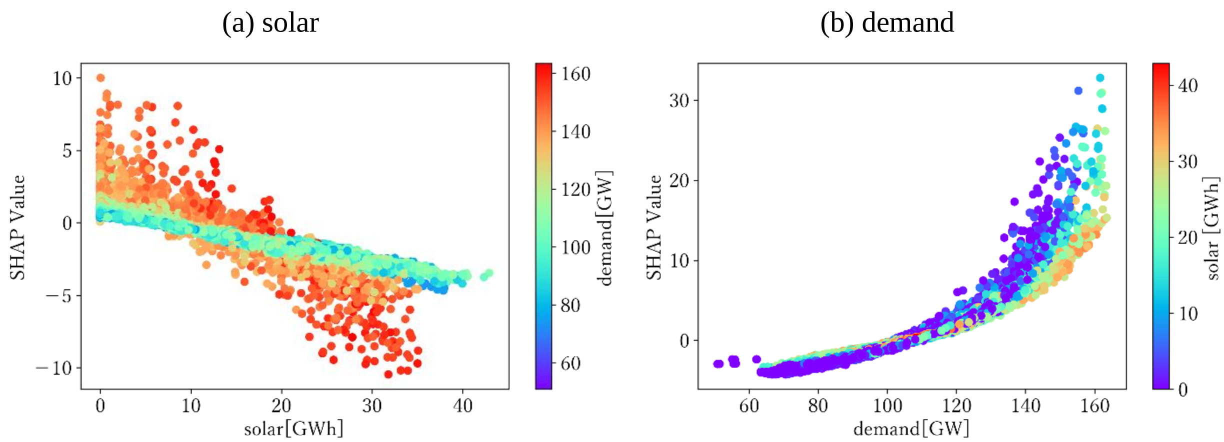

Figure 1 Contribution to the predicted_price of solar (a) and demand (b). X-axis represents the amount of solar generation and the demand, and the Y-axis represents the SHAP value (changes of price from baseline). The values of variables whose interactions were large have been colored (low: blue; high: red).

Conclusions

We conducted detailed research about the effects of VRE on electricity market price in Japan using machine learning. The biggest fluctuation factor in the market was the demand, followed by solar, operation capacity, and fuel prices. Clear effects of wind power on the market price were not observed potentially due to the still small amount of wind generation. The results showed that there is MOE in solar power during daytime; however, the effect varies depending on the time of day, season, and demand. In addition, the results suggest that the market price increases when demand is high and solar generation is low, such as during summer evenings, which may be because of natural gas generation with higher marginal costs. The decrease in the market price owing to VRE may aggravate the profitability of conventional power generation facilities, leading to market instability and price hikes. For smooth transitions to decarbonization, policy support would be needed to manage the pace of plants installation and transition, including conventional power plants, and to introduce appropriately implement flexibility options.

References

Bushnell, J., & Novan, K. (2021). Setting with the Sun: The Impacts of Renewable Energy on Conventional Generation. *Journal of the Association of Environmental and Resource Economists, 8*(4), 759–796.

Cludius, J., Hermann, H., Matthes, F. C., & Graichen, V. (2014). The merit order effect of wind and photovoltaic electricity generation in Germany 2008-2016 estimation and distributional implications. *Energy Economics, 44*, 302–313.