ASYMMETRIC SUPPLY FUNCTION EQUILIBRIUM: CASE STUDIES ON JAPANESE ELECTRICITY MARKETS

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Overview

We calculate asymmetric Supply Function Equilibrium (SFE) based on data of Japanese wholesale electricity market in 2017. Based on calculated supply functions of eight leading generation firms, together with marginal cost functions of fringe firms, hourly market clearing prices were obtained for one year. The SFE model was calibrated to produce the same price level as historical one. Besides the base case, hypothetical cases are analyzed, namely higher variable renewable energy (VRE) penetration cases, low gas price case, and carbon tax cases. The result shows two important policy and economic implications. First, the effectiveness of carbon tax can be suppressed when market power exists in some asymmetric electricity markets. Carbon externality and market power are considered as two main market failures of a deregulated electricity market, and the result illustrates an important interaction between them. The result arises from asymmetric structure of the market. Second, the negative impact of increasing VRE penetration on coal plant profitability is much smaller than the impact of lower gas price, which induces structural fuel-shift from coal to gas. In the United States, increasing penetration of VRE was blamed for as the reason of coal power plants rapidly retiring from the market. The result indicates that shale gas revolution and resulting lower gas price would have played more significant role for lowering profitability of coal plants.

Methods

SFE assumes strategic offering of generation firms to a wholesale electricity market based on each firm's profit maximization behavior. It tries to find an equilibrium in a sense that none of generation firms has an incentive to unilaterally deviate from their offer curves [1,2]. By manipulating and combining first order conditions of all the strategic firms' profit maximization problems, a set of coupled differential equations can be obtained. By solving these equations, SFE is obtained. It is easy to solve these equations when symmetric market structure, where a few leading generation firms have identical generation portfolio, can be assumed. However, this is not the case for many electricity markets, and generation firms often have different capacities of different generation technologies (asymmetric market structure). We apply the computation method proposed in [3], where existence and uniqueness of asymmetric SFE is proved under mild assumptions (e.g. an existence of a price cap and non-zero probability of high enough demand occurrence). With eight strategic firms, the proposed computation method did not work in a straight forward way, and we took some additional procedures to successfully carry out the computation.

We collected publicly open data from webpages of Japanese government and electric utility companies, e.g. benchmark generation cost data, fuel costs, technology-wise generation capacities of each firm, historical hourly generation from each technology, and historical hourly demand. Coal, gas and oil are main dispatchable resources, thus, for SFE computation, we only focus on demand that is supplied by coal, gas and oil. The other technologies are excluded from our computation.

The computation was carried out based on the actual price cap of 1,000 JPY/kWh (about 9.1 USD/kWh), which resulted in much higher price level than the historical price. There could be many reasons for this, e.g. generation firms are currently not fully exercising market power, or the model assumptions may overestimate the degree of market power. One plausible scenario is that Japan is now in the process of fully deregulating the market and market players may not be matured enough (this type of learning process was shown in [4]). To calibrate the price level, we introduced what we call "implicit price cap" of 100 JPY/kWh (about 0.91 USD/kWh), which resulted in similar price level as the historical one.

Results

To illustrate the interaction between market power and carbon tax, we have calculated market clearing and resulting carbon emission based on three market assumptions, namely Marginal Cost, SFE100, and SFE1000. Marginal Cost assumes that all firms act as price takers. For this case, we just did calculations based on marginal cost functions without computing SFE. The other two cases correspond to SFE with implicit price cap of 100 JPY/kWh and SFE with actual price cap of 1000 JPY/kWh, respectively. With Marginal Cost, introducing carbon tax reduces carbon emission by about 45% due to fuel shift from coal to gas. However, with SFE100 and SFE1000, emission reduction effect becomes about a half or less because large portion of gas power plants are owned by large generation firms and, according to the model result, they try to withdraw gas capacities from the market for higher price markup and for their own profit. This behavior cannot be well captured by price taking models or symmetric SFE models.

Increasing penetration of VRE, as well as lower gas price, is considered to have negatively impacted the profitability of coal power plants in the U.S. [5]. Increase of VRE and shale gas revolution happened almost at the same time. Therefore, from historical data, it is hard to quantify which factor had how much impact. To quantitatively evaluate such impacts, we used the most plausible market assumption of SFE100 and calculated coal profitability with Base case (current VRE penetration), RPS1 case (2030 VRE target), RPS2 case (2050 VRE target), and LGP case (low gas price with one third of current gas price). The result shows that Base case with current VRE penetration level produces seemingly sufficient profit for coal plants to recover their investment costs, while LGP resulted in less than half of Base case profitability. When VRE penetration becomes the level of RPS2 case, coal profitability will be similar to LGP case. RPS1 case produced the profitability of about the middle between Base and RPS2 cases.

Conclusions

We successfully carried out asymmetric SFE computation with eight strategic firms. To the best of our knowledge, computation of asymmetric SFE has not yet been done for as many as eight firms previously. We proposed the calibration method to adjust the price level of SFE outcome by introducing “implicit price cap”. By doing so, SFE price level became the same level as historical one. Case studies were carried out with difference market assumptions and hypothetical cases. The result showed two important policy and economic implications. One is that the market power may suppress emission reduction effect of carbon tax due to asymmetric market structure. The other is that current level of VRE penetration does not have much negative impact on coal profitability compared to lower gas price, which induces structural fuel shift.

References

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