UTILITY-SCALE ENERGY STORAGE IN AN IMPERFECTLY COMPETITIVE POWER SECTOR

Vilma Virasjoki, Aalto University, vilma.virasjoki@aalto.fi
Afzal S. Siddiqui, University College London, Stockholm University, Aalto University, afzal.siddiqui@ucl.ac.uk
Fabricio Oliveira, Aalto University, fabricio.oliveira@aalto.fi
Ahti Salo, Aalto University, ahti.salo@aalto.fi

Overview

Energy storage systems' potential to mitigate intermittencies from non-dispatchable variable renewable energy sources (VRES) has enhanced their appeal. However, the impacts of storage vary based on the owner and market conditions. Specifically, storage can be valuable as a profit-making asset for power producers or merchants, while regulated entities such as transmission system operators (TSOs) or independent system operators (ISOs) could benefit from owning storage capacity in order to increase social welfare (Schill and Kemfert, 2011). Allowing for market power, Sioshansi (2014) finds instances of welfare-reducing storage arising from its strategic use. Turning to storage investment, Siddiqui et al. (2019) use a bi-level framework to compare welfare impacts of ownership and market power. They find that a merchant invests more in storage capacity than a welfare maximizer does if the market is perfectly competitive. Under Cournot oligopoly, however, the merchant invests less than the welfare maximizer does to keep price differences high and benefit from temporal arbitrage. Yet, these analyses about the impact of ownership and market power on welfare are conducted in stylized settings without realistic features of the power system, viz., transmission congestion and VRES intermittency. Detailed models of storage investment either ignore market power at the lower level and do not model a network with transmission constraints (Nasrolahpour et al., 2016) or consider transmission congestion but ignore both strategic investors and market power at the lower level (Dvorkin et al, 2018). Thus, in contrast to the extant literature, we conduct a detailed analysis of storage investment in an imperfectly competitive power sector from the perspective of either a profit- or welfare-maximizing storage owner.

Methods

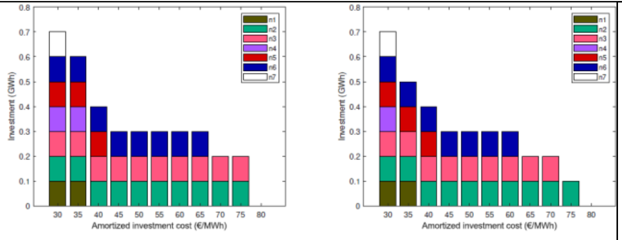
Similar to Siddiqui et al. (2019), we use a bi-level (or Stackelberg) framework in which the upper level comprises storage-investment decisions and the lower level constitutes market operations, viz., generation and storage dispatch. In particular, the upper level consists of either a profit-maximizing merchant investor or a welfare-maximizing investor that decides the size and location of storage capacity to adopt while constrained by market operations at the lower level. Our lower level is similar to that of Virasjoki et al. (2016) with (i) profit-maximizing producers who make decisions about generation (both conventional and VRES) and storage operations, (ii) a welfare-maximizing ISO that determines power flows in the system, and (iii) either profit- or welfare-maximizing storage operations that correspond to the installed capacity determined at the upper level. Market power at the lower level is reflected by allowing the producers to behave à la Cournot. We resolve this bi-level problem as a mathematical program with primal and dual constraints, which may be rendered as a mixed-integer quadratically constrained quadratic program.

Results

We use a fifteen-node Western European test network for our case study with 2017 data on generation and storage capacity, transmission topology, and VRES output (Virasjoki et al., 2016). Hourly VRES output and demand data are clustered into representative weeks (Reichenberg et al., 2018). Assuming a weekly amortized storage investment cost of €50/MWh, a welfare-maximizing investor in a perfectly competitive market (SW-PC) yields effectively the same market equilibrium as under central planning adopting 100 MWh each at nodes n2 (France) together with n3 and n6 (Belgium). This totals 300 MWh of new investment in countries with a generation mix dominated by nuclear power, which provides temporal-arbitrage opportunities from higher and more volatile electricity prices. By contrast, there is no new storage built in the Netherlands, which enjoys enough flexibility from coal and gas plants along with sufficient interconnections to neighboring countries (Figure 1a). The merchant's optimal investment strategy with a perfectly competitive generation sector (M-PC) does not differ from that of SW-PC (Figure 1b). When the competition in the lower-level market is imperfect, total investment is significantly lower as prices increase but vary less over time. A welfare maximizer under Cournot oligopoly (SW-CO) invests 100 MWh only at n1 (Germany) (Figure 2a), which may provide temporal-arbitrage opportunities due to its relatively high VRES output. Again, the merchant's profit-maximizing decision (M-CO) is identical (Figure 2b). Hence, underlying market dynamics, viz., equilibrium prices and their spatio-temporal variations, affect investment decisions more than the type of investor.

Vis-à-vis no storage adoption, storage investment increases social welfare. Under perfect competition, this actually hampers producer surplus more than the investor surplus increases, making consumers the ultimate beneficiaries. New storage decreases the ISO’s grid revenue, which is calculated as the value of net imports. Welfare effects under Cournot oligopoly are qualitatively similar, except for producers, who can also benefit from new installations. However, the effects are significantly smaller, presumably because the investment capacities are smaller and prices are flatter. The results are also sensitive to the storage cost. Under perfect competition, storage investment becomes profitable for costs below €80/MWh. The welfare maximizer and merchant invest at similar nodes but with slightly different cost thresholds (Figure 1). The welfare maximizer's investment is always greater than or equal to that of a merchant. When the investment decisions differ, there is less power-plant ramping with the higher investment of the welfare maximizer. Therefore, the increase in technical flexibility results in a higher economic efficiency.

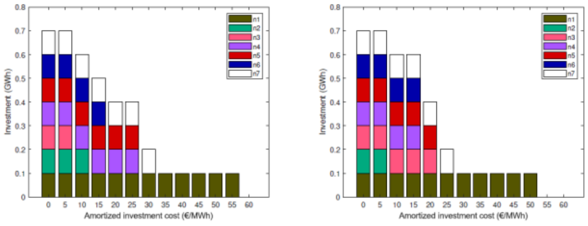
When the lower-level market is a Cournot oligopoly, the investment cost needs to be lower than that in perfect competition to trigger investment (Figure 2). Although market power increases prices, the equilibrium prices become flatter over time, which diminishes temporal-arbitrage opportunities. The optimal investment locations are also reversed: the primary one is n1 (Germany), followed by the Dutch nodes, n4, n5, and n7. These have lower equilibrium prices but more temporal variation than the others do, again perhaps due to their relatively high VRES capacities. Nevertheless, in this setting, there are differences based on the investor type. The welfare maximizer's investment is greater than or equal to that of the merchant at the higher end of the cost spectrum. However, €15/MWh provides a counterexample with the merchant's total investment of 600 MWh exceeding the 500 MWh adoption of the welfare maximizer. The merchant's investment at that specific cost also leads to less power-plant ramping but causes more congestion than the welfare maximizer's investment decision, i.e., arbitrage opportunities relocate to nodes with relatively high VRES output, where prices tend to be lower yet more volatile.



(a) Welfare-maximizing investor

(b) Profit-maximizing merchant

Figure 1. Optimal Storage Investment under Perfect Competition



(a) Welfare-maximizing investor

(b) Profit-maximizing merchant

Figure 2. Optimal Storage Investment under Cournot Oligopoly

Conclusions

We directly compare how the type of storage investor and imperfect competition affect welfare in a detailed model of a realistic power system. We find that market power affects investment more than the investor type. Perfect competition generally leads to higher investment capacity because of higher temporal price differentials, especially in nuclear-dominated Belgium and France. By contrast, Cournot oligopoly leads to higher but smoother prices, which results in storage arbitrage to be sought in Germany due to its high VRES capacity. In both market settings, the welfare maximizer generally invests in at least as much capacity as the merchant. Nevertheless, somewhat surprisingly, an imperfectly competitive electricity market with low storage-investment costs spurs a merchant to adopt more capacity, i.e., to profit from the volume of energy rather than the price differential. Although such a strategy was optimal for a merchant under perfect competition by Siddiqui et al. (2019), it arises here under Cournot oligopoly because ramping and congestion force the merchant to look to additional markets with volatile prices for arbitrage opportunities. Hence, regulators will need to understand such storage-investment incentives to devise welfare-enhancing policies.

References

Dvorkin, Y., R. Fernández-Blanco, Y. Wang, B. Xu, D.S. Kirschen, H. Pandžić, J.-P. Watson, and C.A. Silva-Monroy (2018), "Co-Planning of Investments in Transmission and Merchant Energy Storage," *IEEE Transactions on Power Systems* 33(1): 245–256.

Nasrolahpour, E., S.J. Kazempour, H. Zareipour, and W.D. Rosehart (2016), "Strategic Sizing of Energy Storage Facilities in Electricity Markets," *IEEE Transactions on Sustainable Energy* 7(4): 1462–1472.

Reichenberg, L., A.S. Siddiqui, and S. Wogrin (2018), "Policy Implications of Downscaling the Time Dimension in Power System Planning Models to Represent Variability in Renewable Output," *Energy* 159: 870–877.

Schill, W.-P. and C. Kemfert (2011), "Modeling Strategic Electricity Storage: The Case of Pumped Hydro Storage in Germany," *The Energy Journal* 32(3): 59–87.

Siddiqui, A.S., R. Sioshansi, and A.J. Conejo (2019), "Merchant Storage Investment in a Restructured Electricity Industry," *The Energy Journal* 40(4): 129–163.

Sioshansi, R. (2014), "When Energy Storage Reduces Social Welfare," *Energy Economics* 41: 106–116.

Virasjoki, V., P. Rocha, A.S. Siddiqui, and A. Salo (2016), "Market Impacts of Energy Storage in a Transmission-Constrained Power System," *IEEE Transactions on Power Systems* 31(5): 4108–4117.