FLEXIBLE SUPPLY MEETS FLEXIBLE DEMAND: THE IMPACT OF PROSUMERS ON STRATEGIC HYDRO OPERATIONS

Farzad Hassanzadeh Moghimi, Stockholm University, farzad@dsv.su.se
Yihsu Chen, University of California at Santa Cruz, yihsuchen@ucsc.edu
Afzal S. Siddiqui, Stockholm University and Aalto University, asiddiq@dsv.su.se

Overview

Climate packages envisage both steep reductions in power-sector CO_2 emissions and electrification of the wider economy. For example, the Nordic countries have pledged towards carbon neutrality (Nordic Council, 2019) with stringent measures in line with the European Union (EU) target to reduce CO_2 emissions by at least 55% by 2030 compared to 1990 levels (European Commission, 2020). Underpinning this transformation will be substantial investment in variable renewable energy (VRE) sources, such as wind and solar power. Given its intermittent output, VRE requires flexible resources, e.g., storage and demand response, to integrate it. From this perspective, the Nordic region appears well positioned due to its large hydro reservoirs and transmission links. Yet, the additional need for flexibility and the advent of aggregator-enabled prosumers, i.e., entities that both produce and consume electricity (Ramyar et al., 2020), could give hydro producers more leverage to exert market power. Here, we examine how Nordic hydro producers' ability to manipulate electricity prices via temporal arbitrage (Bushnell, 2003; Tangerås and Mauritzen, 2018) would be affected by (i) VRE-enabled prosumers and (ii) a high CO_2 price.

Methods

This paper applies a bottom-up game-theoretic framework to address strategic behaviour in the power sector. Specifically, we deploy a Nash-Cournot model over a network (Hobbs, 2001) with conventional consumers, power-producing firms, aggregator-enabled prosumers, and an independent system operator (ISO). Conventional consumers are represented passively by nodal inverse-demand curves that indicate their willingness to pay for electricity. Profit-maximising firms own portfolios of hydro, thermal, and VRE capacity in the network. Prosumers are represented by aggregators that operate VRE and decide how much of its output to sell into the electricity market. Moreover, prosumers have their own distinct inverse-demand curves that are distinct from those of conventional consumers and represent additional electricity loads stemming from electrification of the heating or transport sectors. Aggregators decide endogenously to buy or to sell electricity to maximise net-sales revenue plus gross benefit from prosumers' electricity consumption. The surplus-maximising ISO determines consumption and power flows to maintain energy balance. Finally, an exogenous CO_2 price is imposed on thermal generation.

Results

We implement the Nash-Cournot model for a 12-node, 18-line Nordic test network using publicly available data. The full dataset from 2018 includes VRE availabilities, installed generation capacities, firms' ownership, demand parameters, hydro inflows, and reservoir volumes. Four representative weeks, i.e., one for each season, are selected using a clustering procedure such that each problem instance is based on four representative weeks of 168 hours each. Besides a base 2018 scenario with a CO_2 price of €15/t, we also implement two future scenarios for 2030, i.e., 2030AV and 2030AVC, where 2030AV allows for a single aggregator at each node with its own (i) demand function and (ii) VRE capacity. Each aggregator's VRE capacity equals the VRE capacity that belongs to the firms at that node, and the demand function's parameters are tuned so that annual VRE output by each aggregrator equals annual reference consumption by prosumers. Meanwhile, the 2030AVC scenario is the same as the 2030AV scenario except for a €100/t CO_2 price. In order to investigate market power, each scenario is implemented under three test cases as follows:

- Perfect competition (PC): all firms are price takers
- Cournot oligopoly in thermal generation (COG): firms with large capacities, e.g., Vattenfall at node SE3 and Fortum at FI, behave à la Cournot in thermal plants
- Cournot oligopoly in reservoirs (COR): firms with strategic reservoirs, e.g., Vattenfall at SE1 and Norsk Hydro at NO5, behave à la Cournot in hydro generation (generation from reservoirs cannot be less than that under PC)

The results (Table 1) indicate social welfare (SW) as well as its components, viz., consumer surplus (CS), firm surplus (FS), prosumer surplus (PS), merchandising surplus (MS), and government revenue (GR). In addition, the annual CO_2 emissions (EM) and Vattenfall's FS are presented. In the base 2018 scenario, market power under either COG or COR leads to a welfare loss with a transfer from consumers to firms. Under COG, there is also a notable increase in CO_2 emissions, in part due to the withholding of nuclear capacity as Vattenfall at SE3 attempts to force price-taking thermal generators' capacity limits to become binding. By comparing PC and COR, we find that Vattenfall at SE1 transfers water from the winter and fall seasons to spring in order to manipulate prices. This is in spite of the fact that its annual net-hydro generation is regulated at SE1 to being the same as under PC with the consequence that the average price is hardly affected. Thus, Vattenfall's strategic attempt at temporal arbitrage increases prices in the winter and fall but decreases them in the spring, thereby increasing its overall FS by 1.99%.

In the 2030AV scenario, SW, EM, and prices are hardly affected vis-à-vis the base 2018 scenario. However, the benefit to Vattenfall under COG, i.e., an increase of 15.76% in its FS from PC, is relatively low in this 2030AV scenario vis-à-vis the base 2018 scenario, when its FS was boosted by 30.85%. Intuitively, the impact of market power under COG is limited because the aggregators typically switch to becoming net suppliers in all seasons in response to the withholding of output by Vattenfall. Thus, Vattenfall’s withholding its nuclear capacity to induce more price-taking thermal generation at full capacity is mitigated by aggregators’ higher net sales. Next, we focus on the extent to which market power under COR at SE1 exploits the uneven production and consumption patterns of the aggregator. This is because VRE availability and net sales by the aggregator at SE1 are highest during spring and fall, whereas conventional consumption peaks during winter and fall. Consequently, strategic behaviour with hydro reservoirs (COR) is facilitated in the 2030AV scenario since Vattenfall enjoys a 2.46% increase in its FS merely by shifting production from its reservoirs at SE1. This is done by exploiting the fact that the aggregator at SE1 is a net buyer in summer but a net seller in spring and fall under PC. In going from PC to COR, vis-à-vis the base 2018 scenario, Vattenfall withholds more (less) water in summer (fall), thereby adapting its strategy to the VRE availability pattern, which shows relatively low (high) availability in summer (fall).

In the 2030AVC scenario with a CO_2 price of €100/t, emissions decrease by nearly 90% in the PC case from that in the 2030AV scenario. The average electricity price increases from €39.32/MWh to €55.51/MWh. As a result, aggregators act as net sellers across the seasons. The increase in Vattenfall's FS from withholding nuclear output under COG is bolstered to 19.42%, cf. 15.76% in the 2030AV scenario. Intuitively, extremely high prices reduce consumption and entice net sales by aggregators even more. Furthermore, the inability of other flexible plants, viz., gas-fired plants, to respond to higher prices enhances Vattenfall’s incentive to exert market power via its nuclear plants, viz., to withhold output in order to force idle thermal plants to set the market-clearing price. The exertion of market power under COR is also more effective when firms face a high CO_2 price. In particular, Vattenfall's FS increases by 2.91% from PC to COR, cf. 2.46% in the 2030AV scenario. In effect, although the aggregator is a consistent net seller under COR in the 2030AVC scenario, Vattenfall's net-hydro generation at SE1 is also more evenly distributed among the seasons under PC in the 2030AVC scenario than in the 2030AV scenario. This is due to limited generation from price-taking, flexible units, such as gas-fired plants, which gives Vattenfall more scope to exploit the intermittency of VRE generation in spite of the aggregator's countervailing flexibility in net sales.

Table 1. Numerical results (in billion € unless indicated)

	Scenario								
	Base 2018			**2030AV**			**2030AVC**		
Case **Metric**	**PC**	**COG**	**COR**	**PC**	**COG**	**COR**	**PC**	**COG**	**COR**
SW	142.29	140.69	142.21	147.08	145.37	146.99	146.21	144.38	146.11
CS	129.45	117.47	128.94	129.33	119.41	128.81	121.16	108.10	120.38
FS	12.01	21.70	12.20	12.03	19.54	12.23	18.18	28.67	18.64
PS	-	-	-	4.69	4.78	4.69	4.77	5.24	4.78
MS	0.35	0.70	0.59	0.56	0.85	0.77	1.68	1.38	1.90
GR	0.47	0.82	0.48	0.47	0.78	0.48	0.42	0.99	0.41
EM (Mt)	31.46	54.70	32.26	31.59	51.84	31.96	4.16	9.91	4.10
Vattenfall FS	2.01	2.63	2.05	2.03	2.35	2.08	3.09	3.69	3.18

Conclusions

Using a game-theoretic framework and a detailed spatio-temporal representation of the Nordic power system, we explore how strategic operations may be affected by (i) VRE-enabled prosumers and (ii) carbon policy. We find that market power in hydro reservoirs could exploit prosumers’ patterns of net sales to conduct temporal arbitrage more effectively. Meanwhile, a higher CO_2 price would further enhance hydro reservoirs’ market power because flexible, price-taking thermal plants would be unable to check such producers’ strategy to exploit VRE’s intermittency.

References

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