INDUSTRIAL ELECTRIFICATION AND MARKET POWER IN A HYDRO-THERMAL POWER SYSTEM

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Overview

In line with the European Union (EU) target to become climate neutral by 2050 (European Commission, 2020) and in order to combat climate change, the Nordic countries have declared ambitious climate targets. Sweden, for example, has pledged to completely phase out greenhouse-gas emissions by 2045 (Naturvårdsverket, 2017). This transition to carbon neutrality requires continued investments in variable renewable energy (VRE), along with flexible generation, energy storage, and transmission lines as well as electrification of the wider economy. Due to its large hydro reservoirs and transmission links to accommodate VRE's intermittency, the Nordic region is well positioned for this transformation. Yet, the additional need for flexibility and the electrification of industrial processes, such as aluminium or H_2 production (Sundén, 2024; Tangerås et al., 2025), could give hydro and nuclear plants more leverage to exert market power. Via a game-theoretic perspective, we examine how Nordic hydro and nuclear plants' ability to manipulate electricity prices (Bushnell, 2003) would be affected by (i) fixed industrial demand and (ii) fixed onshore capacity to match the additional industrial demand.

Methods

We utilise a game-theoretic framework based on an open-loop Nash-Cournot model over a network with power-producing firms, conventional consumers, and an independent system operator (ISO) (Hassanzadeh Moghimi et al., 2023). Conventional consumers are represented by nodal inverse-demand curves indicating their willingness to pay for electricity. Profit-maximising firms own portfolios of hydro, thermal, and VRE capacity in the network. The surplus-maximising ISO determines consumption and power flows to maintain energy balance. Finally, an exogenous CO_2 price is imposed on emissions. We implement problem instances for a 12-node, 19-line Nordic test network using publicly available data. The full dataset from 2023 includes VRE availabilities, installed generation capacities, firms' ownership, demand parameters, hydro inflows, and reservoir volumes. A clustering procedure is used to select a representative week for each season, such that each problem instance is based on four representative weeks of 168 hours each. Besides a Baseline 2023 scenario, we also implement two future scenarios, viz., Future NE (no expansion) and Future ME (matching expansion). The former builds on Baseline 2023 by introducing a cost-minimising, price-taking industrial consumer with a fixed minimum annual demand of 14 TWh in each of the zones SE1 and SE3 and with limited consumption flexibility. Future ME is identical to Future NE but matches industrial demand with increased onshore-wind capacity, exogenously allocated to small price-taking firms, in zones SE1 and SE3. To investigate the exercise of market power, each scenario is implemented under three cases:

- Perfect competition (PC): all firms are price takers,
- Cournot oligopoly in thermal generation (COG): firms with large nuclear capacities e.g., Vattenfall in zone SE3 and Fortum in FI, behave à la Cournot in thermal plants,
- Cournot oligopoly in reservoirs (COR): firms with strategic reservoirs, e.g., Vattenfall in SE1 and Statkraft in NO4, behave à la Cournot in hydro generation (annual net reservoir generation cannot be less than that under PC).

Results

The results (Table 1) indicate the total social welfare (SW), consisting of consumer surplus (CS), producer surplus (PS), merchandising surplus (MS), cost of electricity purchases by industrial consumers (HC), and government revenue (GR). The annual CO_2 emissions (EM), Vattenfall's PS, and the average price (AP) are also included. Comparing PC to both COG and COR in Baseline 2023 shows an overall shift from CS to PS along with a welfare loss when firms behave strategically. In the case of COG, the possibility of market power by nuclear plants leads to a mild loss in overall welfare but with considerable transfers from consumers to producers. When nuclear plants withhold their output, price-taking fossil-fuelled plants are forced to become marginal producers, thereby clearing the market at a higher equilibrium price. Thus, the average price increases from €59.11/MWh under PC to €66.56/MWh, while total generation decreases by 5%. Such market power specifically benefits Vattenfall's PS with an increase of 19.10%. Under COR, we find that Vattenfall uses its SE1 reservoirs to increase production in the milder spring and summer seasons, which creates scarcity in the winter. By shifting production between seasons to increase peak prices, Vattenfall obtains an extra surplus of 3.37% compared to PC even though the price falls in the off-peak seasons.

In Future NE under PC, the average Nordic electricity price increases by 14% compared to the corresponding case in Baseline 2023. The higher prices result from the inflexible industrial demand, as it requires allocation of the lowestcost resource, i.e., VRE, when available, which, in turn, leads to a reduction of 7% in conventional consumption. Although producers enjoy higher surpluses compared to those in Baseline 2023, they are more constrained in their ability to exert market power. One reason for this limited room for manoeuvre is the already high price under PC, which increases the opportunity cost of lost revenue from withholding output. More specifically, under COG, it is less effective for Vattenfall to reduce generation from its nuclear plants to force more costly plants to be dispatched because the earmarking of VRE to meet industrial demand already leads to expanded output from fossil-fuelled plants. Thus, the potential for nuclear plants to exert market power is reduced. In a similar vein, hydro reservoirs under COR have less flexibility to exploit market power in Future NE. In effect, temporal arbitrage to reduce winter output incurs greater losses from forgone sales, while releasing water in the off-peak seasons could lead to relatively high revenue losses, as the average seasonal prices are already high and would be depressed by this "dumping" of water.

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

	Scenario								
	Baseline 2023			**Future NE**			**Future ME**		
Case / Metric	**PC**	**COG**	**COR**	**PC**	**COG**	**COR**	**PC**	**COG**	**COR**
SW	62.74	62.54	62.44	61.65	61.36	61.31	62.10	61.88	61.76
CS	43.65	40.87	42.26	41.01	39.13	39.68	43.53	40.85	41.85
PS	15.89	18.53	17.15	19.62	21.41	20.80	16.63	19.37	18.19
MS	2.91	2.78	2.70	2.26	2.20	2.09	2.79	2.74	2.64
GR	0.30	0.36	0.33	0.32	0.37	0.36	0.31	0.37	0.33
HC	-	-	-	1.56	1.76	1.62	1.16	1.44	1.25
EM (Mt)	3.59	4.30	3.91	3.78	4.48	4.35	3.70	4.41	3.98
Vattenfall PS	1.78	2.12	1.84	2.89	2.92	2.91	1.91	2.19	2.01
AP (€/MWh)	59.11	66.56	62.17	67.50	73.18	70.70	59.56	66.68	63.47

In Future ME, the matching of VRE capacity to meet industrial demand restores the social welfare and lowers the average price to the level of Baseline 2023. Consequently, total generation under PC increases by 27 TWh compared to that in Baseline 2023, which nearly covers the industrial demand of 28 TWh. Although this future power system is on aggregate in balance, its reliance on a higher proportion of intermittent VRE partially restores the potential for exerting market power. Specifically, under COG, Vattenfall increases its PS by 14.66% from PC by withholding production from its nuclear plants, and while this payoff from market power is greater than in Future NE, it is not as advantageous as in Baseline 2023. The slightly diminished reward for strategic behaviour could be due to the increased intermittency introduced by expanded VRE capacity, which leads to a likelihood of surplus onshore-wind production during the peak winter season. In turn, it becomes more challenging for nuclear plants to withhold production in order to trigger fossil-fuelled plants to set the market-clearing price. By contrast, under COR, temporal arbitrage yields an increase in PS of 5.24% from PC for Vattenfall, cf. 3.37% in Baseline 2023. In tailoring its reservoir-enabled hydro production in SE1 to withhold more during fall and less during winter compared to Baseline 2023, Vattenfall exploits the relative scarcity in fall and surplus in winter rendered by the introduction of additional onshore-wind capacity.

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) increased industrial demand and (ii) matching expansion of onshore-wind power. We find that increased electrification, modelled by fixed industrial demand, diminishes firms' market power but simultaneously leads to a higher average price. Meanwhile, matching the electricity need of industrial demand with onshore-wind capacity lowers the overall price level but reintroduces market power. Interestingly, hydro reservoirs are able to bolster their payoff from the exercise of temporal arbitrage by exploiting seasonal imbalances engendered by the introduction of relatively inflexible industrial demand and VRE capacity.

References

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