Aggregator-Enabled Prosumers' Impact on Strategic Hydro-Thermal Operations

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Abstract

Climate packages envisage decarbonization of the power system and electrification of the wider economy via variable renewable energy (VRE). These trends facilitate the rise of aggregator-enabled prosumers and engender demand for flexibility. By exploiting conducive geography, e.g., in the Nordic region, hydro reservoirs can mitigate VRE's intermittency. Nevertheless, hydro producers may leverage this increased need for flexibility to exert market power through temporal arbitrage. Using a Nash-Cournot model, we examine how aggregator-enabled prosumers with endogenous loads and VRE capacity interact with other agents to affect market outcomes. Based on Nordic data, we find that hydro producers enhance their market power by shifting their production away from periods in which prosumers are net buyers and "dumping" their output during periods in which prosumers are net sellers. Hence, jurisdictions that rely upon (hydro) storage to integrate VRE from prosumers will need to be wary of incumbent firms' incentives to manipulate prices.

Keywords: Market power, game theory, wind power, prosumers, hydro reservoirs.

Nomenclature

Indices and Sets

$e \in \mathcal{E}$: Variable renewable energy (VRE) sources.
$i \in \mathcal{I}$: Firms (producers).
$j \in \mathcal{J}$: Aggregators.
$\ell \in \mathcal{L}$: Transmission lines.
$\ell^{\text{AC}} \in \mathcal{L}^{\text{AC}} \subset \mathcal{L}$: AC transmission lines.
$\mathcal{L}_n^+, \mathcal{L}_n^-$: Transmission line starting/ending at node n.
$n \in \mathcal{N}$: Nodes.
$n^{\text{AC}} \in \mathcal{N}^{\text{AC}} \subset \mathcal{N}$: AC nodes.
n_ℓ^+, n_ℓ^-: Node index for starting/ending node of transmission line ℓ.
$t \in \mathcal{T}$: Time periods.
$u \in \mathcal{U}_{i,n}$: Thermal units of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$.
$w \in \mathcal{W}_{i,n}$: Hydro units of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$.

Parameters

$B_{\ell^{AC}}$: Susceptance of AC line $\ell^{AC} \in \mathcal{L}^{AC}$ (S).
$C_{i,n,t,u}$: Generation cost of thermal unit $u \in \mathcal{U}_{i,n}$ at node $n \in \mathcal{N}$ for firm $i \in \mathcal{I}$ at time $t \in \mathcal{T}$ (€/MWh).
$D^{\text{int}}_{n,t}$: Intercept of linear inverse-demand curve at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh).
$D^{\text{slp}}_{n,t}$: Slope of inverse-demand curve at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh^2).
$D^{\text{int,agg}}_{j,n,t}$: Intercept of marginal utility of aggregator $j \in \mathcal{J}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh).
$D^{\text{slp,agg}}_{j,n,t}$: Slope of marginal utility of aggregator $j \in \mathcal{J}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh^2).
$E^{\text{sto}}_{i,n,w}$: Efficiency of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (m^3/m^{3}h).
$F_{i,n,w}$: Pumped-hydro efficiency of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MWh/m^3).
$\overline{G}_{i,n,u}$: Maximum generation capacity of thermal unit $u \in \mathcal{U}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW).
$G^e_{i,n,t}$: Exogenous output of VRE type $e \in \mathcal{E}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (MWh).
$G^{e,\text{agg}}_{j,n,t}$: Exogenous output of VRE type $e \in \mathcal{E}$ of aggregator $j \in \mathcal{J}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (MWh).
$I_{i,n,t,w}$: Natural inflow to hydro unit $w \in \mathcal{W}_{i,n}$ of firm i at node n in period t (m^3).
$\overline{K}_\ell / \underline{K}_\ell$: Capacity of line $\ell \in \mathcal{L}$ in positive/negative direction (MW).
$P_{i,n,u}$: CO_2 emission rate of thermal unit $u \in \mathcal{U}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (t/MWh).
$Q_{i,n,w}$: Efficiency of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MWh/m^3).

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$\overline{R}_{i,n,w}$/$\underline{R}_{i,n,w}$: Maximum/minimum storage capacity of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (m^3).
$R^{\text{in}}_{i,n,w}$: Maximum charging rate of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (m^3/m^3h).
R^{up}_u/R^{down}_u: Ramp-up/-down limit of thermal unit $u \in \mathcal{U}_{i,n}$ (–).
S: Price of CO_2 emission permits (€/t).
T_t: Duration of period t (h).
V: Scaling factor for power flow (–).
$Y_{i,n,w}$: Maximum generation capacity of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW).
$Z_{i,n}$: Regulation of net-hydro reservoir generation for firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MWh).

Primal Variables

$f_{\ell,t}$: Power flow on line $\ell \in \mathcal{L}$ at time $t \in \mathcal{T}$ (MW).
$g_{i,n,t,u}$: Generation by thermal unit $u \in \mathcal{U}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (MWh).
$q_{n,t}$: Consumers' quantity demanded at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (MWh).
$q^{\text{agg}}_{j,n,t}$: Aggregator $j \in \mathcal{J}$'s quantity demanded at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (MWh).
$r^{\text{in}}_{i,n,t,w}$: Volume of water pumped into hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (m^3).
$r^{\text{sto}}_{i,n,t,w}$: Volume of water stored in hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (m^3).
$v_{n,t}$: Voltage angle of node $n^{AC} \in \mathcal{N}^{\mathcal{AC}}$ at time $t \in \mathcal{T}$ (rad).
$y_{i,n,t,w}$: Volume of water turbined from hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (m^3).
$z_{i,n,t,w}$: Volume of water spilled from hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (m^3).

Dual Variables

$\beta_{i,n,t,u}$: Shadow price of generation capacity of thermal unit $u \in \mathcal{U}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh).
$\beta^{\text{up}}_{i,n,t,u}$/$\beta^{\text{down}}_{i,n,t,u}$: Shadow price of ramp-up/-down limit of thermal unit $u \in \mathcal{U}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh).
$\gamma_{i,n}$: Shadow price of hydro regulation for firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (€/MWh).
$\eta_{\ell^{AC},t}$: Shadow price of energy flow on AC line $\ell^{AC} \in \mathcal{L}^{AC}$ at time $t \in \mathcal{T}$ (€/MWh).
$\theta_{n,t}$: Shadow price of market-clearing condition at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh).
$\overline{\kappa}_{n^{AC},t}$/$\underline{\kappa}_{n^{AC},t}$: Shadow price of maximum/minimum voltage angle at node $n^{AC} \in \mathcal{N}^{AC}$ at time $t \in \mathcal{T}$ (€/rad).
$\lambda^{\text{bal}}_{i,n,t,w}$: Shadow price of water stored in hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/m^3).
$\lambda^{\text{in}}_{i,n,t,w}$: Shadow price of charging rate of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/m^3).
$\lambda^{\text{h}}_{i,n,t,w}$: Shadow price of turbine capacity of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/MWh).
$\lambda^{\text{ub}}_{i,n,t,w}$/$\lambda^{\text{lb}}_{i,n,t,w}$: Shadow price of maximum/minimum capacity of hydro unit $w \in \mathcal{W}_{i,n}$ of firm $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ at time $t \in \mathcal{T}$ (€/m^3).
$\overline{\mu}_{\ell,t}$/$\underline{\mu}_{\ell,t}$: Shadow price of positive/negative capacity of line $\ell \in \mathcal{L}$ at time $t \in \mathcal{T}$ (€/MWh).

1. Introduction

1.1. Background

The Nordic countries have pledged toward carbon neutrality[1] with stringent measures by 2030 in line with the European Union (EU) target to have at least a 55% reduction in CO_2 emissions compared to 1990 levels.[2] Such measures inevitably involve the integration of variable renewable energy (VRE) via the region's flexible resources, viz., hydro reservoirs. Given its large hydro reservoirs and tight integration, the Nordic region is well positioned to absorb VRE capacity, which is a lynchpin of most decarbonization pathways. Nevertheless, profit-maximizing power companies may deploy flexible resources strategically, which would conflict with society's objective to maximize social welfare. Furthermore, the shift of the power sector toward a more active demand side, caused by the electrification of the wider economy, could lead to the advent of entities called prosumers, i.e., agents that both generate and consume electricity as opposed to conventional producers or consumers. Here, we examine how aggregator-enabled prosumers' endogenous decisions to be net buyers or net sellers of electricity (Ramyar et al., 2020) would affect hydro producers' manipulation of electricity prices via temporal arbitrage (Bushnell, 2003; Tangerås & Mauritzen, 2018).

1.2. Literature Review

The anticipated dominance of VRE capacity would make flexible resources an integral part of power-system operations. Its ability to store and move excess energy to periods of scarcity renders (hydro) storage particularly attractive in compensating for VRE's intermittency. However, *strategic (hydro) storage* yields additional leverage for temporal arbitrage to profit-maximizing firms whose objectives are not aligned with welfare maximization (Hassanzadeh Moghimi et al., 2023).

[1] https://www.norden.org/en/declaration/declaration-nordic-carbon-neutrality
[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020PC0563

Indeed, analysis of strategic hydro operations via a stylized model has illustrated that Cournot producers tend to allocate more of their production during off-peak periods compared to price-taking ones (Crampes & Moreaux, 2001). On a related note, a case study of the California hydro-thermal power system reports a similar pattern for strategic reservoir operations (Bushnell, 2003). A Nash-Cournot model of pumped-hydro operations (Schill & Kemfert, 2011) reveals that strategic storage use coupled with ownership of generation capacity can result in welfare losses compared to the no-storage case. Moreover, generic storage operations' welfare impact is investigated rigorously for both perfect (Sioshansi, 2010) and imperfect competition (Sioshansi, 2014).

Future decarbonization pathways also envisage electrification of the wider economy, which may spur the rise of a new entity called the prosumer. With modest generation capacities, individual prosumers are unlikely to be price-making participants. However, to unleash their full potential, prosumers can be represented through aggregators (Bahramara et al., 2018). The consequences of such a transition are investigated via a bottom-up complementarity framework that focuses on *prosumers' strategic behavior* when conventional producers and consumers are price takers (Ramyar et al., 2020). By considering the interplay between a prosumer's decisions and the price-taking agents, it is shown that the prosumer can manipulate market prices by acting strategically as a buyer (seller) to lower (to increase) prices. Also, the impact of the increasing number of aggregator-enabled prosumers on the aggregator's strategic behavior is examined through a bi-level problem (Xiao et al., 2020). It has been demonstrated that the gap between strategic and non-strategic bidding can be greatly enlarged by having more aggregation of prosumers. Nonetheless, the model does not reflect the strategic behavior of incumbent agents such as large power companies with flexible assets that can exploit intermittent VRE output.

Since small-scale aggregated prosumers with modest market shares compared to those of established power-generating firms cannot yet impact market prices, several papers have explored *prosumers' price-taking behavior*. Parvania et al. (2013) develop an optimization framework for market participation of a demand-response (DR) aggregator. The aggregator maximizes its payoff in the day-ahead market while offering several contracts to consumers for curtailment and load shifting. Similarly, an optimal bidding strategy for a microgrid is presented in Liu et al. (2015). Utilizing hybrid stochastic/robust optimization and exogenous forecasted prices, the expected net cost of the microgrid is minimized.

In effect, the extant literature analyzes either (i) strategic behavior by prosumers or (ii) optimal decisions by prosumers under uncertainty given exogenous electricity prices. The *research gap* stems from how flexible incumbent producers, such as those with large hydro reservoirs, could exploit the presence of prosumers with inflexible VRE output and endogenous consumption.[3] Hence, aggregator-enabled prosumers in a hydro-dominated power system, such as the Nordic one, could alter power companies' leverage, the extent of which has not been studied.

1.3. Research Objectives and Contribution

Given this research gap, we examine a hydro-thermal power system's operations by considering firms' strategic behavior. Next, we allow for aggregator-enabled prosumers in order to assess how they affect the strategic operation of reservoirs.

We employ a Nash-Cournot model with a stylized representation of the transmission network, intermittent VRE output, and reservoir constraints. First, we address strategic operations without prosumers by implementing three case studies in which either all firms are perfectly competitive (PC), firms behave à la Cournot in thermal generation (COG), or hydro-reservoir owners behave à la Cournot (COR). Using data from the Nordic grid, we find that the production of hydro units under PC follows the consumption pattern, i.e., higher output occurs during peak periods. While strategic use of thermal generation (COG) leads to reduction of social welfare (SW) and consumer surplus (CS), CO_2 emissions are reduced by over 50% as a result of withholding by thermal units. By contrast, strategic use of hydro reservoirs (COR) has a modest impact on SW and CS because total net-hydro production remains unchanged. Nevertheless, the hydro-owning firm enjoys an increase in its firm surplus (FS) as its temporal arbitrage increases peak prices while reducing the off-peak ones by shifting production away from peak periods (Bushnell, 2003).

Next, we run all three cases in a scenario where aggregator-enabled prosumers own VRE capacity with an exogenous availability profile and endogenous consumption. The introduction of prosumers reduces the average market price at the local node but increases average prices at the other nodes due to their net purchases during some periods. Moreover, the aggregator-enabled prosumers' interaction with the market varies with respect to the prices in the market. For instance, they tend to sell more when the prices are higher under COG, thereby stymieing the thermal producer's exercise of market power. In effect, although

[3] Here, aggregator-enabled prosumers reflect a future power system with an entirely new type of agent that both generates from (inflexible) VRE and brings additional (flexible) loads stemming from the electrification of other sectors, viz., heating and transportation. In effect, the prosumers' objective function captures both gross benefit (or utility) from consumption and the revenue from net sales.

welfare losses are greater when the thermal producer exerts market power under COG as opposed to when the hydro producer exerts market power under COR, the *relative* impact of market power by the hydro producer is bolstered in the Agg100 scenario (due to the advent of prosumers) vis-à-vis the NA scenario. In fact, under COR, periods of relative VRE excess/scarcity enable the hydro producer to shift its reservoir output with greater precision, thereby enhancing its aforementioned temporal arbitrage to take advantage of intermittent net sales by the aggregator. Hence, aggregator-enabled prosumers with intermittent VRE output and flexible demand facilitate a strategic hydro producer's market power.

The rest of this paper is organized as follows. Section 2 outlines the framework for analysis along with the detailed mathematical formulation. Numerical examples are presented in Section 3. Finally, the results and findings are summarized in Section 4, while the Karush-Kuhn-Tucker (KKT) conditions for the optimization problems are in the Appendices.

2. Methodology

We use a bottom-up equilibrium model in which power-generating firms, an independent system operator (ISO), and aggregators play a Nash-Cournot game over a network (Hobbs, 2001). A DC load-flow approximation is utilized to model the transmission network. Consumers are implicitly represented by inverse-demand functions, $D^{\text{int}}_{n,t} - D^{\text{slp}}_{n,t} q_{n,t}$. Profit-maximizing firms' hydro, thermal, and VRE units are restricted by operational, storage, and water-regulatory constraints. Separately, aggregators own VRE capacity and have gross benefit functions for consumption. Their decision to buy or sell electricity is determined endogenously and depends on their objective to maximize net revenue from market interaction plus their gross benefit from consumption. VRE output intermittency is captured through a historical time series that reflects generation relative to installed capacity. A surplus-maximizing ISO determines consumption and power flows to maintain nodal energy balance. In contrast to Chen and Hobbs (2005), an exogenous CO_2 price is imposed on emissions.

2.1. Firm i's Problem

Firm $i \in \mathcal{I}$ is a profit maximizer that may own hydro, thermal, and VRE units at node $n \in \mathcal{N}$, which are denoted by $w \in \mathcal{W}_{i,n}$, $u \in \mathcal{U}_{i,n}$, and $e \in \mathcal{E}_{i,n}$ respectively. Thus, the two main parts of its objective function (1) are the revenue from net-energy sales, $\sum_{u \in \mathcal{U}_{i,n}} g_{i,n,t,u} + \sum_{e \in \mathcal{E}_{i,n}} G^{e}_{i,n,t} + \sum_{w \in \mathcal{W}_{i,n}} \left(Q_{i,n,w} y_{i,n,t,w} - F_{i,n,w} r^{\text{in}}_{i,n,t,w}\right)$, based on the nodal electricity price, $D^{\text{int}}_{n,t} - D^{\text{slp}}_{n,t} q_{n,t}$, and the costs of operation and CO_2 emissions, $\sum_{u \in \mathcal{U}_{i,n}} \left(C_{i,n,t,u} + SP_{i,n,u}\right) g_{i,n,t,u}$. The price of CO_2 emission permits, S, is taken as exogenous by each firm.

Following the Nash assumption, each firm takes the decisions of all other firms, all aggregators, and the ISO as given. In case of market power, total quantity demanded, $q_{n,t}$, in firm i's objective function (1) would not be exogenous since it would be affected by its own decisions, cf. (11). For sake of clarity, KKT conditions (A-1), (A-4), and (A-5) are written to reflect market power in both thermal and hydro generation.

$$\max_{\Gamma^{i}} \sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}} \Bigg[\left(D^{\text{int}}_{n,t} - D^{\text{slp}}_{n,t} q_{n,t}\right) \Bigg(\sum_{u \in \mathcal{U}_{i,n}} g_{i,n,t,u} + \sum_{e \in \mathcal{E}_{i,n}} G^{e}_{i,n,t} + \sum_{w \in \mathcal{W}_{i,n}} Q_{i,n,w} y_{i,n,t,w} - \sum_{w \in \mathcal{W}_{i,n}} F_{i,n,w} r^{\text{in}}_{i,n,t,w} \Bigg) - \sum_{u \in \mathcal{U}_{i,n}} \left(C_{i,n,t,u} + SP_{i,n,u}\right) g_{i,n,t,u} \Bigg] \quad (1)$$

$$\text{s.t. } g_{i,n,t,u} \leq T_t \overline{G}_{i,n,u} : \beta_{i,n,t,u}, \forall n,t,u \in \mathcal{U}_{i,n} \quad (2)$$

$$\beta^{\text{down}}_{i,n,t,u} : -T_t R^{\text{down}}_{u} \overline{G}_{i,n,u} \leq g_{i,n,t,u} - g_{i,n,t-1,u} \leq T_t R^{\text{up}}_{u} \overline{G}_{i,n,u} : \beta^{\text{up}}_{i,n,t,u}, \forall n,t,u \in \mathcal{U}_{i,n} \quad (3)$$

$$r^{\text{sto}}_{i,n,t,w} = \left(1 - E^{\text{sto}}_{i,n,w}\right)^{T_t} r^{\text{sto}}_{i,n,t-1,w} + r^{\text{in}}_{i,n,t,w} - y_{i,n,t,w} - z_{i,n,t,w} + I_{i,n,t,w} : \lambda^{\text{bal}}_{i,n,t,w}, \forall n,t,w \in \mathcal{W}_{i,n} \quad (4)$$

$$\lambda^{\text{lb}}_{i,n,t,w} : \underline{R}_{i,n,w} \leq r^{\text{sto}}_{i,n,t,w} \leq \overline{R}_{i,n,w} : \lambda^{\text{ub}}_{i,n,t,w}, \forall n,t,w \in \mathcal{W}_{i,n} \quad (5)$$

$$r^{\text{in}}_{i,n,t,w} \leq T_t R^{\text{in}}_{i,n,w} \overline{R}_{i,n,w} : \lambda^{\text{in}}_{i,n,t,w}, \forall n,t,w \in \mathcal{W}_{i,n} \quad (6)$$

$$Q_{i,n,w} y_{i,n,t,w} \leq T_t Y_{i,n,w} : \lambda^{\text{h}}_{i,n,t,w}, \forall n,t,w \in \mathcal{W}_{i,n} \quad (7)$$

$$\sum_{t \in \mathcal{T}} \sum_{w \in \mathcal{W}_{i,n}} \left(Q_{i,n,w} y_{i,n,t,w} - F_{i,n,w} r^{\text{in}}_{i,n,t,w}\right) \geq Z_{i,n} : \gamma_{i,n}, \forall n \quad (8)$$

where $\Gamma^{i} = \{g_{i,n,t,u} \geq 0, r^{\text{sto}}_{i,n,t,w} \geq 0, r^{\text{in}}_{i,n,t,w} \geq 0, y_{i,n,t,w} \geq 0, z_{i,n,t,w} \geq 0\}$. Associated dual variables are expressed along with each constraint. (2) indicates the generation limits of thermal units, while (3) represents their ramp limits. Constraints (4)–(6) account for hydro storage balance, bounds on reservoir capacities, and the limit on pumped-hydro storage charging. Moreover, the generation capacity of hydro units is considered in (7). Finally, (8) is used in Cournot settings to ensure that storage-enabled hydro units at nodes where the firm is strategic produce at least as much cumulative net energy as under perfect competition.

2.2. Aggregator j's Problem

The objective function of aggregator $j \in \mathcal{J}$ in (9) comprises (i) the revenue/expenses from market interactions and (ii) the gross benefit from endogenous consumption.[4] Similar to the firm's problem, each aggregator takes the decisions of all other aggregators, all firms, and the ISO as given.

$$\max_{\Gamma^{\mathrm{j}}} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \Bigg[(D^{\mathrm{int}}_{n,t} - D^{\mathrm{slp}}_{n,t} q_{n,t}) \left(\sum_{e\in\mathcal{E}} G^{e,\mathrm{agg}}_{j,n,t} - q^{\mathrm{agg}}_{j,n,t} \right) + D^{\mathrm{int,agg}}_{j,n,t} q^{\mathrm{agg}}_{j,n,t} - \frac{1}{2} D^{\mathrm{slp,agg}}_{j,n,t} \left(q^{\mathrm{agg}}_{j,n,t}\right)^2 \Bigg] \quad (9)$$

where $\Gamma^{\mathrm{j}} = \{q^{\mathrm{agg}}_{j,n,t} \geq 0\}$.

2.3. ISO's Problem

The ISO is responsible for maximizing gross consumer surplus (10) and clearing of the energy market.[5] The ISO considers the decisions of the firms and aggregators as given, while it selects the system's power flows, $f_{\ell,t}$, voltage angles, $v_{n^{AC},t}$, and consumption, $q_{n,t}$, to keep nodal energy balance.

$$\max_{\Gamma^{\mathrm{ISO}}} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left(D^{\mathrm{int}}_{n,t} q_{n,t} - \frac{1}{2} D^{\mathrm{slp}}_{n,t} q^2_{n,t} \right) \quad (10)$$

$$\text{s.t. } q_{n,t} = \sum_{i\in\mathcal{I}} \sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + \sum_{i\in\mathcal{I}} \sum_{e\in\mathcal{E}} G^{e}_{i,n,t} + \sum_{i\in\mathcal{I}} \sum_{w\in\mathcal{W}_{i,n}} (Q_{i,n,w} y_{i,n,t,w} - F_{i,n,w} r^{\mathrm{in}}_{i,n,t,w}) + \sum_{j\in\mathcal{J}} \sum_{e\in\mathcal{E}} G^{e,\mathrm{agg}}_{j,n,t} - \sum_{j\in\mathcal{J}} q^{\mathrm{agg}}_{j,n,t} - \sum_{\ell\in\mathcal{L}^{+}_{n}} V\, T_t f_{\ell,t} + \sum_{\ell\in\mathcal{L}^{-}_{n}} V\, T_t f_{\ell,t} : \theta_{n,t}, \forall n,t \quad (11)$$

$$T_t f_{\ell^{\mathrm{AC}},t} = T_t B_{\ell^{\mathrm{AC}}} \left(v_{n^{+}_{\ell},t} - v_{n^{-}_{\ell},t} \right) : \eta_{\ell^{\mathrm{AC}},t}, \quad \forall \ell^{\mathrm{AC}} \in \mathcal{L}^{\mathrm{AC}}, t \quad (12)$$

$$\underline{\mu}_{\ell,t} : -T_t \underline{K}_{\ell} \leq V T_t f_{\ell,t} \leq T_t \overline{K}_{\ell} : \overline{\mu}_{\ell,t}, \quad \forall \ell, t \quad (13)$$

$$\underline{\kappa}_{n^{\mathrm{AC}},t} : -\pi \leq v_{n^{\mathrm{AC}},t} \leq \pi : \overline{\kappa}_{n^{\mathrm{AC}},t}, \quad \forall n^{\mathrm{AC}} \in \mathcal{N}^{\mathrm{AC}}, t \quad (14)$$

where $\Gamma^{\mathrm{ISO}} = \{q_{n,t} \geq 0, f_{\ell,t} \text{ u.r.s.}, v_{n^{AC},t} \text{ u.r.s.}\}$ and "u.r.s." refers to "unrestricted in sign." The energy-balance constraint in (11) ensures that net generation plus net imports equals consumption at each node and period. AC lines in the network are modeled via DC load flow (12) and limits on nodal voltage angles (14) with lines' thermal capacities given by (13).

2.4. Solution Approach

Under the Nash assumption, each agent takes the decisions of all other agents as fixed. Firms may exert market power as Cournot agents, i.e., they internalize the impact of only their own decisions on the equilibrium price. Since the problem of each agent is convex, it may be replaced by its KKT conditions. A Nash equilibrium arises when each agent satisfies its KKT conditions and has no incentive to deviate unilaterally from the solution. We obtain computational solutions by reformulating the resulting mixed-complementarity problem (MCP) as a quadratic program (QP) (Hashimoto, 1985).

By taking the KKT conditions of the convex optimization problems (1)–(8), $\forall i \in \mathcal{I}$, (9), $\forall j \in \mathcal{J}$, and (10)–(14), the equilibrium problem can be rendered as an MCP, i.e., (A-1)-(A-14), $\forall i \in \mathcal{I}$, (B-1), $\forall j \in \mathcal{J}$, and (C-1)-(C-9), and further recast as a single-agent QP (Hobbs, 2001). An extended-cost term, $-\frac{D^{\mathrm{slp}}_{n,t}}{2} \sum_{i\in\mathcal{I}} (\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + \sum_{w\in\mathcal{W}_{i,n}} (Q_{i,n,w} y_{i,n,t,w} - F_{i,n,w} r^{\mathrm{in}}_{i,n,t,w}))^2$, in the QP's objective function (15) can take market power into account,[6] and problem instances are readily tackled by

[4] Aggregator-enabled prosumers have VRE output, $\sum_{e\in\mathcal{E}} G^{e,\mathrm{agg}}_{j,n,t}$, and their decision variable is how much electricity to consume, $q^{\mathrm{agg}}_{j,n,t}$. Thus, $\sum_{e\in\mathcal{E}} G^{e,\mathrm{agg}}_{j,n,t} - q^{\mathrm{agg}}_{j,n,t}$ is the aggregator's net sales, which could be its net purchases if the expression is negative. The net revenue from such market transactions is accounted for at the equilibrium price, $D^{\mathrm{int}}_{n,t} - D^{\mathrm{slp}}_{n,t} q_{n,t}$, and is the first component of the aggregator's objective function in (9). Next, its gross benefit from electricity consumption is quantified via a quadratic function, $D^{\mathrm{int,agg}}_{j,n,t} q^{\mathrm{agg}}_{j,n,t} - \frac{1}{2} D^{\mathrm{slp,agg}}_{j,n,t} \left(q^{\mathrm{agg}}_{j,n,t}\right)^2$, which captures the diminishing marginal utility from incremental consumption (Ramyar et al., 2020).

[5] In fact, the ISO conducts a welfare-maximizing redispatch in adjusting consumption and transmission flows (Tanaka, 2009). However, since the cost of generation depends on decision variables that are not under the ISO's control, they are taken as given by the ISO, i.e., the Nash assumption. Thus, the ISO effectively maximizes gross consumer surplus.

[6] The derivative of the extended cost with respect to $g_{i,n,t,u}$ is $-D^{\mathrm{slp}}_{n,t}(\sum_{u'\in\mathcal{U}_{i,n}} g_{i,n,t,u'} + \sum_{w\in\mathcal{W}_{i,n}} (Q_{i,n,w} y_{i,n,t,w} -$

commercial solvers such as CPLEX.[7]

$$\max_{\Gamma} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \Bigg[D^{\text{int}}_{n,t} q_{n,t} - \frac{1}{2} D^{\text{slp}}_{n,t} q^2_{n,t}$$

$$+ \sum_{j\in\mathcal{J}} \left(D^{\text{int,agg}}_{j,n,t} q^{\text{agg}}_{j,n,t} - \frac{1}{2} D^{\text{slp,agg}}_{j,n,t} \left(q^{\text{agg}}_{j,n,t}\right)^2 \right)$$

$$- \sum_{i\in\mathcal{I}} \frac{D^{\text{slp}}_{n,t}}{2} \left(\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} \right.$$

$$\left. + \sum_{w\in\mathcal{W}_{i,n}} \left(Q_{i,n,w} y_{i,n,t,w} - F_{i,n,w} r^{\text{in}}_{i,n,t,w}\right) \right)^2$$

$$- \sum_{i\in\mathcal{I}} \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,t,u} + SP_{i,n,u}\right) g_{i,n,t,u} \Bigg] \quad (15)$$

s.t. (2) – (8), $\forall i \in \mathcal{I}$
(11) – (14)

where Γ comprises $\Gamma^{\text{i}}, \forall i \in \mathcal{I}$, $\Gamma^{\text{j}}, \forall j \in \mathcal{J}$, and Γ^{ISO}.

3. Numerical Examples

3.1. Data

A three-node test system (Fig. 1) implements three test cases, viz., PC, COG, and COR,[8] to investigate strategic behavior. A reference scenario, NA, runs the three cases without aggregators and VRE in order to establish a baseline for the exercise of market power. The other scenario, Agg100, includes an aggregator $j1$ at node $n3$ with 100 MW of wind capacity and a gross benefit function. Thus, the Agg100 scenario enables quantification of market power in a future power system. Firm $i1$ operates 378 MW of hydro capacity at node $n1$, while firm $i2$ has 50 MW each of thermal capacity at nodes $n2$ and $n3$ with operating costs of €32/MWh and €48/MWh, respectively. Their emission rates are 0.83 t/MWh and 0.37 t/MWh at nodes $n2$ and $n3$, respectively, i.e., node $n2$ ($n3$) has coal- (gas-) fired capacity. Firm $i1$'s hydro resource comprises solely 1,260 MWh of energy stored in a reservoir that can be used over the 168-hour time horizon, i.e., one week, without exogenous inflows.[9] Moreover, in order to capture the efficiency of pumped-hydro systems, the charging efficiency of the reservoir is considered to be 90%.

Each transmission line has a 10 MW capacity. Demand parameters and VRE profiles for Nordic zones NO4, DK2, and DK1 from 2018 are used for nodes $n1$–$n3$, respectively. The data are clustered into four representative weeks, and data from the winter representative week are used for this study. Accordingly, the aggregator's VRE output at node $n3$ follows the actual wind output pattern in DK1, and consumption at the nodes has the same pattern as that of the selected nodes from the Nordic system during the representative winter week. The price elasticity of demand at the observed price-consumption point is -0.3 for consumers with a lower assumed maximum willingness to pay for prosumers. Finally, we impose a CO_2 price of €15/t (the 2018 EU ETS average) on emissions from thermal units.

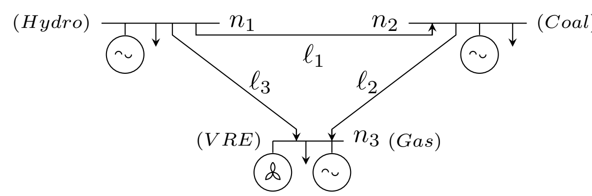

Figure 1. Three-node test system.

3.2. Results

In NA, SW is maximized under PC with 8.56 kt of EM (Table 1).[10] Based on the consumption pattern at the three selected nodes from the Nordic system, peak periods take place mostly between hours 8–13 and 17–20 of each day with some days that experience higher consumption (Fig. 2). Consequently, hydro production under PC increases during these precise periods with respect to the consumption pattern (Fig. 3).

Table 1. NA results (in k€ unless indicated).

Metric \ Case	PC	COG	COR
SW	1164.28	822.98	1162.55
CS	714.28	202.36	707.68
FS	199.93	552.93	204.91
GR	128.37	60.08	128.31
MS	121.69	7.62	121.65
EM (kt)	8.56	4.01	8.55
Firm $i1$ FS	114.02	142.22	116.43
Firm $i2$ FS	85.91	412.41	88.48

$F_{i,n,w} r^{\text{in}}_{i,n,t,w}$)). It reflects the marginal impact of infinitesimally more thermal generation on the equilibrium price. Assuming strictly positive thermal output, this enables the KKT condition in (A-1) to equate marginal revenue with marginal cost in case of Cournot behavior.

[7] https://www.ibm.com/analytics/cplex-optimizer

[8] PC: firms are price takers; COG: firms behave à la Cournot in thermal generation; COR: firms behave à la Cournot in hydro reservoirs.

[9] We prevent "spilling" of water in order to facilitate comparison across cases (Crampes & Moreaux, 2001). This assumption also reflects reality, e.g., the heritage pool in Québec that requires Hydro-Québec to deliver 165 TWh to provincial consumers annually (https://www.hydroquebec.com/projects/planning/ensuring-supply.html).

[10] SW: social welfare; CS: consumer surplus; FS: firm surplus; PS: prosumer surplus; GR: government revenue; MS: mechandising surplus; EM: emissions.

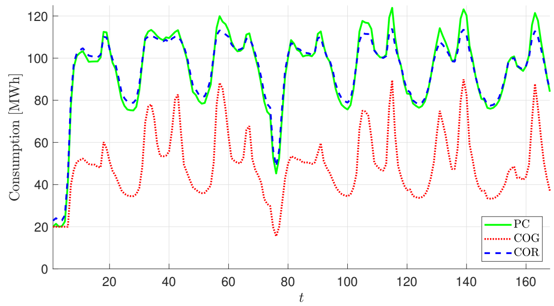

Figure 2. Average consumption in NA (in MWh).

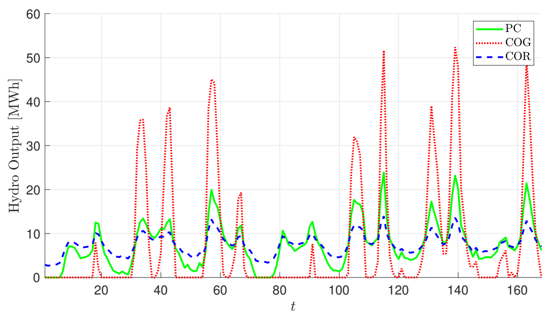

Figure 3. Hydro production in NA (in MWh).

Strategic use of thermal generation under COG leads to noticeable reductions in SW and CS. The withholding of thermal output causes system emissions to decrease by over 50% (Table 1). On the downside, average prices are higher than under PC during all hours throughout the day, causing a shift of surplus from consumers toward the firms (Fig. 4).[11] In particular, average nodal prices are €90.24/MWh, €47.03/MWh, and €61.01/MWh at nodes $n1$, $n2$, and $n3$, respectively, under PC, but

[11]Strategic behavior by a thermal producer in a Nash-Cournot model involves withholding output (Hobbs, 2001; Tanaka, 2009) in order to create scarcity. Since the thermal assets (coal and natural gas) are the only ones that have CO_2 emissions, it, therefore, follows that their exercise of market power under COG decreases consumption (Fig. 2) and CO_2 emissions (Table 1) vis-à-vis PC.

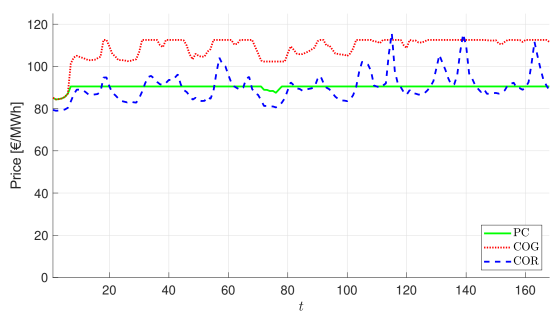

Figure 4. Node $n1$ prices in NA (in €/MWh).

these values become €108.65/MWh, €106.83/MWh, and €106.95/MWh, respectively, under COG. Since hydro is price taking under COG, it responds to the withholding of thermal generation by increasing output during peak periods accordingly (Fig. 3).

COR reveals that strategic use of hydro storage reduces SW and CS marginally (Table 1) compared to PC. Hydro production is withheld during peak periods and increased during off-peak periods, resulting in higher prices during peak periods and lower prices during off-peak periods (Figs. 3–4). Focusing on node $n1$ where the hydro producer is situated, we observe that the relatively flat prices under PC now become more volatile by creation of shortages during peak periods of consumption. Specifically, average nodal prices are €90.38/MWh, €46.64/MWh, and €61.70/MWh at nodes $n1$, $n2$, and $n3$, respectively. Since the hydro producer has to generate at least the same net amount of energy from its reservoir as under PC, i.e., 1,260 MWh, it balances the hike in peak prices by depressing prices during off-peak periods, i.e., essentially "dumping" the water during those times when prices tend to be low anyway. By merely shifting production, the hydro-owning firm $i1$ enjoys a 2.11% increase in profit.

In Agg100, SW is higher vis-à-vis NA (Table 2) as the aggregator at node 3 adds VRE output plus its own consumption (Fig. 5).[12] Since the aggregator is occasionally a net buyer under PC, its VRE output does not depress prices uniformly. In fact, the 100 MW of wind capacity at node $n3$ renders average prices of €91.36/MWh, €48.13/MWh, and €57.43/MWh at nodes $n1$, $n2$, and $n3$, respectively, under PC, i.e., a slight increase at nodes $n1$–$n2$ from NA due to higher average consumption (Fig. 6). Nevertheless, there is a moderate increase in CS overall due to a higher CS at node $n3$ that outweighs the loss in CS at nodes $n1$ and $n2$. In a similar vein, FS is relatively unchanged because firm $i1$ enjoys higher prices at node $n1$, while firm $i2$'s gain in surplus from higher prices at node $n2$ is outweighed by its losses at node $n3$. Not surprisingly, CO_2 emissions are also lower at 8.01 kt than in the NA scenario due to the introduction of VRE.

Under COG, both SW and CS are reduced from PC, while FS and PS are increased. The aggregator benefits from higher prices under COG by becoming a net seller during hours 114–148 in contrast to PC (Fig. 5), thereby actually mitigating the thermal firm $i2$'s exercise of market power. Indeed, the thermal firm $i2$'s FS increases by 380% (168%) when going from PC to COG in the NA (Agg100) scenario. As in the

[12]Overall, the aggregator in the PC case of the Agg100 scenario adds 6,266 MWh of VRE generation and 4,322 MWh of consumption. Thus, the aggregator's net sales (1,894 MWh) are modest, which is evident from comparing the welfare components of Tables 1–2.

Table 2. Agg100 results (in k€ unless indicated).

Metric \ Case	PC	COG	COR
SW	1566.43	1245.54	1563.81
CS	725.43	327.55	723.80
FS	199.23	362.28	200.23
PS	391.99	450.65	390.77
GR	120.13	43.11	119.95
MS	129.65	61.96	129.05
EM (kt)	8.01	2.87	8.00
Firm $i1$ FS	115.55	138.22	118.15
Firm $i2$ FS	83.68	224.06	82.09

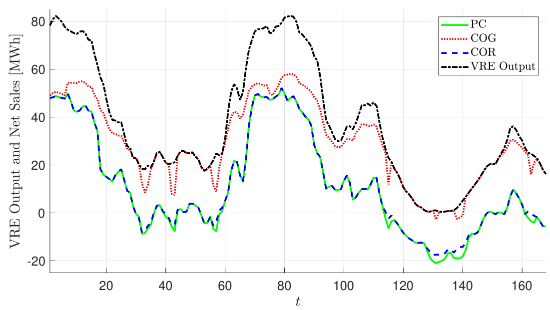

Figure 5. VRE output and prosumer net sales in Agg100 (in MWh).

NA scenario, Fig. 8 reveals an increase in COG prices vis-à-vis PC, viz., €107.88/MWh, €95.85/MWh, and €83.82/MWh at nodes $n1$, $n2$, and $n3$, respectively.

Due to water regulation, hydro production under COR again merely shifts between time periods (Fig. 7). While COR results follow a similar pattern to those in NA, the glut (paucity) of VRE output during hours 1–24 (114–148) creates an opportunity for the hydro producer to exploit the resulting intermittency. In effect, the hydro producer is able to "dump" relatively more water at the week's beginning (when the aggregator is a net seller)

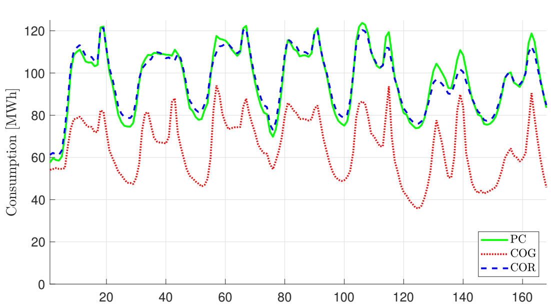

Figure 6. Average consumption in Agg100 (in MWh).

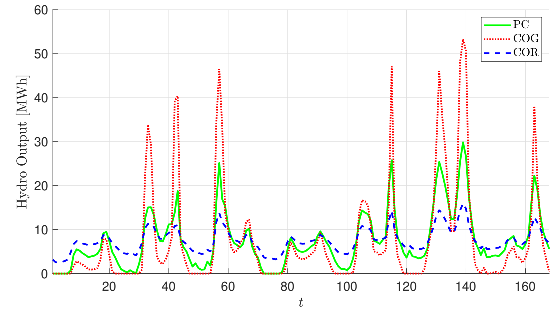

Figure 7. Hydro production in Agg100 (in MWh).

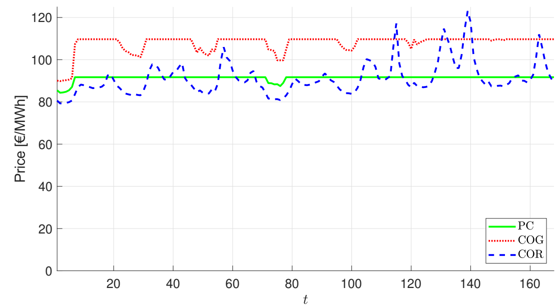

Figure 8. Node $n1$ prices in Agg100 (in €/MWh).

and to withhold more at its end (when the aggregator is a net buyer), cf. Figs. 3 and 7. Hence, the aggregator's intermittent net sales enable the hydro firm $i1$ to increase its FS by 2.25% under COR vis-à-vis PC, cf. 2.11% in NA, despite the seemingly limited overall welfare impact.

4. Discussion and Conclusions

A fully carbon-neutral power sector necessitates the utilization of VRE, yet it introduces intermittent production and net sales by aggregators. While (hydro) storage could mitigate such intermittencies, the resulting increased leverage of hydro reservoirs owned by profit-maximizing firms under these circumstances may exacerbate strategic behavior. However, the extant literature has focused on either aggregators' risk management given exogenous prices or their strategic behavior, e.g., as either Cournot or Stackelberg players. Using a game-theoretic framework, we investigate a more subtle consequence of the transformation of the power sector, viz., strategic operations by incumbent firms in a hydro-dominated power system such as the Nordic region's. Such interactions have ramifications for other regions not only because of the advent of aggregator-enabled prosumers but also due to the importance of storage in integrating VRE.

Given that incumbent firms may have the leverage to exert market power via their flexible thermal or storage assets, we examine how aggregator-enabled prosumers could bolster temporal arbitrage conducted by strategic hydro-owning firms. We find that the aggregator with its VRE output reduces overall average prices and slightly increases CS. However, due to its endogenous consumption, the aggregator's impact on prices is not uniform across the periods. Hence, the aggregator's pattern of net sales can be exploited by the hydro producer to enhance the impact of hydro's temporal arbitrage vis-à-vis the scenario without aggregators.

Future work could extend this framework in several ways with consequences for not only hydro-dominated power systems but also those in which storage is likely to play a more prominent role (Williams & Green, 2022). First, we considered only a single season, but temporal arbitrage could further exploit seasonal imbalances in hydro inflows, VRE availability, and consumption. Second, the problem instances could be scaled up to tackle a more realistic test network.[13] Third, aggregators themselves could be allowed to be strategic in order to study their impact on the incumbent firms' market power.

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Appendix A: KKT Conditions for Firm i's Optimization Problem (1)–(8)

$$0 \le g_{i,n,t,u} \perp C_{i,n,t,u} + SP_{i,n,u} - \left(D^{\text{int}}_{n,t} - D^{\text{slp}}_{n,t} q_{n,t}\right)$$

$$+ D^{\text{slp}}_{n,t} \left(\sum_{u' \in \mathcal{U}_{i,n}} g_{i,n,t,u'} \right.$$

$$\left. + \sum_{w \in \mathcal{W}_{i,n}} \left(Q_{i,n,w} y_{i,n,t,w} - F_{i,n,w} r^{\text{in}}_{i,n,t,w} \right) \right)$$

[13] The computational approach is valid for a 12–node, 18–line Nordic system excluding prosumers with four representative weeks (Hassanzadeh Moghimi et al., 2023), i.e., the QP problem instance solves to optimality in a few seconds on a standard laptop using CPLEX. An extension to the full test network with prosumers is ongoing.

$$+\beta_{i,n,t,u}+\beta^{\text{up}}_{i,n,t,u}-\beta^{\text{up}}_{i,n,t+1,u}+\beta^{\text{down}}_{i,n,t+1,u}$$

$$-\beta^{\text{down}}_{i,n,t,u}\geq 0,\ \forall n,t,u\in\mathcal{U}_{i,n} \quad \text{(A-1)}$$

$$0\leq r^{\text{sto}}_{i,n,t,w}\perp\lambda^{\text{bal}}_{i,n,t,w}-(1-E^{\text{sto}}_{i,n,w})^{T_t}\lambda^{\text{bal}}_{i,n,t+1,w}$$

$$+\lambda^{\text{ub}}_{i,n,t,w}-\lambda^{\text{lb}}_{i,n,t,w}\geq 0,\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-2)}$$

$$0\leq z_{i,n,t,w}\perp\lambda^{\text{bal}}_{i,n,t,w}\geq 0,\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-3)}$$

$$0\leq r^{\text{in}}_{i,n,t,w}\perp F_{i,n,w}\left(D^{\text{int}}_{n,t}-D^{\text{slp}}_{n,t}q_{n,t}\right)$$

$$-F_{i,n,w}D^{\text{slp}}_{n,t}\left(\sum_{u\in\mathcal{U}_{i,n}}g_{i,n,t,u}\right.$$

$$\left.+\sum_{w'\in\mathcal{W}_{i,n}}\left(Q_{i,n,w'}y_{i,n,t,w'}-F_{i,n,w'}r^{\text{in}}_{i,n,t,w'}\right)\right)$$

$$-\lambda^{\text{bal}}_{i,n,t,w}+\lambda^{\text{in}}_{i,n,t,w}+F_{i,n,w}\gamma_{i,n}\geq 0,$$

$$\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-4)}$$

$$0\leq y_{i,n,t,w}\perp -Q_{i,n,w}\left(D^{\text{int}}_{n,t}-D^{\text{slp}}_{n,t}q_{n,t}\right)$$

$$+Q_{i,n,w}D^{\text{slp}}_{n,t}\left(\sum_{u\in\mathcal{U}_{i,n}}g_{i,n,t,u}\right.$$

$$\left.+\sum_{w'\in\mathcal{W}_{i,n}}\left(Q_{i,n,w'}y_{i,n,t,w'}-F_{i,n,w'}r^{\text{in}}_{i,n,t,w'}\right)\right)$$

$$+\lambda^{\text{bal}}_{i,n,t,w}+Q_{i,n,w}\lambda^{\text{h}}_{i,n,t,w}-Q_{i,n,w}\gamma_{i,n}\geq 0,$$

$$\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-5)}$$

$$\lambda^{\text{bal}}_{i,n,t,w}\text{ u.r.s., }r^{\text{sto}}_{i,n,t,w}-(1-E^{\text{sto}}_{i,n,w})^{T_t}r^{\text{sto}}_{i,n,t-1,w}$$

$$-r^{\text{in}}_{i,n,t,w}+y_{i,n,t,w}+z_{i,n,t,w}-I_{i,n,t,w}=0,$$

$$\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-6)}$$

$$0\leq\beta_{i,n,t,u}\perp T_t\overline{G}_{i,n,u}-g_{i,n,t,u}\geq 0,\forall n,t,u\in\mathcal{U}_{i,n} \quad \text{(A-7)}$$

$$0\leq\beta^{\text{up}}_{i,n,t,u}\perp T_tR^{\text{up}}_u\overline{G}_{i,n,u}+g_{i,n,t-1,u}-g_{i,n,t,u}\geq 0,$$

$$\forall n,t,u\in\mathcal{U} \quad \text{(A-8)}$$

$$0\leq\beta^{\text{down}}_{i,n,t,u}\perp T_tR^{\text{down}}_u\overline{G}_{i,n,u}+g_{i,n,t,u}-g_{i,n,t-1,u}$$

$$\geq 0,\forall n,t,u\in\mathcal{U} \quad \text{(A-9)}$$

$$0\leq\lambda^{\text{in}}_{i,n,t,w}\perp T_tR^{\text{in}}_{i,n,w}\overline{R}_{i,n,w}-r^{\text{in}}_{i,n,t,w}\geq 0,$$

$$\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-10)}$$

$$0\leq\lambda^{\text{h}}_{i,n,t,w}\perp T_tY_{i,n,w}-Q_{i,n,w}y_{i,n,t,w}\geq 0,$$

$$\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-11)}$$

$$0\leq\lambda^{\text{ub}}_{i,n,t,w}\perp\overline{R}_{i,n,w}-r^{\text{sto}}_{i,n,t,w}\geq 0,\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-12)}$$

$$0\leq\lambda^{\text{lb}}_{i,n,t,w}\perp r^{\text{sto}}_{i,n,t,w}-\underline{R}_{i,n,w}\geq 0,\forall n,t,w\in\mathcal{W}_{i,n} \quad \text{(A-13)}$$

$$0\leq\gamma_{i,n}\perp\sum_{t\in\mathcal{T}}\sum_{w\in\mathcal{W}_{i,n}}\left(Q_{i,n,w}y_{i,n,t,w}-F_{i,n,w}r^{\text{in}}_{i,n,t,w}\right)$$

$$-Z_{i,n}\geq 0,\forall n \quad \text{(A-14)}$$

Appendix B: KKT Conditions for Aggregator j's Optimization Problem (9)

$$0\leq q^{\text{agg}}_{j,n,t}\perp\left(D^{\text{int}}_{n,t}-D^{\text{slp}}_{n,t}q_{n,t}\right)-D^{\text{int,agg}}_{j,n,t}$$

$$+D^{\text{slp,agg}}_{j,n,t}q^{\text{agg}}_{j,n,t}\geq 0,\forall n,t \quad \text{(B-1)}$$

Appendix C: KKT Conditions for the ISO's Optimization Problem (10)–(14)

$$0\leq q_{n,t}\perp -\left(D^{\text{int}}_{n,t}-D^{\text{slp}}_{n,t}q_{n,t}\right)+\theta_{n,t}\geq 0,\forall n,t \quad \text{(C-1)}$$

$$f_{\ell,t}\text{ u.r.s., }T_t\eta_{\ell^{\text{AC}},t}+V\ T_t\overline{\mu}_{\ell,t}-V\ T_t\underline{\mu}_{\ell,t}+V\ T_t\theta_{n^+_\ell,t}$$

$$-V\ T_t\theta_{n^-_\ell,t}=0,\forall\ell,t \quad \text{(C-2)}$$

$$v_{n^{\text{AC}},t}\text{ u.r.s., }-\sum_{\ell\in\mathcal{L}^+_n}T_tB_{\ell^{\text{AC}}}\eta_{\ell^{\text{AC}},t}+\sum_{\ell\in\mathcal{L}^-_n}T_tB_{\ell^{\text{AC}}}\eta_{\ell^{\text{AC}},t}$$

$$+\overline{\kappa}_{n^{\text{AC}},t}-\underline{\kappa}_{n^{\text{AC}},t}=0,\forall n^{\text{AC}}\in\mathcal{N}^{\text{AC}},t \quad \text{(C-3)}$$

$$\theta_{n,t}\text{ u.r.s., }q_{n,t}-\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{i,n}}g_{i,n,t,u}-\sum_{i\in\mathcal{I}}\sum_{e\in\mathcal{E}}G^e_{i,n,t}$$

$$-\sum_{i\in\mathcal{I}}\sum_{w\in\mathcal{W}_{i,n}}\left(Q_{i,n,w}y_{i,n,t,w}-F_{i,n,w}r^{\text{in}}_{i,n,t,w}\right)$$

$$-\sum_{j\in\mathcal{J}}\sum_{e\in\mathcal{E}}G^{e,\text{agg}}_{j,n,t}+\sum_{j\in\mathcal{J}}q^{\text{agg}}_{j,n,t}+\sum_{\ell\in\mathcal{L}^+_n}V\ T_tf_{\ell,t}$$

$$-\sum_{\ell\in\mathcal{L}^-_n}V\ T_tf_{\ell,t}=0,\forall n,t \quad \text{(C-4)}$$

$$\eta_{\ell^{\text{AC}},t}\text{ u.r.s., }T_tB_{\ell^{\text{AC}}}\left(v_{n^+_\ell,t}-v_{n^+_\ell,t}\right)-T_tf_{\ell^{\text{AC}},t}=0,$$

$$\forall\ell^{\text{AC}}\in\mathcal{L}^{\text{AC}},t \quad \text{(C-5)}$$

$$0\leq\underline{\mu}_{\ell,t}\perp T_t\underline{K}_\ell+VT_tf_{\ell,t}\geq 0,\forall\ell,t \quad \text{(C-6)}$$

$$0\leq\overline{\mu}_{\ell,t}\perp T_t\overline{K}_\ell-VT_tf_{\ell,t}\geq 0,\forall\ell,t \quad \text{(C-7)}$$

$$0\leq\underline{\kappa}_{n^{\text{AC}},t}\perp\pi+v_{n^{\text{AC}},t}\geq 0,\forall n^{\text{AC}}\in\mathcal{N}^{\text{AC}},t \quad \text{(C-8)}$$

$$0\leq\overline{\kappa}_{n^{\text{AC}},t}\perp\pi-v_{n^{\text{AC}},t}\geq 0,\forall n^{\text{AC}}\in\mathcal{N}^{\text{AC}},t \quad \text{(C-9)}$$