Strategic Storage Use in a Hydro-Thermal Power System with Carbon Constraints

Sébastien Debia[a] Pierre-Olivier Pineau[a] Afzal S. Siddiqui[b]

[a] HEC Montréal

[b] University College London, Stockholm University, HEC Montréal, and Aalto University,
e-mail address: afzal.siddiqui@ucl.ac.uk

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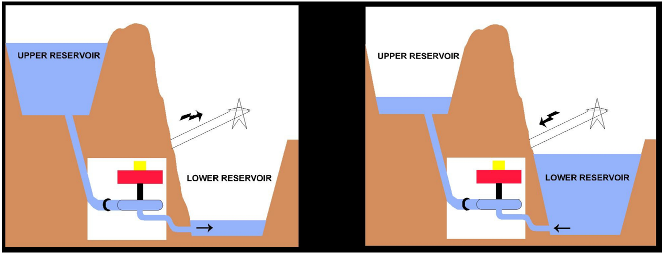
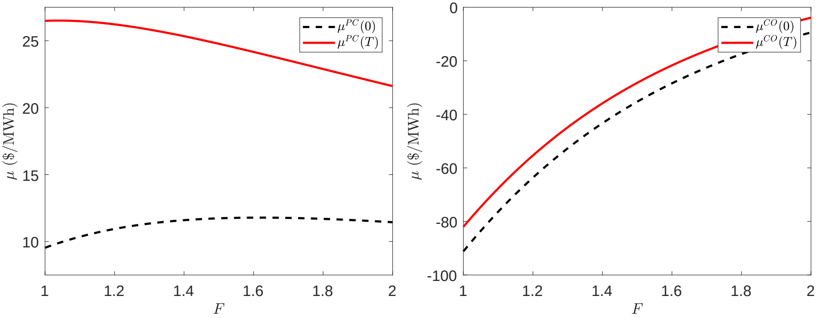
Introduction

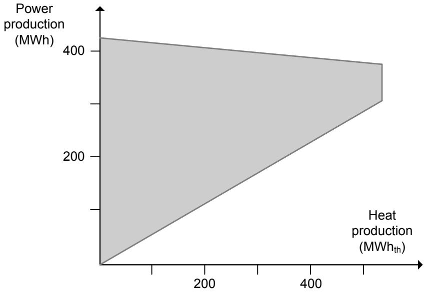
Is Energy Storage the Answer? (https://www.climatetechwiki.org/technology/jiqweb-ph)

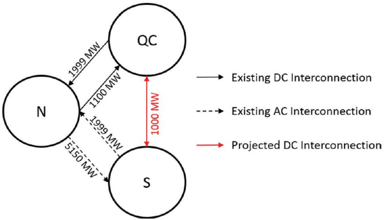


Conflicting Objectives (Debia et al., 2019)



Leveraging Flexibility (Virasjoki et al., 2018 and Debia et al., 2018)

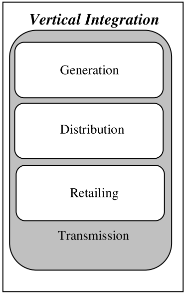


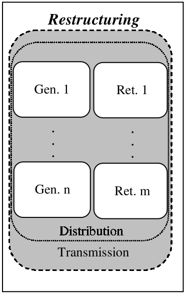


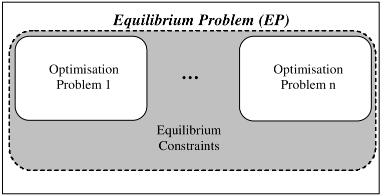
Equilibrium Analysis of Storage

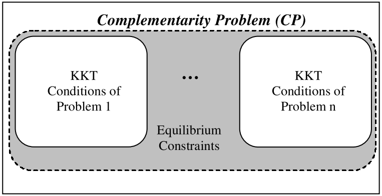
- Crampes and Moreaux (2001) show theoretically how market power may lower water value and even render it negative
- Bushnell (2003) finds empirical support via a complementarity analysis of the California hydro-thermal system
    - Sioshansi (2010) analyses the welfare impacts of storage use via a stylised partial-equilibrium model with perfectly competitive electricity generation and how storage can reduce welfare (Sioshansi, 2014)
    - Virasjoki et al. (2018) illustrate how CHP could be used to exploit the link between heat and power sectors
    - Debia et al. (2018) identify instances of welfare reduction due to the addition of an HVDC interconnection
    - Debia et al. (2019) demonstrate conflicting objectives between storage operations and social welfare
- Local market power continues to plague electricity industies (Tangerås and Mauritzen, 2018)

Restructuring and Games

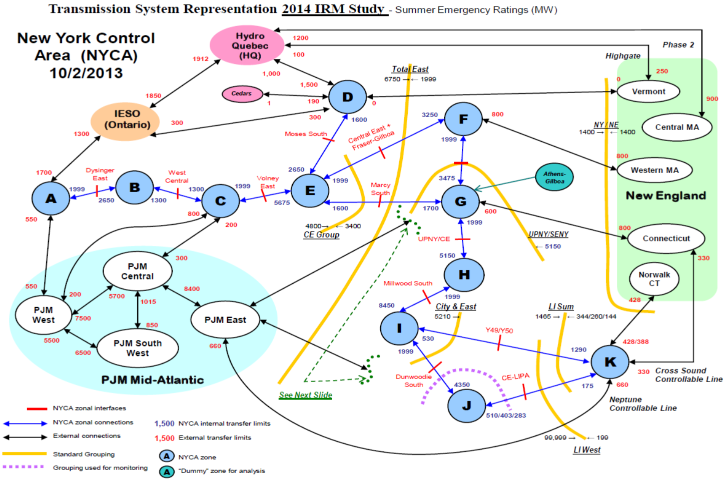








NPCC: NYCA and RGGI C&T



Research Objective and Findings

- Stringent CO_2 caps and variable renewable energy source (VRES) integration give more leverage to flexible producers
  - How are hydro operations, producer profit, and social welfare affected by market power, carbon policy, and reservoirs?
  - Use an equilibrium model (Hobbs, 2001) with stylised representation of NYCA-QC power system
- Case study: HQ shifts production à la Bushnell (2003), which could be mitigated by tighter regulatory cap on net imports
  - Conversely, a more stringent requirement on net imports could increase market power of NY thermal producers and increase CO_2 permit price

Mathematical Formulation

Assumptions

- Linear inverse demand, $A_{n,t} - Z_{n,t}c_{n,t}, \forall n \in \mathcal{N}, t \in \mathcal{T}$
- Firm $i \in \mathcal{I}$ may own conventional, VRES, or hydro capacity
  - Conventional plant $u \in \mathcal{U}_{i,n}$ has capacity $G_{i,n,u}$, operating cost $C_{i,n,u}$, and CO_2 emission factor $E_{i,n,u}$
  - VRES output $R_{i,n,t}$ is non-controllable
  - Hydro unit $w \in \mathcal{W}_{i,n}$ has reservoir limits $\overline{X}_{n,i,w}, \underline{X}_{n,i,w}$
- Transmission capacity of line $\ell \in \mathcal{L}$ is K_ℓ with susceptance B_ℓ for DC load-flow approximation of AC lines
- Welfare-maximising ISO manages transmission flows (Sauma and Oren, 2007)
- CO_2 emission cap $\overline{E}$ and water regulation by H_i and $\overline{R}_i$

ISO's Problem

$$\max_{\Omega^{\text{ISO}}} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left[A_{n,t} c_{n,t} - \frac{1}{2} Z_{n,t} c_{n,t}^2 \right] \tag{1}$$

$$\text{s.t. } c_{n,t} - \sum_{i\in\mathcal{I}} q_{i,n,t} - V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) = 0 : \ \lambda_{n,t}, \forall n, t \tag{2}$$

$$f_{\ell,t} - B_\ell \left(v_{n_\ell^+,t} - v_{n_\ell^-,t} \right) = 0 : \ \psi_{\ell,t}, \forall t, \ell \in \mathcal{L}^{AC} \tag{3}$$

$$\underline{\mu}_{\ell,t} : \ -K_\ell \leq V f_{\ell,t} \leq K_\ell : \ \overline{\mu}_{\ell,t}, \forall \ell, t \tag{4}$$

$$\underline{\kappa}_{n,t} : \ -\pi \leq v_{n,t} \leq \pi : \ \overline{\kappa}_{n,t}, \forall n, t \tag{5}$$

$$\overline{R}_i \leq \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} (P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] : \ \hat{\gamma}_i, \forall i \in \mathcal{I} \tag{6}$$

$$c_{n,t} \geq 0, \forall n, t \tag{7}$$

$$f_{\ell,t} \text{ free}, \forall \ell, t \tag{8}$$

$$v_{n,t} \text{ free}, \forall n, t \tag{9}$$

where $\Omega^{\text{ISO}} \equiv \{c_{n,t}, f_{\ell,t}, v_{n,t}\}$

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Firm i's Problem

$$\max_{\Omega^i} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left\{ q_{i,n,t} \left[A_{n,t} - Z_{n,t} \left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right) \right] - \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,u} + \rho E_{i,n,u} \right) g_{i,n,t,u} \right\} \quad (10)$$

$$\text{s.t. } q_{i,n,t} - \left[\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) \right] = 0 : \xi_{i,n,t}, \forall n, t \quad (11)$$

$$g_{i,n,t,u} \le G_{i,n,u} : \beta_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \quad (12)$$

$$\underline{\beta}_{i,n,t,u} : \underline{G}_{i,n,u} \le g_{i,n,t,u} - g_{i,n,t-1,u} \le \overline{G}_{i,n,u} : \overline{\beta}_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \quad (13)$$

$$r_{i,n,t} - R_{i,n,t} = 0 : \nu_{i,n,t}, \forall n, t \quad (14)$$

$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w} \right) - \sum_{w'\in\mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'} \right) = 0 : \alpha_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (15)$$

$$\underline{\omega}_{i,n,t,w} : \underline{X}_{i,n,w} \le x_{i,n,t,w} \le \overline{X}_{i,n,w} : \overline{\omega}_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (16)$$

$$P_{i,n,w} y_{i,n,t,w} \le Y_{i,n,w} : \delta_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (17)$$

$$\overline{R}_i \le \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] : \overline{\gamma}_i \quad (18)$$

$$g_{i,n,t,u} \ge 0, \forall n, t, u \in \mathcal{U}_{i,n} \quad (19)$$

$$q_{i,n,t} \text{ free}, r_{i,n,t} \ge 0, \forall n, t \quad (20)$$

$$s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \ge 0, \forall n, t, w \in \mathcal{W}_{i,n} \quad (21)$$

where $\Omega^i \equiv \{ q_{i,n,t}, g_{i,n,t,u}, r_{i,n,t}, s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \}$

Firm i's Problem

$$\max_{\Omega^i} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left\{ q_{i,n,t} \left[A_{n,t} - Z_{n,t} \left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right) \right] - \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,u} + \rho E_{i,n,u} \right) g_{i,n,t,u} \right\} \quad (10)$$

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$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w} \right) - \sum_{w'\in\mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'} \right) = 0 : \alpha_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (15)$$

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$$\max_{\Omega^i} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left\{ q_{i,n,t} \left[A_{n,t} - Z_{n,t} \left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right) \right] - \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,u} + \rho E_{i,n,u} \right) g_{i,n,t,u} \right\} \quad (10)$$

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$$q_{i,n,t} - \left[\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) \right] = 0 \ : \ \xi_{i,n,t}, \forall n, t \quad (11)$$

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$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w} \right) - \sum_{w'\in\mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'} \right) = 0 \ : \ \alpha_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (15)$$

$$\underline{\omega}_{i,n,t,w} \ : \ \underline{X}_{i,n,w} \le x_{i,n,t,w} \le \overline{X}_{i,n,w} \ : \ \overline{\omega}_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (16)$$

$$P_{i,n,w} y_{i,n,t,w} \le Y_{i,n,w} \ : \ \delta_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (17)$$

$$\overline{R}_i \le \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] \ : \ \overline{\gamma}_i \quad (18)$$

$$g_{i,n,t,u} \ge 0, \forall n, t, u \in \mathcal{U}_{i,n} \quad (19)$$

$$q_{i,n,t} \text{ free}, r_{i,n,t} \ge 0, \forall n, t \quad (20)$$

$$s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \ge 0, \forall n, t, w \in \mathcal{W}_{i,n} \quad (21)$$

where $\Omega^i \equiv \{q_{i,n,t}, g_{i,n,t,u}, r_{i,n,t}, s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w}\}$

Firm i's Problem

$$\max_{\Omega^i} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left\{ q_{i,n,t} \left[A_{n,t} - Z_{n,t} \left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right)\right)\right] - \sum_{u\in\mathcal{U}_{i,n}} (C_{i,n,u} + \rho E_{i,n,u})\, g_{i,n,t,u} \right\} \tag{10}$$

$$\text{s.t. } q_{i,n,t} - \left[\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w\in\mathcal{W}_{i,n}} (P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}) \right] = 0 : \ \xi_{i,n,t}, \forall n, t \tag{11}$$

$$g_{i,n,t,u} \le G_{i,n,u} : \ \beta_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \tag{12}$$

$$\underline{\beta}_{i,n,t,u} : \ \underline{G}_{i,n,u} \le g_{i,n,t,u} - g_{i,n,t-1,u} \le \overline{G}_{i,n,u} : \ \overline{\beta}_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \tag{13}$$

$$r_{i,n,t} - R_{i,n,t} = 0 : \ \nu_{i,n,t}, \forall n, t \tag{14}$$

$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + (y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w}) - \sum_{w'\in\mathcal{A}(w)} (y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'}) = 0 : \ \alpha_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \tag{15}$$

$$\underline{\omega}_{i,n,t,w} : \ \underline{X}_{i,n,w} \le x_{i,n,t,w} \le \overline{X}_{i,n,w} : \ \overline{\omega}_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \tag{16}$$

$$P_{i,n,w} y_{i,n,t,w} \le Y_{i,n,w} : \ \delta_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \tag{17}$$

$$\overline{R}_i \le \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} (P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] : \ \overline{\gamma}_i \tag{18}$$

$$g_{i,n,t,u} \ge 0, \forall n, t, u \in \mathcal{U}_{i,n} \tag{19}$$

$$q_{i,n,t} \text{ free}, r_{i,n,t} \ge 0, \forall n, t \tag{20}$$

$$s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \ge 0, \forall n, t, w \in \mathcal{W}_{i,n} \tag{21}$$

where $\Omega^i \equiv \{q_{i,n,t}, g_{i,n,t,u}, r_{i,n,t}, s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w}\}$

Firm i's Problem

$$\max_{\Omega^i} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left\{ q_{i,n,t} \left[A_{n,t} - Z_{n,t} \left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right) \right] - \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,u} + \rho E_{i,n,u} \right) g_{i,n,t,u} \right\} \quad (10)$$

$$\text{s.t. } q_{i,n,t} - \left[\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) \right] = 0 : \ \xi_{i,n,t}, \forall n, t \quad (11)$$

$$g_{i,n,t,u} \le G_{i,n,u} : \ \beta_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \quad (12)$$

$$\underline{\beta}_{i,n,t,u} : \ \underline{G}_{i,n,u} \le g_{i,n,t,u} - g_{i,n,t-1,u} \le \overline{G}_{i,n,u} : \ \overline{\beta}_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \quad (13)$$

$$r_{i,n,t} - R_{i,n,t} = 0 : \ \nu_{i,n,t}, \forall n, t \quad (14)$$

$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w} \right) - \sum_{w'\in\mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'} \right) = 0 : \ \alpha_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (15)$$

$$\underline{\omega}_{i,n,t,w} : \ \underline{X}_{i,n,w} \le x_{i,n,t,w} \le \overline{X}_{i,n,w} : \ \overline{\omega}_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (16)$$

$$P_{i,n,w} y_{i,n,t,w} \le Y_{i,n,w} : \ \delta_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (17)$$

$$\overline{R}_i \le \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] : \ \overline{\gamma}_i \quad (18)$$

$$g_{i,n,t,u} \ge 0, \forall n, t, u \in \mathcal{U}_{i,n} \quad (19)$$

$$q_{i,n,t} \text{ free}, r_{i,n,t} \ge 0, \forall n, t \quad (20)$$

$$s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \ge 0, \forall n, t, w \in \mathcal{W}_{i,n} \quad (21)$$

where $\Omega^i \equiv \{q_{i,n,t}, g_{i,n,t,u}, r_{i,n,t}, s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w}\}$

Firm i's Problem

$$\max_{\Omega^i} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \left\{ q_{i,n,t} \left[A_{n,t} - Z_{n,t} \left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right) \right] - \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,u} + \rho E_{i,n,u} \right) g_{i,n,t,u} \right\} \quad (10)$$

$$\text{s.t. } q_{i,n,t} - \left[\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) \right] = 0 : \ \xi_{i,n,t}, \forall n, t \quad (11)$$

$$g_{i,n,t,u} \le G_{i,n,u} : \ \beta_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \quad (12)$$

$$\underline{\beta}_{i,n,t,u} : \ \underline{G}_{i,n,u} \le g_{i,n,t,u} - g_{i,n,t-1,u} \le \overline{G}_{i,n,u} : \ \overline{\beta}_{i,n,t,u}, \forall n, t, u \in \mathcal{U}_{i,n} \quad (13)$$

$$r_{i,n,t} - R_{i,n,t} = 0 : \ \nu_{i,n,t}, \forall n, t \quad (14)$$

$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w} \right) - \sum_{w'\in\mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'} \right) = 0 : \ \alpha_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (15)$$

$$\underline{\omega}_{i,n,t,w} : \ \underline{X}_{i,n,w} \le x_{i,n,t,w} \le \overline{X}_{i,n,w} : \ \overline{\omega}_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (16)$$

$$P_{i,n,w} y_{i,n,t,w} \le Y_{i,n,w} : \ \delta_{i,n,t,w}, \forall n, t, w \in \mathcal{W}_{i,n} \quad (17)$$

$$\overline{R}_i \le \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] : \ \overline{\gamma}_i \quad (18)$$

$$g_{i,n,t,u} \ge 0, \forall n, t, u \in \mathcal{U}_{i,n} \quad (19)$$

$$q_{i,n,t} \text{ free}, r_{i,n,t} \ge 0, \forall n, t \quad (20)$$

$$s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \ge 0, \forall n, t, w \in \mathcal{W}_{i,n} \quad (21)$$

where $\Omega^i \equiv \{ q_{i,n,t}, g_{i,n,t,u}, r_{i,n,t}, s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \}$

Firm i's Problem

$$\max_{\Omega^i} \sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} \Bigg\{ q_{i,n,t}\left[A_{n,t} - Z_{n,t}\left(\sum_{i'\in\mathcal{I}} q_{i',n,t} + V\left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t}\right)\right)\right] - \sum_{u\in\mathcal{U}_{i,n}} \left(C_{i,n,u} + \rho E_{i,n,u}\right) g_{i,n,t,u} \Bigg\} \tag{10}$$

$$\text{s.t. } q_{i,n,t} - \left[\sum_{u\in\mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}\right)\right] = 0 \,:\, \xi_{i,n,t}, \forall n,t \tag{11}$$

$$g_{i,n,t,u} \le G_{i,n,u} \,:\, \beta_{i,n,t,u}, \forall n,t,u\in\mathcal{U}_{i,n} \tag{12}$$

$$\underline{\beta}_{i,n,t,u} \,:\, \underline{G}_{i,n,u} \le g_{i,n,t,u} - g_{i,n,t-1,u} \le \overline{G}_{i,n,u} \,:\, \overline{\beta}_{i,n,t,u}, \forall n,t,u\in\mathcal{U}_{i,n} \tag{13}$$

$$r_{i,n,t} - R_{i,n,t} = 0 \,:\, \nu_{i,n,t}, \forall n,t \tag{14}$$

$$x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w}\right) - \sum_{w'\in\mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'}\right) = 0 \,:\, \alpha_{i,n,t,w}, \forall n,t,w\in\mathcal{W}_{i,n} \tag{15}$$

$$\underline{\omega}_{i,n,t,w} \,:\, \underline{X}_{i,n,w} \le x_{i,n,t,w} \le \overline{X}_{i,n,w} \,:\, \overline{\omega}_{i,n,t,w}, \forall n,t,w\in\mathcal{W}_{i,n} \tag{16}$$

$$P_{i,n,w} y_{i,n,t,w} \le Y_{i,n,w} \,:\, \delta_{i,n,t,w}, \forall n,t,w\in\mathcal{W}_{i,n} \tag{17}$$

$$\overline{R}_i \le \sum_{t\in\mathcal{T}}\sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}\right) + V\left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t}\right)\right] \,:\, \overline{\gamma}_i \tag{18}$$

$$g_{i,n,t,u} \ge 0, \forall n,t,u\in\mathcal{U}_{i,n} \tag{19}$$

$$q_{i,n,t} \text{ free}, r_{i,n,t} \ge 0, \forall n,t \tag{20}$$

$$s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w} \ge 0, \forall n,t,w\in\mathcal{W}_{i,n} \tag{21}$$

where $\Omega^i \equiv \{q_{i,n,t}, g_{i,n,t,u}, r_{i,n,t}, s_{i,n,t,w}, x_{i,n,t,w}, y_{i,n,t,w}, z_{i,n,t,w}\}$

Regulatory Constraint on Hydro and GNE

- **Hydro must use a minimum share of its potential (Bushnell, 2003)**
  - **Production at one node impacts the network-wide dispatch**
  - **ISO considers the regulation in its optimal dispatch**
  - **Similar to the "heritage pool" in Québec**
- **Since duplicate constraints, (6) and (18), appear in both problems, this leads to a generalised Nash equilibrium (GNE)**
  - **Resolve the GNE by supposing that each firm i and the ISO trade "regulatory rights" at a common price, γ_i, and market clears**
  - **Absent market power in such rights, the GNE is rendered as an MCP with common dual variables, γ_i, without the need to specify the rights traded, cf. Oggioni et al. (2011)**
  - **(6) and (18) may be replaced by a common regulatory constraint treated as exogenous by both the ISO and each firm i with the understanding that the impact of trading "regulatory rights" at the prevailing common shadow price, γ_i, has been internalised**

Equilibrium Constraints

$$0 \leq \gamma_i \perp \overline{R}_i \leq \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}_{i,w}} \left[\sum_{w \in \mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell \in \mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell \in \mathcal{L}_n^+} f_{\ell,t} \right) \right], \forall i \in \mathcal{I} \quad (22)$$

$$0 \leq \rho \perp \overline{E} - \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}} \sum_{u \in \mathcal{U}_{i,n}} E_{i,n,u} g_{i,n,t,u} \geq 0 \quad (23)$$

$$\text{where } \overline{R}_i \equiv \min \left\{ \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}_{i,w}} \frac{A_{n,t}}{Z_{n,t}},\ H_i \sum_{n \in \mathcal{N}} \sum_{w \in \mathcal{W}_{i,n}} \overline{P}_{i,n,w} \left(X^0_{i,n,w} + \sum_{t \in \mathcal{T}} I_{i,n,t,w} \right) \right\}$$

Equilibrium Constraints

$$0 \leq \gamma_i \perp \overline{R}_i \leq \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}_{i,w}} \left[\sum_{w \in \mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell \in \mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell \in \mathcal{L}_n^+} f_{\ell,t} \right) \right], \forall i \in \mathcal{I} \quad (22)$$

$$0 \leq \rho \perp \overline{E} - \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}} \sum_{u \in \mathcal{U}_{i,n}} E_{i,n,u} g_{i,n,t,u} \geq 0 \quad (23)$$

$$\text{where } \overline{R}_i \equiv \min \left\{ \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}_{i,w}} \frac{A_{n,t}}{Z_{n,t}} , \; H_i \sum_{n \in \mathcal{N}} \sum_{w \in \mathcal{W}_{i,n}} \overline{P}_{i,n,w} \left(X^0_{i,n,w} + \sum_{t \in \mathcal{T}} I_{i,n,t,w} \right) \right\}$$

ISO's KKT Conditions

$$0 \leq c_{n,t} \quad \perp \quad \lambda_{n,t} - A_{n,t} + Z_{n,t} c_{n,t} \geq 0, \ \forall n, t \tag{24}$$

$$f_{\ell,t} \quad \text{free}, \quad \psi_{\ell,t} + V \left(\lambda_{n_\ell^+,t} - \lambda_{n_\ell^-,t} - \underline{\mu}_{\ell,t} + \overline{\mu}_{\ell,t} + \sum_{i \in \mathcal{I}_{n_\ell^+,w}} \gamma_i - \sum_{i \in \mathcal{I}_{n_\ell^-,w}} \gamma_i \right) = 0, \ \forall \ell, t \tag{25}$$

$$v_{n,t} \quad \text{free}, \quad -\sum_{\ell \in \mathcal{L}_n^+} B_\ell \psi_{\ell,t} + \sum_{\ell \in \mathcal{L}_n^-} B_\ell \psi_{\ell,t} - \underline{\kappa}_{n,t} + \overline{\kappa}_{n,t} = 0, \ \forall n, t \tag{26}$$

$$\lambda_{n,t} \quad \text{free}, \quad c_{n,t} - \sum_{i \in \mathcal{I}} q_{i,n,t} - V \left(\sum_{\ell \in \mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell \in \mathcal{L}_n^+} f_{\ell,t} \right) = 0, \forall n, t \tag{27}$$

$$\psi_{\ell,t} \quad \text{free}, \quad f_{\ell,t} - B_\ell \left(v_{n_\ell^+,t} - v_{n_\ell^-,t} \right) = 0, \forall t, \ell \in \mathcal{L}^{AC} \tag{28}$$

$$0 \leq \underline{\mu}_{\ell,t} \quad \perp \quad K_\ell + V f_{\ell,t} \geq 0, \forall t, \ell \tag{29}$$

$$0 \leq \overline{\mu}_{\ell,t} \quad \perp \quad K_\ell - V f_{\ell,t} \geq 0, \forall t, \ell \tag{30}$$

$$0 \leq \underline{\kappa}_{n,t} \quad \perp \quad \pi + v_{n,t} \geq 0, \forall t, n \tag{31}$$

$$0 \leq \overline{\kappa}_{n,t} \quad \perp \quad \pi - v_{n,t} \geq 0, \forall t, n \tag{32}$$

Firm i's KKT Conditions

$$q_{i,n,t} \quad \text{free,} \quad \xi_{i,n,t} - A_{n,t} + Z_{n,t}\left[\sum_{i' \in \mathcal{I}} q_{i',n,t} + V\left(\sum_{\ell \in \mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell \in \mathcal{L}_n^+} f_{\ell,t}\right)\right] + Z_{n,t} q_{i,n,t} = 0, \ \forall n,t \tag{33}$$

$$0 \leq g_{i,n,t,u} \quad \perp \quad -\xi_{i,n,t} + \left(C_{i,n,u} + \rho E_{i,n,u}\right) + \beta_{i,n,t,u} + \left(\overline{\beta}_{i,n,t,u} - \underline{\beta}_{i,n,t,u}\right) + \left(\underline{\beta}_{i,n,t+1,u} - \overline{\beta}_{i,n,t+1,u}\right) \geq 0, \ \forall n,t,u \in \mathcal{U}_{i,n} \tag{34}$$

$$0 \leq r_{i,n,t} \quad \perp \quad -\xi_{i,n,t} + \nu_{i,n,t} \geq 0, \ \forall n,t \tag{35}$$

$$0 \leq s_{i,n,t,w} \quad \perp \quad F_{i,n,w}\left(\xi_{i,n,t} + \gamma_i\right) - \alpha_{i,n,t+1,w} + \sum_{w' \in \mathcal{C}(w)} \alpha_{i,n,t,w'} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{36}$$

$$0 \leq y_{i,n,t,w} \quad \perp \quad P_{i,n,w}\left(\delta_{i,n,t,w} - \xi_{i,n,t} - \gamma_i\right) + \alpha_{i,n,t,w} - \sum_{w' \in \mathcal{C}(w)} \alpha_{i,n,t+1,w'} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{37}$$

$$0 \leq z_{i,n,t,w} \quad \perp \quad \alpha_{i,n,t,w} - \sum_{w' \in \mathcal{C}(w)} \alpha_{i,n,t+1,w'} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{38}$$

$$0 \leq x_{i,n,t,w} \quad \perp \quad -\alpha_{i,n,t+1,w} + \alpha_{i,n,t,w} - \underline{\omega}_{i,n,t,w} + \overline{\omega}_{i,n,t,w} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{39}$$

$$\xi_{i,n,t} \quad \text{free,} \quad q_{i,n,t} - \left[\sum_{u \in \mathcal{U}_{i,n}} g_{i,n,t,u} + r_{i,n,t} + \sum_{w \in \mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}\right)\right] = 0, \ \forall n,t \tag{40}$$

$$0 \leq \beta_{i,n,t,u} \quad \perp \quad G_{i,n,u} - g_{i,n,t,u} \geq 0, \ \forall n,t,u \in \mathcal{U}_{i,n} \tag{41}$$

$$0 \leq \underline{\beta}_{i,n,t,u} \quad \perp \quad -\underline{G}_{i,n,u} + g_{i,n,t,u} - g_{i,n,t-1,u} \geq 0, \ \forall n,t,u \in \mathcal{U}_{i,n} \tag{42}$$

$$0 \leq \overline{\beta}_{i,n,t,u} \quad \perp \quad \underline{G}_{i,n,u} - g_{i,n,t,u} + g_{i,n,t-1,u} \geq 0, \ \forall n,t,u \in \mathcal{U}_{i,n} \tag{43}$$

$$\nu_{i,n,t} \quad \text{free,} \quad r_{i,n,t} - R_{i,n,t} = 0, \ \forall n,t \tag{44}$$

$$\alpha_{i,n,t,w} \quad \text{free,} \quad x_{i,n,t,w} - I_{i,n,t,w} - x_{i,n,t-1,w} + \left(y_{i,n,t,w} + z_{i,n,t,w} - s_{i,n,t-1,w}\right) - \sum_{w' \in \mathcal{A}(w)} \left(y_{i,n,t-1,w'} + z_{i,n,t-1,w'} - s_{i,n,t,w'}\right) = 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{45}$$

$$0 \leq \underline{\omega}_{i,n,t,w} \quad \perp \quad -\underline{X}_{i,n,w} + x_{i,n,t,w} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{46}$$

$$0 \leq \overline{\omega}_{i,n,t,w} \quad \perp \quad \overline{X}_{i,n,w} - x_{i,n,t,w} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{47}$$

$$0 \leq \overline{\delta}_{i,n,t,w} \quad \perp \quad Y_{i,n,w} - P_{i,n,w} y_{i,n,t,w} \geq 0, \ \forall n,t,w \in \mathcal{W}_{i,n} \tag{48}$$

QP Formulation

$$\max_{\Omega} \sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}}\Bigg\{\left(A_{n,t}c_{n,t}-\frac{1}{2}Z_{n,t}c_{n,t}^2\right) - \sum_{i\in\mathcal{I}}\left(Z_{n,t}\frac{q_{i,n,t}^2}{2}+\sum_{u\in\mathcal{U}_{i,n}}C_{i,n,u}g_{i,n,t,u}\right)\Bigg\} \quad (49)$$

s.t. $$\sum_{t\in\mathcal{T}}\sum_{n\in\mathcal{N}_{i,w}}\Bigg[\sum_{w\in\mathcal{W}_{i,n}}\left(P_{i,n,w}y_{i,n,t,w}-F_{i,n,w}s_{i,n,t,w}\right) + V\left(\sum_{\ell\in\mathcal{L}_n^-}f_{\ell,t}-\sum_{\ell\in\mathcal{L}_n^+}f_{\ell,t}\right)\Bigg] - \overline{R}_i \geq 0 : \gamma_i,\ \forall i\in\mathcal{I} \quad (50)$$

$$\overline{E}-\sum_{i\in\mathcal{I}}\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}}\sum_{u\in\mathcal{U}_{i,n}}E_{i,n,u}g_{i,n,t,u}\geq 0 : \rho \quad (51)$$

(2) − (5), (7) − (9)

(11) − (17), (19) − (21), $\forall i\in\mathcal{I}$

where $\Omega = \Omega^{\text{ISO}}\cup\Omega^i$

QP Formulation

$$\max_{\Omega} \sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}}\Bigg\{\left(A_{n,t}c_{n,t}-\frac{1}{2}Z_{n,t}c_{n,t}^2\right) - \sum_{i\in\mathcal{I}}\left(Z_{n,t}\frac{q_{i,n,t}^2}{2}+\sum_{u\in\mathcal{U}_{i,n}}C_{i,n,u}g_{i,n,t,u}\right)\Bigg\} \quad (49)$$

s.t.
$$\sum_{t\in\mathcal{T}}\sum_{n\in\mathcal{N}_{i,w}}\left[\sum_{w\in\mathcal{W}_{i,n}}(P_{i,n,w}y_{i,n,t,w}-F_{i,n,w}s_{i,n,t,w}) + V\left(\sum_{\ell\in\mathcal{L}_n^-}f_{\ell,t}-\sum_{\ell\in\mathcal{L}_n^+}f_{\ell,t}\right)\right]-\overline{R}_i \geq 0 : \gamma_i, \quad \forall i\in\mathcal{I} \quad (50)$$

$$\overline{E}-\sum_{i\in\mathcal{I}}\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}}\sum_{u\in\mathcal{U}_{i,n}}E_{i,n,u}g_{i,n,t,u}\geq 0 : \rho \quad (51)$$

(2) – (5), (7) – (9)

(11) – (17), (19) – (21), $\forall i\in\mathcal{I}$

where $\Omega = \Omega^{\text{ISO}}\cup\Omega^i$

QP Formulation

$$\max_{\Omega} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \Bigg\{ \left(A_{n,t} c_{n,t} - \frac{1}{2} Z_{n,t} c_{n,t}^2 \right) - \sum_{i\in\mathcal{I}} \left(Z_{n,t} \frac{q_{i,n,t}^2}{2} + \sum_{u\in\mathcal{U}_{i,n}} C_{i,n,u} g_{i,n,t,u} \right) \Bigg\} \tag{49}$$

$$\text{s.t.} \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \Bigg[\sum_{w\in\mathcal{W}_{i,n}} (P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w}) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \Bigg] - \overline{R}_i \geq 0 : \gamma_i, \ \forall i \in \mathcal{I} \tag{50}$$

$$\overline{E} - \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \sum_{u\in\mathcal{U}_{i,n}} E_{i,n,u} g_{i,n,t,u} \geq 0 : \rho \tag{51}$$

$$(2)-(5),\ (7)-(9)$$

$$(11)-(17),\ (19)-(21),\ \forall i \in \mathcal{I}$$

where $\Omega = \Omega^{\text{ISO}} \cup \Omega^i$

QP Formulation

$$\max_{\Omega} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \Bigg\{ \left(A_{n,t} c_{n,t} - \frac{1}{2} Z_{n,t} c_{n,t}^2 \right) - \sum_{i\in\mathcal{I}} \left(Z_{n,t} \frac{q_{i,n,t}^2}{2} + \sum_{u\in\mathcal{U}_{i,n}} C_{i,n,u} g_{i,n,t,u} \right) \Bigg\} \tag{49}$$

s.t. $$\sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}_{i,w}} \left[\sum_{w\in\mathcal{W}_{i,n}} \left(P_{i,n,w} y_{i,n,t,w} - F_{i,n,w} s_{i,n,t,w} \right) + V \left(\sum_{\ell\in\mathcal{L}_n^-} f_{\ell,t} - \sum_{\ell\in\mathcal{L}_n^+} f_{\ell,t} \right) \right] - \overline{R}_i \geq 0 : \gamma_i, \quad \forall i \in \mathcal{I} \tag{50}$$

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(2) – (5), (7) – (9)

(11) – (17), (19) – (21), $\forall i \in \mathcal{I}$

where $\Omega = \Omega^{\text{ISO}} \cup \Omega^i$

QP Formulation

$$\max_{\Omega} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} \Bigg\{ \left(A_{n,t} c_{n,t} - \frac{1}{2} Z_{n,t} c_{n,t}^2 \right) - \sum_{i\in\mathcal{I}} \left(Z_{n,t} \frac{q_{i,n,t}^2}{2} + \sum_{u\in\mathcal{U}_{i,n}} C_{i,n,u} g_{i,n,t,u} \right) \Bigg\} \quad (49)$$

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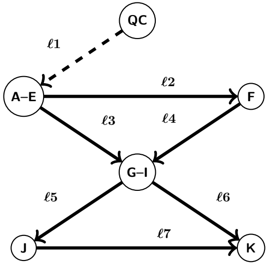
(2) − (5), (7) − (9)

(11) − (17), (19) − (21), $\forall i \in \mathcal{I}$

where $\Omega = \Omega^{\text{ISO}} \cup \Omega^i$

Numerical Examples

Transmission



Line	Type	K_ℓ	B_ℓ
$\ell 1$	DC	1500	–
$\ell 2$	AC	1999	7.5
$\ell 3$	AC	2150	4.7
$\ell 4$	AC	3475	9.4
$\ell 5$	AC	4450	13.4
$\ell 6$	AC	1290	15.2
$\ell 7$	AC	235	14.3

Hydro Production (Debia et al., 2018)

$P_{i,n,w}$	1	Inflows are expressed in energy content
$F_{i,n,w}$	$\frac{1}{0.73}$	Blenheim-Gilboa efficiency rate is 73%
$\overline{X}_{i,n,w}\ (QC)$	176 TWh	Estimated total water reservoir capacity
$\overline{X}_{i,n,w}\ (NY)$	$3 \times Y_{i,n,w}$	PHS can produce at most for 3 hours

- Inflows in NY are calibrated to fit observed hydro production in a particular month
- Inflows in QC are calibrated à la Bushnell (2003)
  - Heritage regulation: HQ Production sells 165 TWh to HQ Distribution annually
  - Assume that this 165 TWh is available at the beginning of the year and that HQ must use all of it
  - Since ROR plants are all situated downstream of RES plants, as a first approximation, water in reservoir can theoretically be turbined twice
  - Hence, the volume of water available is 82.5 TWh equivalent

Thermal Generation Costs, Emission Rates, and Ramp Rates

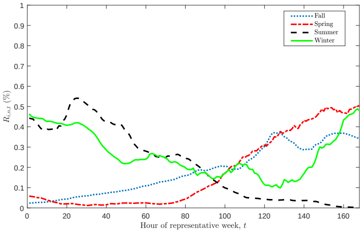
Technology	$C_{i,n,u}$	$E_{i,n,u}$	$\underline{G}_{i,n,u} (= \overline{G}_{i,n,u})$ (%)
Nuclear	15	0	0.1
CC	30	0.3	0.5
ST	45	0.8	0.3
GT	60	0.6	1

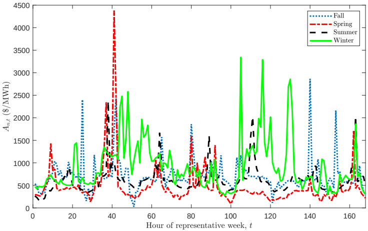
- Steam turbines (ST) covers coal, natural gas, and fuel oil
- Gas turbines (GT) covers natural gas, fuel oil, jet fuel, and kerosene
- New York CO_2 emission cap of 29.2 Mt

Firms' Installed Capacities by Node and Unit (MW)

n	i	Nuclear	CC	ST	GT	RES	ROR	PS
QC	HQ		411			22583	13517	
A–E	Edison		80		2			
	NRG			2107				
	NYPA						3957	240
	Fringe	3345	2146	1199	137		760	
F	Edison		77					
	NYPA						23	1160
	Fringe		2824	21	10		477	
G–I	Edison			1208				
	NYPA						48	
	Fringe	2055		1312	104		59.4	
J	Astoria		1093	925	847			
	Edison		551	322	94			
	NYPA		459		412			
	TC		217	1699	289			
	Fringe		877		460			
K	LIPA		503	2482	1878			
	NYPA		134		51			
	Fringe		50		152			

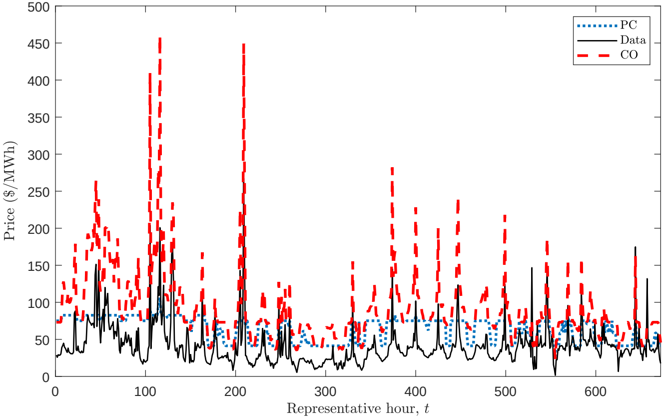
VRES and Demand





- **Wind turbines: 1348 MW at QC, 1746 MW at A–E**
- **Demand: construct nodal inverse-demand functions via estimates of own-price elasticities (Debia et al., 2018)**
- **Time resolution: representative weeks for each of the four seasons**

Price Calibration



Test Cases

Regulation \ Market	Perfect Competition	Cournot Oligopoly
No Regulation	PC	–
Hydro Only	–	CO-B2003
Hydro Plus Net Imports	–	CO-B2003-NI

Impact (in billion $) of Market Power under Existing CO_2 Emission Cap

Metric \ Case	PC	CO-B2003	CO-B2003-NI
SW	111.79	111.50	110.57
CS	99.52	97.32	95.58
PS	10.74	12.70	12.71
MS	0.43	0.83	0.09
GR	1.10	0.64	2.19
CO_2 price ($/t)	37.66	21.88	75
HQ	7.31	7.83	5.06
NRG	0.01	0.16	0.19

Impact (in billion $) of Market Power under Existing CO_2 Emission Cap

Metric \ Case	PC	CO-B2003	CO-B2003-NI
SW	111.79	111.50	110.57
CS	99.52	97.32	95.58
PS	10.74	12.70	12.71
MS	0.43	0.83	0.09
GR	1.10	0.64	2.19
CO_2 price ($/t)	37.66	21.88	75
HQ	7.31	7.83	5.06
NRG	0.01	0.16	0.19

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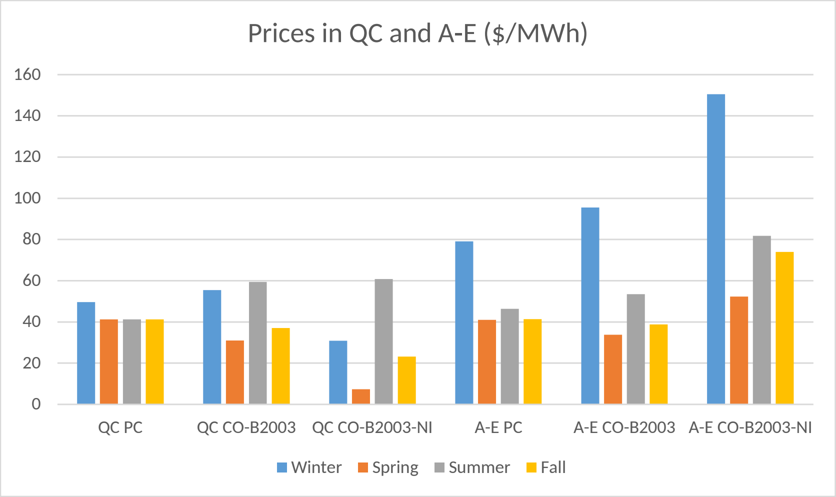
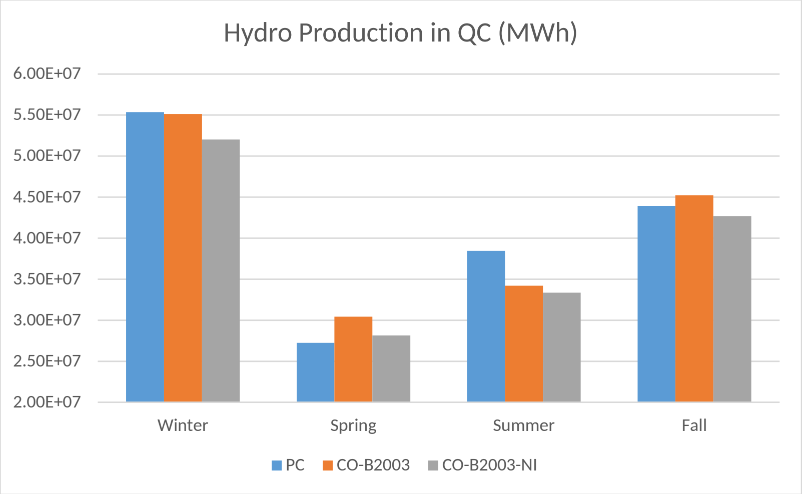
NRG	0.01	0.16	0.19

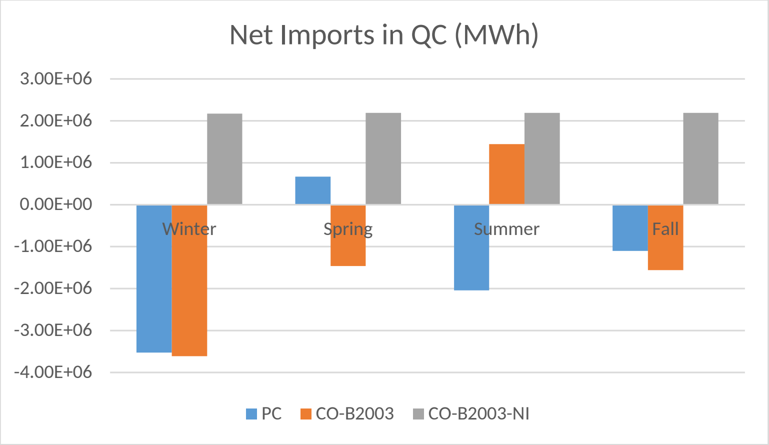
Impact of Market Power on Prices



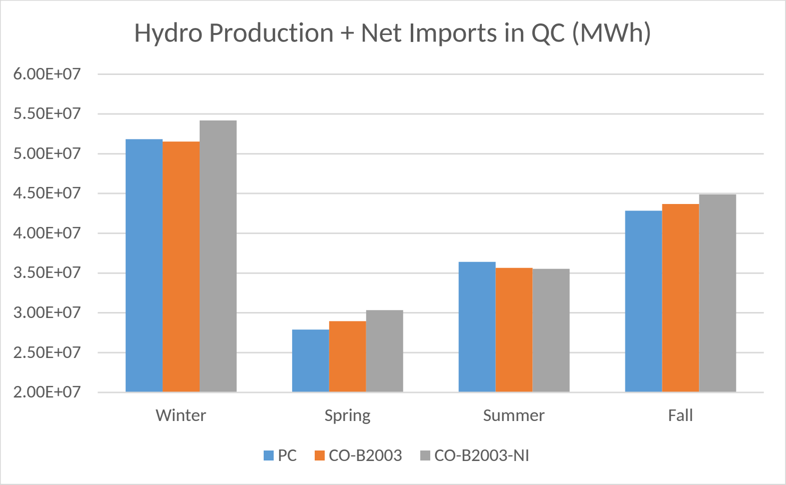
Impact of Market Power on QC Hydro Production



Impact of Market Power on QC Net Imports



Impact of Market Power on QC Hydro Production Plus Net Imports



Conclusions

Summary

- **Transformation of power sector with higher VRES penetration gives more leverage to flexible producers**
- **Examine the impacts of carbon policy, hydropower production, and regulation on market equilibria**
- **Storage may be deployed not only in a socially optimal manner but also in order to increase profits**
- **Case study reveals Bushnell (2003)-like behaviour by HQ under CO**
    - **Inclusion of net imports in regulatory constraint limits the extent of distortion due to shifting hydropower production but may increase CO_2 permit price and enhance market power of NY firms with thermal portfolios**
- **Ongoing work: improved calibration, representative weeks, roles of carbon policy and regulation**