Comparing Profit-Maximizing Offer Behavior of Generators in Centrally Versus Self-Committed Wholesale Electricity Markets

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Introduction, Background, and Research Question

- A dichotomy in electricity-market design: who makes unit-commitment decisions
- U.S. markets have evolved towards centrally committed designs—the market operator (MO) collects complex multi-part offers and solves unit-commitment problem to co-ordinate these decisions
- Other markets use self-committed designs—generators determine unit commitments individually and MO clears demand against supply based on simple energy offers
- Centralized commitment is more efficient if the auction is incentive-compatible [Sioshansi et al., 2008b]
- Research Question: How do the two market designs compare, accounting for incentive properties?

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Self-Committed Design

$$\max \sum_{t \in \mathcal{T}} \left[(\omega_t - c_i^v) x_{i,t} - c_i^f u_{i,t} \right]$$

$$\text{s.t.}\ 0 \le b_i^v \le \bar{b}^v$$

$$u_{i,t} \in \{0, 1\}; \forall t \in \mathcal{T}$$

(1)–(3)

where:

$$\min \sum_{j \in \mathcal{G}, t \in \mathcal{T}} b_j^v x_{j,t} \qquad (1)$$

$$\text{s.t.} \sum_{j \in \mathcal{G}} x_{j,t} = D_t; \forall t \in \mathcal{T} \qquad (\omega_t) \qquad (2)$$

$$0 \le x_{j,t} \le K_j u_{j,t}; \forall j \in \mathcal{G}, t \in \mathcal{T} \qquad (3)$$

- Impose some standard assumptions
- Transform bi-level self-committed model into a single-level problem by replacing lower-level market-clearing problem (1)–(3) with its necessary and sufficient KKT conditions

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Centrally Committed Design

$$\max \sum_{t \in \mathcal{T}} \left[(\eta_t - c_i^v) x_{i,t} - c_i^f u_{i,t} \right]$$

$$\text{s.t.} \; 0 \leq b_i^v \leq \bar{b}^v$$

$$0 \leq b_i^f \leq \bar{b}^f$$

$$(4)\text{–}(7)$$

where:

$$\min \sum_{j \in \mathcal{G}, t \in \mathcal{T}} \left(b_j^v x_{j,t} + b_j^f u_{j,t} \right) \quad (4)$$

$$\text{s.t.} \sum_{j \in \mathcal{G}} x_{j,t} = D_t; \forall t \in \mathcal{T} \quad (5)$$

$$0 \leq x_{j,t} \leq K_j u_{j,t}; \forall j \in \mathcal{G}, t \in \mathcal{T} \quad (6)$$

$$u_{j,t} \in \{0, 1\}; \forall j \in \mathcal{G}, t \in \mathcal{T}; \quad (7)$$

- Lower-level market-clearing problem (4)–(7) is mixed-integer, so there are no simple optimality conditions with which to convert this to a single-level problem
- Added Wrinkle: Centrally committed designs use make-whole payments:

$$\max \left\{ 0, \sum_{t \in \mathcal{T}} \left[(b_i^v - \eta_t) x_{i,t} + b_i^f u_{i,t} \right] \right\}$$

to mitigate reported economic confiscation [O'Neill et al., 2005, Sioshansi, 2014]

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General Approach [Huppmann and Siddiqui, 2018]

- General mixed-binary problem:

$$
\begin{aligned}
&\min f(x, y) \\
&\text{s.t.}\, h(x, y) = 0 \\
&\quad g(x, y) \leq 0 \\
&\quad x \in \mathbb{R}^n, y \in \{0, 1\}^m
\end{aligned}
$$

- If we fix $y = \bar{y}$, KKT conditions for x are as usual:

$$
\nabla_x f(x, \bar{y}) + \lambda^\top \nabla_x h(x, \bar{y}) + \mu^\top \nabla_x g(x, \bar{y}) = 0
$$
$$
h(x, \bar{y}) = 0
$$
$$
g(x, \bar{y}) \leq 0 \perp \mu \geq 0
$$

- Solution technique:
  1. Enumerate all possible $\bar{y}$, gives a set $\mathcal{Y}$
  2. For each $y \in \mathcal{Y}$ find associated $x^*(y)$, $\lambda^*(y)$, $\mu^*(y)$ using KKT conditions
  3. Select the best $x^*(y)$ & y
- This gives a single-level mixed-binary (usually nonlinear) problem, with the number of auxiliary variables and KKT conditions growing exponentially with m

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Previous Literature

- Centralized commitment finds near-optimal solutions with different prices and generator profits [Johnson et al., 1997, Sioshansi et al., 2008a, Sioshansi and Tignor, 2012]
- Comparison of the two designs *vis-à-vis* supply and demand flexibility, resource remuneration, and market power and efficiency [Ahlqvist et al., 2022]
- Aforementioned works assume truthful revelation by generators
  - ➥ Limited works that consider strategic offering behavior and incentive properties

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Key Findings

- With symmetric duopoly and single operating period, the offer caps markets can be set so the two designs are expected-cost equivalent [Sioshansi and Nicholson, 2011]
- This equivalence breaks-down with multi-firm oligopoly, due to uniform-price requirement of a self-committed design [Duggan, Jr. and Sioshansi, 2019]
  - ➥ Price under self-committed design must be high enough for the marginal generator to recover its fixed cost, which yields positive economic rents to inframarginal generator(s)
- Higher cost and productive-efficiency losses of self-committed design with asymmetric firms
  - Discriminatory make-whole payment provides an additional degree of freedom for rent-seeking behavior under centrally committed design
  - Under self-committed design, the only avenue for rent-seeking is to increase the uniform energy price

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Contributions

- Relax partially the symmetry assumption by allowing generators with different costs but same capacities
- Compute partial equilibrium—profit-maximizing offers for one firm, holding rival offers fixed
- Capture multiple operating periods that are linked by long-lived offers
- Key technical contribution: an efficient approach to solving profit-maximization for a centrally committed market design

Solution Approach

Overview

- Because of symmetric-capacity assumption ($K_j = K, \forall j \in \mathcal{G}$), an optimal solution to the MO's problem results in each generator being either:
  - inframarginal ($x_{j,t} = K$),
  - marginal ($x_{j,t} = r_t$), or
  - inactive ($x_{j,t} = 0$)

  during each $t \in \mathcal{T}$
- Thus, generator i's optimal offers yields one of only $3^{|\mathcal{T}|}$ candidate production profiles
- For each candidate production profile, $\hat{x}_i$, we have a necessary and sufficient constraint set, $\mathcal{B}_{\hat{x}_i}$, which characterizes generator-i offers that make $\hat{x}_i$ optimal in MO's problem
- For each candidate $\hat{x}_i$, solve an auxiliary problem with the constraint set, $\mathcal{B}_{\hat{x}_i}$, to determine offers that yield $\hat{x}_i$ as a production profile and resultant maximized profit

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Example

Non-Zero Rival Fixed Costs

- Three firms, three time periods
- Capacities: $K = 20$ MW
- $c_i^f = \$10$, c_i^v varies

Table: Cost Data

j	c_j^v	c_j^f
1	4	10
2	5	10

Table: Demand Data

t	D_t
1	25
2	34
3	38

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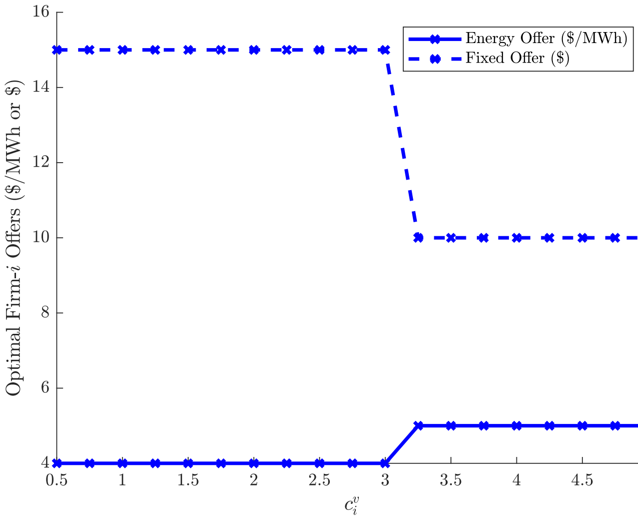
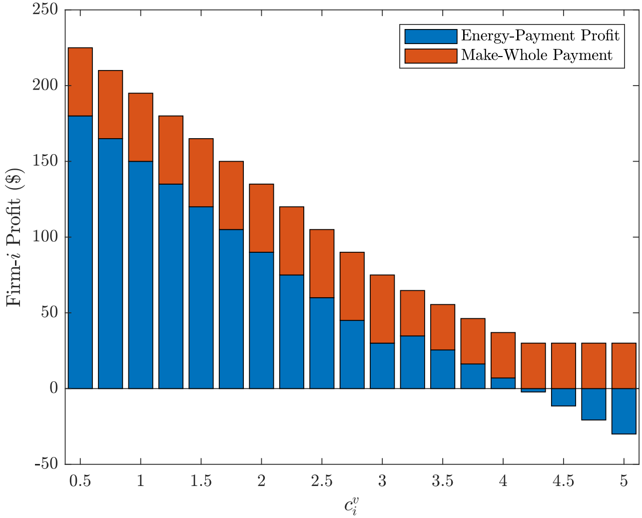
Optimized Offers



Firm-i Profit



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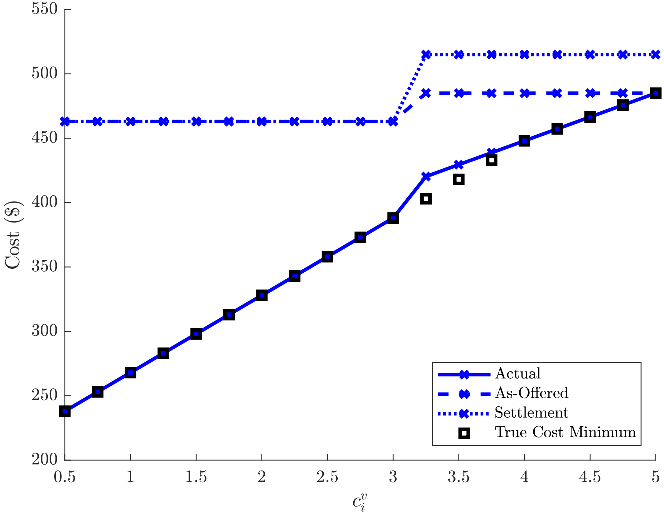
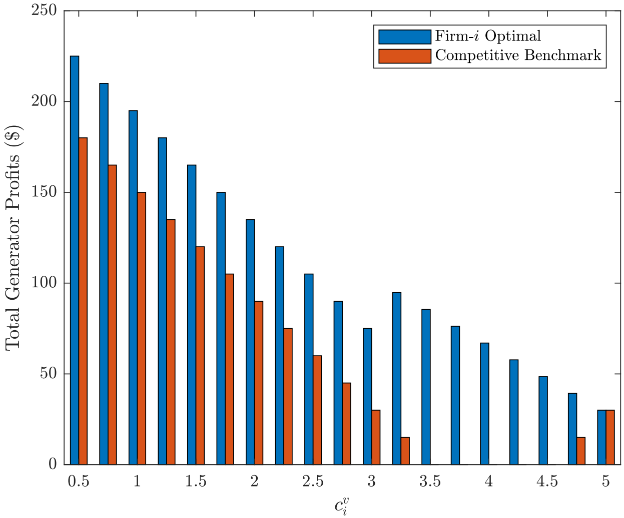
Operation Cost



Total Profit



Example

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Table: Cost Data

j	c_j^v	c_j^f
1	5	0
2	6	0

Table: Demand Data

t	D_t
1	25
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3	38

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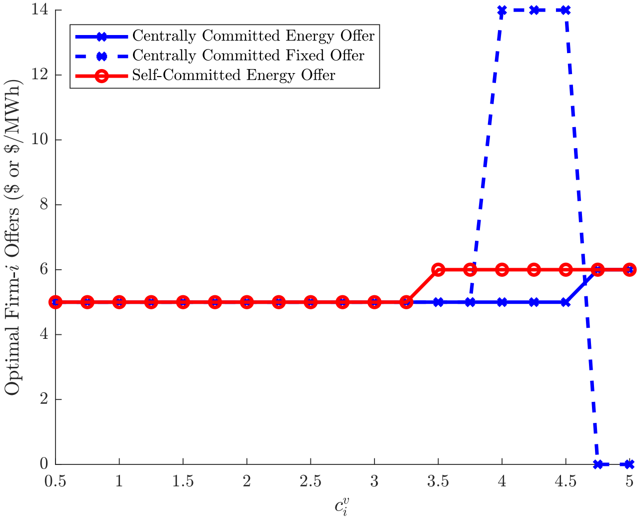
Optimized Offers



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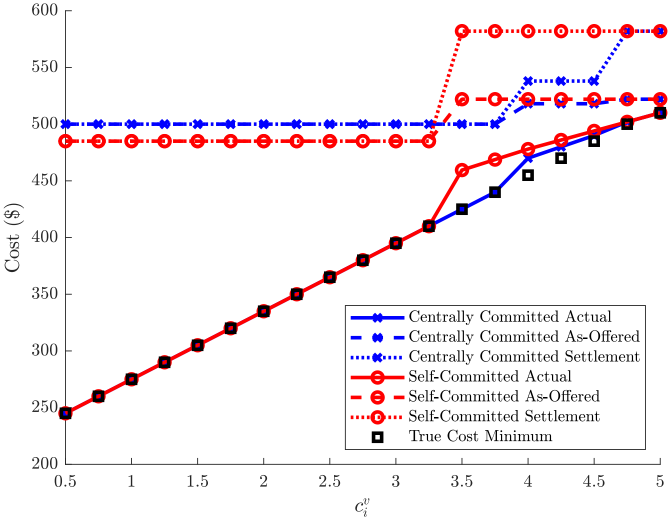
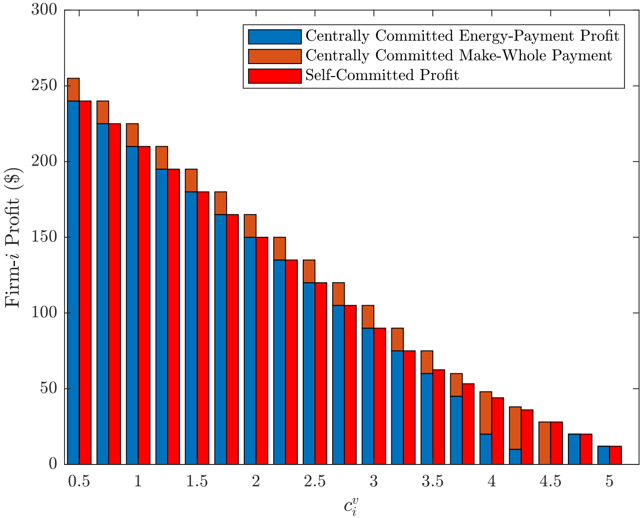
Operation Cost



Optimized Profit



Computational Performance

- Generate random instances of problem with different numbers of firms, $|\mathcal{G}|$, and hours, $|\mathcal{T}|$
- Solve each with 12-hour time limit
- Programmed using Python 3.7 and solved with Gurobi 9.1.1
- Computer with two 2.90-GHz cores and 16.0 GB memory

Table: Average Computation Time (s)

$\|\mathcal{G}\|$	$\|\mathcal{T}\|$	[Huppmann and Siddiqui, 2018]	Proposed Algorithm
2	2	0.176	0.066
2	3	2.572	0.098
2	4	70.073	0.212
2	5	5827.641	0.319
3	2	5.167	0.086
3	3	1159.978	0.153
3	4	∞	0.296
3	5	∞	0.660
4	2	∞	0.061
4	3	∞	0.135
4	4	∞	0.275
4	5	∞	0.531
5	2	∞	0.068
5	3	∞	0.146
5	4	∞	0.302
5	5	∞	0.651

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To Summarize and Conclude

- Self-committed designs appear to be more expensive to consumers and have greater productive-efficiency losses
- Firms exercise market power in a self-committed design solely through raising energy prices, which are paid to everyone
- Make-whole payments in centrally committed design give generators a discriminatory mechanism for rent-seeking
- Some unanswered questions:
  - How do these comparisons change with multiple profit-maximizing firms (*i.e.*, complete equilibrium)?
  - Absent a complete equilibrium, incorporate uncertainty into firm *i*'s problem

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Thank you!

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