Pricing and Capacity Provision in Electricity Markets: An Experimental Study

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Introduction

Long tradition of discussing price caps in power markets

- California, 2002:
  - July 9, CAISO cuts price cap by nearly 40% to 57.14 \$/MWh
  - July 11, FERC returned to region-wide cap 91.87 \$/MWh
  - Low caps *"could cause severe supply disruptions... We act now because we cannot expose customers in California and other Western states to the risks of a low price cap."* (FERC, 2002)
- Texas, 2015:
  - Public Utility Commission increased price cap threefold 2012 to 2015
  - *" It is important to send a strong signal at this time. One thing we can't do is ignore this and move forward blindly and have faith that we will have enough electricity."* (PUC Chairman Donna Nelson, 2012)

Introduction

How much compensation do firms need for providing peak load electricity?

- Peak capacity only required for very few hours during the year
- Generation capacity is 'slow variable' and risky long-run investment decision
- Power prices only peak during short number of hours and only then allow for reimbursing investment (if price sufficiently high)
- Price competition usually 'fast', e.g. hourly or 15-min granularity
- Profit-maximizing investors will avoid overcapacity

Introduction

Two classes of solutions to this: energy-only and capacity market design

- Energy-only approach
  - Sales of electricity only source of revenue
  - Generators have to cover their current marginal costs plus earlier capacity investment costs
  - Price spikes in times of peak demand are necessary and reflect return on investment into peak capacity, contain scarcity information; need somewhat high price cap
- Capacity payments
  - Capacity payments create second revenue stream, rewarding availability of generation capacity rather than generation
  - Can be pre-defined payment or determined in capacity market; regulator demands capacity

Research question

Basic idea, approach, and main findings

- Basic idea: Compare designs in their ability to provide generation capacity
  - Do market rules create right price signals?
  - Do market rules encourage system reliability?
  - How do market rules affect gaming?
- Experimental approach:
  - Empirical strategy challenging as counterfactual market outcomes do not exist
  - Instead, use experimental setting to compare different regulatory regimes within a well-defined environment
- Main findings:
  - All regimes perform as theory suggest and deliver according capacity; low price caps cause underinvestment
  - High price caps do not fully translate into higher prices
  - Capacity market does not reduce market power per se

Related literature

Theoretical, empirical, and experimental...

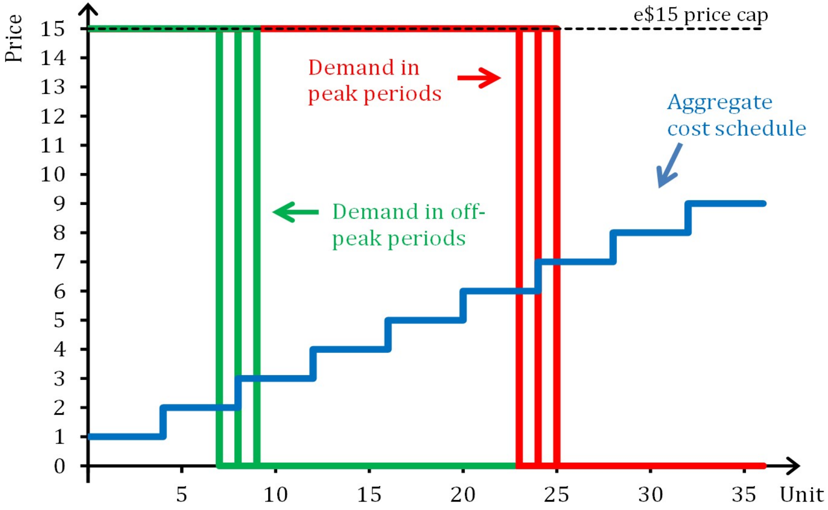
- Theoretical literature on power market design: Joskow and Tirole (2007), Creti and Fabra (2007)
- Empirical work on market design, price caps, capacity markets: Wolfram (1999), Schwenen (2015)
- Experimental literature:
  - General literature on multi-unit (electricity) auctions (Abbink et al. 2003, van Koten and Ortmann 2013, Brandts et al. 2014)
  - On firm-specific price caps (Kiesling and Wilson 2006), non-binding price caps (Vossler et al., 2009), or automated market power mitigation (Schawhan et al., 2011)

Experimental Design

Experimental design
Overview

- Subjects in the role of firms; 4 firms per market
- This quadropoly market was played 10 rounds with 6 periods each (more on timing later)
- Cost function:
  - Fixed cost for each unit of e$7
  - Increasing marginal costs: Unit 1 costs e$1, unit 2 costs e$2, ... unit 9 costs e$9
  - Capacity constraints: investment up to 9 units
- Demand:
  - Perfectly inelastic but fluctuates (off-peak and peak)

Inelastic demand and increasing marginal costs schedule



Experimental design

Overview, con't

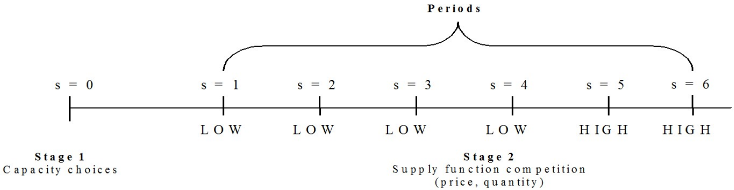
- **Timing:** One *round* consists of six *periods*: in each period, subjects compete in prices on the spot market for electricity
- Each market lasts 10 rounds
  - Rounds 1 - 2: capacities are given and 9 for each subject
  - Rounds 3 - 10: capacities are chosen at the beginning of each round
- Treatment variables: (i) price cap, (ii) capacity market
- Three treatments:

	Price cap = 15	Price cap = 30
No capacity market	*LowCap*	*HighCap*
Capacity market	*CapMarket*	

More on timing

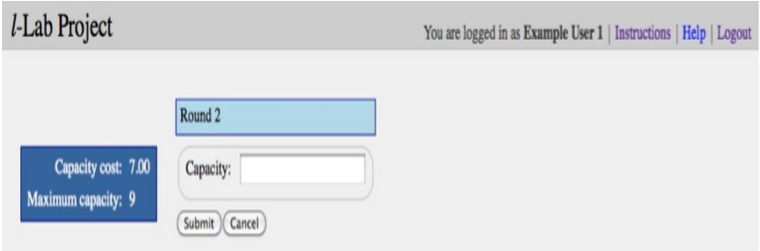
Capacity choices

- Capacity choices are made at the beginning of each round, knowing only the distribution of demand



- Stage 1: simultaneous capacity choices (up to 9 units) under demand uncertainty
  - Fixed cost for each unit (=e\$7) + Increasing MC: 1 unit costs e\$1; 2 units cost e\$2 etc.

Stage 1: Capacity choices

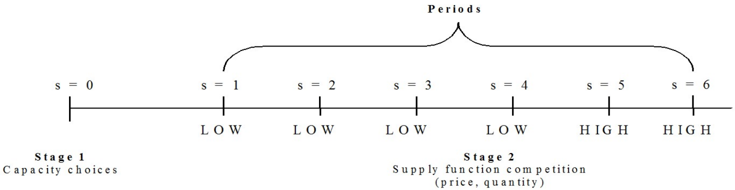


- Capacity choices publicly revealed before competing in price

Still more on timing

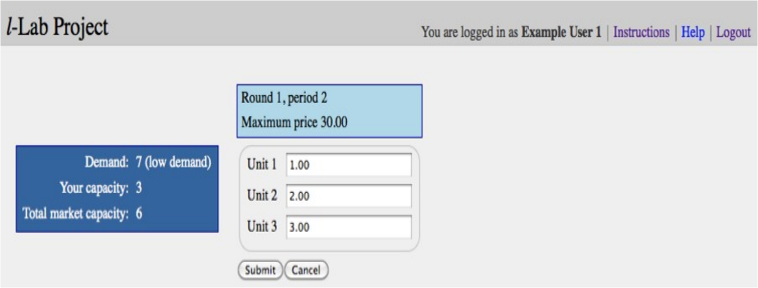
Price competition

- Prices are chosen at the beginning of each round, knowing the realization of demand



- Stage 2: price competition for 6 periods with uniform-price auction
  - Demand is realized for each period: Low (D=7,8,9) and High (D=23,24,25)
  - Subjects bid independently and simultaneously: for each unit, bid between MC and price cap

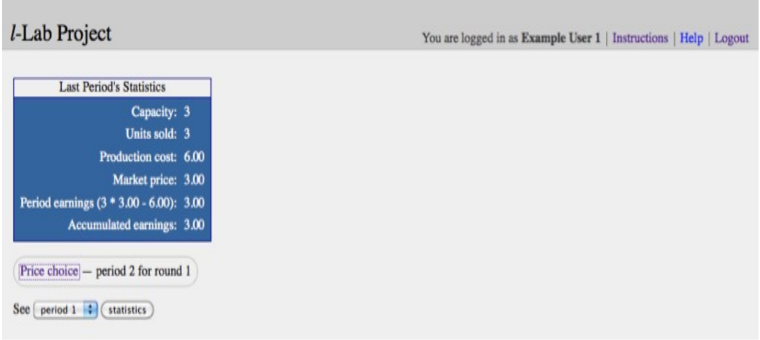
Stage 2: Price competition



- Subjects only pay production costs for dispatched units

Stage 3: Market allocation revealed

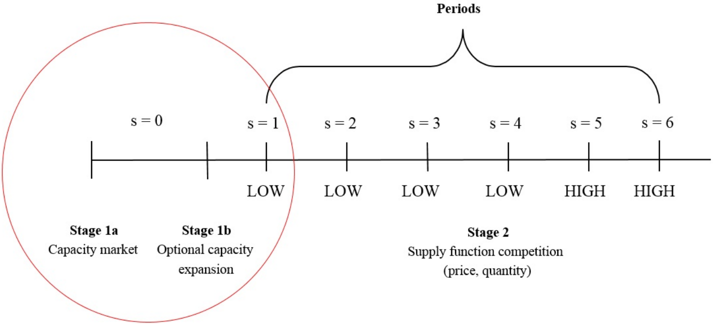
- Market supply function: computer ranks bids from the lowest to the highest
- Market price: intersection of market supply function with inelastic demand



Yet more on timing

Capacity market

- Regulator procures 25 units of capacity; there is a spot market price cap of e$15 and a capacity market price cap of e$30



Treatments and experimental procedure

- **Three treatments**
  - Price cap = e$15 in LowCap
  - Price cap = e$30 in HighCap
  - Price cap = e$15 and capacity market in CapMarket
- **Experimental procedure**
  - 92 students
  - Two sessions for each treatment, 3-4 independent markets per session
  - Avg. payment $24

Theory & Hypotheses

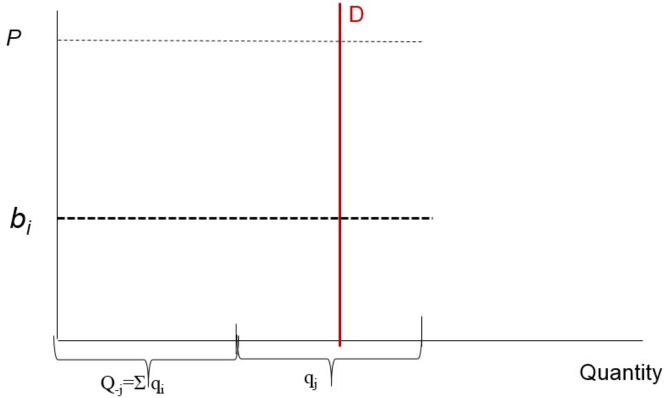
Theoretical prediction 1

Equilibrium bidding

- We refer to the concept of pivotal bidding
  - von der Fehr and Harbord (1993)
  - Fabra et al. (2006)

Residual demand and pivotal bidding

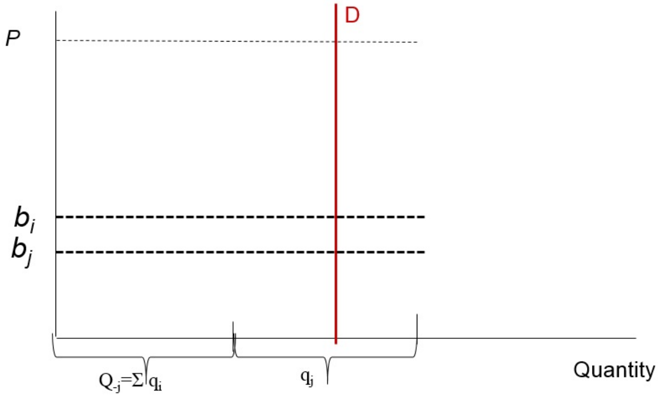
- Suppose firm j is pivotal, that is $D - Q_{-j} > 0$



Residual demand and pivotal bidding

Continued

- Given some rivals' b_i, shall firm j undercut?



Residual demand and pivotal bidding

Continued

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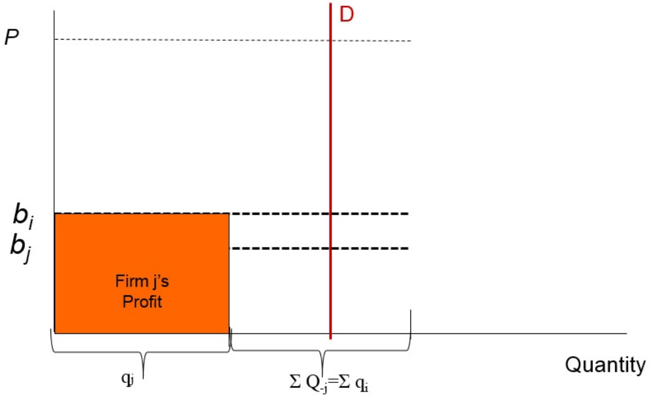
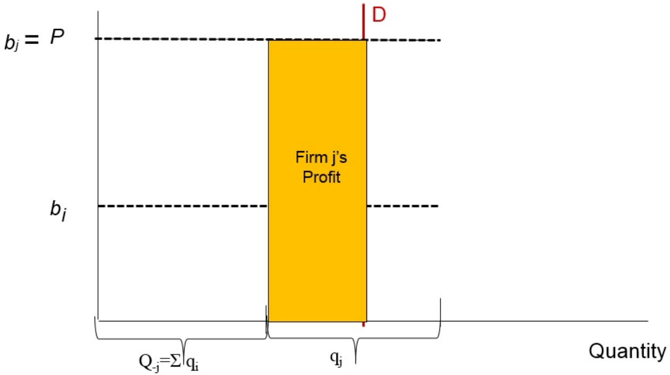


Residual demand and pivotal bidding

Continued

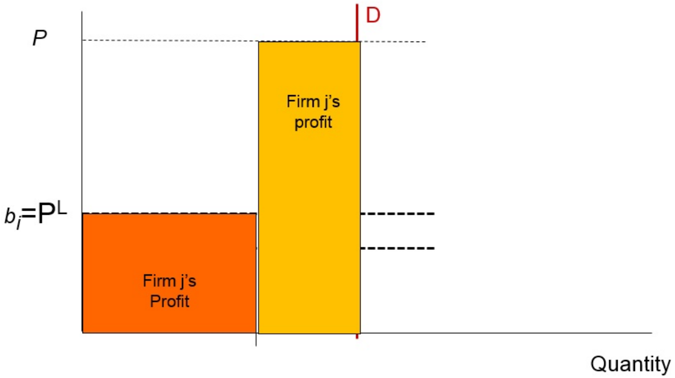
- Or shall firm j maximize against residual demand and $b_j = P$?



Residual demand and pivotal bidding

Continued

- Profit of either choice depend on b_i; define P^L as critical bid of firm i; if $b_i < P^L$ then $b_j = P$



Hypothesis 1

Equilibrium market price

- Definition:
  - Define a pivotal firm j such that $D - Q_{-j} > 0$ where $Q_{-j} \equiv \bar{q}_{j \neq i}$
- Prediction:
  - With at least one pivotal firm, the energy market equilibrium price is the price cap (assuming that non-price setting firms bid low enough)
- **Hypothesis 1:**
  (i) With at least one pivotal bidder, the equilibrium market price equals the price cap, irrespective of the treatment.
  (ii) When no pivotal bidder exists, the market price equals the marginal costs of the last dispatched unit.

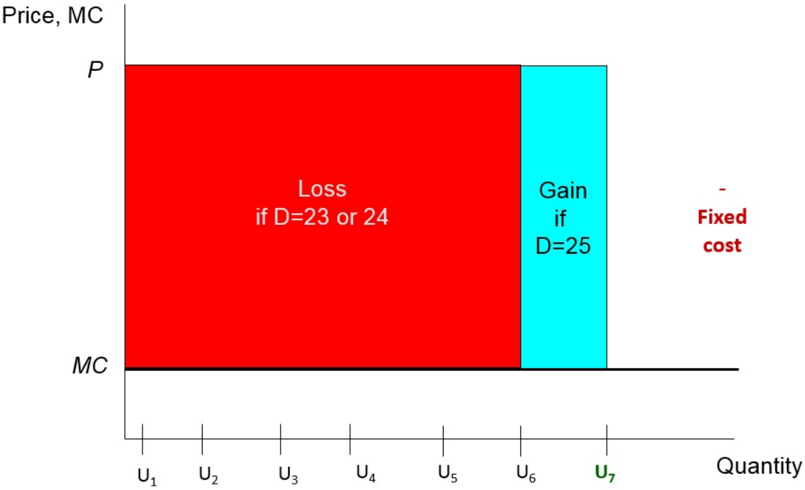
Theoretical prediction 2

Equilibrium capacity

- Question here: What is the incentive to invest in unit 25?
- We focus on (quasi-)symmetric equilibrium
  - e.g. for all firms $i \in (1, 2, 3, 4)$ we have (6,6,6,7)
- Other equilibria possible

Increasing from 6 to 7 units

... given all rivals hold 6 units



Hypotheses 2 & 3

Equilibrium capacity

- Prediction: Pure strategy equilibria in capacities are for any $i \in (1, 2, 3, 4)$
  - $q_i = 6$ in *LowCap*
  - $q_i = 7$ and $q_{-i} = 6$ in *HighCap*
  - $q_i = 7$ and $q_{-i} = 6$ in *CapMarket* if capacity price $f > \frac{5}{3}$
- **Hypotheses 2 & 3:**
  (i) Underinvestment occurs in the LowCap treatment. Sufficient investment occurs in HighCap.
  (ii) Sufficient investment occurs in CapMarket, if capacity price $f > \frac{5}{3}$.

Results

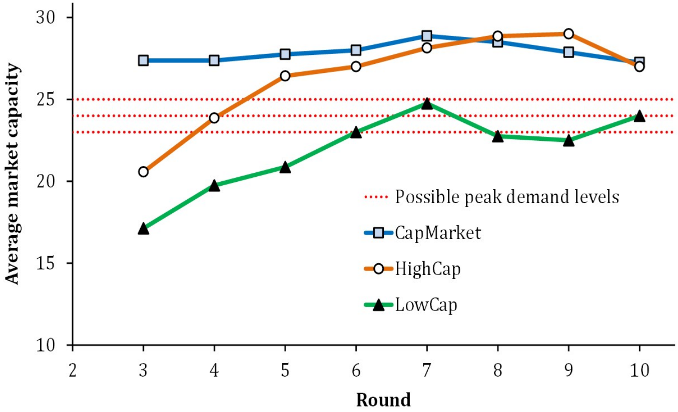
Result 1: Avg. market capacity

	Treatment	Mean	SD	Min	Median	Max	Rationing†
Rounds 3-10	LowCap	21.8	4.2	11	23	29	55.5%
	HighCap	26.2	3.9	15	27	33	26.0%
	CapMarket	27.9	2.3	25	27.5	34	0.0%
Rounds 8-10	LowCap	23.1	2.7	17	23.5	27	52.1%
	HighCap	28.4	1.6	25	29	32	0.0%
	CapMarket	27.9	2.3	25	27.5	32	0.0%

†Rationing = Number of peak periods where demand > supply, divided by total number of peak periods.

- Constant underinvestment in *LowCap*, sufficient in *HighCap* and *CapMarket*
- Hypotheses 2 & 3 confirmed

Result 1: Avg. market capacity



- *HighCap* and *CapMarket* show very similar capacity towards the end of the experiment

Result 2: Avg. market price (during peak demand)

Pivotal player(s)	Treatment	MC price	Avg. price	Price cap
None	LowCap	6.25	7.20	15.00
	HighCap	6.32	7.75	30.00
	CapMarket	6.33	8.46	15.00
At least one	LowCap	6.50	13.23	15.00
	HighCap	6.69	25.14	30.00
	CapMarket	7.05	10.78	15.00

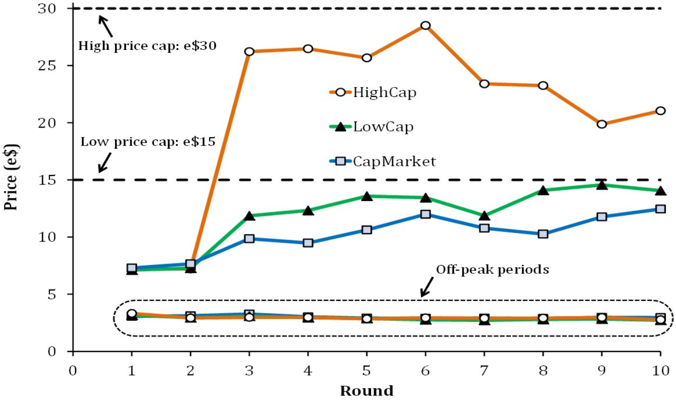
- Hypothesis 1 confirmed: in all treatments, price close to price cap, when pivotal bidder exists

Result 2: Avg. market price (off-peak)

Treatment	MC Price	Avg. price	Price cap
LowCap	2.39	2.89	15.00
HighCap	2.36	2.96	30.00
CapMarket	2.36	3.00	15.00

- Hypothesis 1 confirmed: in all treatments, price equal to (roughly) marginal costs (no pivotal bidders exist)

Result 2: Avg. market price



- Fierce competition off-peak
- Upward trend for *LowCap* and *CapMarket*, but not *HighCap*

Result 3: Price, pivotal bidding, and relative capacity

	Dependent variable: Markup					
	LowCap		HighCap		CapMarket	
	Rounds 1-10	Rounds 8-10	Rounds 1-10	Rounds 8-10	Rounds 1-10	Rounds 8-10
Pivotal	5.800*** (0.000)	7.425*** (0.000)	18.844*** (0.000)	16.417*** (0.009)	2.501*** (0.000)	1.283 (0.277)
RelCap	0.009 (0.496)	0.053 (0.246)	−0.005 (0.881)	−0.145 (0.624)	−0.058*** (0.002)	−0.164*** (0.003)
RelCap × Pivotal	−0.095*** (0.007)	−0.240*** (0.000)	−0.540*** (0.000)	−1.013** (0.033)	−0.156** (0.040)	−0.085 (0.512)
Round	0.040 (0.130)	−0.016 (0.889)	−0.091 (0.170)	−1.146** (0.018)	0.035 (0.205)	0.154 (0.361)
Number of females	−0.272*** (0.000)	−0.033 (0.756)	−0.346 (0.150)	−1.425*** (0.006)	−0.185** (0.025)	−0.040 (0.790)
Constant	0.884** (0.020)	−0.179 (0.833)	2.010** (0.039)	8.591 (0.192)	2.000*** (0.000)	3.700*** (0.003)
N	480	144	384	90	480	144
Adjusted R^2	0.741	0.902	0.847	0.808	0.388	0.535

*,** and *** indicates significance at the 10%, 5% and 1% level, respectively (p-values in parentheses).

- Significant effect of 'pivotal', however not for *CapMarket* rounds 8-10

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- Competition-enhancing effect of additional capacity, stronger over time

Result 4: Treatment effect on DMPA=$100 * \frac{p-p_{MC}}{P-p_{MC}}$

	Dependent variable: DMPA in rounds 8-10			
	Markets with at least one pivotal firm		Markets without pivotal firms	
HighCap	−24.023***	−2.941	−2.364**	−3.688
	(0.001)	(0.846)	(0.044)	(0.726)
CapMarket	−28.763***	−9.714	1.171	44.521***
	(0.000)	(0.317)	(0.342)	(0.000)
RelCap		−3.196**		0.257
		(0.042)		(0.266)
HighCap × RelCap		−1.490		−0.012
		(0.680)		(0.982)
CapMarket × RelCap		−2.651		−2.295***
		(0.292)		(0.000)
Round	3.411	1.560	−0.199	−0.596
	(0.286)	(0.625)	(0.708)	(0.190)
Number of females	3.064	−0.381	−0.874*	−1.164***
	(0.295)	(0.901)	(0.067)	(0.007)
Constant	75.927***	85.677***	6.536***	4.209
	(0.000)	(0.000)	(0.000)	(0.303)
N	123	123	255	255
Adjusted R^2	0.202	0.271	0.058	0.346

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- *HighCap* effect due to higher market capacity

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- Likewise, *CapMarket* effect due to higher market capacity

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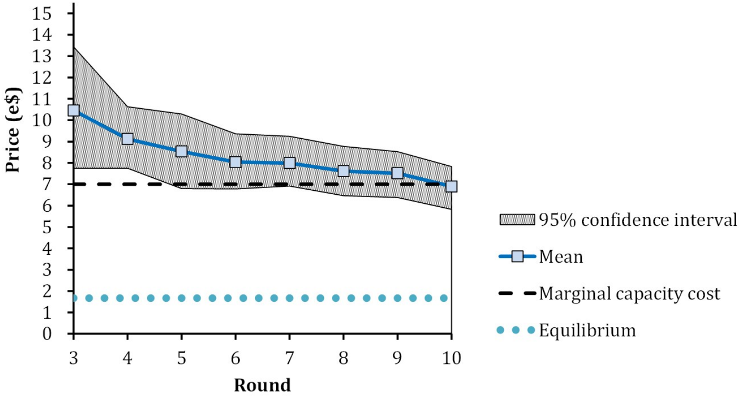
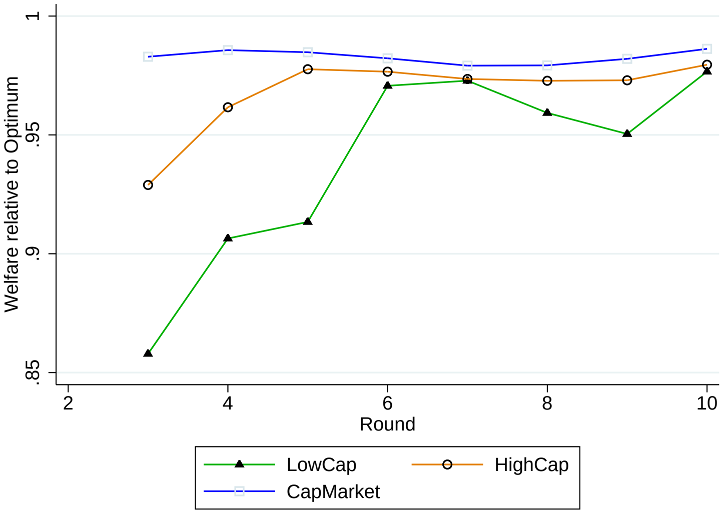
- Off-peak *CapMarket* effect more nuanced

Result 5: Avg. capacity market price



- Capacity prices show downward trend, not competitive

Result 6: Welfare comparison (preliminary)



- After learning rounds, *HighCap* and *CapMarket* somewhat similar, *LowCap* ranks third

Conclusion

Experimental analysis of three different designs for capacity provision in power markets

- We find underinvestment if price cap is too low; both alternative designs cure underinvestment problem
- We observe market power abuse in all treatments
- In *HighCap*, sufficient capacity comes with high energy prices
  - However, additional investment keeps higher prices in check
- In *CapMarket*, capacity price stimulates sufficient capacity
  - Capacity prices higher than expected and not competitive
- Here, *CapMarket* seems to outperform *HighCap*, but comparison highly depends on chosen price cap
- More treatments could include demand-side bidding

Appendix

A.1: Number of pivotal bidders

Pivotal player(s)	Treatment	Obs	Mean	Std. Dev.	Min	Max
No	LowCap	248	2.8	.4	2	4
	HighCap	203	3.1	1.4	2	20.1
	CapMarket	263	3.3	1.7	2	15
Yes	LowCap	136	12.7	3.6	3	15
	HighCap	97	25.1	6.8	6	30
	CapMarket	121	10.8	3.2	6.6	15

A.2: Capacity market prices