The Efficiency of Uniform-Price Electricity Auctions: Evidence from Bidding Behavior in ERCOT

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(research joint with Ali Hortacsu, University of Chicago)
Outline of Presentation

• What makes an electricity market “efficient”?
• Do balancing auctions provide incentives for generators to bid in a manner that promotes efficiency?
• Evidence from ERCOT:
  – How much inefficiency?
  – What is the cause of inefficient bidding behavior?
• Implications for two types of stakeholders:
  – Market monitors
  – Generators
What Is an “Efficient” Wholesale Market?

• Price is the marginal cost (MC), or the cost of last MWh required to serve load

• Short run:
  – If most efficient units not scheduled day-ahead, signals optimal “reshuffling” of generation to get least cost dispatch.

• Long run:
  – Signals value/location of new generation
Problems with Generators Submitting Bids ≠ Marginal Cost

• Typical concern: large generator bidding (INC) substantially above MC
  – Prices “high”
  – May withhold low cost units to raise the price
• Small generator bidding (INC) substantially above MC
  – Prices “high”
  – Inefficient dispatch
• Any generator bidding (DEC) substantially below MC
  – Prices too low!
  – Inefficient dispatch
Simple Example

- Units have MC varying from $30 to $120
- Given load, least cost dispatch → Price=$80
- Generator A:
  - Owns $100 unit
  - Signed bilateral deal so schedules unit day-ahead
- Generator B:
  - Owns $60 unit
  - Only scheduled half of capacity day-ahead
- Efficiency: A will DEC, B will INC
- Bad outcome:
  - A submits a (low) $40 DEC bid
  - B submits a (high) $120 INC bid
Market Power in a Balancing Market

• Suppose no further contract obligations upon entering balancing market

• INCremental demand periods
  – Bid above MC to raise revenue on inframarginal sales
  – Just “monopolist on residual demand”

• DECremental demand periods
  – Bid below MC to reduce output
  – Make yourself “short” but drive down the price of buying your short position (monopsony)
Texas Electricity Market

• ERCOT balancing market opened August 2001
• Incumbents
  – Implicit contracts to serve non-switching customers at regulated price
• Various merchant generators
Electricity Market Mechanics

• Forward contracting
  – Generators contract w/ buyers beforehand for a delivery quantity and price
  – Day before production: fixed quantities of supply and demand are scheduled w/ grid operator
  – (Generators may be net short or long on their contract quantity)

• Spot (balancing) market
  – Centralized market to balance realized demand with scheduled supply
  – Generators submit “supply functions” to increase or decrease production from day-ahead schedule
Balancing Energy Market

• Approx 2-5% of energy traded ("up" and "down")
  – "up" → bidding price to receive to produce more
  – "down" → bidding price to pay to produce less
• Uniform-price auction using hourly portfolio bids that clear every 15-minute interval
• Bids: monotonic step functions with up to 40 "elbow points" (20 up and 20 down)
• Market separated into zones if transmission lines congested – we focus on uncongested hours
## Who are the Players?

<table>
<thead>
<tr>
<th>Owner</th>
<th>% of Installed Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXU</td>
<td>24</td>
</tr>
<tr>
<td>Reliant</td>
<td>18</td>
</tr>
<tr>
<td>City of San Antonio Public Service</td>
<td>8</td>
</tr>
<tr>
<td>Central Power &amp; Light</td>
<td>7</td>
</tr>
<tr>
<td>City of Austin</td>
<td>6</td>
</tr>
<tr>
<td>Calpine</td>
<td>5</td>
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<tr>
<td>Lower Colorado River Authority</td>
<td>4</td>
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<tr>
<td>Lamar Power Partners</td>
<td>4</td>
</tr>
<tr>
<td>Guadalupe Power Partners</td>
<td>2</td>
</tr>
<tr>
<td>West Texas Utilities</td>
<td>2</td>
</tr>
<tr>
<td>Midlothian Energy</td>
<td>2</td>
</tr>
<tr>
<td>Dow Chemical</td>
<td>1</td>
</tr>
<tr>
<td>Brazos Electric Power Cooperative</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>16</td>
</tr>
</tbody>
</table>
Empirical Strategy

Price

MR = Revenue from selling one more MWh
MC = Cost of producing one more MWh
RD = Max market willing to pay for one more MWh purchased
Empirical Strategy

MR = Revenue from selling one more MWh
MC = Cost of producing one more MWh
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Empirical Strategy

MR = Revenue from selling one more MWh
MC = Cost of producing one more MWh
RD = Max market willing to pay for one more MWh purchased
S = Profit-maximizing bid curve
MR = Revenue from selling one more MWh
MC = Cost of producing one more MWh
RD = Amount market willing to pay for one more MWh purchased

Price

Empirical Strategy

MR = Revenue from selling one more MWh
MC = Cost of producing one more MWh
RD = Amount market willing to pay for one more MWh purchased
Reliant on June 4, 2002  6:00-6:15pm

- Balancing Market Quantity (MW)
- Price ($/MWh)

- Reliant’s Residual Demand
- Reliant’s MC
- Ex Post Optimal Bid Schedule
- Reliant’s Bid Schedule
Preview of Results

• Largest firm bids close to benchmarks for optimal bidding
• Small firms significantly deviate, but there’s some evidence of improvement over time
• Efficiency losses from “unsophisticated” bidding at least as large as losses from “market power”
Uniform-Price Auction Model of ERCOT

• Setup
  – Static game, $N$ firms, costs of generation $C_{it}(q)$
  – Contract quantity ($QC_{it}$) and price ($PC_{it}$)
  – Total demand $\tilde{D}_t = D + \varepsilon_t$
  – Generators bid supply functions $S_{it}(p)$

• Market-clearing price ($p^c$) given by (removing $t$ subscript from now on):

$$\sum_{i=1}^{N} S_i(p^c) = \tilde{D}$$
Model (cont’d)

• Ex-post profit:

\[ \pi_i = S_i(p^c)p^c - C_i(S_i(p^c)) - (p^c - PC_i)QC_i \]

• Information Structure
  – \( C_i(q) \) common knowledge
  – Private information:
    • \( QC_i \)
    • \( PC_i \) – but does not affect maximization problem
  – \( \tilde{D} \) is unknown

→ important sources of uncertainty from perspective of bidder \( i \)
  • Rival contract positions (\( QC_{-i} \)) and total demand (\( \varepsilon \))
Characterization of Bayesian Nash Equilibrium*

Strategies: $S_i(p,QC_i)$

$QC_{-i}, \tilde{D}$ have joint distribution $F(QC_{-i}, \tilde{D} \mid QC_i)$ (possibly correlated)

Following Wilson's (1979) share auction model, define the probability distribution of market-clearing price, conditional on supply function $\hat{S}_i(p)$ and $QC_i$, given that other firms follow strategy profile $S_{-i}(p,QC_{-i})$:

$$H(p, \hat{S}_i(p)) \equiv \Pr \{p^c \leq p \mid QC_i, \hat{S}_i(p)\}$$

$$= \Pr \{\sum_{j \neq i} S_j(p,QC_j) + \hat{S}_i(p) \geq \tilde{D} \mid QC_i, \hat{S}_i(p)\}$$

$$= \int_{QC_{-i} \times \varepsilon} 1\{\sum_{j \neq i} S_j(p,QC_j) + \hat{S}_i(p) \geq D + \varepsilon\} \, dF(QC_{-i}, \varepsilon \mid QC_i)$$

* NE = A bidding outcome where bidders can’t improve profitability by changing their bid.
Equilibrium (cont’d)

Bidders choose supply functions to maximize expected profits

$$\max_{\hat{S}_i(p)} \int_{\hat{S}_i(p)}^p p\hat{S}_i(p) - C_i(\hat{S}_i(p)) - (p - PC_i)QC_i \ dH_i(p, \hat{S}_i(p); QC_i)$$

If $H(.)$ is differentiable, necessary condition for pointwise optimality of $S_i^*(p)$:

$$p - C'_i(S_i^*(p)) = (S_i^*(p) - QC_i) \frac{H_S(p, S_i^*(p); QC_i)}{H_p(p, S_i^*(p); QC_i)}$$
CLAIM: If we restrict the class of supply functions:

\[ S_i(p) = \alpha_i(p) + \beta_i(QC_i) \]

then (ex ante) equilibrium bids are ex post best responses:

\[ p - C_i'(S_i^*(p)) = \frac{RD_i(p) - QC_i}{RD_i'(p)} \]

where

\[ RD_i(p) = D(p) - \sum_{j \neq i} S_j(p) \]
Computing Ex Post Optimal Bids

Ex post best response is Bayesian Nash Eqbm

- Uncertainty shifts residual demand parallel in & out
  (observed realization of uncertainty provides “data” on $RD_i'(p)$ for all other possible realizations)

- Can trace out ex post optimal/equilibrium bid point for every realization of uncertainty (distribution of uncertainty doesn’t matter)

$$p - MC_i(S_i^*(p)) = \frac{S_i^*(p) - QC_i}{RD_i'(p)} \quad ("inverse \text{ elasticity rule")}$$
Data (Sept 2001 thru Jan 2003)

- 6:00-6:15pm each day
- Bids
  - Hourly firm-level bids
- Demand in balancing market – assumed perfectly inelastic
- Marginal Costs for each operating fossil fuel unit
  - Fuel efficiency – average “heat rates”
  - Fuel costs – daily natural gas spot prices & monthly average coal spot prices
  - Variable O&M
  - SO2 permit costs
  - Each unit’s daily capacity & day-ahead schedule
Measuring Marginal Cost in Balancing Market

• Use coal and gas-fired generating units that are “on” and the daily capacity declaration
• Calculate how much generation from those units is already scheduled == Day-Ahead Schedule

[Diagram showing price, balancing MC, total MC, MW, and day-ahead schedule.]
Reliant (biggest seller) Example
Reliant on February 26, 2002 6:00-6:15pm

- Residual Demand
- Ex-post optimal bid
- MC curve
- Actual Bid curve

Price ($/MWh) vs. Balancing Market Quantity (MW)
TXU (2nd biggest seller) Example

TXU on March 6, 2002  6:00-6:15pm

- Residual Demand
- Ex-post optimal bid
- MC curve
- Actual Bid curve
Guadalupe (small seller) Example

Guadalupe on May 3, 2002  6:00-6:15pm

- Residual Demand
- Ex-post optimal bid
- MC curve
- Actual Bid curve
<table>
<thead>
<tr>
<th>Firm</th>
<th>Percent Achieved Relative to</th>
<th>Producer Surplus ($/hour)</th>
<th>Upper Bound of Total Profitability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ex-post Optimal Naïve Best Response</td>
<td>Actual Naïve Best Resp. Ex-post Optimal</td>
<td></td>
</tr>
<tr>
<td>Reliant</td>
<td>79% 80%</td>
<td>3,422 4,268 4,333</td>
<td>98%</td>
</tr>
<tr>
<td>Brownsville PUB</td>
<td>50% 50%</td>
<td>173 343 343</td>
<td>88%</td>
</tr>
<tr>
<td>City of Bryan</td>
<td>45% 45%</td>
<td>221 488 488</td>
<td>85%</td>
</tr>
<tr>
<td>Tenaska Gateway Partners</td>
<td>41% 41%</td>
<td>456 1,111 1,115</td>
<td>88%</td>
</tr>
<tr>
<td>TXU</td>
<td>39% 41%</td>
<td>1,243 3,056 3,159</td>
<td>97%</td>
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<tr>
<td>Calpine Corp</td>
<td>37% 38%</td>
<td>820 2,168 2,214</td>
<td>91%</td>
</tr>
<tr>
<td>Denton Municipal Electric</td>
<td>35% 35%</td>
<td>11 31 31</td>
<td>98%</td>
</tr>
<tr>
<td>Ingleside Cogeneration</td>
<td>31% 31%</td>
<td>171 541 541</td>
<td>79%</td>
</tr>
<tr>
<td>City of Austin</td>
<td>30% 31%</td>
<td>581 1,889 1,907</td>
<td>84%</td>
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<tr>
<td>Rio Nogales LP</td>
<td>28% 28%</td>
<td>109 393 393</td>
<td>93%</td>
</tr>
<tr>
<td>Lower Colorado River Auth</td>
<td>25% 25%</td>
<td>367 1,471 1,488</td>
<td>88%</td>
</tr>
<tr>
<td>City of San Antonio</td>
<td>23% 24%</td>
<td>290 1,221 1,241</td>
<td>90%</td>
</tr>
<tr>
<td>Gregory Power Partners</td>
<td>20% 20%</td>
<td>143 720 722</td>
<td>82%</td>
</tr>
<tr>
<td>Midlothian Energy</td>
<td>17% 17%</td>
<td>171 1,016 1,024</td>
<td>86%</td>
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<tr>
<td>Cogen Lyondell Inc</td>
<td>16% 16%</td>
<td>408 2,523 2,523</td>
<td>67%</td>
</tr>
<tr>
<td>Tractebel Power Inc</td>
<td>16% 16%</td>
<td>127 795 795</td>
<td>79%</td>
</tr>
<tr>
<td>Brazos Electric Power Coop</td>
<td>15% 15%</td>
<td>101 676 677</td>
<td>79%</td>
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<tr>
<td>Lamar Power Partners</td>
<td>15% 15%</td>
<td>266 1,800 1,808</td>
<td>79%</td>
</tr>
<tr>
<td>Mirant Wichita Falls</td>
<td>14% 14%</td>
<td>16 114 114</td>
<td>83%</td>
</tr>
<tr>
<td>BP Energy</td>
<td>14% 14%</td>
<td>134 993 994</td>
<td>80%</td>
</tr>
<tr>
<td>City of Garland</td>
<td>13% 13%</td>
<td>128 1,018 1,019</td>
<td>80%</td>
</tr>
<tr>
<td>Hays Energy</td>
<td>8% 8%</td>
<td>64 775 777</td>
<td>82%</td>
</tr>
<tr>
<td>West Texas Utilities</td>
<td>8% 8%</td>
<td>132 1,635 1,635</td>
<td>82%</td>
</tr>
<tr>
<td>Central Power &amp; Light</td>
<td>8% 8%</td>
<td>185 2,375 2,407</td>
<td>80%</td>
</tr>
<tr>
<td>Guadalupe Power Partners</td>
<td>6% 6%</td>
<td>140 2,356 2,380</td>
<td>77%</td>
</tr>
</tbody>
</table>

Incumbent Utility  Municipal Utility  Merchant Generator  Cooperative
What the Traders Say about Suboptimal Bidding

1. Lack of sophistication at beginning of market
   • Some firms’ bidders have no trading experience; are employees brought over from generation & distribution

2. Heuristics
   • Most don’t think in terms of “residual demand”

3. Newer generators
   • If a unit has debt to pay off, bidders follow a formula of % markup to add

4. TXU
   • “old school” – would prefer to serve it’s customers with own expensive generation rather than buy cheaper power from market

5. Small players (e.g. munis)
   • “scared of market” – afraid of being short w/ high prices
Possible Explanations for Deviations from Benchmarks

1. Unmeasured “adjustment costs”
2. Transmission constraints
3. Collusion / dynamic pricing
4. Type of firm
5. Stakes matter
Adjustment Costs?

1. Flexible gas-fired units often are marginal
   - 70-90% of time for firms serving as own bidders

2. “Bid-ask” spread smaller for firms closer to benchmark
   - Decreases over time for higher-performing firms

Table 5: Characteristics of Bid Functions By Percent Achieved

<table>
<thead>
<tr>
<th>Firm</th>
<th>Percent Achieved</th>
<th>Mean Bid Points</th>
<th>Mean Bid-Ask Spread ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliant</td>
<td>79%</td>
<td>22.2</td>
<td>$2.06</td>
</tr>
<tr>
<td>City of Bryan</td>
<td>45%</td>
<td>6.5</td>
<td>$22.58</td>
</tr>
<tr>
<td>TXU</td>
<td>39%</td>
<td>12.6</td>
<td>$20.60</td>
</tr>
<tr>
<td>Calpine Corp</td>
<td>37%</td>
<td>7.5</td>
<td>$12.55</td>
</tr>
<tr>
<td>City of Austin</td>
<td>30%</td>
<td>10.0</td>
<td>$25.92</td>
</tr>
<tr>
<td>Lower Colorado River Authority</td>
<td>25%</td>
<td>9.1</td>
<td>$25.98</td>
</tr>
<tr>
<td>City of Garland</td>
<td>13%</td>
<td>6.1</td>
<td>$20.32</td>
</tr>
<tr>
<td>South Texas Electric Coop</td>
<td>3%</td>
<td>3.7</td>
<td>$68.66</td>
</tr>
</tbody>
</table>
Transmission Constraints?

• Does bidding strategy from congested hours spillover into uncongested hours?

Table 6: Relationship Between Profitability and Transmission Congestion

<table>
<thead>
<tr>
<th>Dependent Variable: Monthly PercentAchieved by Firm i</th>
<th>All Firms</th>
<th>Own Bidders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pct Intervals Congested</td>
<td>-0.16</td>
<td>-0.17</td>
</tr>
<tr>
<td></td>
<td>(0.09)</td>
<td>(0.14)</td>
</tr>
<tr>
<td>Volume Optimal Output (GWh)</td>
<td>0.34</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>(0.21)</td>
<td>(0.25)</td>
</tr>
<tr>
<td>Monthly Fraction DEC</td>
<td>-0.05</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>(0.06)</td>
<td>(0.11)</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.48</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Model includes firm fixed effects.
Robust standard errors in parentheses.
Note: PercentAchieved is the monthly fraction of potential profits achieved relative to not bidding, defined in section 4.2.

1 std dev increase in percent congestion ➔ only 3% ↓Pct Achieved
Collusion?

- Collusion not consistent with large bid-ask spreads
  - Collusion $\rightarrow$ smaller sales than ex-post optimal
  - Bid-ask spread $\rightarrow$ no sales
- Would be small(!) players - unlikely
Do Stakes Matter?

![Graph showing the relationship between fraction from no bidding to optimal and volume of optimal output for various utilities. The y-axis represents the fraction from no bidding to optimal, ranging from 0 to 1. The x-axis represents the volume of optimal output, ranging from 0 to 500. The utilities are labeled as follows: Reliant, Bryan, City of Austin, City of Garland, Calpine, TXU, South TX Elec Coop, LCRA. The graph indicates that there is a positive correlation between the two variables.]

* = Investor Owned Utility  ** = Municipal Utility/Cooperative
Efficiency Losses from Observed Bidding Behavior

• Which source of inefficiency is larger?
  – Exercise of market power by large firms?
  – Bidding “to avoid the market” by “unsophisticated” firms?

<table>
<thead>
<tr>
<th>Bidding Counterfactual</th>
<th>Average Production Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Bids for all firms</td>
<td>$29,874</td>
</tr>
<tr>
<td>“Strategic” firms Bid MC, Others Bid Actual</td>
<td>$28,671</td>
</tr>
<tr>
<td>All Firms Bid MC (Vickrey auction)</td>
<td>$23,571</td>
</tr>
</tbody>
</table>

Total Efficiency Losses
  – “Strategic Bidders” = $1,203
  – “Non-Strategic Bidders” = $5,100

– Total efficiency loss = 27%
– Fraction “strategic” = 19%  Fraction “unsophisticated”=81%!!
Implications for Market Design

• Production inefficiencies arise from both:
  – Sophistication ("market power")
  – and lack of sophistication ("avoid the market")
• More participation by small players ➔ less market power for large players
• Market monitor should concern itself with:
  – Bidding by smaller players
  – Market power on DEC side
• Market design
  – If strategic complexity imposes large participation costs, may wish to choose mechanisms with dominant strategy equilibrium (e.g. Vickrey auction)
For more details, see:

http://econweb.tamu.edu/puller/AcadDocs/Hortacsu_Puller.pdf

Thank You!