Research Challenges and Opportunities for Optimization in the Energy Sector

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Motivation

Mismatch of mathematical convenience and practical reality:

- Mathematical conveniences
  - Single centralized controls
  - Continuous, linear and convex relationships
- Practical realities
  - Distributed independent agents
  - Discontinuous and non-convex relationships

- Need: bridging theory and tools

Outline

- Common elements of service sector networks
- Regulated and deregulated markets
- Lessons from the electricity market
- Challenges for modelers

Networked Resources

Industries:

- Energy
- Water
- Finance
- Communications
- Transportation
- Information
- Media
- Healthcare
- Public resources

Common Elements:

- Multiple agents
- Limited resources
- Complex interactions
- Increasing complexity
- Discontinuity in outcome
- Uncertainty in effect
- Individual needs

Results of Network Complexity

- Common failures
  - Energy – blackouts, California crisis
  - Financial - bubble, crashes, firm failures
  - Communications – regional losses
  - Health – epidemic spreads
  - Media – disinformation spreads
- Why?
  - Lack of central control
  - Lack of awareness, visibility
  - Interdependencies
- What to do?
  - New form of modeling
  - New analyses and computation

Complexity Increase Example: Regulated to Deregulated Markets

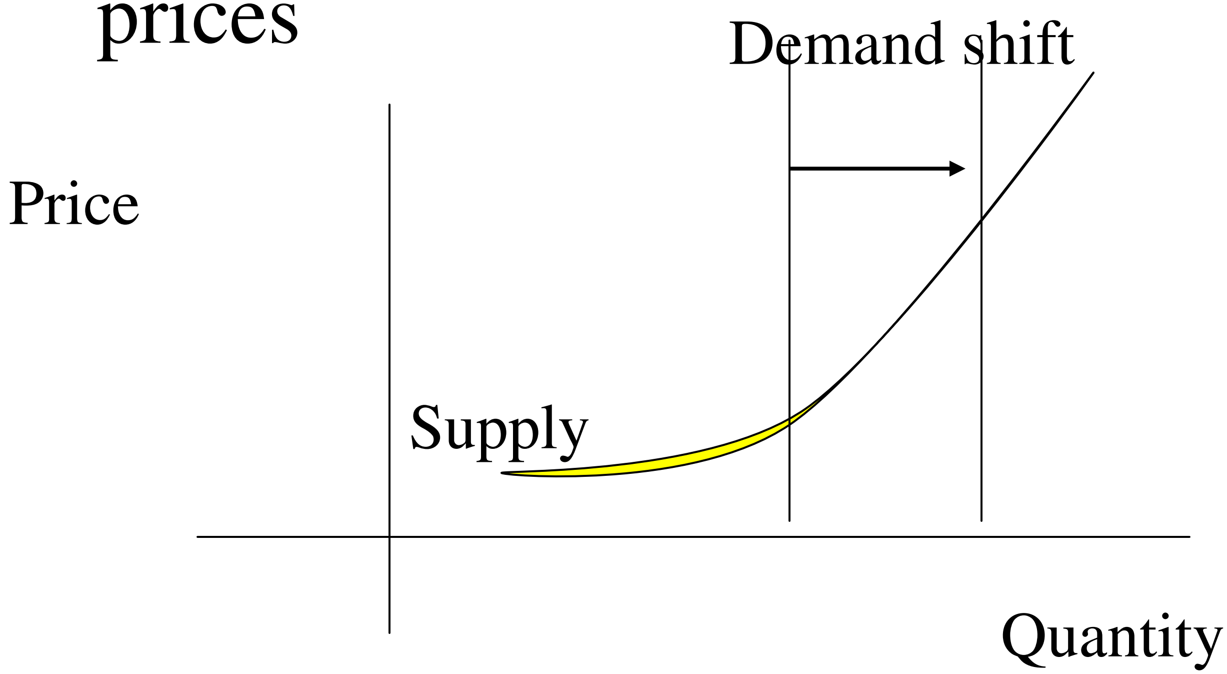
- Regulated
  - Single or few producers
  - Prices controlled by commission
  - Costs passed to consumers (eventually)
  - Little incentive for efficiency
- Deregulated
  - Multiple producers
  - Prices governed by market mechanism
  - Potential for market power (vary supply to manipulate price)
  - Questions about security (sufficient capacity)

Additional Issues in Electricity Markets

- Inelastic demand
- Variable demand
- Limited transmission capacity
- Limited (unavailable) storage capacity
- Rapid change – equilibrium appropriate representation?

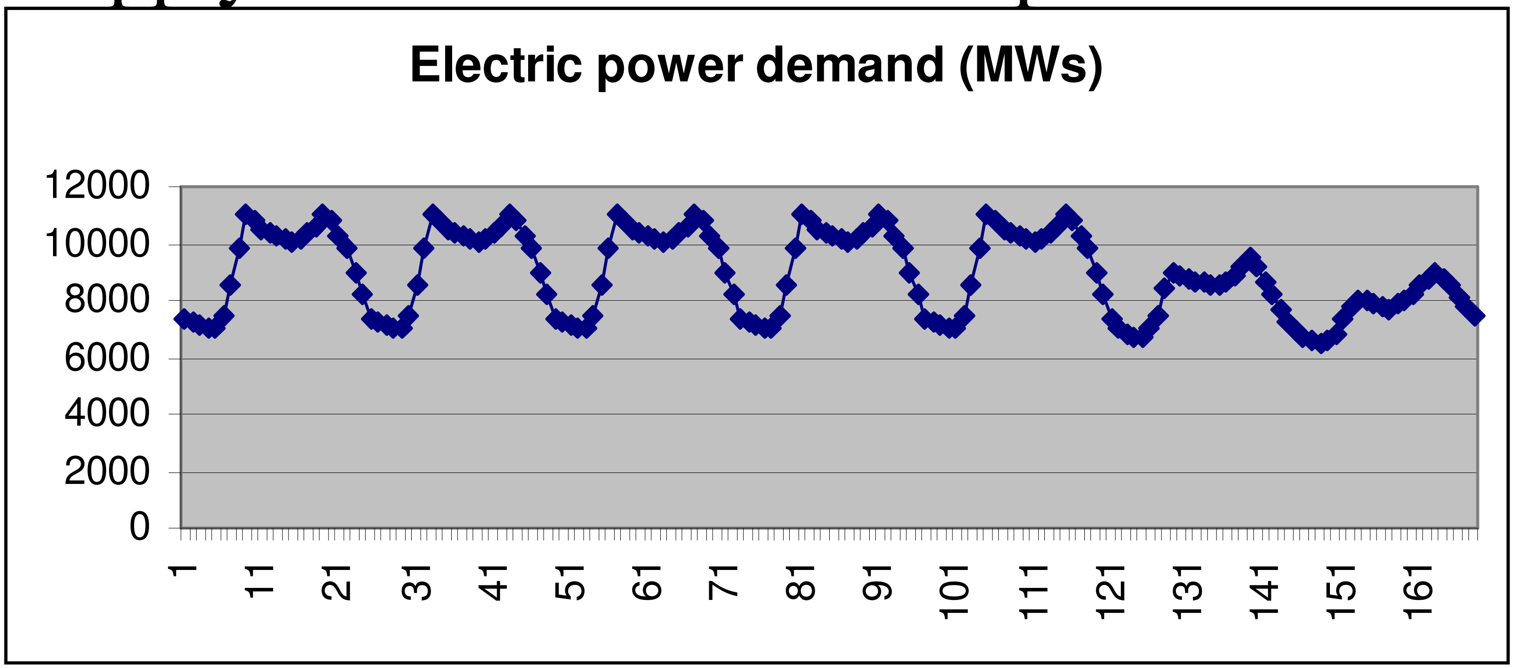
Inelastic Demand

- Demand increases can sharply increase prices



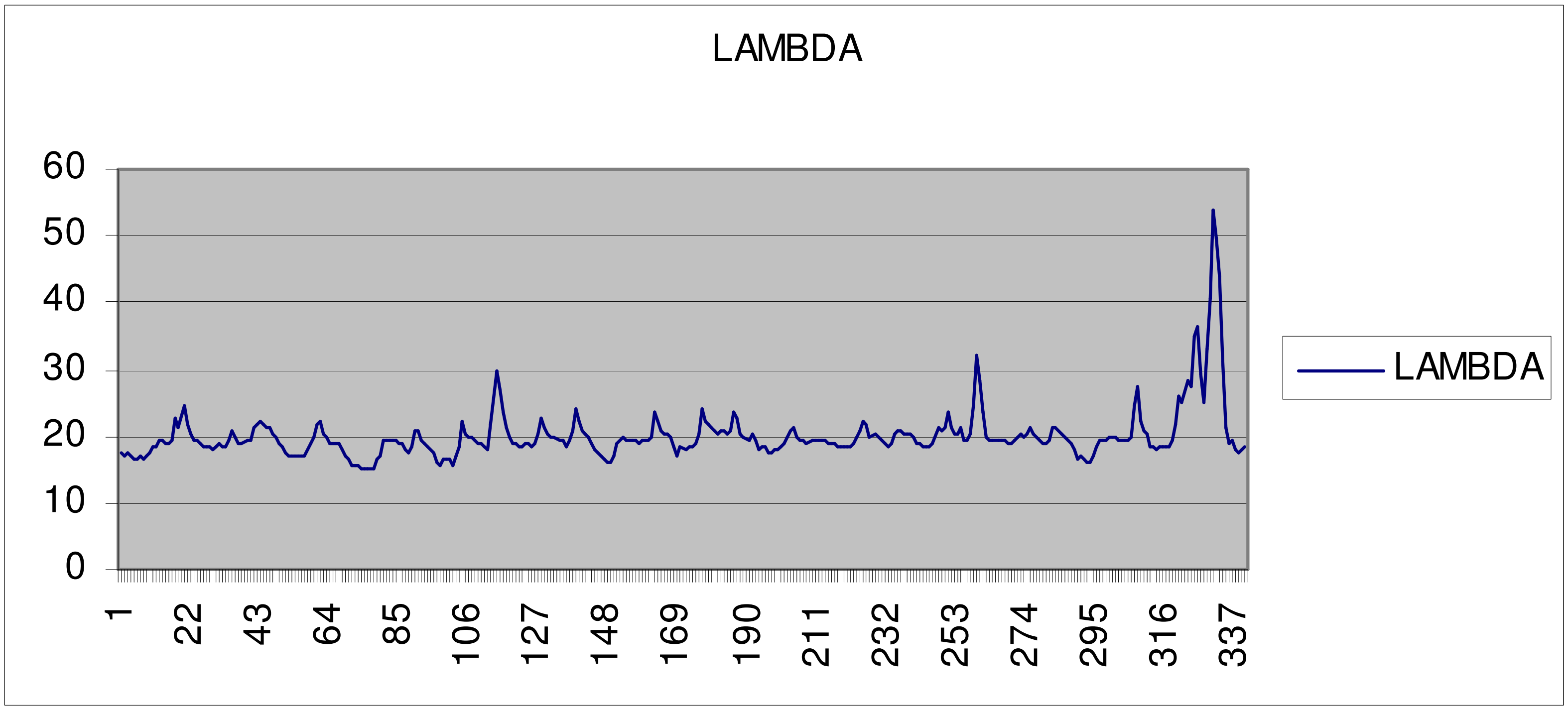
Supply/Demand Mismatch

- Demand varies continuously - often doubles (or more) during peak hours
- Supply restricted to fixed output levels



Result of Mismatch: Price Spikes

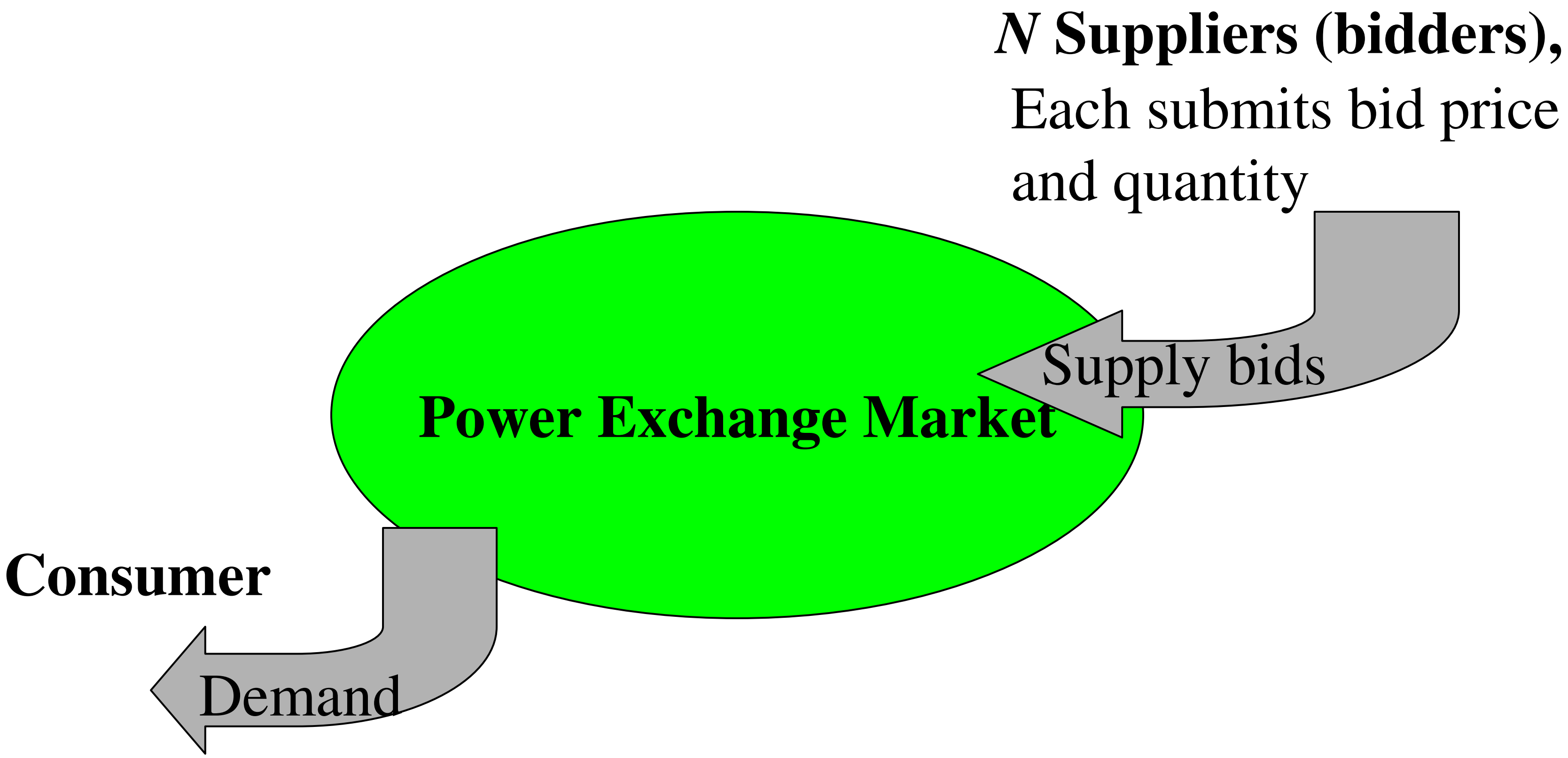
- California Power Exchange Data



Comparisons to Traditional Markets

- High Volatility
  - 10 to 100 times that of common stock
  - Prices from 0 to $10,000 per MWhr
- Difficulty in storage
  - Electricity close to un-storable
    - Difficulty substitution (liquidity)
  - Dynamics not consistent with previous models of prices

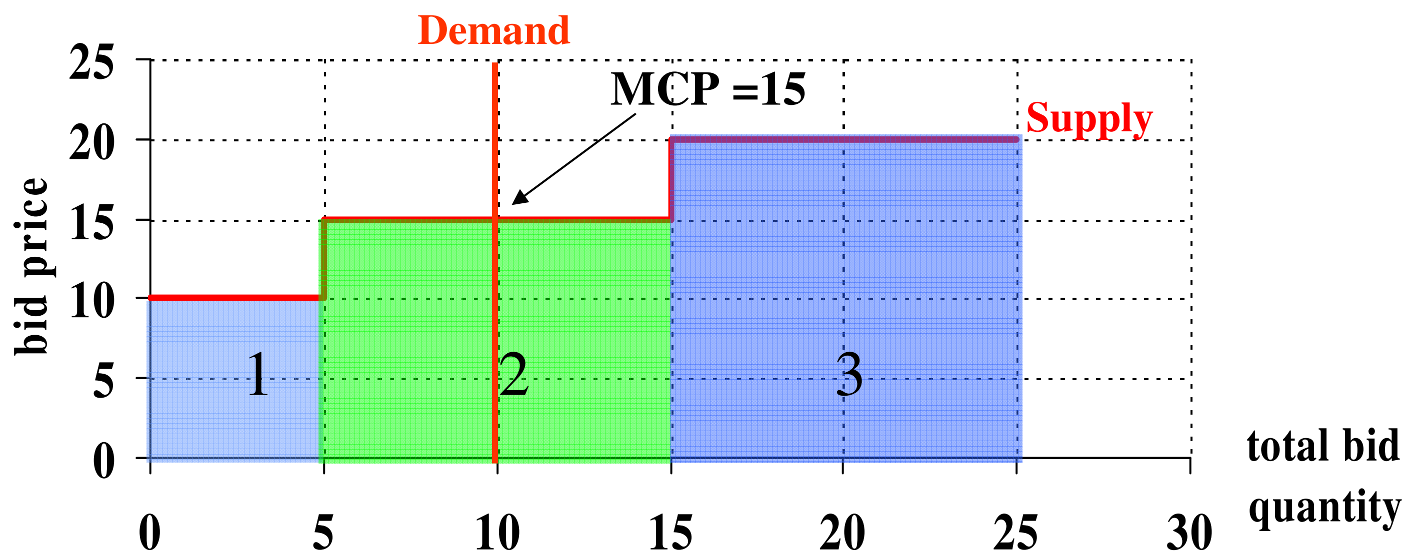
Competitive Electric Power Markets



Market Clearing Process

Supplier 1 : 5MWh @ \$10
Supplier 2 : 10MWh @ \$15
Supplier 3 : 10MWh @ \$20

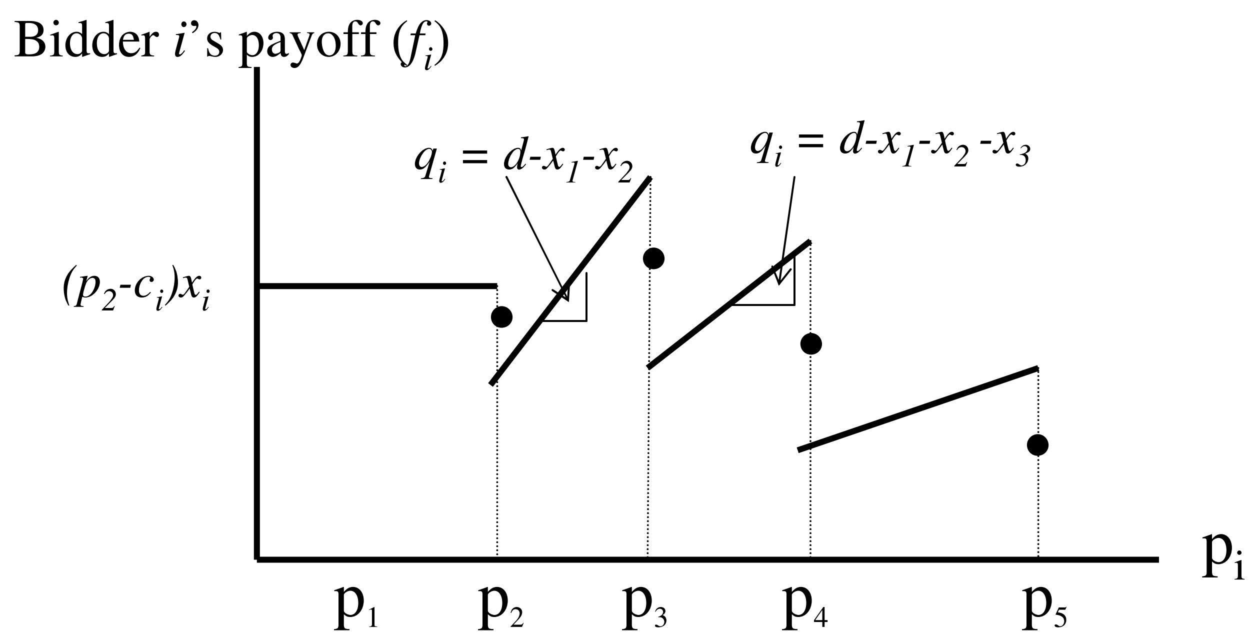
Demand is 10



Problem: find optimal bidding strategies and the resulting MCP

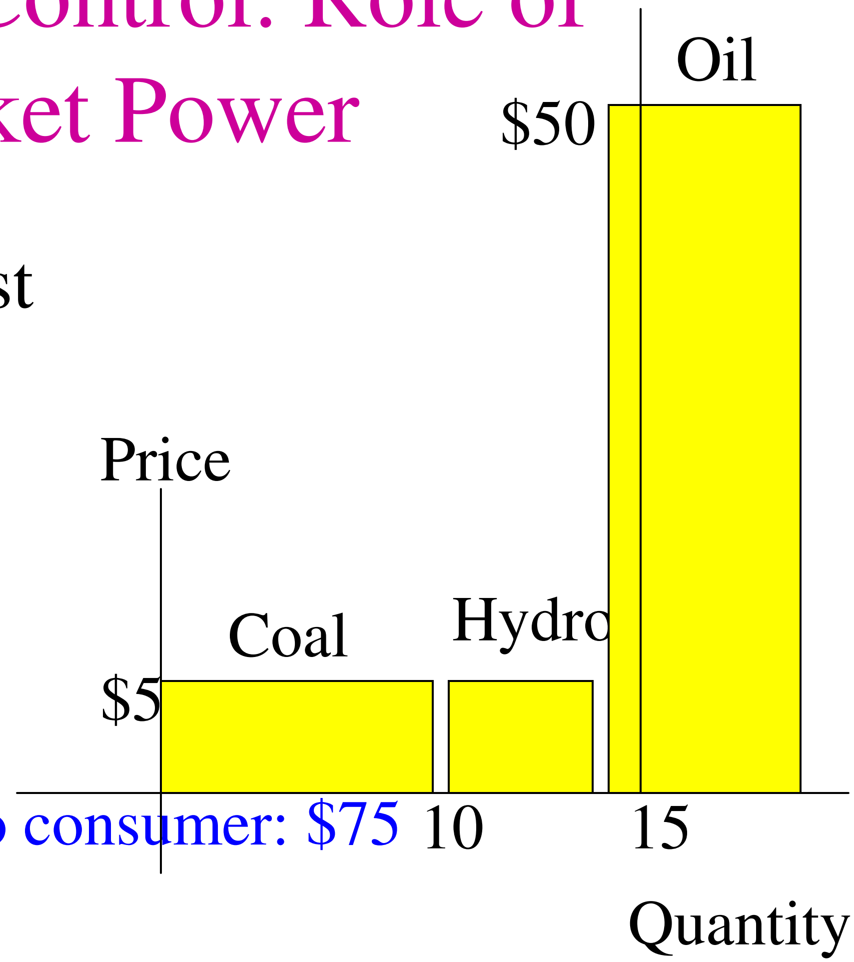
Payoff Function

- Given other bidders' bid prices and demand



Change from Central Control: Role of Agents and Market Power

- Generators: Capacity, Cost
  - Coal, 10, $5
  - Oil, 10, $50
  - Hydro, 10, 0
- Demand: 15
- Cheapest dispatch
  - Hydro, 10; Coal, 5; Cost to consumer: $75
- Market power of hydro
  - Bid only 4 into market, now oil also used
  - Coal, 10; Hydro, 4; Oil, 1; Cost to consumer: $750



Change from Central Control: Anomalous Price Changes

Suppose 2 demand periods

- Period 1 - demand=50
- Period 2 - demand=100 or 200 equally likely

Capacities:

- Hydro - 100 total
- Coal - 60 at once
- Oil - 1

Costs:

- Hydro – 0
- Coal – 5
- Oil - 50

Optimal Bids

- Hydro - Bid only in Period 2, 100 at 5-ε
- Coal - Bid 5
- Oil - Bid 50

Result: Period 1 price=5; Period 2 price: 5-ε or 50

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Lessons from Energy Market

- Must consider separate agents to find system behavior
- Multiple equilibria and lack of equilibria (dynamics)
- Uncertainty affect on observations, behavior
- Discontinuous effects
- Behavior may be counter-intuitive (so traditional controls have unintended consequences)
- Possibility for catastrophic failures

Modeling Needs

- Multiple agents
- Multiple “solutions”
- Combinations of discrete and continuous models
- Dynamic and transient behavior
- Uncertainty in observation and action – model of dynamics
- Understanding form of equilibrium (if any)

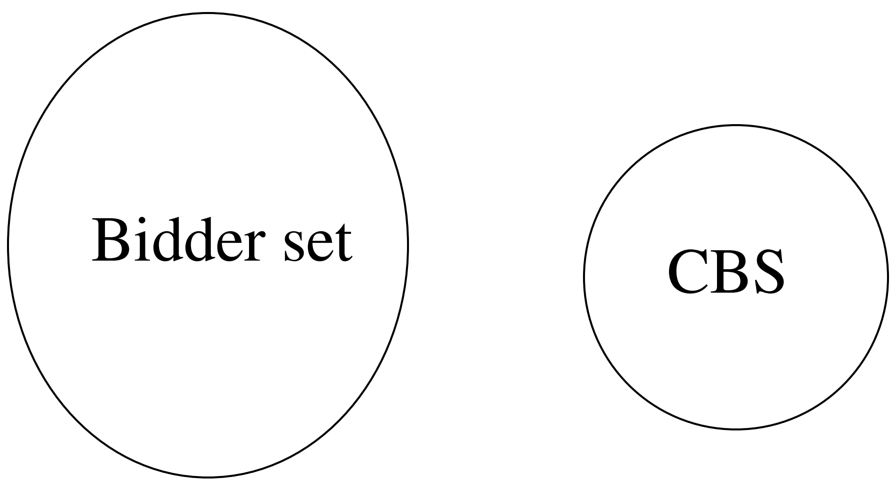
Defining Equilibrium Sets

- Standard equilibrium results
  - Concave utility functions for agents
  - Consistent information sets
  - Unique equilibrium with strict concavity
- Realistic markets
  - Market mechanisms (and other things) negate concavity assumptions
  - Inconsistent and varying information sets
  - Multiple, disconnected equilibria (or disequilibrium)
- Goal: Find the set of equilibria (worst case?)
- Consider electric power market

Competitive Bidder Set (CBS)

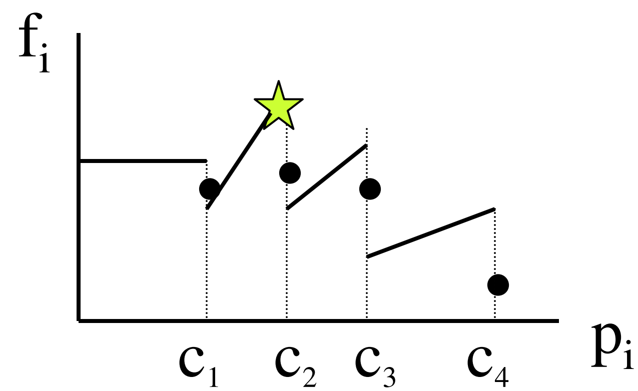
- CBS: bidders with the lowest costs and satisfy the market stability condition

$$\overline{D} \leq \sum_{\forall i \neq j} x_i \quad \text{for } j = 1, \ldots, N$$



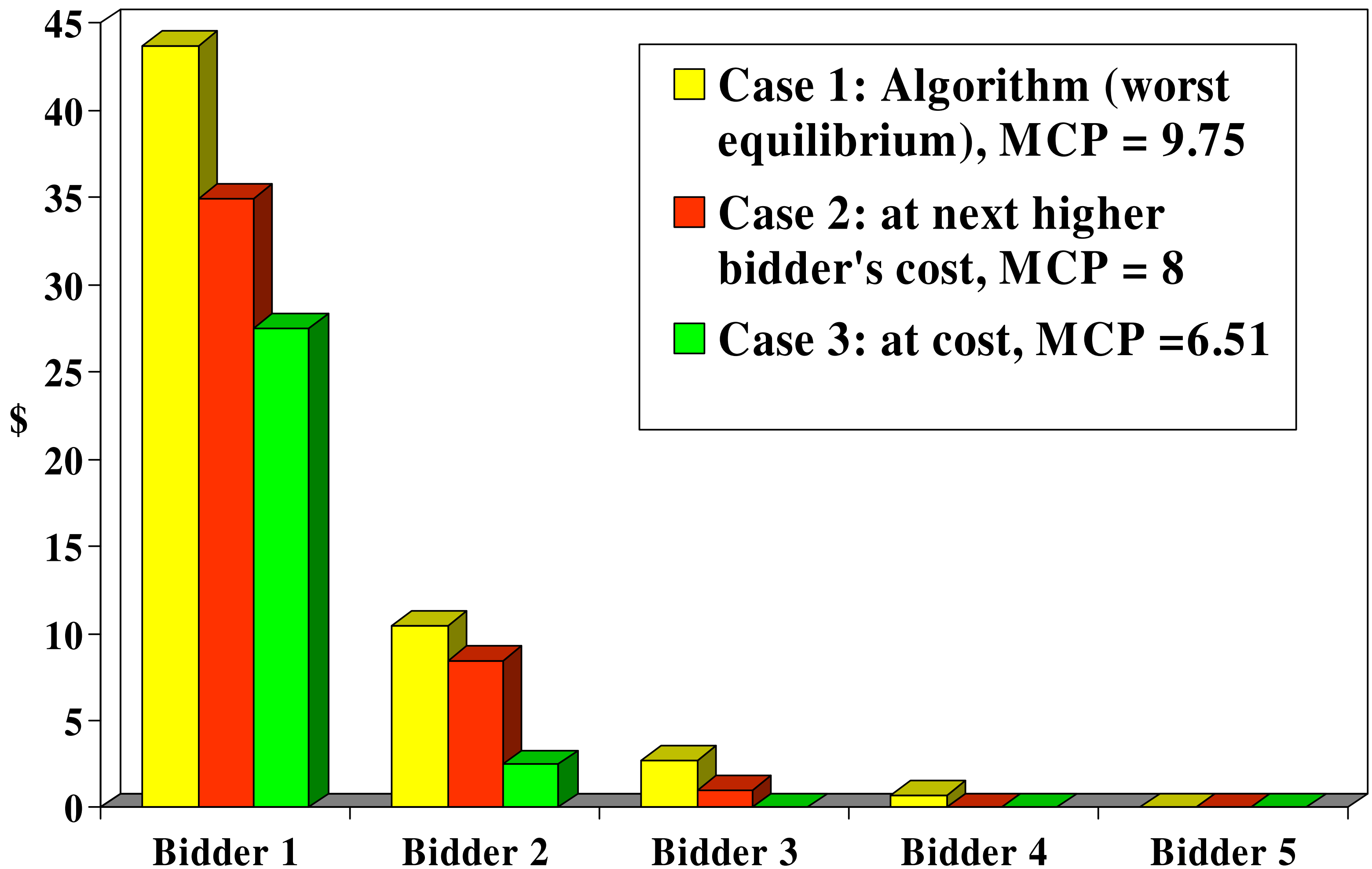
Example of Equilibrium Set Search: Algorithm for Finding the Highest MCP Equilibrium Point

- Constructing CBS
- Condition on each bidder to be marginal while others bid at cost
- Find the optimal bid price



- Pick producer with the highest optimal bid price to be the marginal bidder; others bid at costs

Comparison of Payoffs



Challenges and Opportunities with Competition

- Multiple equilibria, discontinuities and non-convexities
- In some cases, can find highest market clearing price (equilibrium point)
- How to do this efficiently?
- When is this possible in general?
- How to design market toward “socially optimal” points?

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Dynamic Formulation

Optimization for each agent:

$\Phi_{\{its\}}(\pi, w) = \max_{\pi_{t+\tau}\, y_{its}, w_{its}, x_{its}} \pi\, x_{its} - K_i\, sgn(w_{its} - w)$
$- c_i(x_{its}) + \rho_{its}(x_{its}) + \mu_{its}(y_{its} - \beta_i x_{its}) + \sum_{j \text{ connected to } i} \mu_{jts} \gamma_{ji} x_{its}$
$+ \sigma_{its}\, \pi_{it+\tau s} + E[\Phi_{i,t+\{\tau\},s'}(\pi_{i,t+\tau,s'}, w)]$

s.t.

$w_{its} l_i \cdot x_{its} \cdot w_{its}\, u_i,\ y_{its}$¸ $0,\ w_{its} 2\ [0,1]$

where π is the bid price set, w is the up/down status, x is generation, and y is additional state (e.g., reservoir); ρ, μ, σ multipliers and γ reflects state connections (e.g., water flows)

Questions: Convergence? Overall optimization? Equilibrium set?

Addition Challenges

- Recognizing and including individual preferences
- Interpreting data from large populations
- Analyzing effects of organizational interactions
- Combining real-time, continuous actions with discrete policy and preferences

Conclusions

- Modeling and controlling networked energy resources requires:
  - Identifying preferences
  - Interpreting massive amounts of data
  - Incorporating organizational interactions
  - Combining continuous and discrete phenomena
  - Exploring multiple alternative states and complex interactions
- Need and opportunity for new mathematical models, theory, and computational tools to address these issues