Complexity in Energy Networks under Uncertainty

John Birge
The University of Chicago
Graduate School of Business
Outline

• Complexity effects in networks
• Static equilibria in electricity markets
• Algorithms for finding dynamic equilibria
• Challenges for modelers
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 and highly 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

Electric power demand (MWs)
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

$N$ Suppliers (bidders),
Each submits bid price and quantity

Power Exchange Market

Consumer

Demand

Supply bids
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

Bidder $i$’s payoff ($f_i$)

\[(p_2 - c_i)x_i\]

\[q_i = d - x_1 - x_2\]

\[q_i = d - x_1 - x_2 - x_3\]
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 - ∞

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
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?)
Competitive Bidder Set (CBS)

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

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

Case 1: Algorithm (worst equilibrium), MCP = 9.75
Case 2: at next higher bidder's cost, MCP = 8
Case 3: at cost, MCP = 6.51
Dynamic Formulation

Optimization for each agent:

\[
\Phi_{\{\text{its}\}}(\pi, w) = \max_{\pi_{t+\tau}} \pi_{t+\tau} \mu_{\text{its}} w_{\text{its}} x_{\text{its}} - K_i \text{sgn}(w_{\text{its}} - w) \\
- c_i(x_{\text{its}}) + \rho_{\text{its}}(x_{\text{its}}) + \mu_{\text{its}}(y_{\text{its}} - \beta x_{\text{its}}) + \sum_j \text{connected to } i \mu_{\text{jts}} \gamma_j x_{\text{its}} \\
+ \sigma_{\text{its}} \pi_{it+\tau} + E[\Phi_{i,t+\{\tau\},s}(\pi_{i,t+\tau}, w)]
\]

s.t.

\[w_{\text{its}} l_i \leq x_{\text{its}} \leq w_{\text{its}} u_i, y_{\text{its}} \geq 0, w_{\text{its}} \in [0, 1]\]

where \(\pi\) is the bid price set, \(w\) is the up/down status, \(x\) is generation, and \(y\) is additional state (e.g., reservoir); \(\rho, \mu, \sigma\) multipliers and \(\gamma\) 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