Evaluating Electricity Generation, Energy Options, and Complex Networks

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Outline

• Derivatives
• Real options and electricity markets
• Asset evaluation
• Model and solution
• Network complications
• Challenges and extensions
• Conclusions
Energy and Weather Derivatives

• Exchange-traded options: CBOT and NYMEX
• Over-the-counter: Many weather applications
• Uses:
  - Reducing risks
  - Finding value of plant (difference in prices)
Interest in Energy Derivatives

• 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)
Electricity Price Example: USA

- California Power Exchange
Electricity Price Example: Norway

- NOK Prices
Observations on Data

• Price follows:
  – Mean reversion
  – Seasonality
  – Jumps

• Need:
  – Model to capture
  – Possible evaluation
Use of Valuation Formula

• Now, can value options

• What to use for?
  – Plant is worth something when price above cost to produce
  – Suppose constant production cost:
Constant Production Cost

• Value is like call on production cost at all times
• What if costs vary?
  – Other commodity
  – Example: Oil or natural gas
• Can value as difference between prices
• Some traded varieties
Modeling the Cost

• Suppose 2 futures prices $F_1(t,T^*)$ is the future price at $T^*$ for unit of electricity at time $t$; $F_2(t,T^*)$ is the same for fuel
• $K$ is the conversion factor from fuel to electricity
• So, plant has value if $F_1(t,T^*)-F_2(t,T^*)>0$
• For $S_i(T)=F_i(T,T)$, the plant is worth
  \[ A' \int_0^T E^*[P[0,t] (S_1(t)-KS_2(t))^+]dt \]
  where $A'$ relates to plant capacity, $P[0,t]$ is present value of zero-coupon bond maturing at $t$, $E^*$ is expectation under a risk neutral measure.
The Generation Option (Spark Spread)

Under mean-reverting processes with same rates $\beta$ of mean reversion with $S(t)=J(t)K(t)$ where $J$ is a jump process with Poisson rates $\lambda \zeta_i$ and lognormal jump sizes with log-mean $\gamma_i$, st.dev. $\delta_i$, correlation $\rho$, $K$ is O-U process with mean rate $\alpha_i$, and covariance $\Sigma$

$$E^*(P(0,T)\{S_1(T)-S_2(T)\}^+) = P(0,T)\sum_{n=1}^{\infty} e^{-\lambda T} [(\lambda T^n/n!)*\psi(F^{(1,n)}(0,T^*),F^{(2,n)}(0,T^*),T,(\sigma^2(T,T^*)+n\delta^2)/T)]$$

where…..
Parameter Definitions

\[ \psi (x_1, x_2, T, a^2) = x_1 \Phi\left(\frac{\log(x_1/x_2) + (a^2/2)T}{aT^{0.5}}\right) \]
- \[ x_2 \Phi\left(\frac{\log(x_1/x_2) - (a^2/2)T}{aT^{0.5}}\right) \],

\[ F^{(i,n)}(0, T) = c_i(T)e^{-\lambda(1+\zeta_i)T(1+\zeta_i)^n}, \]

\[ c_i(T) = \exp\left\{ e^{-\beta t}\left\{ \log(S_i(0)) + \alpha_i \int_0^t e^{\beta u} du \right\} \right\} \]
* \[ \exp\left\{ (1/2)e^{-2\beta t}\sigma_i^2 \int_0^t e^{2\beta u} du \right\} \]

\[ \delta^2 = \delta_1^2 + \delta_2^2 - 2\rho \delta_1 \delta_2, \]

\[ \sigma^2(t,T) = \sigma^2 \int_0^t e^{-2\beta(T-u)} du, \]

\[ \sigma^2 = \sigma_1^2 + \sigma_2^2 - 2\rho \sigma_1 \sigma_2. \]
Additional Complications

• Real costs:
  – Cost to start operating
  – Cost to stop operating

• Need:
  – Policy for operating the plant
  – Price to start and price to stop
Example
Valuation

- Must value integral over transition time from start to stop point
- Count the number of cycles in a period
- Evaluate average cycle value
- Include correction for end effects
Conclusions

• Electricity and other real options large part of market
• Important for valuation of assets
• Treat as Brownian motion and jumps
• Can price by traditional techniques
• Difficulties with fixed costs and imperfect markets – uses of utilities and equilibria
Complex Networks

- 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)](chart.png)
Result of Mismatch: Price Spikes

- California Power Exchange Data
Competitive Electric Power Markets

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

Power Exchange Market

Supply bids

Consumer
Demand
Market Clearing Process

Problem: find optimal bidding strategies and the resulting MCP
Payoff Function

- Given other bidders’ bid prices and demand

\[ p_i \]

\[ (p_2 - c_i) x_i \]

\[ q_i = d - x_1 - x_2 \]

\[ q_i = d - x_1 - x_2 - x_3 \]
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

\[ \begin{align*}
\pi & \quad f_i \\
\quad \quad \quad c_1 & \quad c_2 & \quad c_3 & \quad c_4 & \quad p_i
\end{align*} \]

- 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:

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

s.t.

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

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)
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