Incorporating Physical Constraints and Transaction Costs into Option-Based Valuation of Real Assets

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Background

- In the vertical integrated utility industry generation assets were traditionally valued using production simulation coupled with discounted cash flow analysis
- With the emergence of the electric industry restructuring market-based approaches employing "real options" valuation techniques are gaining popularity.
- Financial option based valuation methods employ financial instruments as models of generation assets (e.g. Spark Spread call options [Deng, et al. ,1997]) while abstracting physical constraints and transaction costs.
- Here we explicitly consider physical operating constraints and transaction costs in an approximate way to examine the impact of such aspects on the valuation.

A Few Questions to Address

- What is the implication on capacity valuation by assumptions on electricity prices?
- How significant are the impacts on capacity valuation by operational constraints of power generation assets

Divestiture of Generation Assets

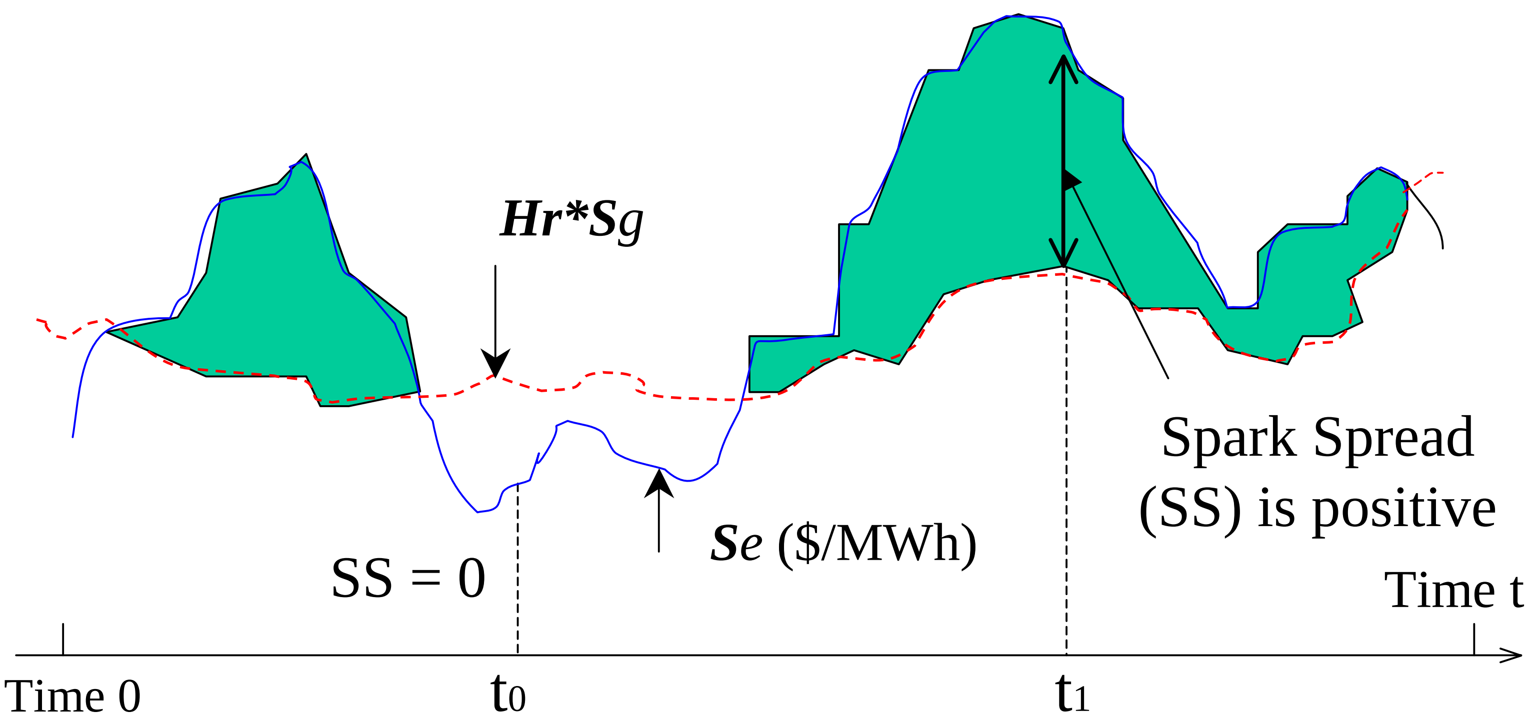
- State restructuring initiatives and strategic decisions of electric utilities.
- Late 1997 ~ Sept. 1999, 51 IOUs (32%) have divested or are in the process of divesting power generation capacity.
  - Divested capacity so far: 133GW (17% of US total in 1998).
  - NE: 20.3GW/88% of NE; PJM/NY: 31GW/39%; CA: 26GW/35%.
  - Forecast: up to 364 GW (50% US) in US in 10 years.
- Types of divested generation assets.
  - Coal-fired: 46GW (15% of total US coal generation capacity).
  - Gas-fired: 41GW (28% of total gas-fired capacity).
  - Coal- and gas-fired power plants accounts for 64% of US electricity generation capacity.

A Few Market Transactions

- In 7/98, PG&E closed the sales of 2 gas-fired power plants & 1 oil-fired (2645MW) to Duke Energy for $501 million.
  - Implied capacity value: $189/kW.
  - Book value: $346 million.
- In 4/99, PG&E closed the sales of 3 gas-fired power plants (3065MW) to Southern Energy for $801 million.
  - Implied capacity value: $261/kW
  - Book value: $256 million.

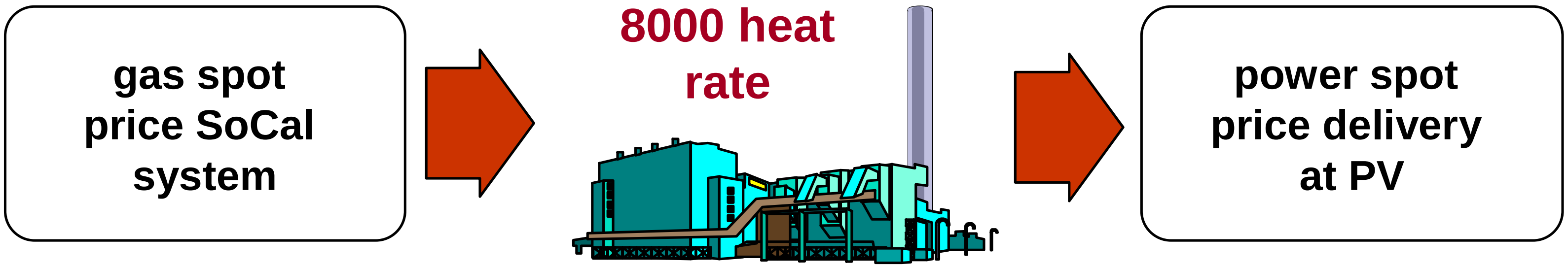
What is a Spark Spread?

- Spark spread option is an option with payoff being the positive part of electricity price less generating fuel cost.



Real Asset Valuation

Question: How much to bid for a power plant?



A natural gas fired unit can be viewed as a series of spark spread call options.

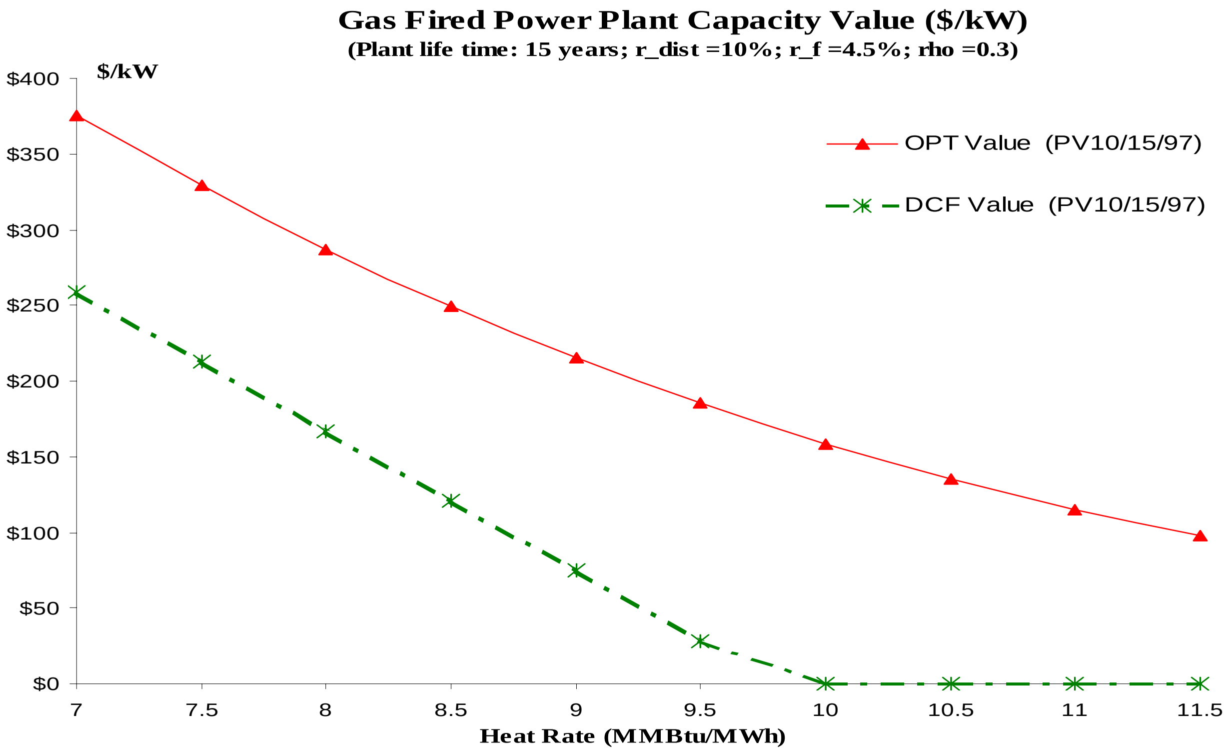
When the spot market implied heat rate is above the unit operating heat rate, generator should buy gas and sell power.

When the spot market implied heat rate is below the unit operating heat rate, generator should shut down.

Capacity Valuation: financial option based approach.

$$\text{Value of power plant} = \sum_{t=1}^{T} \frac{CF(t)}{(1+r_{\beta})^{t}} = \sum_{t=1}^{T} \frac{\left(P_e - HR\,P_g\right)q}{(1+r_{\beta})^{t}}$$

$$\text{Value of power plant} = \sum_{t=1}^{T} \text{spark spread call option}(t)\,q$$



Comparison to the Market Valuation

- Four gas-fired plants (2172MW) of Southern California Edison were sold to Houston Industries at a total price of $237 million. (Implied capacity value is $110/kW)
- The Coolwater plant is the most efficient among the four plants. (heat rate: ~9500).
- Option-based capacity value: $185/kW. (Using NYMEX Palo Verde electricity forward curves and Henry Hub natural gas forward curves on 10/15/97)
- DCF capacity value: $29/kW

UNIT COMMITMENT PROBLEM

(Solved for each hour a week ahead on a rolling horizon basis)

Transition Cost

Commitment state {0,1}

Generation cost

$$\underset{\{x_{it},p_{it}\}}{Minimize} \sum_{t=1}^{T}\sum_{i=1}^{I}[S_{it}(x_{(i,t-1)},x_{it}) + C_{it}(p_{it})]$$

Resource i

Time t

Generation level

$$subject\ \ to \ \ \sum_{i=1}^{I} p_{it} = D_t, \quad t = 1,\ldots,T$$

Demand constraint

$$\sum_{i=1}^{I} p_i^{\max} u_i(x_{it}) \geq R_t, \quad t = 1,\ldots,T$$

Spinning reserve requirement

Resource fraction available given state

$$p_{it}^{\min} u_i(x_{it}) \leq p_{it} \leq p_{it}^{\max} u_i(x_{it}), i = 1,\ldots,I, t = 1,\ldots,T$$

Intertemporal constraints

$$\bar{x}_i \in \bar{X}_i, \quad i = 1,\ldots,I$$ Where $$\bar{x}_i = (x_{i1}, x_{i2}, \ldots, x_{iT})$$

Commitment constraints

LAGRANGIAN RELAXATION OF UNIT COMMITMENT PROBLEM

DECOMPOSITION BY RESOURCE

Energy Prices

Spinning capacity prices

$$\underset{\bar{\lambda}\geq 0,\bar{\mu}\geq 0}{Maximize} \quad q(\bar{\lambda},\bar{\mu}) = \sum_{i=1}^{I} q_i(\bar{\lambda},\bar{\mu}) + \sum_{t=1}^{T} \lambda_t D_t + \sum_{t=1}^{T} \mu_t R_t$$

Optimal commitment and dispatch of the i-th resource given the price vector for energy and spinning capacity over the scheduling horizon

$$q_i(\bar{\lambda},\bar{\mu}) = \underset{\{x_{it},p_{it}\}}{Min} \sum_{t=1}^{T} [S_{it}(x_{(i,t-1)}, x_{it}) + C_{it}(p_{it})] - \sum_{t=1}^{T} [\lambda_t p_{it}] - \sum_{t=1}^{T} [\mu_t p_i^{\max} u_i(x_{it})]$$

$$subject \quad to \quad \bar{x}_i \in \bar{X}_i,$$

$$p_{it}^{\min} u_i(x_{it}) \leq p_{it} \leq p_{it}^{\max} u_i(x_{it}), \quad t = 1, ..., T.$$

SUBGRADIENT UPDATING OF PRICES

$$\bar{\lambda}^k = \bar{\lambda}^{k-1} + \beta^k \bar{g}^k \text{ and } \bar{\mu}^k = \bar{\mu}^{k-1} + \beta^k \bar{f}^k$$

where

$$g_t = D_t - \sum_{i=1}^{I} p_{it} \text{ and } f_t = \max[0, \; R_t - \sum_{i=1}^{I} p_i^{\max} u_i(x_{it})]$$

Operational Constraints and Transaction costs for Fossil Fuel Plants

- Heat rate is a function of operating conditions.
  - Heat rate of a power plant is at its lowest level when the plant is operated at the maximum capacity level.
  - Heat rate is at its highest level when the plant is operated at the minimum capacity level.
- Start-up costs.
- Ramp up time.

ApproximateValuation Methodology

- Construct a discrete-time stochastic processes which describe the price dynamics of electricity and the generating fuel, e.g. natural gas.
- A stochastic dynamic programming approach.
  - The value function represents the value of a fossil fuel power plant.
  - Incorporating physical operating constraints.

Step 1. Constructing the Price Lattice : Mean-Reversion

- Suppose Ln(S_e) and Ln(S_g) follow two mean-reverting processes in continuous-time.

$$dX_t = \kappa_e(\theta_e - X_t)dt + \sigma_e dB_t^1$$
$$dY_t = \kappa_g(\theta_g - Y_t)dt + \sigma_g dB_t^2$$
$$\text{where} \quad Cov(dB_t^1, dB_t^2) = \rho dt$$

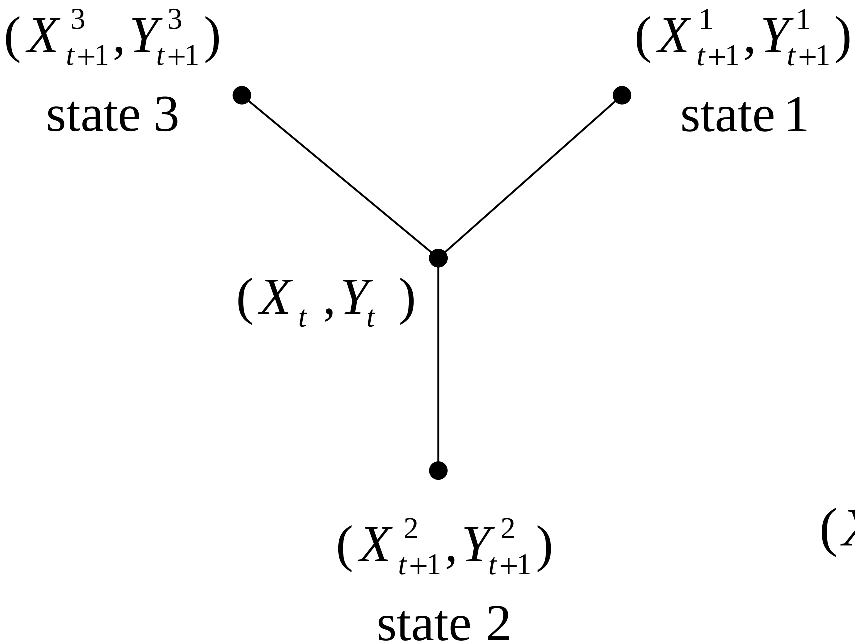
θ_e : long-term mean of $Ln(S_t^e)$.

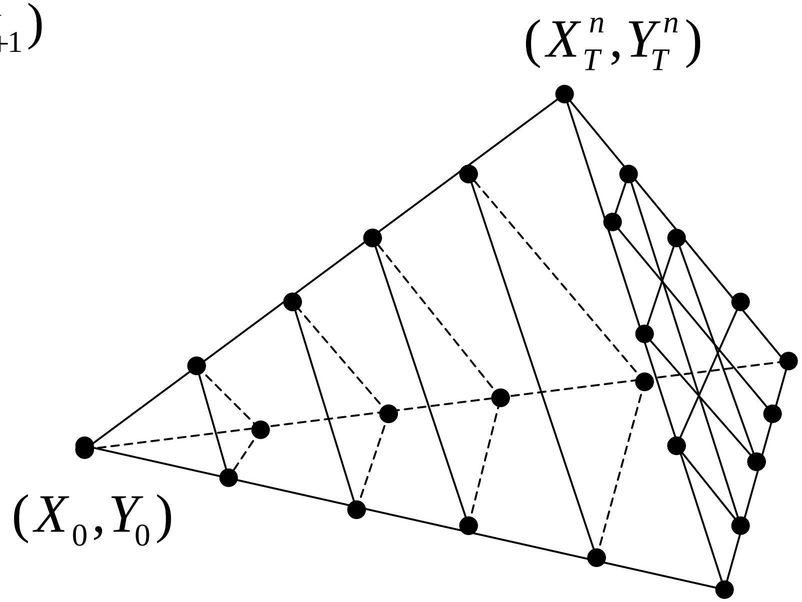
κ_e : mean-reverting coefficient measuring how fast X_t is pulled towards its long-term mean θ_e.

σ_e : instantaneous volatility of $Ln(S_t^e)$.

Step 1. Constructing the Price Lattice (I)

- 3 branches out of each node.





Step 1. Constructing the Trinomial Tree (Cont'd): GBM

- Define the price state vector.

$$X_{t+1} = \begin{cases} X_t + \mu_e \Delta t + \sigma_e \sqrt{\tfrac{3}{2}} \sqrt{\Delta t} & \text{(state1)} \\ X_t + \mu_e \Delta t & \text{(state2)} \\ X_t + \mu_e \Delta t - \sigma_e \sqrt{\tfrac{3}{2}} \sqrt{\Delta t} & \text{(state3)} \end{cases}$$

$$Y_{t+1} = \begin{cases} Y_t + \mu_g \Delta t + \sqrt{\tfrac{3}{2}} \rho \sigma_g \sqrt{\Delta t} + \sqrt{\tfrac{1}{2}} \sqrt{1-\rho^2} \sigma_g \sqrt{\Delta t} & \text{(state1)} \\ Y_t + \mu_g \Delta t - \tfrac{2}{\sqrt{2}} \sqrt{1-\rho^2} \sigma_g \sqrt{\Delta t} & \text{(state2)} \\ Y_t + \mu_g \Delta t - \sqrt{\tfrac{3}{2}} \rho \sigma_g \sqrt{\Delta t} + \sqrt{\tfrac{1}{2}} \sqrt{1-\rho^2} \sigma_g \sqrt{\Delta t} & \text{(state3)} \end{cases}$$

Proposition 1.

- The discrete price lattice (I), with risk-neutral probabilities (1/3,1/3,1/3), weakly converges to the following correlated Geometric Brownian motion processes.

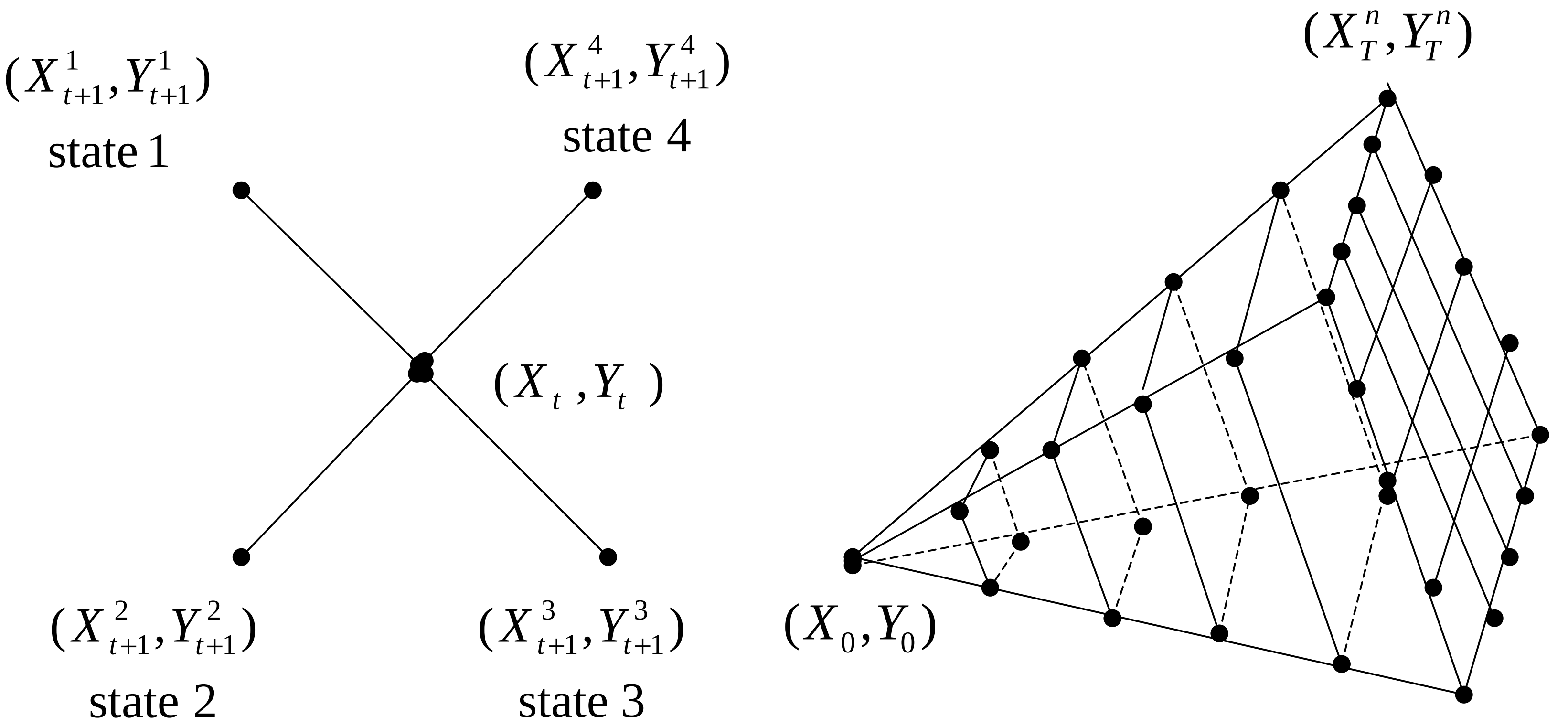
$$dX_t / X_t = \mu_e dt + \sigma_e dB_t^1$$

$$dY_t / Y_t = \mu_g dt + \sigma_g dB_t^2$$

$$\text{where} \quad Cov(dB_t^1, dB_t^2) = \rho dt$$

Step 1. Constructing the Price Lattice (II)

- 4 branches out of each node.



Proposition 2.

- The discrete price lattice (II), with risk-neutral probabilities given in Deng and Oren (1999), weakly converges to the previous shown continuous-time mean-reverting processes

Step 2. Formulation of the Stochastic DP

- State space: (X_t, Y_t, w)
- Action space: $A \equiv \{on_{\max}, on_{\min}, off\}$
- Value function.

$V_t(X_t, Y_t, w) \equiv$ Value of a fossil fuel power plant at time t when the electricity and the generating fuel prices are S_e and S_g, and the state of the plant is $w =$ "ready" or "off"

Step 2. Formulation of the Stochastic DP (Cont'd)

When $w = 0$ (or equivalently, $w =$ "*off*")

- Recursive equation of the value function:

$$V_t(X_t, Y_t, 0) = \max_{a \in A} \begin{bmatrix} a = on_{\max} & : -c_{start} + \beta E_t[V_{t+1}(X_{t+1}, Y_{t+1}, 1)] \\ a = on_{\min} & : -c_{start} + \beta E_t[V_{t+1}(X_{t+1}, Y_{t+1}, 1)] \\ a = off & : \beta E_t[V_{t+1}(X_{t+1}, Y_{t+1}, 0)] \end{bmatrix}$$

where $\beta = \exp(r \cdot \Delta t)$ is the one period discount factor.

Step 2. Formulation of the Stochastic DP (Cont'd)

When $w = 1$ (or equivalently, $w =$ "*on*")

- Recursive equation of the value function:

$$V_t(X_t, Y_t, 1) = \max_{a \in A} \begin{bmatrix} a = on_{\text{max}} \ : \ \overline{Q} \cdot (e^{X_t} - \overline{HR} \cdot e^{Y_t}) + \\ \qquad \beta E_t[V_{t+1}(X_{t+1}, Y_{t+1}, 1)] \\ a = on_{\text{min}} \ : \ \underline{Q} \cdot (e^{X_t} - \underline{HR} \cdot e^{Y_t} - c_{op}) + \\ \qquad \beta E_t[V_{t+1}(X_{t+1}, Y_{t+1}, 1)] \\ a = off \ : \ \beta E_t[V_{t+1}(X_{t+1}, Y_{t+1}, 0)] \end{bmatrix}$$

where $\beta = \exp(r \cdot \Delta t)$ is the one period discount factor.

Solution of the SDP

- Barrier control as the optimal control policy.
- There exist a no-action band when start-up costs are non-zero.

Numerical Examples: model parameters of physical constraints

- A natural gas fired power plant with 100 MW capacity.
- Time horizon of valuation: 10 years (or, 1040 periods)

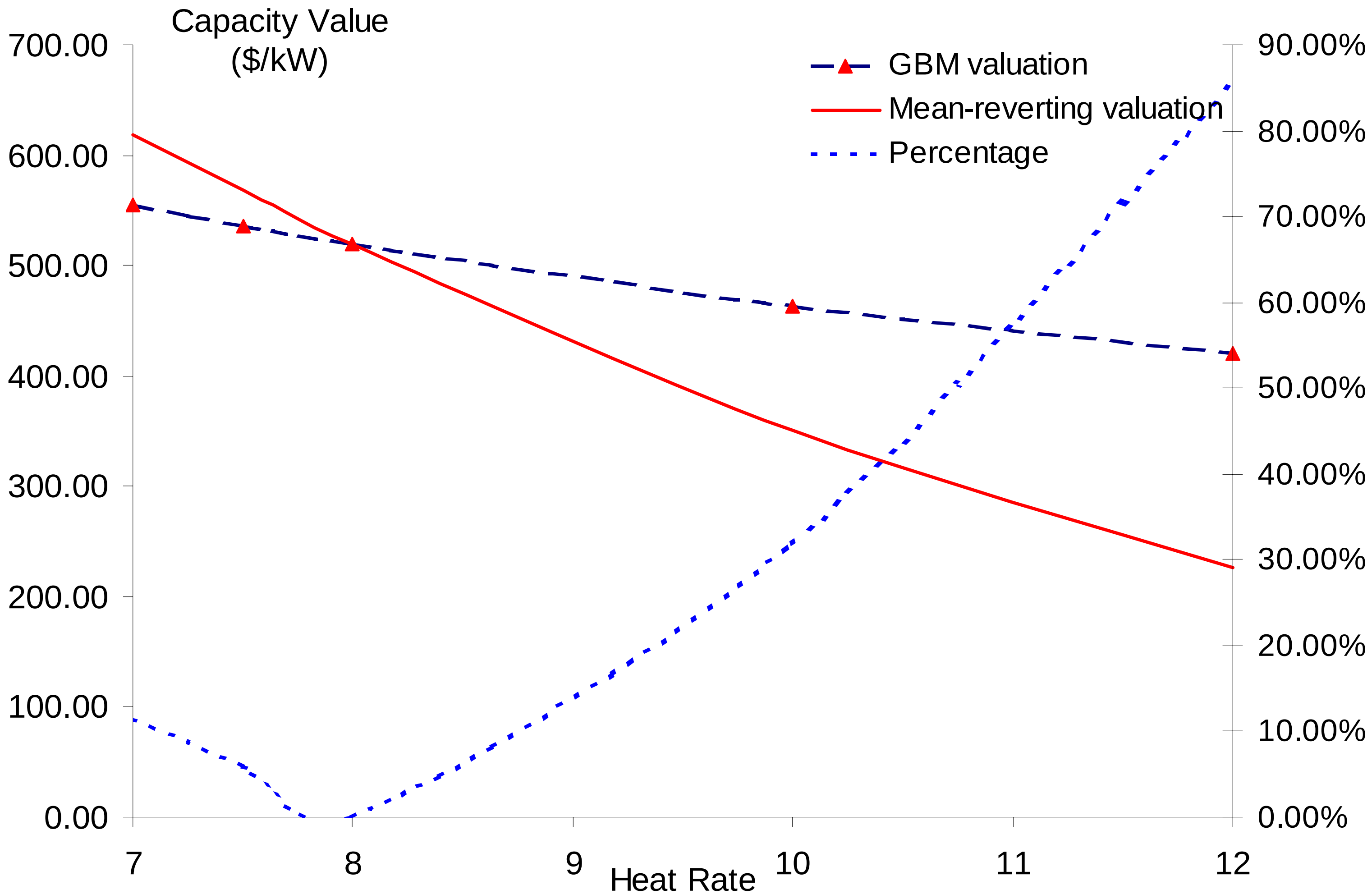
- Ratio of min_heat_rate to max_heat_rate: 1/1.4.
- Start-up cost: $5000/start-up or $8000/start-up.
- Min. capacity level: 60%.
- Ramp up time: 1 period.

Numerical Example II: Mean-reversion price models

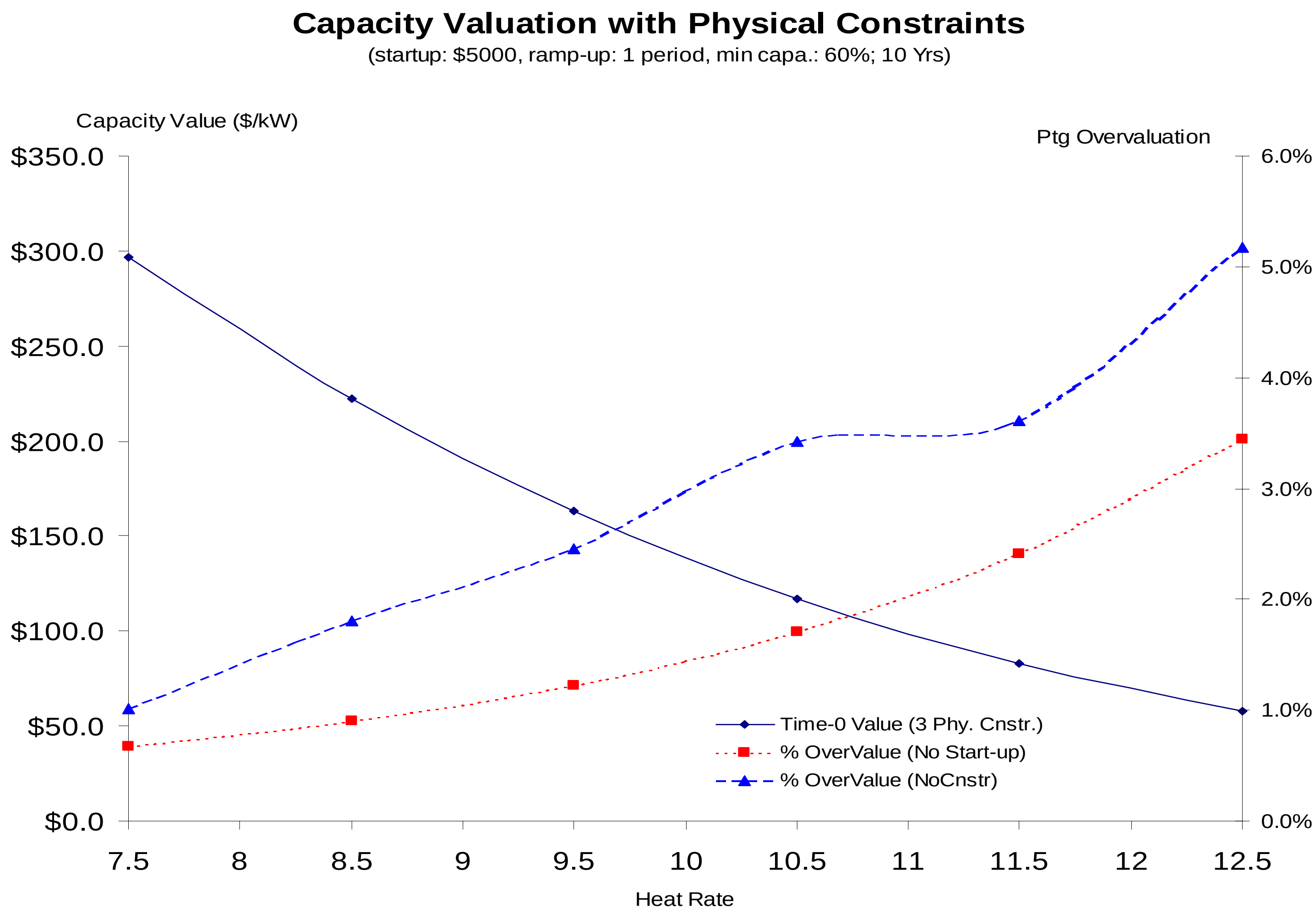
- Electricity spot price: $21.7/MWh
- Natural gas (NG) spot price: $3.16/MMBtu

- Electricity log-price long-term mean (θ_e): 3.15
- Electricity mean-reverting coefficient (κ_e): 3
- Electricity price volatility (σ_e): 75%
- NG log-price long-term mean (θ_g): 0.87
- NG mean-reverting coefficient (κ_g): 2.25
- NG price volatility (σ_g:) 60%
- Price correlation between electricity and NG (ρ): 0.3

Capacity Valuation: GBM vs. Mean-reverting



Impact of Operating Characteristics on Capacity Valuation (Mean-reversion price models)



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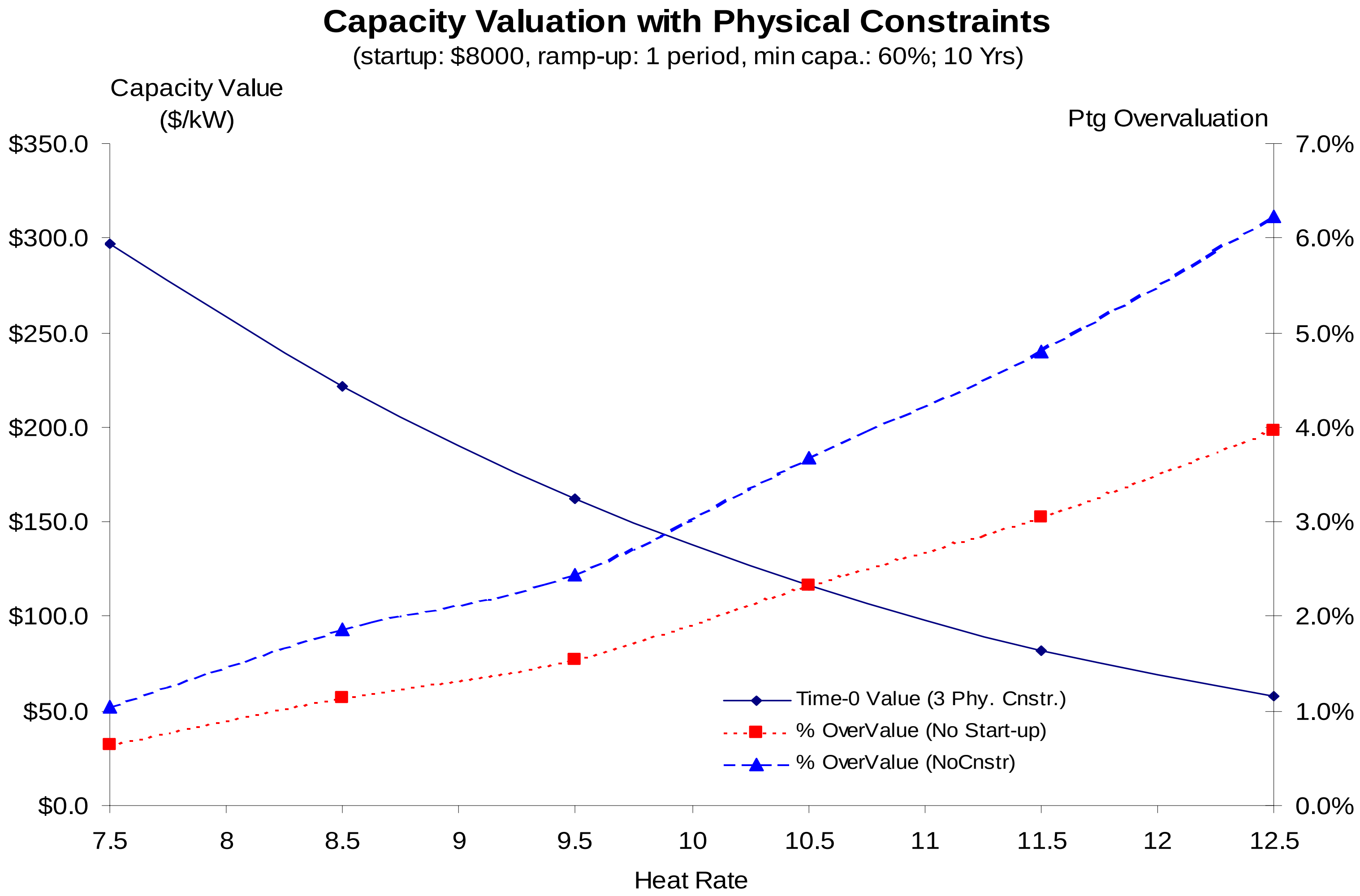

Observations

- Assumptions on the dynamics of electricity price matter
  – Lead to significant over-valuation/under-valuation.
- Operational constraints strip off some embedded optionality in power generation assets.
  – In particular, start-up costs and ramp-up constraints impose cost to exercise spark spread options embedded in the plant.
- The impacts of physical constraints on the valuation of power plants increase with heat rate (largest for least efficient plants)
- Within a plausible range of parameters, start-up cost has the most significant effect on plant value.