Pricing in a Stochastic Environment

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The Purpose of (Electricity) Markets

**Commodities Markets**
- Spot price formation which clears supply and demand.
- Efficient deployment of capital.

**Electricity Markets**
- More than just real-time balance of supply and demand.
- Reliability
  - Ancillaries (short time-scale)
  - Capacity (long time-scale)
- Investment
  - Cost: Build assets that are likely to lower cost.
  - Locational: Try to build assets where they are needed.

Transparency and stability of market mechanics yields more efficient investment.
What Trades and Why?

Forward Energy Markets

- Buy/sell electricity for a future delivery month.
  - Delivered uniformly over a bucket (e.g. peak hours).

- The following figure shows PJM Western Hub forwards.
  - Each value represents the price ($/MWh) at close-of-business for uniform delivery of on-peak power over the month.
  - Derived from exchange settles (ICE,CME) and Bloomberg.
What Trades and Why?

Forward Energy Markets

- Forward prices “exist” for most delivery zones.
- Liquidity can vary substantially.
  - Benchmarks are liquidity centers—in this case PJMWH.
- Forward markets depend on stability and integrity of ISO/RTO price formation.
What Trades and Why?

Forward Energy Markets

- The forward price is the market value for the distribution of future spot prices.
  - This figure shows a simulated (to be discussed) distribution of PSEG monthly average peak spot prices for Jul2020.

- The driver for trading activity is the management of end-user risks.
  - Companies wanting to protect futures cashflows by hedging.
  - Lenders requiring asset developers to hedge cashflows.

- Forwards are the risk transfer work horses.
  - Many types of derivatives trade, but all are “anchored” to forwards.
What Trades and Why?

High-Dimensional Market

Why do all of these forwards trade? Under the LMP paradigm:
- People want hedges as “close” to their assets as possible.
- Generation assets (and some loads) settle on nodal spot prices.
- Most load settles at zonal prices.

Project Finance Example
- Asset build funded by debt; lenders insist on a hedge that protects the asset cashflows.
- The hedge is a derivative (commonly heat rate call options or revenue puts).
- Asset cashflows driven by nodal prices; but dealers insist on zonal (or hub) prices for the hedge.
- Modeling is required to ensure that:
  - The interest payments are covered by the annuity from the hedge.
  - The asset cashflows cover the payoff of the hedge.
Things get complicated quickly.

- No known asset produces a constant volume with certainty.
- Conventional generation assets are complicated things.
- Nodal prices can behave erratically.
- Short load positions are inevitably stochastic in nature.

Models fill gaps.

- The results below are simulated payoffs for a CCGT and a load transaction.
- The analytics required to produce such results are nontrivial.
Typical Organization of Simulation Framework

Weather Simulations

where e.g.:

\[ \tau_d = \mu_d + \sigma_d X_d \]

- \( \mu_d = \alpha_0 + \alpha_1 (d - d_0) + \sum_{k=1}^{K} c_k \sin(2\pi k\phi(d)) + \ldots \)
- Calibrated to decades of quasi-stationary historical data.
- The residuals \( X \) are often modeled as ARMAs.
- Correlation structure between different locations is nontrivial

Demand Simulations

\[ L_d = \alpha + \beta (d - d_0) + \sum_{k=1}^{K} \theta^k (\tau_d) + \sigma_d e_d \]

where \( \theta \) mollifies temperatures.

- Calibrated to a few years of historical data.
- Load growth handled by drift term.
- Additional seasonality can be handled by Fourier terms.
- Hourly loads from stochastic shaping coefficients \( s_d \):

\[ \bar{L}_d = \bar{s}_d L_d \]

Fuel Spot Price Simulations

Spot Price Simulations

Regression Based (bucket level):

\[ \log \left[ \frac{P_d}{\bar{P}_d} \right] = \alpha + \gamma \bar{p}_d + \sum_{k=1}^{K} \theta^k (\tau_d) + e_d \]

Hourly prices:

\[ \bar{p}_d = \bar{s}_d P_d \]

Stack Based:

\[ \bar{p}_d = \Psi s \left[ \bar{L}_d \bar{F}_d \right] + \bar{e}_d \]
Coupling Across Many Processes

- To understand a portfolio (or an ISO/RTO) a large number of processes must be realistically coupled.

- For weather parametric forms (e.g. standard time series) are very challenging—replace with bootstrap of residuals.

- For spot prices hierarchical organization renders regressions/simulations tractable.

- Each bond represents a regression, and residuals are coupled via bootstrap.
Some Practical Considerations

- All of the analysis above presumes stability of physical system.
  - Discontinuities in price formation algorithms or topology are challenging.
  - Partially mitigated by calibration to traded market prices.

- Non-Energy Costs:
  - Capacity markets:
    - Annual auctions provide a visible well-defined value(cost) to generation(load).
    - Limited trading activity—difficult to hedge.
    - Limited tenor—roughly 3 years.

- Ancillaries:
  - Essentially no hedging activity.
  - Difficult to model with the precision required to use energy as proxy hedges.
  - “Review invoices.”
As Things Stand Now

Deterministic algorithms (SCED) minimize cost:

- **Inputs:**
  - Forecasted loads.
  - Generation offers (including constraints).
  - Anticipated system configuration and contingencies.

- **Results:**
  - Locational marginal prices (shadow prices for incremental increase in locational demand).
  - Ancillary prices arising from rules-based requirements.

**Comments:**

- **Sources of Randomness:**
  - Load *has been* the primary source of “Gaussian” randomness.
  - Generators are the primary sources of “Poisson” randomness—outages.

- **Cost of Randomness:**
  - Handled (in arrears) via unit flexibility, ancillaries and uplift.
  - Load (the short) pays for most of it.

- **Incentives:**
  - Load is penalized for forecasting errors.
  - Generators are rewarded for reliability by capacity payments and energy/ancillary margin.
Price Formation in a Stochastic Setting

Sources of Randomness

Intermittency in renewables production is a new and pronounced source of randomness.

- The nature of the hourly dynamics differs from load.
  - Load is primarily temperature driven.
  - This figure shows the results of factor analysis of forecasting errors at KABI (Abilene).
  - The time series used are 24 hourly forecasting errors (-1d) for temperature and wind from 2015 to the present.
  - Note the slower decay in wind spectrum—dynamics of wind forecasting error is “rougher.”
  - Similar at other locations (e.g. KPHL).
Non-LMP “Stylized” Setting

Setup
- 24 hour setting.
- Dispatchable Generation
  - Allowed generation levels $\tilde{g}_j \in {\cal A}_j$ for $j = 1, \ldots, J$.
  - Cost $c_j(\tilde{g}_j)$; depends on generation levels, fuels and constraints.
- Load Net of Intermittent Supply
  - $\tilde{L}_* = \sum_{k=1}^K \tilde{L}_k$.
  - Each $\tilde{L}_k$ is a stochastic 24-dimensional process.

Deterministic Optimization (The “current” way)
- Minimize the cost to serve the expected net load $\bar{\mu}_L$:

$$C(\bar{\mu}_L) = \min_{\hat{g} \in \bar{A}_*} \sum_j c_j(\tilde{g}_j) \quad \text{where} \quad \bar{A}_* = \left\{ \hat{g} \in \bar{A} : \bar{1}^t \hat{g} = \bar{\mu}_L \right\}$$

- Spot prices are marginal incremental cost: $\tilde{p} = \nabla_{\bar{\mu}_L} C(\bar{\mu}_L)$.
Non-LMP “Stylized” Setting

- You need to decide before $\bar{L}_*$ is realized how you are going to handle matters.
- A single set of clearing prices cannot simultaneously balance loads while rewarding “good” participants and penalizing the “bad”.
- Introduce generation offers $\pi_j$ to participate in the DA market—a “daily capacity” market.
- ISO/RTO chooses which to accept—accept flag $F_j \in \{0, 1\}$.
- The new optimization problem is:

$$
\min_{\vec{F}} \left( E \left[ \min_{g. \in A_*} \sum_j c_j (\vec{g}_j) \right] + \vec{\pi}^T \vec{F} \right)
$$

where $A_* = \begin{cases} g. \in A. & \vec{1}^T g. = \bar{\mu}_{L*} \\
\vec{g}_j \equiv 0 & \text{if } F_j = 0 \end{cases}$

- This is saying that you select generators competively based upon their bids $\pi$ and their flexibility.
- Spot prices remain the marginal cost of the realized load $\bar{L}_*$: $\vec{p} = \nabla_{\bar{L}_*} C (\bar{L}_*)$.
- The marginal cost of each factor (PCA) of the total load $\bar{L}_*$ is computed by perturbation.
- The “daily capacity” cost is allocated to each $L_k$ based upon contribution to each factor.
Price Formation in a Stochastic Setting

Non-LMP “Stylized” Setting

- On the Positive Side
  - A key input to such an approach is credible modeling of the joint behavior of a large number of contributing loads and supply $\vec{L}_k$. This is already within reach of existing technology.
  - The calculation of the marginal capacity cost to changes in the covariance of $\vec{L}_*$ is directly analogous to marginal VaR calculations in other areas of finance.

- Neutral
  - The calculation of marginal capacity costs will require dealing with the “lumpiness” of the $\vec{\pi}^t \vec{F}$ term. This is also an issue that is being dealt with in existing dispatch calculations.
  - It is likely that constraints on bid behavior will be required—restrictions on who can submit positive offers and how high such can be. Similar issues already arise in existing capacity markets.

- On the Negative Side
  - Balancing accurate modeling of the joint loads $\vec{L}_k$ with transparency to those on the receiving end of the daily capacity cost will be challenging.
  - The calculations required for stochastic optimization are daunting—even in say a lower-dimensional zonal setting.

- A Likely Tradeoff
  - Keep LMP as is and deploy a calculation like the above to reward flexibility on longer length scales.
  - Roll LMP back to say zonal prices to facilitate a single spot price / flexibility price calculation.