Pricing in a Stochastic Environment

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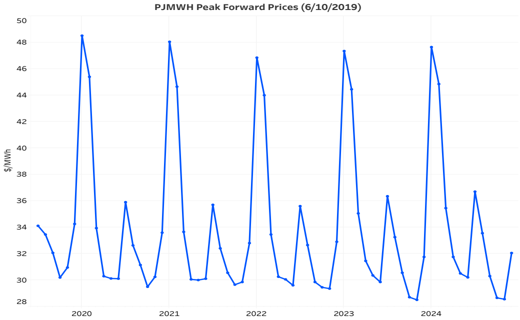
The Purpose of (Electricity) Markets

- 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.

Forward Energy Markets

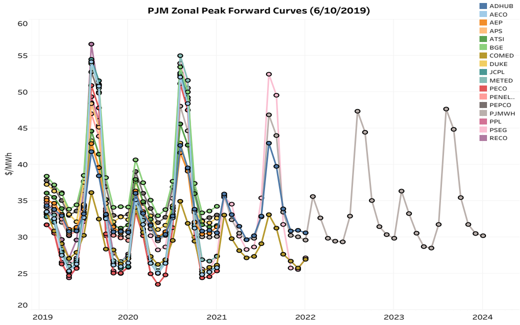
- Buy/sell electricity for a future delivery month.
  - Delivered uniformly over a bucket (e.g. peak hours).
- The following figure shows PJM Western Hub forwards.
  - Each value represents the price ($/MWh) at close-of-business for uniform delivery of on-peak power over the month.
  - Derived from exchange settles (ICE,CME) and Bloomberg.



What Trades and Why?

Forward Energy Markets

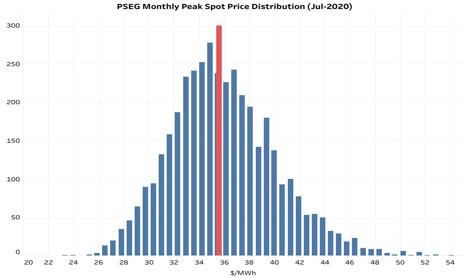
- Forward prices "exist" for most delivery zones.
- Liquidity can vary substantially.
  - Benchmarks are liquidity centers—in this case PJMWH.
- Forward markets depend on stability and integrity of ISO/RTO price formation.



What Trades and Why?

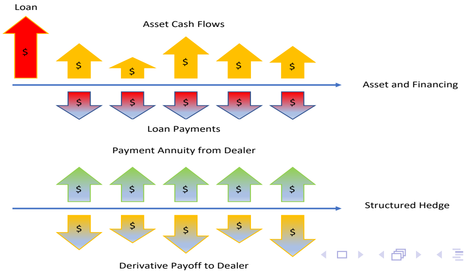
Forward Energy Markets

- 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.



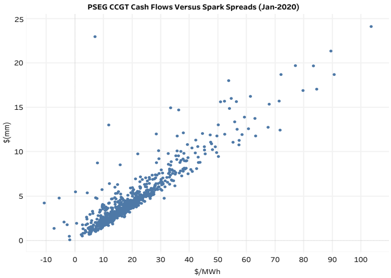
High-Dimensional Market

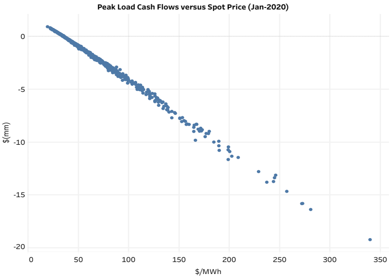
- Why do all of these forwards trade? Under the LMP paradigm:
  - People want hedges as "close" to their assets as possible.
  - Generation assets (and some loads) settle on nodal spot prices.
  - Most load settles at zonal prices.
- Project Finance Example
  - Asset build funded by debt; lenders insist 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.



Valuing and Hedging Assets

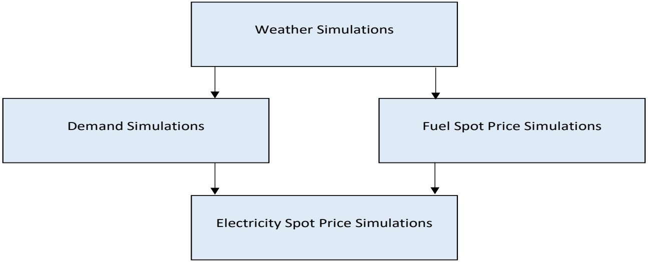
- Things get complicated quickly.
  - No known asset produces a constant volume with certainty.
  - Conventional generation assets are complicated things.
  - Nodal prices can behave erratically.
  - Short load positions are inevitably stochastic in nature.
- Models fill gaps.
  - The results below are simulated payoffs for a CCGT and a load transaction.
  - The analytics required to produce such results are nontrivial.





Stochastic Modeling

Typical Organization of Simulation Framework



Weather Simulations

$$\tau_d = \mu_d + \sigma_d X_d$$

where e.g.:

$$\mu_d = \alpha_0 + \alpha_1(d - d_*) + \sum_{k=1}^{K}\left[c_k \sin(2\pi k \varphi(d)) + \cdots\right]$$

- Calibrated to decades of h quasi-stationary historical data.
- The residuals X are often modeled as ARMAs.
- Correlation structure between different locations is nontrivial

Demand Simulations

$$L_d = \alpha + \beta(d - d_*) + \sum_{k=1}^{K}\theta^k(\tau_d) + \sigma_L \varepsilon_d$$

where θ 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 $\vec{s}_d$:

$$\vec{L}_d = \vec{s}_d L_d$$

Spot Price Simulations

Regression Based (bucket level):

$$\log\left[\frac{p_d}{\tilde{p}_d}\right] = \alpha + \gamma \tilde{p}_d + \sum_{k=1}^{K}\theta^k(\tau_d) + \varepsilon_d$$

Hourly prices:

$$\vec{p}_d = \vec{s}_d p_d$$

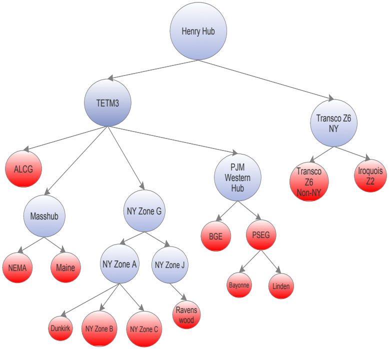
Stack Based:

$$\vec{p}_d = \Psi_{G_\cdot}\left[\vec{L}_d \,\middle|\, \vec{F}_d\right] + \vec{\varepsilon}_d$$

Stochastic Modeling

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

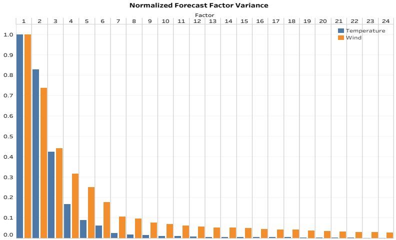
- All of the analysis above presumes stability of physical system.
  - Discontinuities in price formation algorithms or topology are challenging.
  - Partially mitigated by calibration to traded market prices.
- Non-Energy Costs:
  - Capacity markets:
    - Annual auctions provide a visible well-defined 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 configuation 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 reliablity by capacity payments and energy/ancillary margin.

Sources of Randomness

- Intermittency in renewables production is a new and pronounced source of randomess.
  - 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).



Price Formation in a Stochastic Setting

Non-LMP "Stylized" Setting

- Setup
  - 24 hour setting.
  - Dispatchable Generation
    - Allowed generation levels $\vec{g}_j \in \mathcal{A}_j$ for $j = 1, \ldots J$.
    - Cost $c_j(g_j)$; depends on generation levels, fuels and constraints.
  - Load Net of Intermittent Supply
    - $\vec{L}_* = \sum_{k=1}^{K} \vec{L}_k$.
    - Each $\vec{L}_k$ is a stochastic 24-dimensional process.
- Deterministic Optimization (The "current" way)
  - Minimize the cost to serve the expected net load $\vec{\mu}_{L_*}$:

$$C\left(\vec{\mu}_{L_*}\right) = \min_{g_\cdot \in \mathcal{A}_*} \sum_j c_j\left(\vec{g}_j\right) \quad \text{where} \quad \mathcal{A}_* = \begin{cases} g_\cdot \in \mathcal{A}_\cdot \\ \vec{\mathbf{1}}^t g_\cdot = \vec{\mu}_{L_*} \end{cases}$$

  - Spot prices are marginal incremental cost: $\vec{p} = \nabla_{\vec{\mu}_{L_*}} C\left(\vec{\mu}_{L_*}\right)$.

Non-LMP "Stylized" Setting

- With Randomness

  - You need to decide before $\vec{L}_*$ is realized how you are going to handle matters.
  - A single set of clearing prices cannot simulataneously balance loads while rewarding "good" participants and penalizing the "bad".
  - Introduce generation offers π_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:

$$\min_{\vec{F}} \left(E \left[\min_{g. \in \mathcal{A}_*} \sum_j c_j \left(\vec{g}_j \right) \right] + \vec{\pi}^t \vec{F} \right) \quad \text{where} \quad \mathcal{A}_* = \begin{cases} g. \in \mathcal{A}. \\ \vec{\mathbf{1}}^t g. = \vec{\mu}_{L_*} \\ \vec{g}_j \equiv 0 \quad \text{if} \quad F_j = 0 \end{cases}$$

  - This is saying that you select generators competively based upon their bids π and their flexibility.
  - Spot prices remain the marginal cost of the realized load $\vec{L}_*$: $\vec{p} = \nabla_{\vec{L}_*} C \left(\vec{L}_* \right)$.
  - The marginal cost of each factor (PCA) of the total load $\vec{L}_*$ 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 flexilbilty on longer length scales.
  - Roll LMP back to say zonal prices to facilitate a single spot price / flexibility price calculation.