Pricing in a Stochastic Environment

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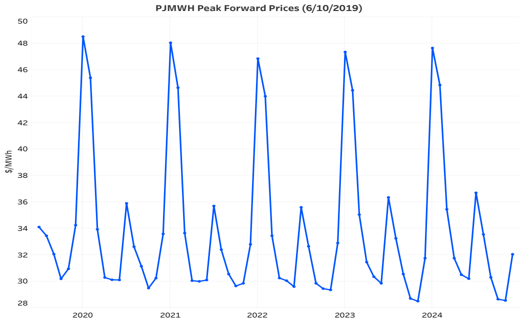
The Purpose of (Electricity) Markets

- 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

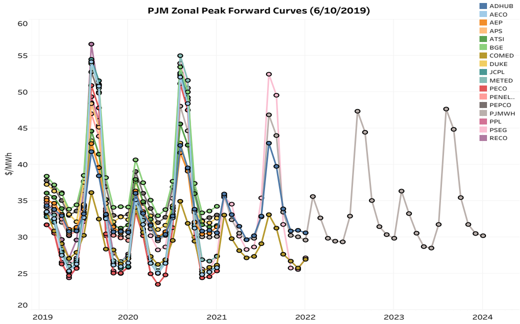
- Buy/sell electricity for a future delivery month.
  - Delivered uniformly over a bucket (e.g. peak hours).
- The following figure shows PJM Western Hub forwards.
  - Each value is the monthly price (\$/MWh) for uniform on-peak delivery.
  - Derived from exchange settles (ICE,CME) and Bloomberg.



What Trades and Why?

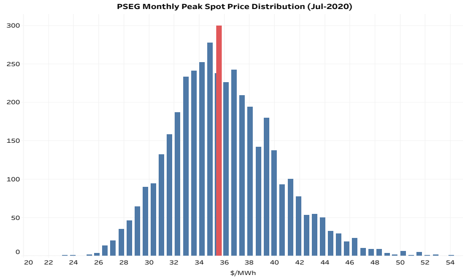
Forward Energy Markets

- 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.



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.



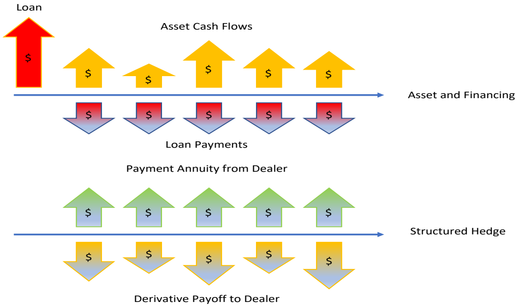
High-Dimensional Market

- 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 often a derivative.
    - Heat rate call options — designed to mimic the "call option nature" of generation assets.
    - Revenue puts — compound options designed to protect a drop in asset value.
  - Asset cashflows driven by nodal prices; **but** dealers almost always insist on zonal (or hub) prices for the hedge.

What Trades and Why?

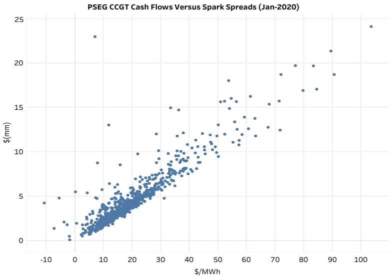
High-Dimensional Market

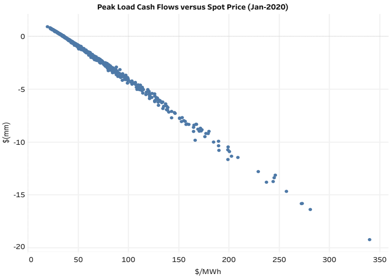
- Project Finance Example (cont)
  - Modeling is required to ensure that:
    - The interest payments are covered by the annuity from the hedge.
    - The asset cashflows cover the payoff of the hedge.



Valuing and Hedging Assets

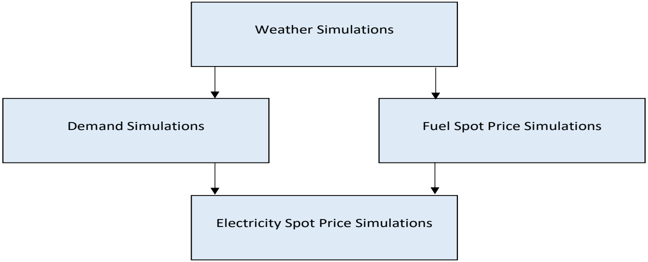
- Things get complicated quickly.
  - No known asset produces a constant volume with certainty.
  - Conventional generation assets are complicated things.
  - Nodal prices can behave erratically.
  - Short load positions are inevitably stochastic in nature.
- Models fill gaps.
  - The results below are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

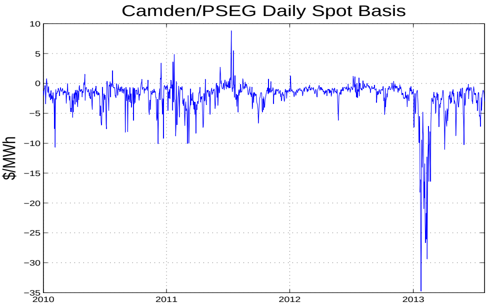
$$\vec{p}_d = \vec{s}_d p_d$$

Stack Based:

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

Some Practical Considerations

- All of the analysis above presumes stability of physical system.
  - Rational investment requires a reasonable level of predictive power.
  - Discontinuities in price formation algorithms or topology are challenging.
  - Nodal price risk is a chronic impediment to investment decisions.



Capacity Markets

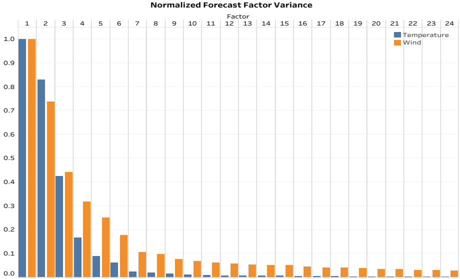
- Consumers (the load) pays for reliability services as well as energy.
- Reliability products can be a nontrivial part of revenues/costs.
  - Capacity.
  - Ancillary services.
- Capacity (in many electricity markets) can rival energy in magnitude of cost.
  - Consumers are obligated to purchase a "piece" of a generator during a given delivery period.
  - Generators receive these revenues, thereby encouraging "extra" capacity.
  - It is the moral equivalent of storage that supports reliability in other energy markets (e.g. natural gas).
  - Prices are set via ISO-defined requirements and periodic auctions.

Capacity Markets

- Key Points:
  - The amount of capacity that a generator can sell depends upon the size of the unit *and* a broad measure of how reliable it is.
  - ISOs have recently modified capacity products to claw back revenues for failure to produce during low-reserve margin periods.
  - This is the only sense in which generation "pays" for contributing to reliability problems.
- As energy prices have fallen (shale gas) the relative contribution of capacity costs in a consumers bill has increased.
- Capacity is a blunt instrument in the quest for sufficient and reliable generation.

Sources of Randomness

- 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 actor analysis of forecasting errors at KABI (Abilene).
  - 24 hour (-1d) hourly forecasting errors (2015 to mid-2019).
  - Slower decay in wind spectrum—the forecasting error is “rougher.”



Sources of Randomness

- A Stylized Dichotomy
  - Load *has been* the primary source of "Gaussian" randomness.
  - Generators are the primary sources of "Poisson" randomness—outages.
- Electricity markets in the U.S. are sustaining a dramatic increase in renewables generation.
  - Load pays for reliability while generation contributes increasingly to "Gaussian" randomness.
  - Capacity markets do little to reward flexibility and encourage predictable production on short time-scales.
- Can current market design support new methods production?

Price Formation in a Stochastic Setting

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 demand).
    - Ancillary prices arising from rules-based requirements.
- 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.

Non-LMP “Stylized” Setting

- Setup (24 hour window)
  - 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 $\vec{\mu}_{L_*}$:

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

Non-LMP "Stylized" Setting (cont)

- Comments
  - Spot prices are the marginal incremental cost: $\vec{p} = \nabla_{\vec{\mu}_{L_*}} C(\vec{\mu}_{L_*})$.
  - Ancillaries—which generators to you want to have on "stand by" and what do you pay them?
    - Often prescribed in a scenario-based fashion.
    - Decision "co-optimized" with energy price formation.
- No obvious way to allocate reliability costs to contributors of randomness.

Price Formation in a Stochastic Setting

Non-LMP "Stylized" Setting — A Daily Capacity Market

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

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

A Daily Capacity Market (cont)

- Implicit joint optimization of energy production and reserves.
  - Generators are selected based upon their offers $\vec{\pi}$ and their flexibility.
  - Spot prices remain a marginal cost incremental load $\vec{L}_*$: $\vec{p} = \nabla_{\vec{L}_*} C\left(\vec{L}_*\right)$.
- Allocation of reliability costs achievable in a rigorous fashion.
  - Compute the marginal cost of each factor (PCA) of the (random) net load $\vec{L}_*$ by perturbation.
  - The "daily capacity" cost is allocated to each L_k based upon contribution to each factor.

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 analogous to marginal VaR calculations in other areas of finance.

- Neutral
  - The calculation of marginal capacity costs would 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 would be required
    - Who can submit positive offers and how high such can be.
    - Similar issues already arise in existing capacity markets.

Non-LMP "Stylized" Setting

- Challenges
  - Balancing accurate modeling of the joint loads $\vec{L}_k$ with transparency to those on the receiving end of the daily capacity cost is not trivial.
  - 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 zonal pricing.
- Conclusion
  - Nodal pricing is of dubious value in capital allocation; zonal pricing may be better and should allow the above to be computationally feasible.
  - Hedges would then involve derivatives on $\vec{\pi}$.
  - The above sketch essentially shifts price formation away from energy prices to a total contribution to system performance.