Electricity Market Structure: Spot, Forward, and Balancing Markets

Quant Insider

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Objective: Provide a technical and visual overview of the electricity market structure, covering the spot, forward, and balancing markets, and their quantitative modeling foundations.

1 1. Spot Market (Day-Ahead and Real-Time)

The **spot market** operates closest to physical delivery and includes two main layers:

- **Day-Ahead Market (DAM):** Energy is traded one day before delivery. Prices are set by market clearing algorithms minimizing system cost subject to constraints.
- **Real-Time Market (RTM):** Adjusts deviations from day-ahead schedules every 5–15 minutes.

Locational Marginal Pricing (LMP)

Each node in the grid has a unique price reflecting energy, congestion, and loss components:

$$\text{LMP} = P_{\text{energy}} + P_{\text{congestion}} + P_{\text{loss}}. \tag{1}$$

Interpretation: The LMP indicates the marginal cost of delivering an additional MWh at a specific node, including network effects.

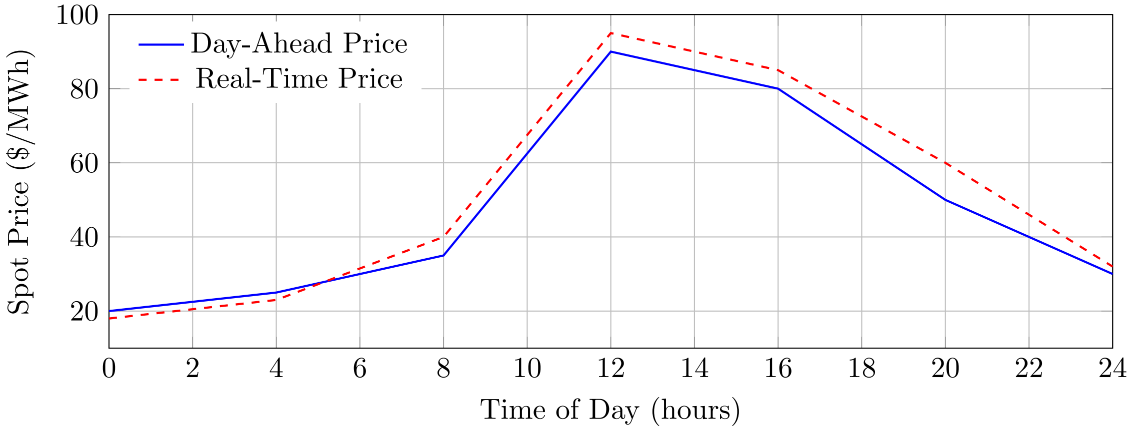

Figure 1: Illustrative day-ahead vs. real-time price patterns showing midday peak and evening ramp.

Volatility Drivers

Spot price volatility is high due to non-storability of electricity, driven by:

- Sudden changes in demand (weather, load spikes)
- Intermittent renewable output (solar, wind)
- Transmission congestion and outages

2 2. Forward and Futures Markets

The **forward market** allows participants to lock in prices for future delivery periods, enabling hedging and price discovery.

Forward Pricing Relationship

Electricity forwards represent expectations of future spot prices under a risk-neutral measure:

$$F(t,T) = \mathbb{E}_t[S_T]. \tag{2}$$

Unlike storable commodities, electricity lacks a cost-of-carry relationship, so:

$$F(t,T) \neq S_t e^{r(T-t)}. \tag{3}$$

Spot Dynamics

Spot prices are typically modeled as **mean-reverting jump diffusions**:

$$dS_t = \kappa(\theta_t - S_t)\,dt + \sigma_t\,dW_t + J_t\,dN_t, \tag{4}$$

where κ is the mean-reversion rate, θ_t the seasonal mean, J_t jump size, and N_t a Poisson process.

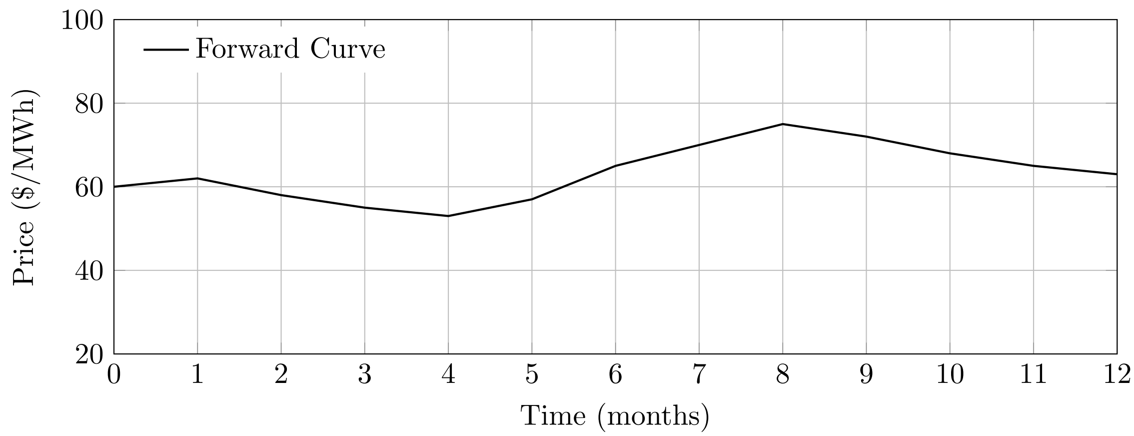

Figure 2: Typical forward curve exhibiting seasonality (winter premium).

Note: Forward prices smooth out short-term volatility but embed seasonal expectations, risk premia, and delivery profile adjustments.

3 3. Balancing Market (System Services)

Even after day-ahead scheduling, supply and demand mismatches occur in real time. The balancing market maintains frequency and voltage stability.

Mechanism

Balancing energy prices penalize deviations from day-ahead commitments:

$$\Pi_i = (Q_i^{\text{actual}} - Q_i^{\text{scheduled}}) \times (P_{\text{imb}} - P_{\text{DA}}), \tag{5}$$

where P_{DA} is the day-ahead price, P_{imb} the imbalance price.

Reserve Types

Reserve Product	Description	Activation Time
Primary (FCR)	Automatic frequency control, continuous response	Seconds
Secondary (aFRR)	Automated generation control, restores frequency	¡5 minutes
Tertiary (mFRR)	Manual dispatch, energy rebalancing	15–30 minutes

Table 1: Balancing reserve products and response characteristics.

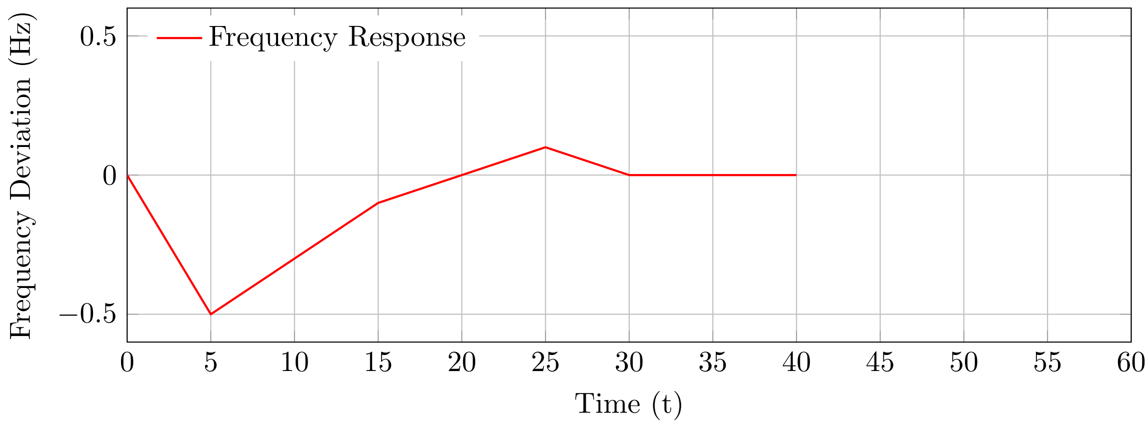

Figure 3: Balancing actions restore system frequency after a disturbance.

4 4. Market Interplay

Layer	Function	Horizon	Volatility	Main Users
Forward/Futures	Hedge price risk	Months–Years	Low–Moderate	Utilities, Traders, Industrials
Day-Ahead Spot	Optimize dispatch	1 Day	High	Generators, Retailers
Balancing	Maintain reliability	Real-Time	Very High	TSOs, Storage, Flexible assets

Table 2: Comparison of electricity market layers.

Quant Implication: These layers are temporally nested. Forward curves encode expectations of future spot prices, while balancing prices reflect real-time volatility and flexibility value.

5 5. Quantitative Takeaways

- Spot market models require **mean reversion and jumps**.
- Forward pricing links to expected spot under **risk-neutral measure**.
- Balancing markets price **real-time optionality** from flexible assets.
- Understanding the covariance between forward and spot changes is critical for **hedge ratio** estimation.

$$h^* = \rho \frac{\sigma_S}{\sigma_F}. \tag{6}$$

Summary: Electricity markets integrate physical and financial mechanisms across time horizons. Quantitative understanding of these layers enables effective risk management and trading strategies.