Markets and Pricing

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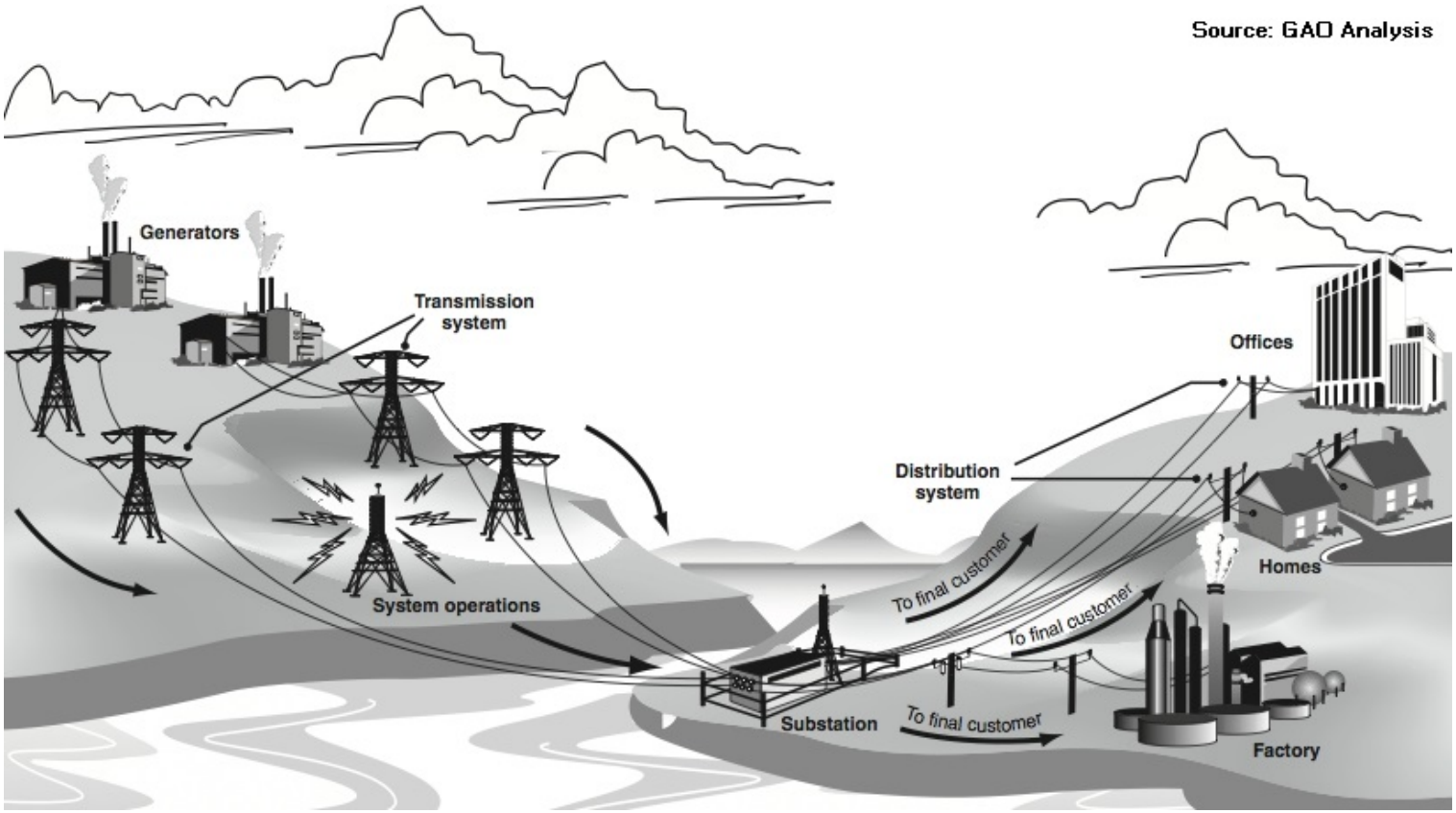
Power, energy and electricity

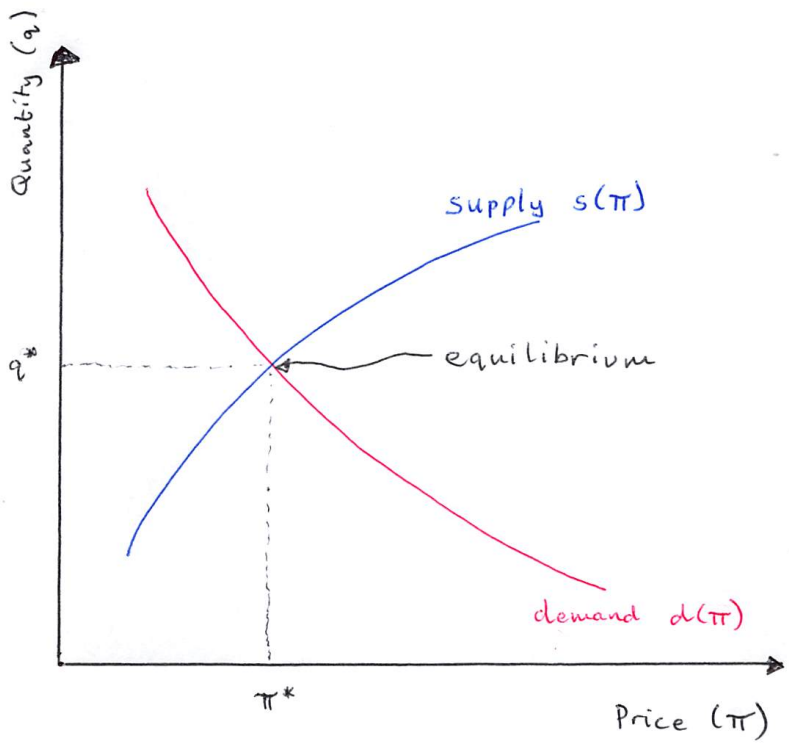
- We note that energy is the capability to do work.
- Power is how fast energy is used or transmitted - power is the amount of energy divided by the time it took to use the energy (a rate).
- Multiplying a value of power and the period of time over which it is used gives an amount of energy.
- This is why a kilowatt is a unit of power but a kilowatt-hour (1 kilowatt times 1 hour) is a unit of energy.
- Electricity is a secondary energy source, created by converting primary energy sources like fossil fuels, wind and solar, into electricity.
- It is a particularly useful form of energy because it can be quickly and efficiently transported over long distances and is readily usable in a multitude of settings (lighting, heat, mechanics, transport, etc).
- Electricity could be termed an energy carrier, as it can be reconverted to other forms of energy such as mechanical energy or heat.

Power generation, transmission and distribution



- Determine generators' output to reliably meet the load
  - $\sum$ Gen MW $\geq \sum$ Load MW, at all times.
  - Power flows cannot exceed lines' transfer capacity.

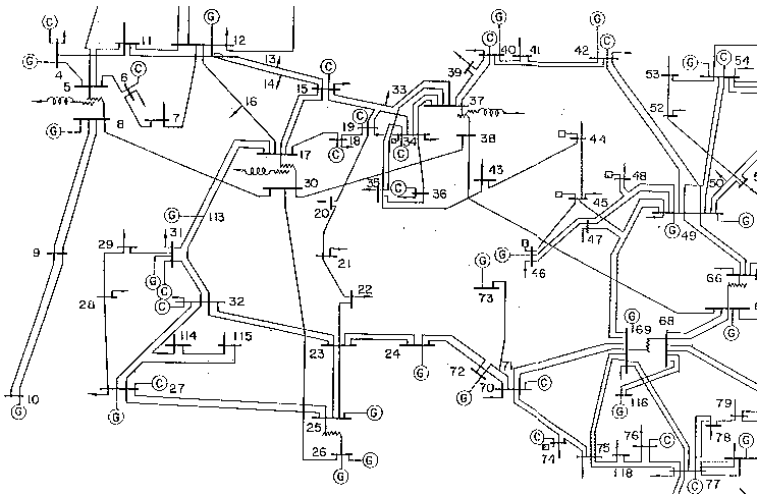
How to set the price: a market



- Walras: $0 \leq s(\pi) - d(\pi) \perp \pi \geq 0$
- Single market, single good: equilibrium price
- How to ascertain these curves accurately?
- Inelastic demand: demand curve is flatter

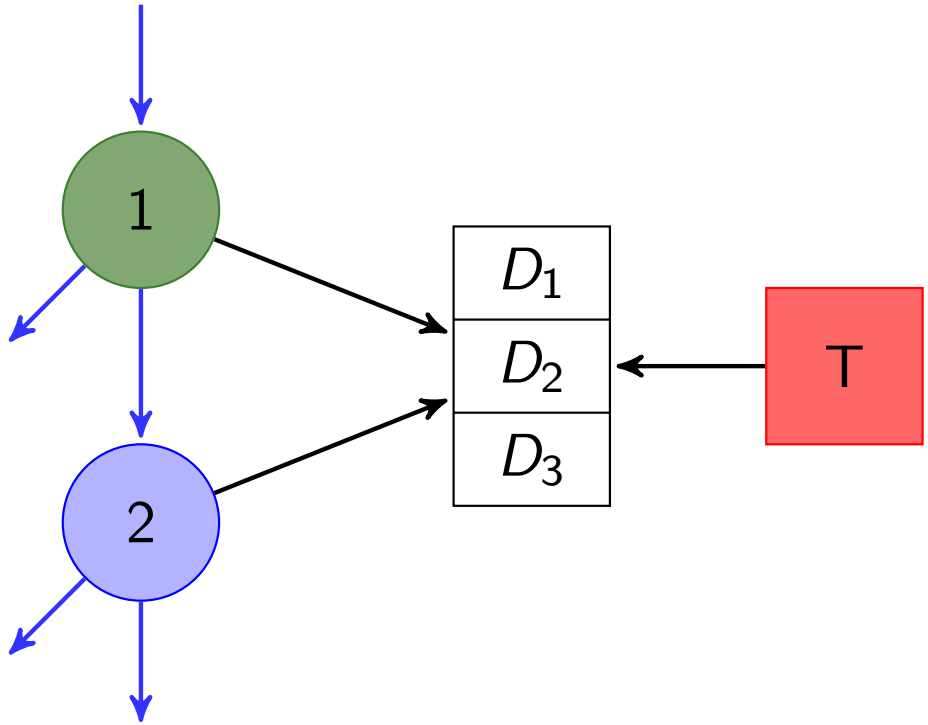
Not that simple: complications abound

- Supply arises often from a generator offer curve (lumpy)
- Technologies and physics affect production and distribution



- Spatial extension: Locational Marginal Prices (LMP) at nodes (buses) in the network

- Vertical integration vs competition
- Each firm minimizes objective independently



The motivation & issues for deregulation/liberalization

- Increase investment by eliminating restrictions for new businesses to enter markets and increase competition
- Increasing competition encourages innovation, and can lower prices
- Usually viewed as replacing tight regulation of vertically integrated monopolies with light regulation of functionally specialized firms and supervision of competitive markets
- Standard economic policy concerns such as productive and allocative efficiency and mitigation of market power
- Concern for closing loopholes in procedural rules and avoiding "screwups"

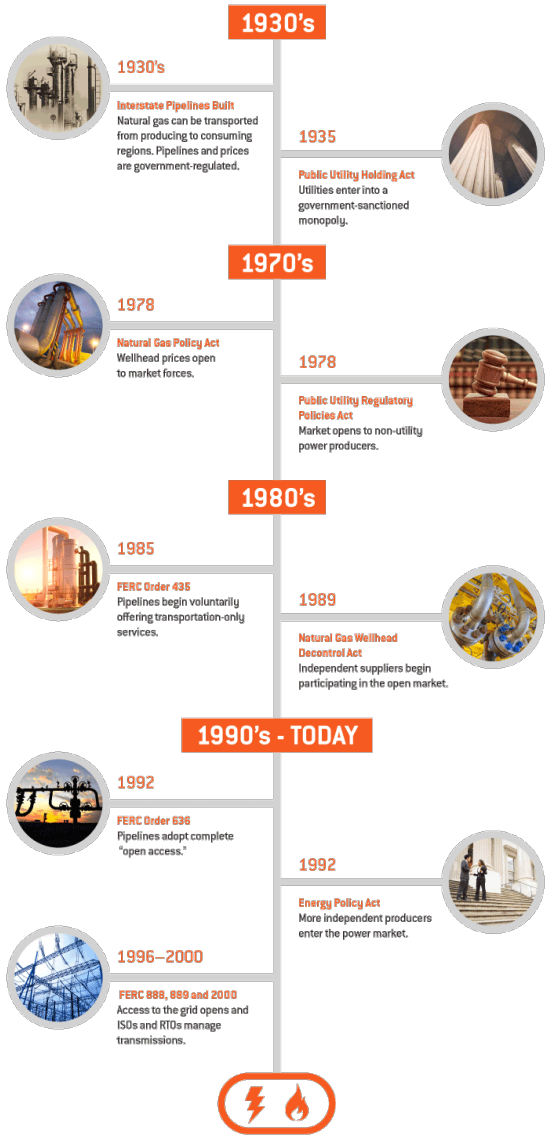
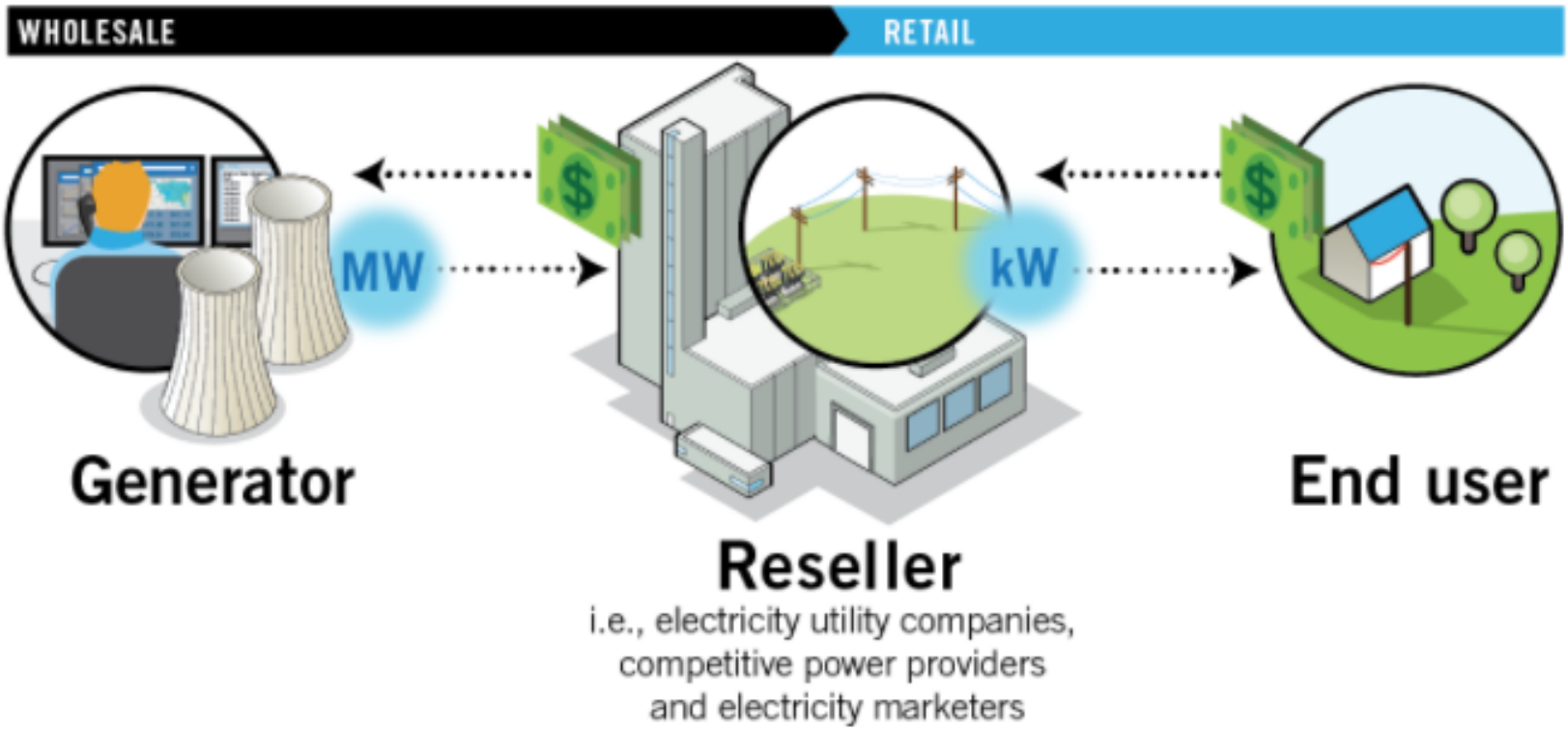


Image source: Direct Energy Business

Types of market Image source: learn.pjm.com

- Electricity is bought, sold and traded in wholesale and retail markets, which operate similarly to wholesale and retail markets for other products



- Market design and rules to foster competitive behavior/efficiency

FERC: wholesale electricity markets (courtesy FERC)

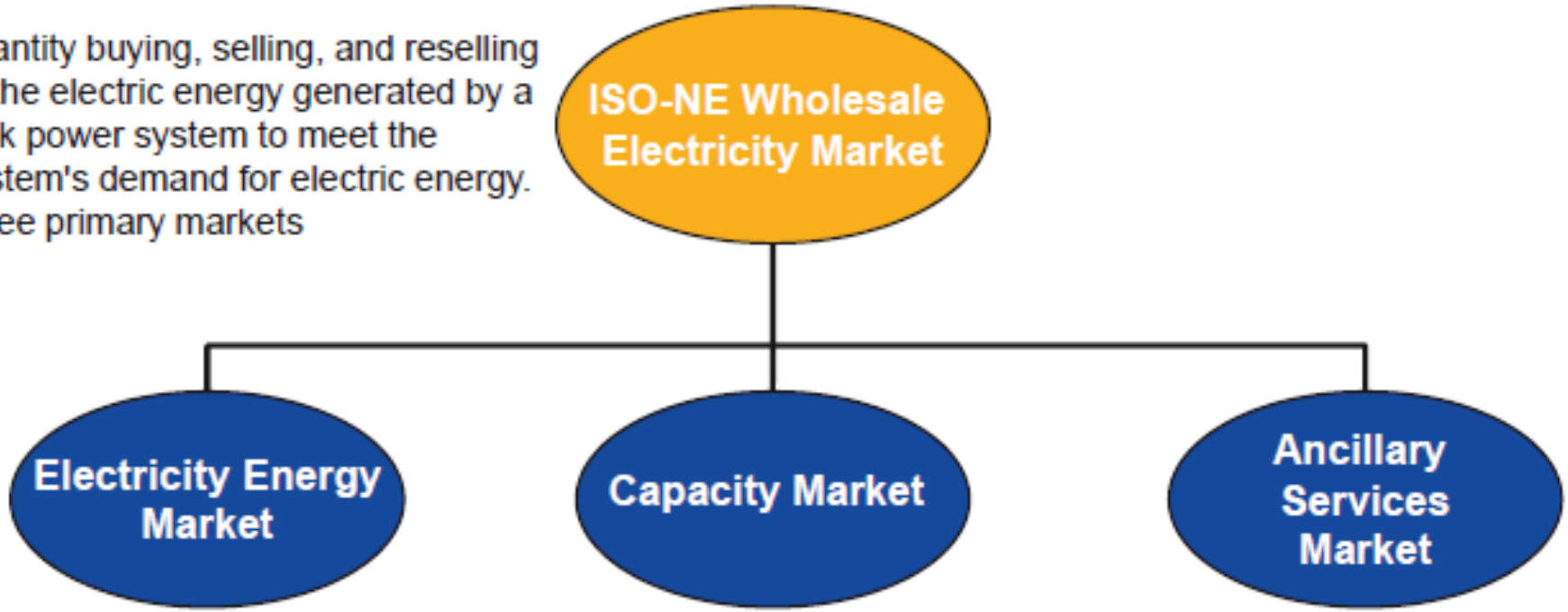
- Independent System Operators (ISOs) formed to promote competition for energy generation
- FERC encouraged utilities to join Regional Transmission Organizations (RTOs) to manage transmission equitably
- ISO/RTOs have energy and ancillary services markets and use bid-based markets to determine economic dispatch
- Northwest, Southeast and Southwest: vertically integrated utilities (including some bilateral transactions)

- 2/3 of US electric load served in RTO regions
- FERC Order 1920 (2024): mandates 20-year forward-looking regional transmission plans
- FERC Order 2023: cluster-based "first-ready, first-served" interconnection to address 2,600+ GW queue backlog

Emerging challenge: data center and AI load growth

- Projections of 30–80+ GW of new data center load over the next decade
- "Behind-the-meter" and co-located arrangements at existing plants (especially nuclear) draw FERC scrutiny on cost allocation and reliability
- FERC opened proceedings on large load interconnection policies
- Interconnection queue backlog (>2,600 GW nationally) delays new generation needed to serve growing demand
- Tension: thermal retirements accelerating while replacement resources are slow to connect
- RTOs refining participation models for hybrid and standalone storage; CAISO and PJM updated state-of-charge management and bidding rules

- Quantity buying, selling, and reselling of the electric energy generated by a bulk power system to meet the system's demand for electric energy.
- Three primary markets



watt-hours

watts

Economic Dispatch Model

$$\min_{F,\theta,P} \sum_f \sum_{j \in G_f} c_j(P_j)$$

$$\text{s.t.} \sum_{k \in j} P_k - \sum_{ji \in \mathcal{E}} (1 + \frac{\alpha_{ji}}{2}) F_{ji} + \sum_{ij \in \mathcal{E}} (1 - \frac{\alpha_{ij}}{2}) F_{ij}$$

$$= d_j + g_j, \forall j \in N$$

$$F_{ij} = \Omega_{ij}(\theta_i - \theta_j), \forall ij \in \mathcal{E}$$

$$(F, \theta, P) \in \mathcal{X}$$

F_{ij}: Real power flow along line ij

P_j: Real power generated at bus j

θ_i: Voltage phase angle at bus i

Ω_{ij}: Susceptance of line ij

α_{ij}: proportional loss of line ij

g_j: Shunt conductance (typically neglected)

and $\mathcal{X}$ captures constraints related to scheduling, unit commitment and ancillary services such as contingencies, operating and spinning reserve, thermal unit (minimum up and down times), ramp rates, network security, and congestion management.

PJM: Locational Marginal Prices (3:30pm April 20, 2021)

Locational marginal pricing: accounts for patterns of load, generation, and physical limits of transmission

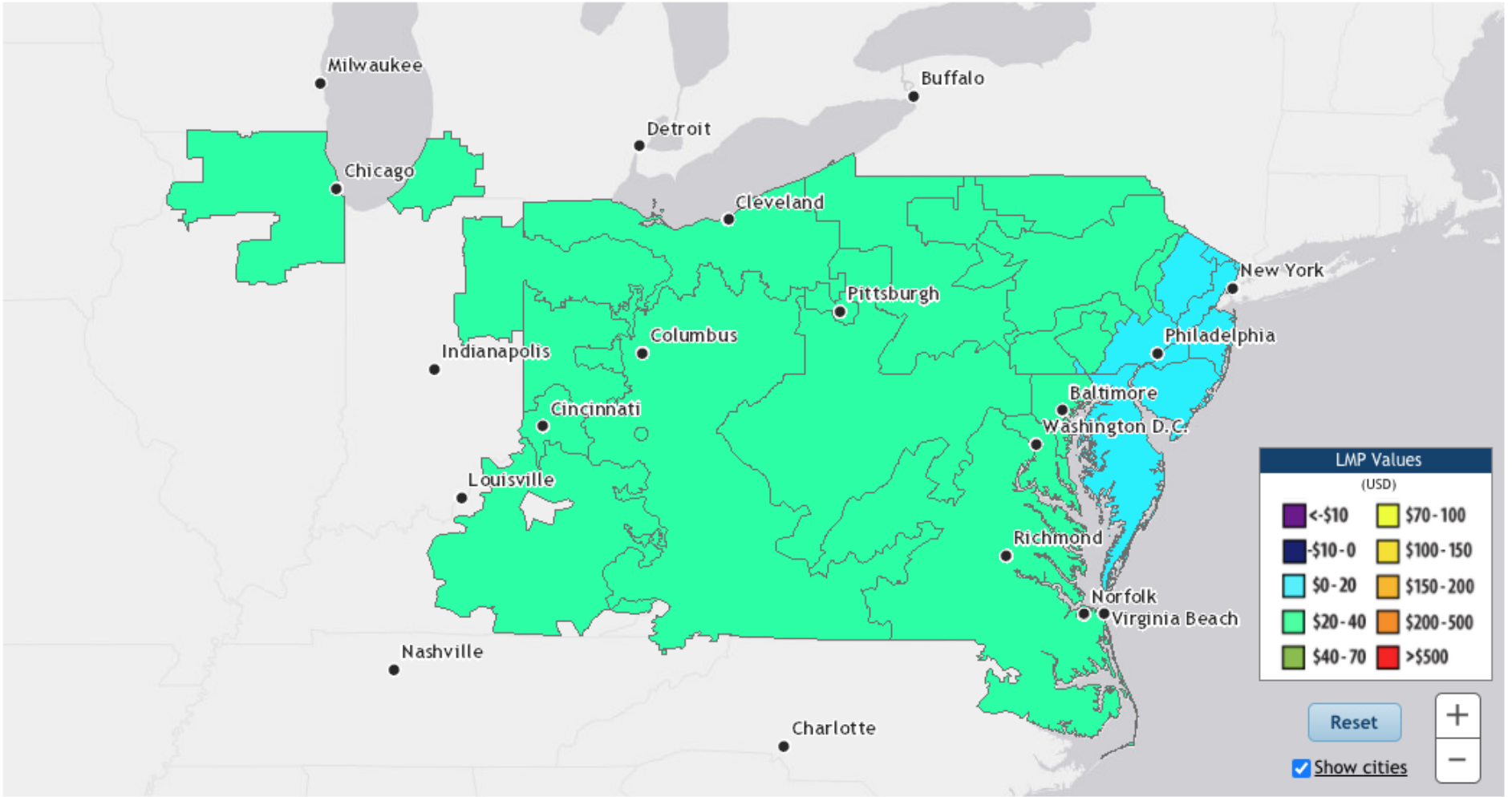
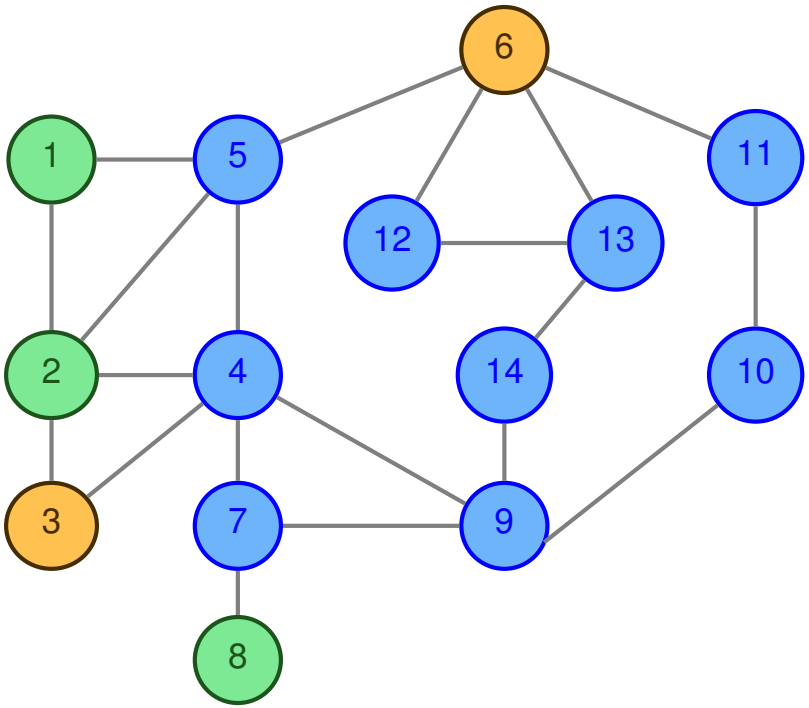


Image source: pjm.com

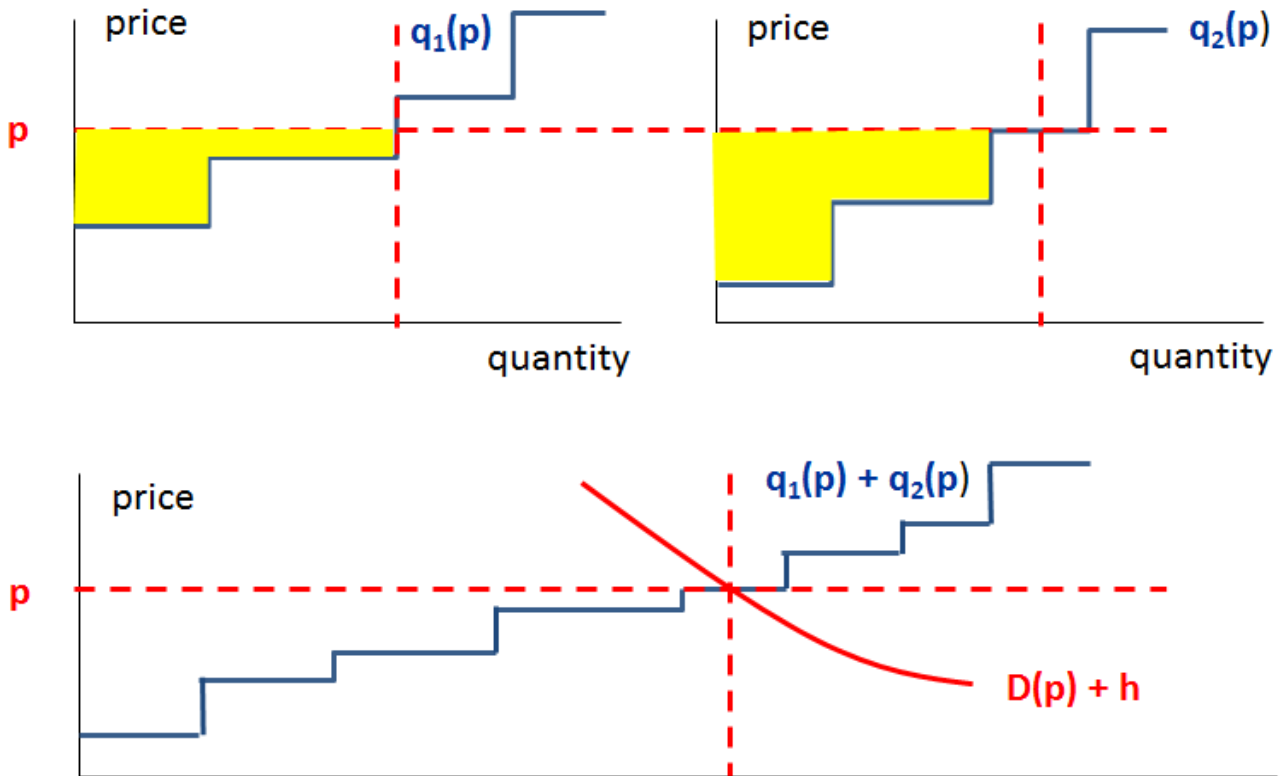
Economic dispatch in energy markets



- One spot market for energy, the real-time "balancing market" conducted continuously by the system operator as an integral part of its management of transmission
- Independent System Operator (ISO) determines who generates what
- Current prices (called locational marginal prices - LMP) are calculated at five-minute intervals based on actual grid operating conditions.

- The dispatch problem form depends on the particular market design.
- If every participant optimizes their profit, then what will happen?
- This gives rise to a non-cooperative game
- FERC (regulator) writes the rules - how to implement?

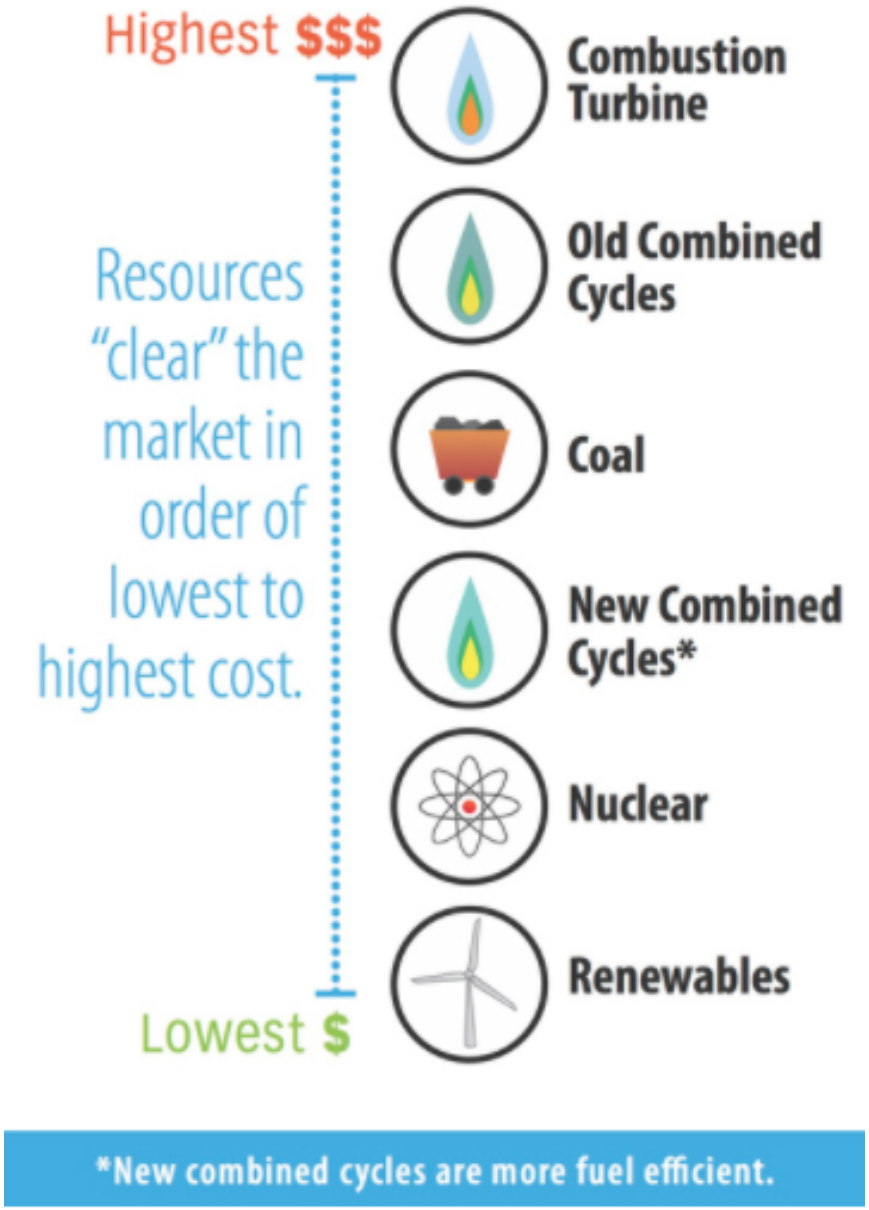
Offer curves



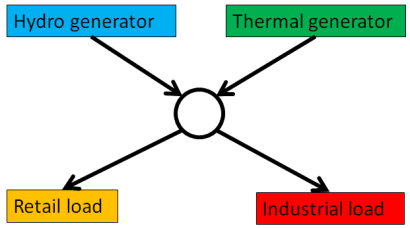
- Market design and rules aim to ensure that offer curve reflects true participant costs
- e.g. paid at clearing price, not at offer price

Merit order: Clearing the wholesale market

Image source: learn.pjm.com



Components of Economic Dispatch



- Real-time spot market for physical dispatch and balancing settlements.
  - No one owns power per se; rather, qualified market participants obtain privileges to inject or withdraw power from the network at specific locations.
  - Privileges bring obligations to comply with technical rules and procedures for settling accounts based on metered injections and withdrawals.
  - Continuous convex economic dispatch
    - System marginal costs provide locational, market-clearing, linear prices.
    - Locational prices to underly financial transmission rights (FTRs).
  - The transmission grid is highly complex and vulnerable to instability, cascading failures, or collapse at great cost.
  - End result: scope of the operator's authority extends over a longer period before real-time to cope with the many implicit coordination tasks and unpriced scarce resources affecting performance.

Day-ahead dispatch and scheduling

- System operator manages forward (day-ahead) markets
- Financially binding, settled 10 hours before start of delivery day
- Demand forecasting
- Bid-based, security constrained, economic dispatch.

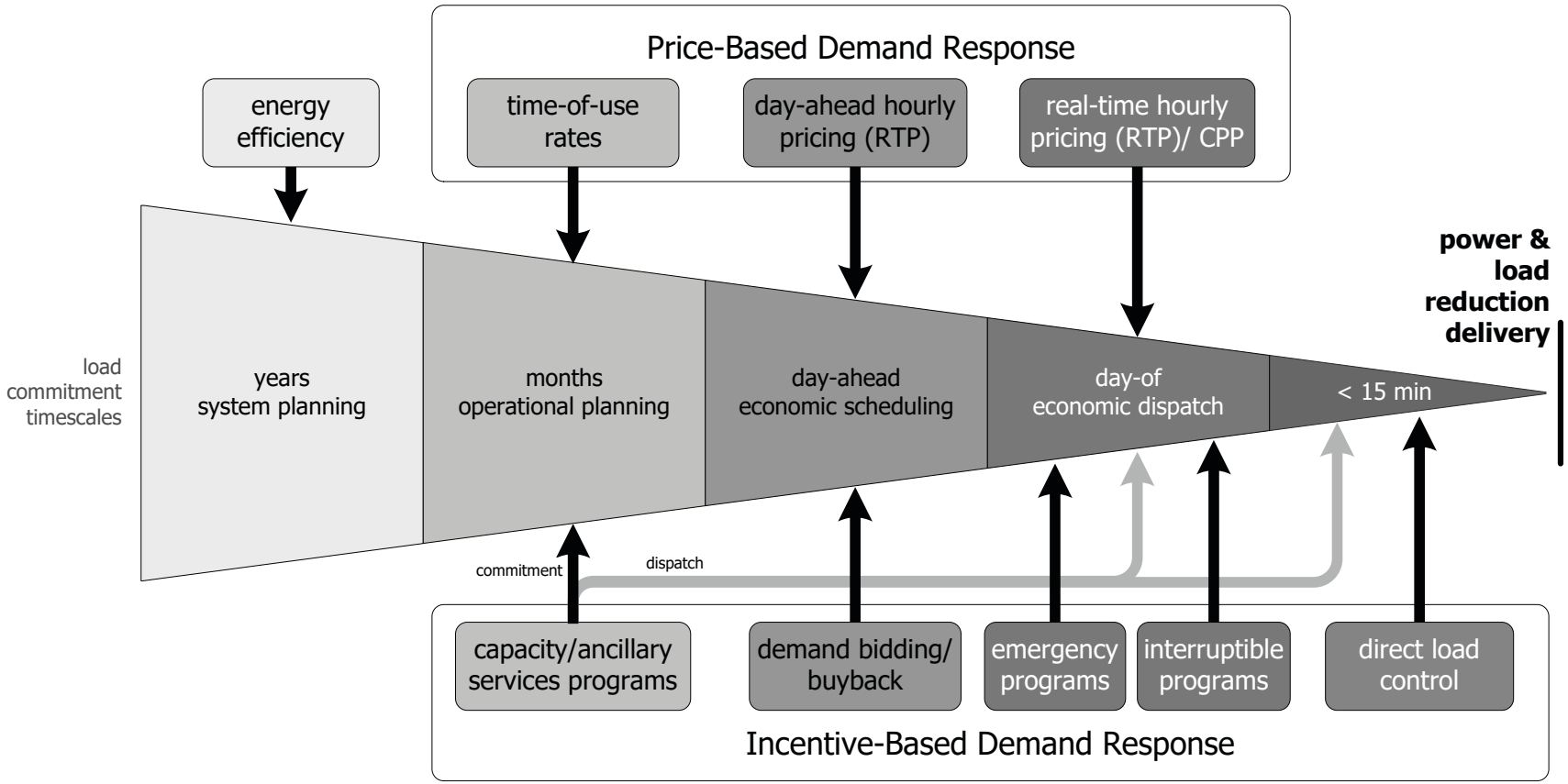
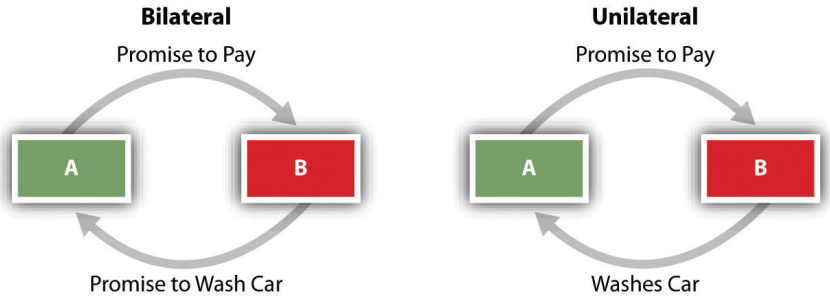


Image source: FERC



Bilateral contracts

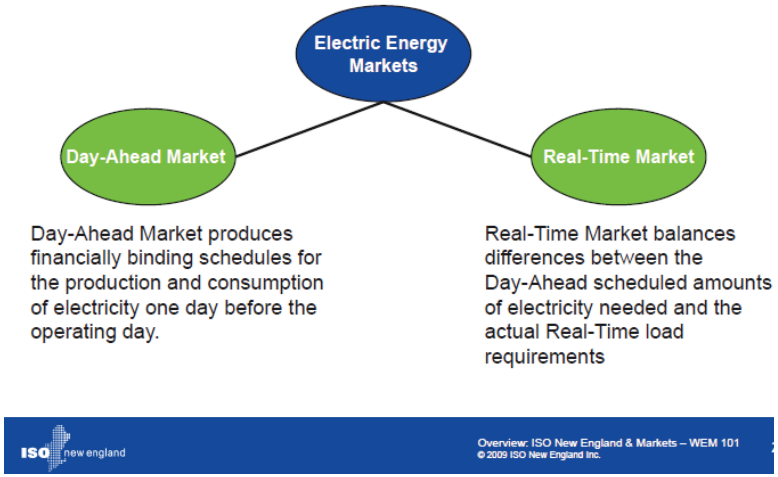
- Bilateral or over-the-counter (OTC) transactions not done within RTO/ISO
- State regulation of vertically integrated monopoly utilities (non-RTO)
- Wholesale sales are conducted bilaterally, through direct contact and negotiation
- Bilateral-only areas have comparatively low liquidity, in part because trading requires greater negotiation.
- MISO, CAISO and SPP consist primarily of monopoly-utility service territories (grid control by RTO/ISO)
- Utilities or independent power producers, also known as merchants, can engage in bilateral trades outside or within RTO/ISOs.
- RTO/ISOs use standardized electricity products in short-term (energy and ancillary service) markets
- May interact with financial transmission rights (FTR's)

Image source: Lumen Learning

Day-ahead markets

- Forward (day-ahead) optimization of all generation (net of bilateral trades), transmission, and reserves.
- The optimization includes intertemporal factors such as startup commitments and constraints on generators' ramping rates and reservoirs' potential energy (possible make-whole payments)
- The resulting schedules are indicative plans, since they are re-optimized on a shorter time frame (hour-ahead) and again in real-time operations.
- Pricing and settlements are based on system-wide opportunity costs as measured by shadow prices on system constraints, such as the necessary equality of energy supply and demand in real time, and limits on transmission capacity.
- Forward markets, both medium term and long term, complement the spot market for wholesale electricity.

Cleaning up



Source: ISO-NE

- Real-time: the actual 5-minute dispatch of the power system. Almost the same optimization problem as day-ahead but generally without as many integer variables and a shorter horizon
- Day-ahead markets help address incompleteness, illiquidity, security: they reduce risk, mitigate market power, and coordinate new investment.
- Two-settlement system: The deviation between your real-time output/consumption and your day-ahead schedule is priced at the real-time price. This is key to getting everything to work.
- Virtuals: are used by market participants to hedge physical positions and by traders to profit from differences between day-ahead and real-time prices - sometimes termed convergence bidding.

Resource adequacy

- Ensuring adequate resources are available to serve the electricity needs
- Consumed essentially at same time as generated
- Important to maintain system frequency
- Market enhancements for demand response, storage, scarcity/reliability pricing
- Capacity requirement, local resource zones
- 2025–2026: Multiple RTOs warned of tightening reserve margins driven by thermal retirements, rapid load growth (data centers, AI), and new resources stuck in interconnection queues
- Projected 30–80+ GW of new data center load over next decade raises adequacy alarms across PJM, ERCOT, MISO

Energy-only or capacity markets

- Energy-only market only compensates energy that has been consumed
- Capacity market compensates the mere readiness, or capacity, for power production
- Critics of the energy-only market view the sufficient provision of secured capacity as problematic: It is difficult to find investors for peak-load installations that only run for a few hours a year; these few hours are also the only times when peak-load prices are realized

Image source: policyschool.ca

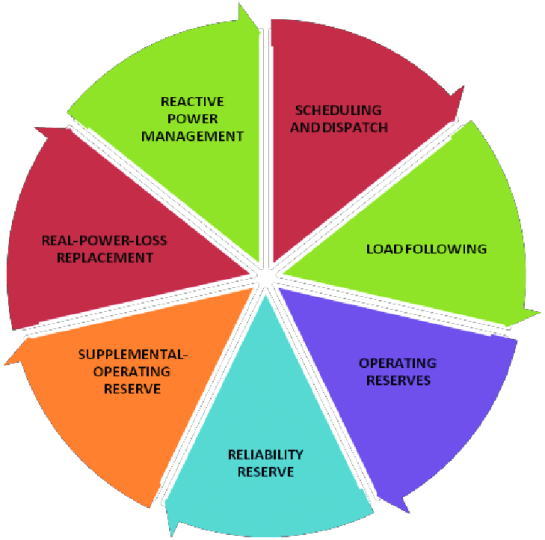
Capacity markets and auctions

- Purpose: long-term security of supply.
- Payment for commitment to increase supply or reduce demand by the amount they offered at some time (years) in the future.
- Single clearing price, determined by auctions
- In addition to payments for energy and ancillary services
- Capacity market participants offer power supply resources into the market that provide supply or reduce demand.
- These resources include new and existing generators, upgrades for existing generators, demand response (consumers reducing electricity use in exchange for payment), energy efficiency and transmission upgrades.

2025 update: PJM's 2025/2026 capacity auction cleared at ~$269/MW-day ($\sim$10$\times$ prior auction) driven by tighter margins, retirements, and revised Effective Load-Carrying Capability (ELCC) accreditation for renewables.

Ancillary services markets

- Two types: Regulation and reserves



- Reserves help to recover system balance by making up for deficiencies if there is unexpected loss (of a large generator of other piece of equipment)

- Regulation is used to control small mismatches between load and generation
  - Maintaining a system frequency of 60 Hertz
  - Tracking moment-to-moment fluctuations in customer electricity use
  - Correcting for unintended fluctuations in generation (such as a large generating unit disconnecting from the system)
  - Managing differences between forecasted or scheduled power flow and actual power flow on the system
  - Participants: steam, combustion turbine, hydro, storage, demand response, distributed energy resources (DER)

Reserves

- Generation reserves are the electricity supplies that are not currently being used but can be quickly available in the case of an unexpected loss of generation.
- Different time scales and features: operating (unexpected mismatch), primary, synchronized (spinning), quick start, supplemental
- Markets treat and value these differently
- Often co-optimized with dispatched energy (uses scenarios or security constraints in stochastic dispatch)

Image source: dreamstime.com

Transmission rights markets

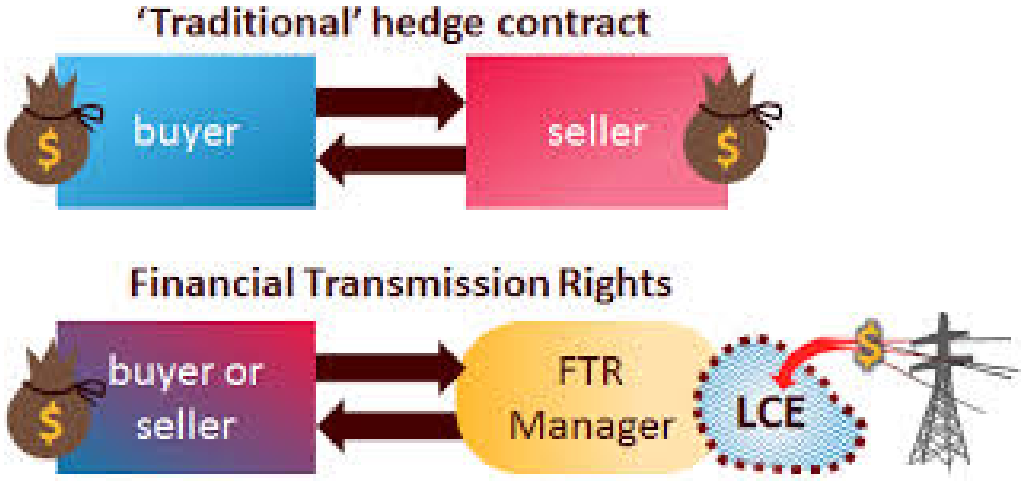


Image source: ea.nz.gov

- Financial transmission rights (FTR) are a hedge product designed to help parties manage the risk they face from large, unpredictable differences in wholesale electricity prices
- Congestion management instrument
- Financial transmission rights and auction revenue rights: FTRs are purchased in monthly, seasonal, or annual auctions administered by the ISOs and settled in the day-ahead market.
- Auction revenue rights (ARR) are awarded to owners of the transmission system (or LSE) and are settled in the FTR auctions.

Financial Markets

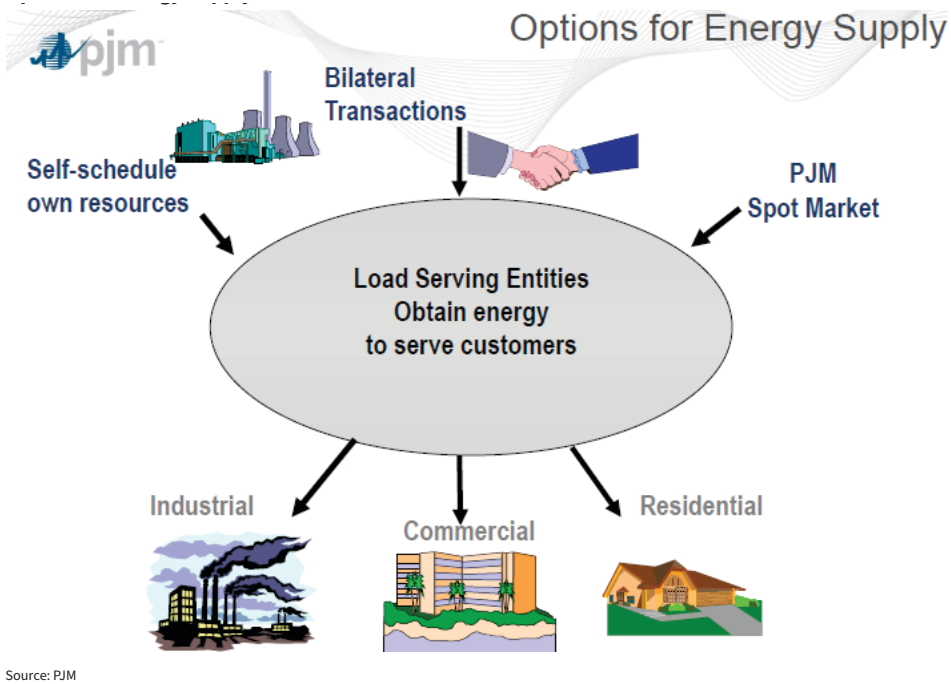
- ISO administered markets include both physical and financial products.
- Technically, the ISO administered day-ahead market is a forward market, but more commonly "Forward Electricity Markets" refer to exchange traded products such as those traded on the Intercontinental Exchange (ICE) and the New York Mercantile Exchange (NYMEX).
- Financial markets (e.g. ICE and NYMEX) deal in derivatives, help traders to manage price risk and volatility.
- Derivatives are financial instruments that derive their value from an underlying fundamental
- Key point: the prices from the ISO administered markets are used to settle many derivative products.
- Participation and volume of these forward (financial) markets dwarfs the participation and volume of the ISO markets.
- Types of contract: Forward contract, Futures contract, Swap contract, Options contract (call or put)

What do the ISO/RTOs do?

- CAISO: ISO with competitive wholesale markets - energy (day-ahead and real-time), ancillary services, congestion revenue rights, energy imbalance, manages grid reliability
- MISO: RTO operates transmission system, Financial Transmission Rights (FTR), day-ahead and real-time markets, and a co-optimized ancillary services market, capacity auction. Tight capacity in North/Central; seasonal auction reforms
- ISO-NE: RTO has wholesale power markets in electricity, capacity, transmission congestion contracts and administers capacity auctions
- NYISO: ISO very similar to ISO-NE
- PJM: RTO operates a competitive wholesale electricity market (day-ahead and real-time energy, capacity and ancillary services) and manages the transmission grid reliability. Capacity market reform: marginal ELCC accreditation
- SPP: RTO manages grid and has energy markets (day-ahead and real-time), an operating reserve market, and a transmission congestion rights market. Joint transmission planning with MISO
- ERCOT: ISO manages reliability; transitioning from pure energy-only to Performance Credit Mechanism (PCM), a reliability-oriented capacity-like overlay (PUCT approved 2023–2025)
- AESO and IESO in Canada

Conclusions: Interplay of physical and financial markets

- Extensions to make things work - issues remain, e.g. distributed supply, storage, environment



Source: PJM

- New pressures: rapid load growth from data centers/AI, interconnection queue reform (FERC Orders 1920, 2023), capacity market redesigns (PJM, ERCOT PCM), and tightening reserve margins across RTOs
- Are electricity spot markets in their current form sustainable in a future of renewable, volatile generation that has low or zero operational marginal cost and high fixed costs?

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Self-scheduling (SS)

- Self-scheduling a resource is when a lead market participant commits, or schedules, a resource to provide energy in an hour, whether or not the ISO would have scheduled or dispatched the resource to provide the service.
- May exercise market power by withholding
- Can reduce variance in generator profits (tradeoff against expected profit)
- Can do demand response (in PJM) by SS load reductions (just change demand)
- Can deviate from day-ahead cleared schedule by SS (in MISO) unless presents a reliability concern.
- Costs (inefficiencies) accrue to consumers and ISO

DER integration into wholesale markets

- Distributed Energy Resource (DER)
- DERs can provide a new source of operational flexibility and competition, reducing energy and ancillary services market costs, resource adequacy capacity requirements, and transmission charges for load-serving entities
- Implement market design changes to enable market-based approaches to load participation during the operating day
- Use of aggregators (contracts with DER and consumer demand response to provide a large virtual power plant)