Overview of Electricity Markets

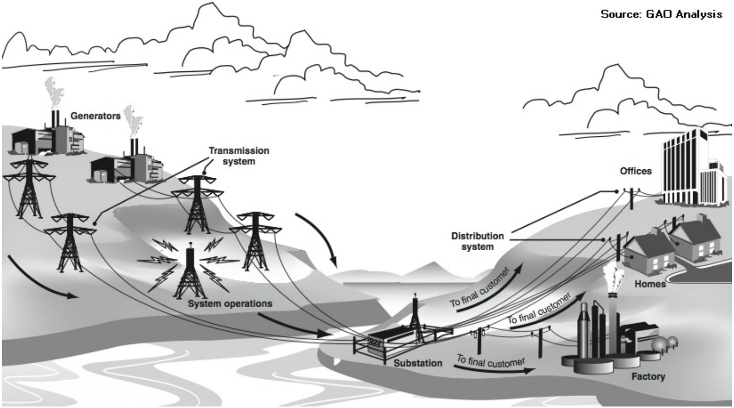
Michael C. Ferris

Jacques-Louis Lions Chair, and Stephen Kleene Professor of Computer Science
Computer Sciences Department and
Wisconsin Institute for Discovery, University of Wisconsin, Madison

Joint work with Andy Philpott, University of Auckland

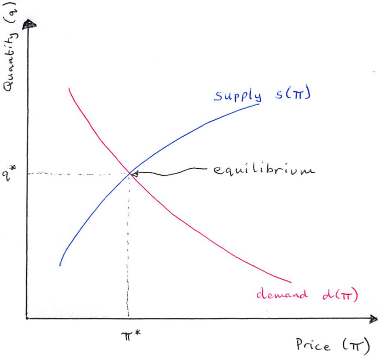
Wisconsin Public Utilites Institute
Regional Transmission Organization Fundamentals 2020:
Background, Purpose, Future
May 6, 2020

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.

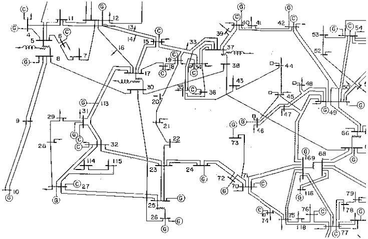
Single market, single good: equilibrium



Walras: $0 \leq s(\pi) - d(\pi) \perp \pi \geq 0$

Supply arises often from a generator offer curve (lumpy)

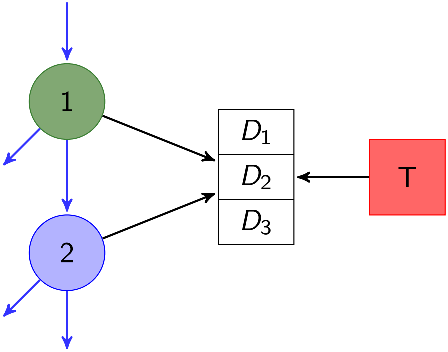
- Technologies and physics affect production and distribution



- Spatial extension: Locational Marginal Prices (LMP) at nodes (buses) in the network
- Market design and rules to foster competitive behavior/efficiency

Vertical integration vs competition: XMGD

- Two hydros on same river: '1' is above '2': spill or release with generation
- Thermal generator 'T' and consumer



- Competing firms (collections of consumers, or generators in energy market)
- Each firm minimizes objective independently
- Label consumer as 'D' (but can be partitioned into 'D_1','D_2','D_3')
- Vertical integration (joint ownership of entities represented by colors: X, M, G, D) can hedge against random effects

The motivation for deregulation/liberalization

- This process is usually viewed as replacing tight regulation of vertically integrated monopolies with light regulation of functionally specialized firms and supervision of competitive markets
- Standard concerns of economic policy such as productive and allocative efficiency and mitigation of market power
- Concern for closing loopholes in procedural rules and avoiding "screwups"

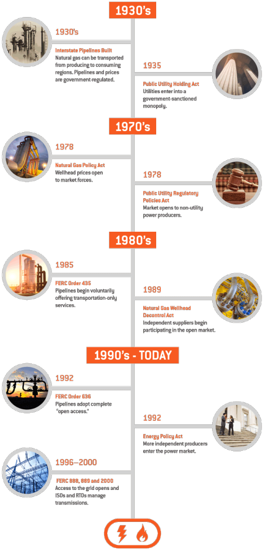


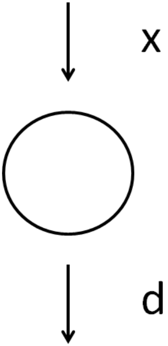
Image source: Direct Energy Business

FERC: wholesale electricity markets (courtesy FERC)

- Northwest, Southeast and Southwest: vertically integrated utilities (including some bilateral trades)
- 2/3 of US electric load served in RTO regions

- 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

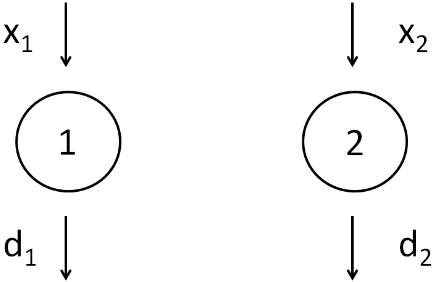
Economic Dispatch in a single location



Cost of dispatch is $C(x) = x^2$. The demand at price p is $d(p) = 2 - \frac{1}{2}p$.

The optimal dispatch is when electricity price satisfies $p = 2x$ and markets clear so $2 - \frac{1}{2}p = x$. So $p = 2$ and $x = 1$.

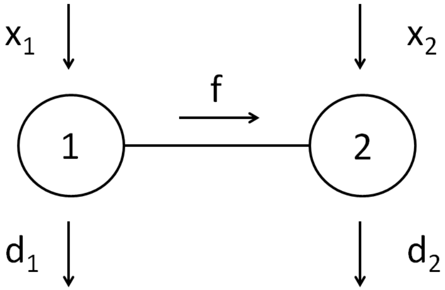
Economic Dispatch with two locations, inelastic demand



$$C_1(x_1) = x_1^2,\ C_2(x_2) = 2x_2^2,\ d_1(p_1) = 1,\ d_2(p_2) = 4.$$

In node 1 we obtain $x_1 = 1$, $p_1 = 2$. In node 2 we obtain $x_2 = 4$, $p_2 = 16$. Total cost of supply is 33.

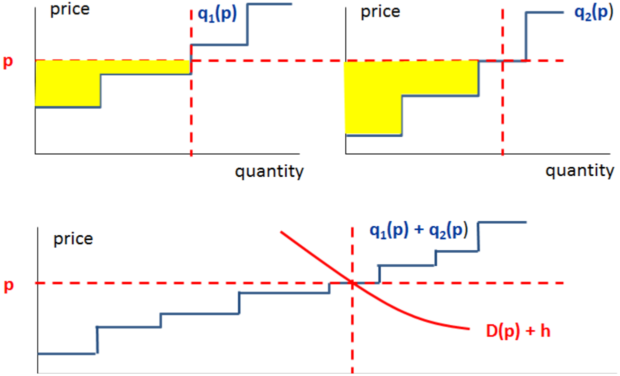
Economic Dispatch with a transmission line



$C_1(x_1) = x_1^2$, $C_2(x_2) = 2x_2^2$, $d_1(p_1) = 1$, $d_2(p_2) = 4$, transmission line capacity equals 1.

In a market for transmission, the transmission owner chooses f to maximize their surplus by charging a price ρ for each MWh transported that is at least the difference in price $p_2 - p_1$.

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

Economic dispatch and equilibrium in energy markets

- There can be only 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
- Current prices (called locational marginal prices) are calculated at five-minute intervals based on actual grid operating conditions.
- In existing markets, the economic dispatch problem is deterministic.
- 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 for which we seek a Nash equilibrium: A set of actions, one for each agent that is optimal for them given the actions of other agents.
- Equilibrium provides prediction of market outcomes ex-ante.

John Nash: Equilibrium - a beautiful mind

The problem we have just studied is an example of a non cooperative game. Generator 1 and its competitors are called players or agents in such a game. There are many solution concepts for such games, the most well known being a Nash equilibrium (due to John Nash, 1951):

Each player in the game solves an optimization problem to maximize their individual profit. A key idea underlying the Nash equilibrium is that of a self-enforcing agreement. Suppose generator 1 and its competitor agree to produce (x_1^*, x_2^*). Then neither has any incentive to unilaterally alter their strategy from these choices.

We solve the optimality conditions for each player as simultaneous equations. The result of the equilibrium is generally NOT the same as the optimal solution the maximizes total welfare.

Welfare theorems of partial equilibrium

Perfect competition:

- Generators do not anticipate the effect of their action on market price.
- The optimal supply function $q(p)$ is then the marginal cost of generation.
- First welfare theorem: Any perfectly competitive equilibrium maximizes welfare.
- Second welfare theorem: An optimal solution that maximizes welfare gives prices that support a competistive equilibrium.
- Revenues cover each partys costs
- How much of a second-best solution will an equilibrium give compared with the best solution?
- Depends on which of five assumptions hold.

Image source: spreadshirt.com

Five key assumptions for welfare theorems

- convexity
  - decentralized decision making needs decomposition.
- information
  - all agents must have the same information.
- completeness
  - there must be enough traded instruments.
- liquidity
  - low participation in trading can lead to inefficiency.
- competition
  - agents need to behave as price takers.

Image source: Photospin.com

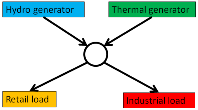
What is the takeaway message?

- Economic dispatch problem is a surrogate for market transactions assuming competitive prices for services that might not be easily provided in real time by auction mechanisms (e.g. transmission).
- Wholesale markets for electricity are inherently incomplete and imperfectly competitive.
- Some incompleteness is inevitable because power is a flow (or field) of energy that cannot be monitored perfectly, and storing potential energy is expensive.
- The surrogate works because of the welfare theorems of economics but we need assumptions to make these match.
- In the example, a price for transmission was needed to make the market efficient.

Image source: channelfutures.com

And a host of other issues...

- No one owns power per se; rather, qualified market participants obtain privileges to inject or withdraw power from the network at specific locations.
- These privileges bring obligations to comply with technical rules and procedures for settling accounts based on metered injections and withdrawals.
- The transmission grid is highly complex and vulnerable to instability, cascading failures, or collapse at great cost.
- The end result in many systems is that the scope of the operators authority extends over a longer period before real-time to cope with the many implicit coordination tasks and unpriced scarce resources affecting performance.
- An important design issue is thus the scope of the system operators authority to manage forward markets



Components of Economic Dispatch

- Deterministic
  - Real-time spot market for physical dispatch and balancing settlements.
  - Day-ahead dispatch and scheduling.
- Security conditions
  - Contingency constraints.
  - Operating reserves.
- Competitive assumption for market design
  - Price-taking behavior by market participants.
  - Bid-based, security constrained, economic dispatch.
  - Market power mitigation (with consistent offer caps).
- Continuous convex economic dispatch
  - System marginal costs provide locational, market-clearing, linear prices.
  - Locational prices to underly financial transmission rights (FTRs).

Forward 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.
- 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.
- The forward markets address incompleteness, illiquidity, security: they reduce risk, mitigate market power, and coordinate new investment.

Energy-only or capacity markets

- Energy-only market only compensates power that has been produced
- 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

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, centrally dispatched market and ancillary services market
- 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
- SPP: RTO manages grid and has energy markets (day-ahead and real-time), an operating reserve market, and a transmission congestion rights market
- ERCOT: ISO manges reliability and uses an energy-only market with real-time, day-ahead, and ancillary service markets
- AESO and IESO in Canada

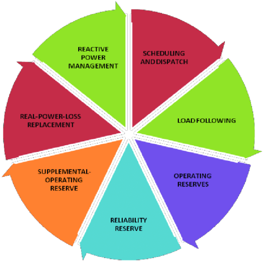
Takeaway questions

- Question 1: what about nonconvexity e.g. integer variables from unit commitment?
- Question 2: what about lack of information (uncertainty)?
- Question 3: what about incompleteness (e.g. lack of instruments to trade risk)?
- Question 4: What about illiquidity (e.g. from vertical integration of generators and retailers)?
- Question 5: What about strategic behaviour (e.g. generators trying to influence prices)?

Image source: channelfutures.com

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

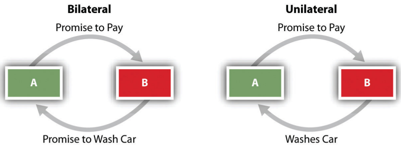
Image source: dreamstime.com

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.

Image source: Windpower monthly

Bilateral contracts



- 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

Transmission rights markets

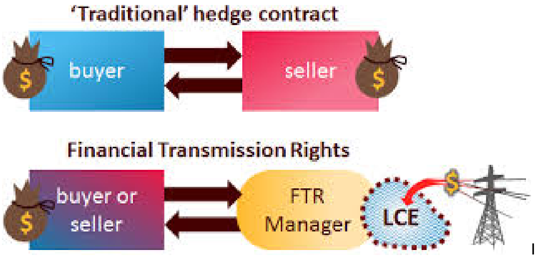


Image source: ea.nz.gov

- Physical: three (connected) electricity grids - Eastern, Western, Texas
- Locational Marginal Prices (LMPs)
- Financial Transmission Rights (FTRs) and Auction Revenue Right (ARRs)/Hedging
- Congestion Management
- Market Participants

Market failures (courtesy Hobbs)

- Market failures need attention
- Externalities (e.g. Kirchoff's laws)
- Nonconvexities (e.g. discrete decisions, natural monopoly)
- Market power (e.g. California 2001)
- Incomplete markets (e.g. Lack of investment, reliability problems, etc)

Four market designs to overcome market failures

- Ramsey pricing to efficiently recover fixed network costs
- Make-whole payments to recover nonconvex costs by generators in spot markets
- Clean Power Plan to fix environmental externalities (CO2 control)
- Capacity markets to fix "missing money" in spot markets

Image source: Investopedia

Conclusions

- Market design: a journey, not a destination
- Interplay between:
  - a need for optimal solutions, supporting prices and market designs for many issues;
  - and use of economic insights and modeling skills