ECEN 460
Power System Operation and Control
Spring 2025

Lecture 13: Security-Constrained OPF (SCOPF), Power Markets

Prof. Tom Overbye

Dept. of Electrical and Computer Engineering

Texas A&M University

overbye@tamu.edu

Security Constrained OPF

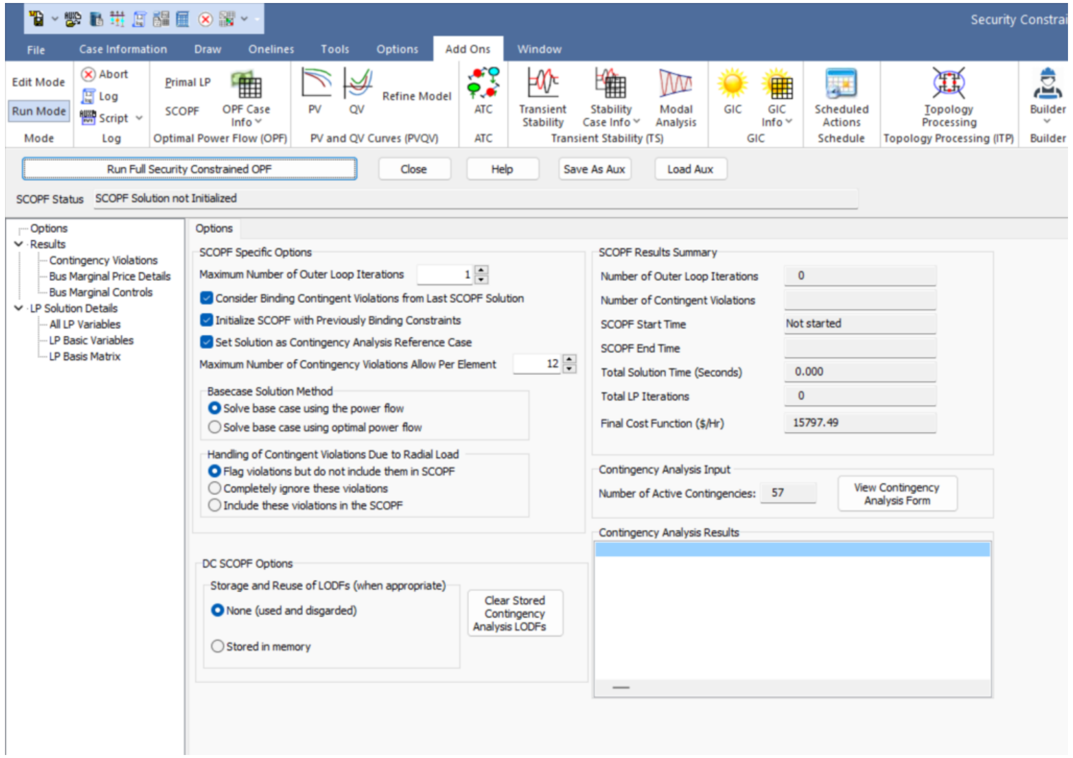
- Security constrained optimal power flow (SCOPF) is similar to OPF except it also includes contingency constraints
  - Again the goal is to minimize some objective function, usually the current system cost, subject to a variety of equality and inequality constraints
  - This adds significantly more computation, but is required to simulate how the system is actually operated (with N-1 reliability)
- A common solution is to alternate between solving a power flow and contingency analysis, and an LP

Security Constrained OPF, cont.

- With the inclusion of contingencies, there needs to be a distinction between what control actions must be done pre-contingent, and which ones can be done post-contingent
  - The advantage of post-contingent control actions is they would only need to be done in the unlikely event the contingency actually occurs
- Pre-contingent control actions are usually done for line overloads, while post-contingent control actions are done for most reactive power control and generator outage re-dispatch

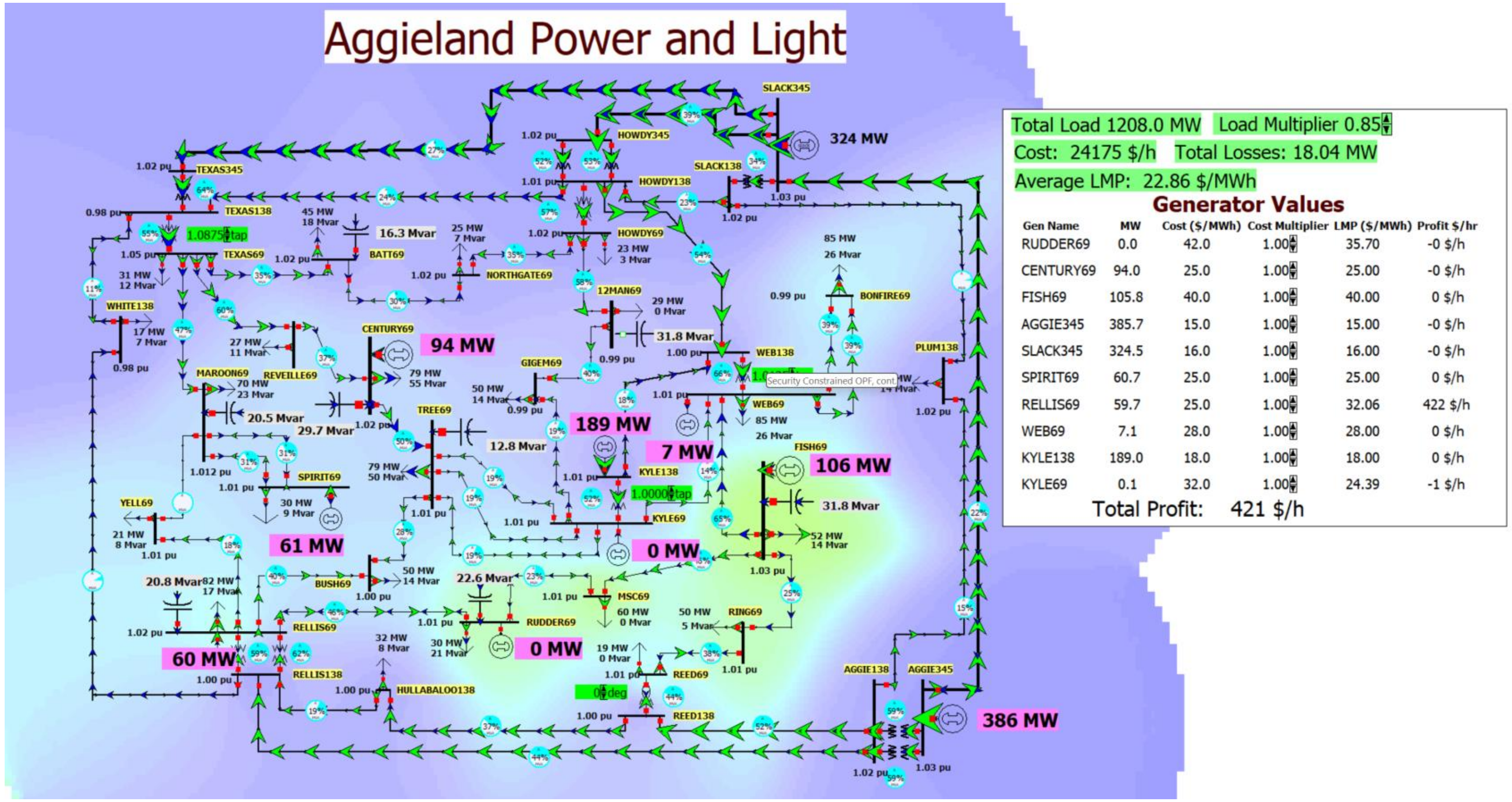
PowerWorld SCOPF Application

- To see the PowerWorld SCOPF application, first open the Lab_AGLSCOPF case; then select **Tools, Contingency Analysis** to verify that some contingencies have been defined; change the load multiplier to 0.85
  - On the **Contingency Analysis** form click **Start Run** to do the contingency analysis; verify there are some violations
- Select **Add Ons, SCOPF** to open the SCOPF
- Click **Run Full Security Constrained OPF**



37 Bus Case SCOPF Results

- Keeping the SCOPF form open, contour the bus LMPs
- What had been a relatively boring OPF solution indicates some major issues
- Looking at the SCOPF form Results, Contingency Violations indicates there are some contingencies with unenforceable constraints



LP OPF and SCOPF Issues

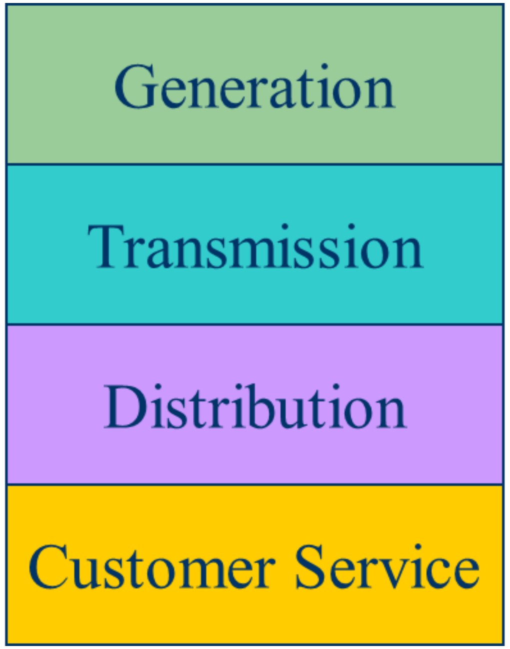
- The LP approach is widely used for the OPF and SCOPF, particularly when implementing a dc power flow approach
- A key issue is determining the number of binding constraints to enforce in the LP tableau
  - Enforcing too many is time-consuming, enforcing too few results in excessive iterations
- The LP approach is limited by the degree of linearity in the power system
  - Real power constraints are fairly linear, reactive power constraints much less so

Additional OPF and SCOPF Solution Methods

- There are several additional approaches for solving the OPF and SCOPF
- It continues to be an area of active research
- More general commercial optimization packages are being applied to the problem, including Gurobi and CPLEX
  - Over the years there has been great progress in this area, including with the solution of mixed-integer programming problems (speedups of up to 1 million times have been reported since 1991 with new algorithms and faster computers)

Electricity Markets History

- For decades electric utilities operated as vertical monopolies, with their rates set by state regulators
- Utilities had an obligation to serve and customers had no choice
  - There was little third party generation
- Major change in US occurred in 1992 with the National Energy Policy Act that mandated utilities provide "nondiscriminatory" access to the high voltage grid
- Goal was to setup true competition in generation



Markets Versus Centralized Planning

- With the vertically integrated utility, a small number of entities (typically utilities) did most of the planning
  - For example, which new generators and/or lines to build
  - Planning was coordinated and governed by regulators
  - Regulators needed to know the utilities actual costs so they could provide them with a fixed rate of return
- With markets the larger number of participants often make individual decisions in reaction to prices
  - For example, whether to build new generation
  - Generator owners in general to not need to reveal their true costs; rather they make offers into the market

Overall Goal

- Goal is to maximize the economic surplus (or total welfare), which is the sum of the consumer surplus and the producer surplus (i.e., their profit)
- Generation owners have to decide their offer prices
- If their price is too high, they are not selected to generate
- At the wholesale level, the consumers often just see a price, though there can be price responsive load bids

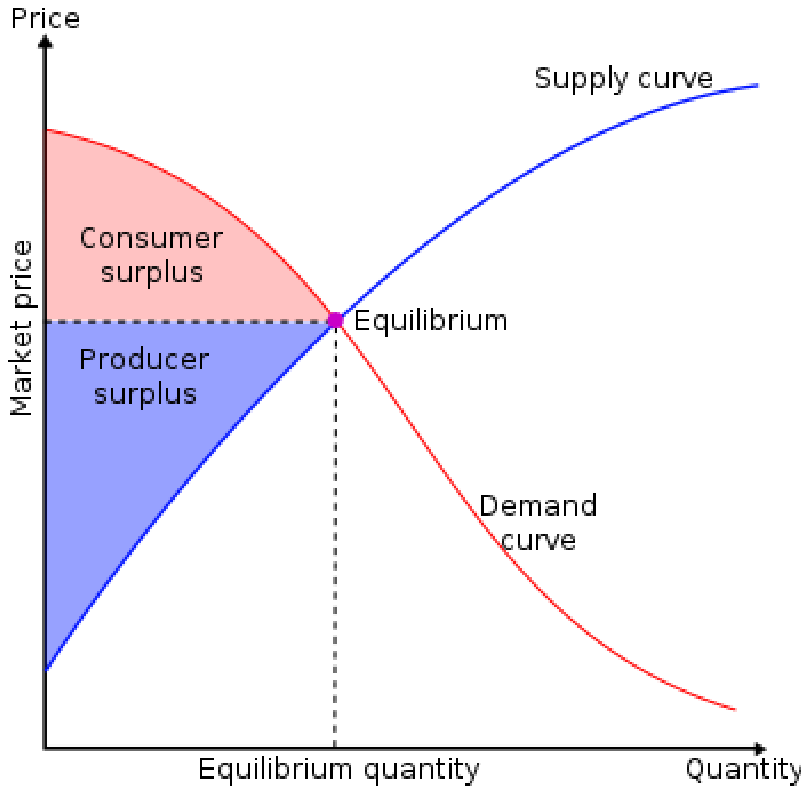


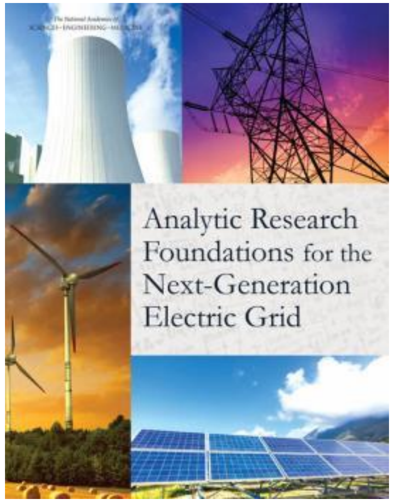
Image Source: en.wikipedia.org/wiki/Economic_surplus#/media/File:Economic-surpluses.svg

Electricity Market History

- Power pools have been used for almost 100 years, in which utilities created agreements to buy and sell electricity with their neighbors
  - PJM (originally Pennsylvania-New Jersey-Maryland) formed in 1927
- The methodology used to determine the price was the production cost; each utility calculated how much it would cost them to produce more power (sell price), or how much they would say if they produced less (buy price); if the sell price for one utility was less than the buy price for another, then they would transact, usually splitting the savings
- In the 1990's there was a goal of creating more flexible electricity markets

Multidisciplinary Research in Power and Economics

- The development of true power markets required collaboration between power engineers and economists with the nice description of how some of this developed within the Power Systems Engineering Research Center (PSERC, with Texas A&M a member) described in Chapter 8 of [1]
  - One of the challenges was agreeing on notation, with the power engineers treating P and Q as power, and the economics as price and quanity



- The Hawaiian International Conference on Science Sciences (HICSS) also played a major role, with one of the participants winning the Nobel Price for Economics in 2002 (Vernon Smith) (he was a TAMU Hagler Fellow in class of 2012-2013)

[1] US National Academies, Analytic *Research Foundations for the Next-Generation Electric Grid*, 2016

Example Vernon Smith Paper from HICSS (1998)

First two pages

Spot Market Mechanism Design and Competitivity Issues in Electric Power

Michael J. Denton
Utilities International, Inc.
mdenton@utilinc.com

Stephen J. Rassenti
Econ Sci Lab, Univ of Arizona
rassenti@econlab.arizona.edu

Vernon L. Smith
Econ Sci Lab, Univ of Arizona
smith@econlab.arizona.edu

ABSTRACT

Continuing previous research on market power issues in electricity markets [2], we report new experiments which compare the sealed bid offer (SBO) market mechanism, studied in [2], with a uniform price double auction mechanism (UPDA) that updates nodal prices and allocations continuously as new bids and offers arrive in real time down to the close when the market is "called" and all standing accepted bids and offers become binding spot contracts. We compare the performance of the SBO and UPDA institutions in terms of their impact on incentives affecting market efficiency (the ability to exhaust the gains from exchange), generator and wholesale buyer profitability, and delivery price. Under each of the two trading institutions we compare markets in which the available generator capacities and their costs are held by three versus six independent companies.

1. Experimental Environment

In all experiments we use a three-node radial network consisting of 4 wholesale buyers at the center demand node, B, 2 (or 4) generators companies at the left supply node, G_1, and 1 (or 2) generators at the right node, G_2. The network diagram is shown in Figure 1 for one experiment/period using SBO. (Reproduced from Figure 3 in [2]). This Figure shows the network layout, the incoming bid (offer) messages, and the realized (Re.) and competitive equilibrium (Eq.) quantity flows and prices.

1.1: Generator Parameters

Most large capacity turbine generators have minimum and maximum loaded capacity constraints, with modestly increasing marginal heat rates (and fuel costs) over the range from minimum to maximum capacity. Average cost varies little on baseload units over this capacity range, most often declining slightly until maximum capacity. Minimum loaded capacity is typically 40-50% of maximum capacity, often more. This is in part because marginal cost is declining up to "minimum" capacity and it is not generally optimal, in terms of minimizing energy cost, for on-line generators to operate where outputs exhibit declining marginal cost. We approximate these characteristics with the cost and capacity parameters for all generators shown in Table 1.

Table 1.
Induced Supply Schedule

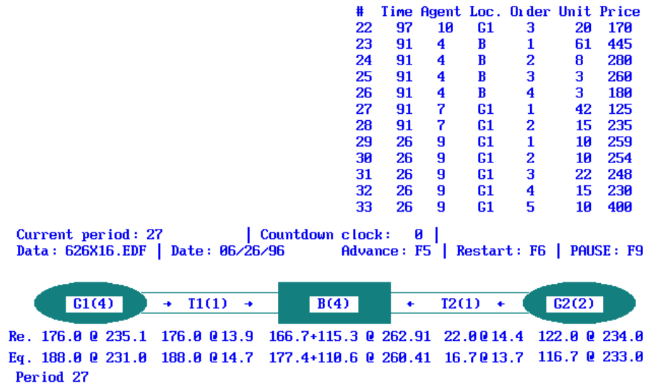
Gen. Number[a]	Sunk Cost (tokens/ period)	Max Output @ Marginal Cost (Mwh@tokens/Mwh)
1-1, 1-2, 1-3, 1-4	25,000	420[b] @ 121 150 @ 231 100 @ 406
2-1, 2-2	25,000	450[b] @ 122 170 @ 233 110 @ 413

a. - Each generator has one owner. In treatments with 3 power suppliers, each generator combination (1-1 and 1-2, 1-3 and 1-4, 2-1 and 2-2) has one owner.
b. - Each generator incurs a "must-run" avoidable cost of 125,000 tokens if output falls below 50% (100%) of this first step

Each power plant facility consists of three generators whose respective marginal costs are constant up to maximum capacity: (i) a low cost baseload unit with a minimum loaded "must-run" (the industry term) capacity of 50% of maximum in one treatment condition , and 100% of maximum capacity in a second treatment; (ii) a medium level marginal cost unit which can operate at any output up to the maximum capacity; and (iii) a high marginal cost unit also operable at any capacity up to maximum. Thus, generator (plant) 2-1, at node G_2 consists of a baseload unit whose maximum capacity is 450MW at a marginal cost of 122 (tokens/Mwh)[1] , a 170 MW maximum output unit with a marginal cost of 233, and a "peaking" unit capable of 110MW at a marginal cost of 413. Each baseload unit also incurs an avoidable fixed penalty cost of 125,000 (tokens) if output falls below 50% (100%) of maximum capacity. This penalty is intended to account for all startup, ramping and suboptimal operational costs whenever the unit is operated below its capacity specifications. The owners of such units are therefore under considerable cost pressure to offer them in the spot market on terms that assure commitment at outputs that are not below the minimum specified. The medium and high cost units are flexible and incur no such avoidable fixed cost whatever might be their commitment levels. Finally, each three-generator unit plant incurs an unavoidable sunk cost of 25,000 tokens per operating period.

[1] We use "tokens" for the experimental currency to avoid expressing value/cost using any particular country's currency. This has facilitated market demonstrations using the trading software with a variety of industry/government officials in New Zealand, Australia, Argentina and Spain.

Figure 1.
...ical SBO Results for a Mid Demand Period: Revealed and Equilibrium Prices and Quantities



1.2: Demand Representation and Parameters

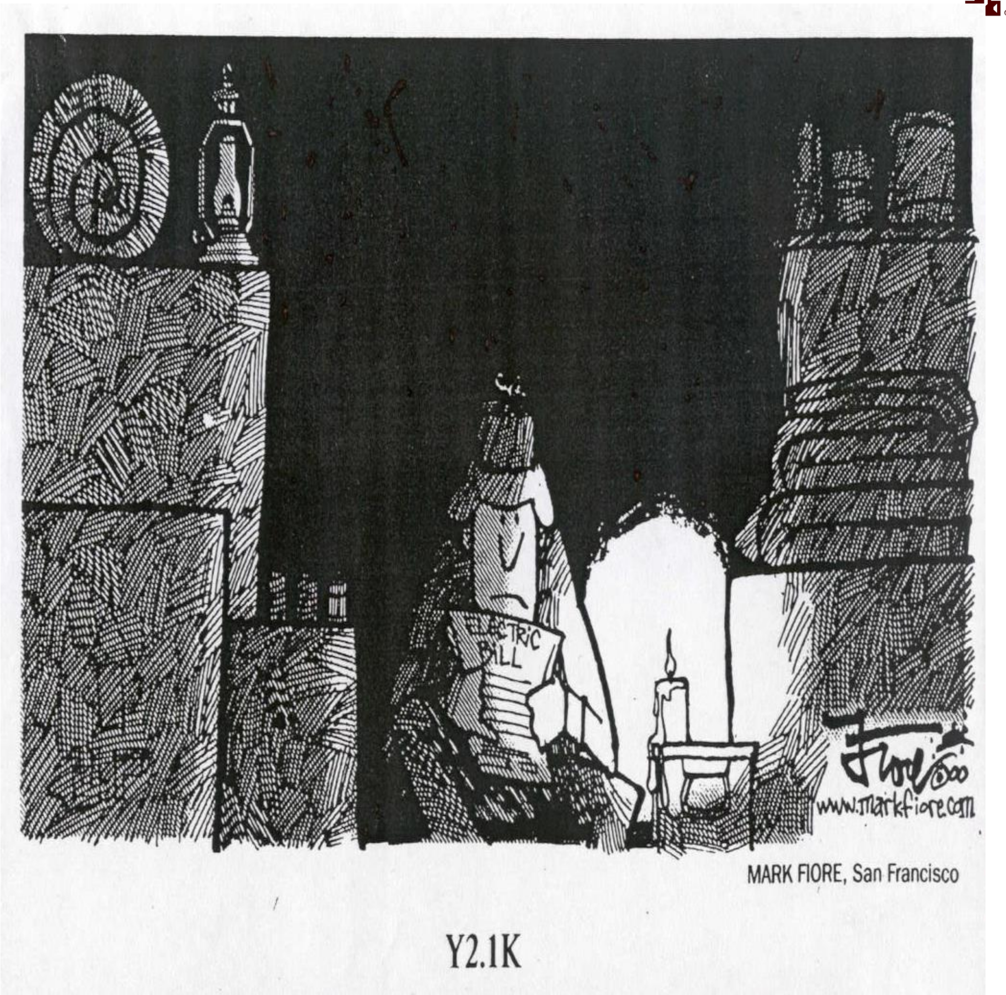
Demand is a 6-phase cycle consisting of two peak levels, then one shoulder mid-level demand, followed by two off-peak demands, and ending with another shoulder demand. These cycles correspond to the typical industry urban peaks in the range from about 10am-6pm, weekdays, off-peak at nighttime from about 10pm-6am, with intermediate levels on the shoulders between troughs and peaks. In the current environment, resale prices are constant and regulated for the "must-serve" portion of demand which cannot be interrupted without political/regulatory penalties if people "lose their lights". This is indicated in Table 2 for 4 identical wholesale buyers with blocks of must-serve demand at 900, 610 and 370 MWh at peak, shoulder and off peak respectively over the daily demand cycle, with resale values fixed at 450 (tokens per MWh) for all buyers. Interruptible demands are 80 and 60 MWh at lower corresponding values. Any wholesale buyer who fails to purchase all of the required must-serve demand incurs an avoidable penalty of 250,000 (tokens).

Table 2.
Induced Demand Schedules (tokens/Mwh)

Buyer	1	2	3	4
Sunk Cost	12,500	12,500	12,500	12,500
Peak				
900 @	450	450	450	450
80 @	435	410	385	360
60 @	185	225	275	320
Mid-Level				
610 @	450	450	450	450
80 @	435	410	385	360
60 @	185	225	275	320
Off Peak				
370 @	450	450	450	450
80 @	435	410	385	360
60 @	185	225	275	320

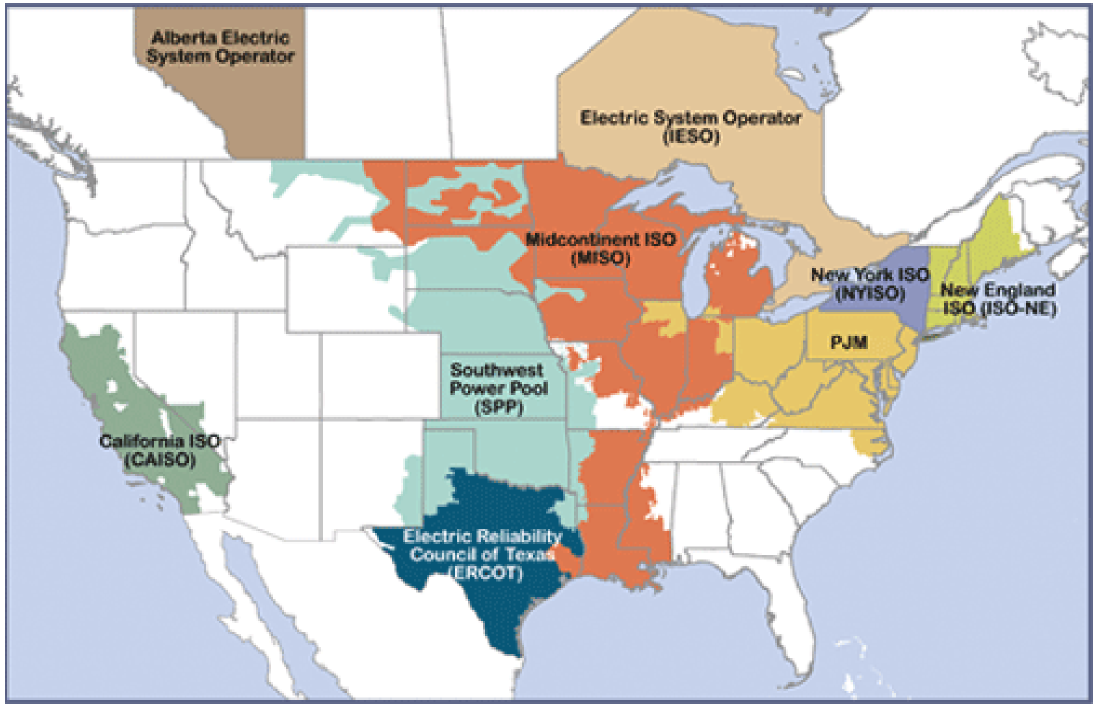
The California Politicians Ran Ahead of the Research, Resulting in Their 2000-2001 Crisis

- In 1996 California decided to create an electricity market even though the risks in doing this were not fully known
- During 2000 their wholesale electricity prices jumped by 800% due in part to market manipulation



Electricity Markets Today in North America

- Starting in about 1995 electricity markets gradually started to develop, both in the US and elsewhere
- In North America more than 60% of the load is supplied via wholesale electricity markets; markets differ but they all have certain common features



  - The terms regional transmission organizations (RTOs) and independent system operators (ISOs) are used (RTOs are more functionality and most are actually RTOs
- Image source: www.ferc.gov/industries-data/electric/power-sales-and-markets/rtos-and-isos

Electricity Markets Common Features

- Day ahead market – this is needed because time is required to make decisions about committing generators
  – Generation owners submit offers for how much generation they can supply and at what price; accepted offers are binding
- Real-time energy market – needed because day ahead forecasts are never perfect, and unexpected events can occur
- Co-optimization with other "ancillary services" such as reserves

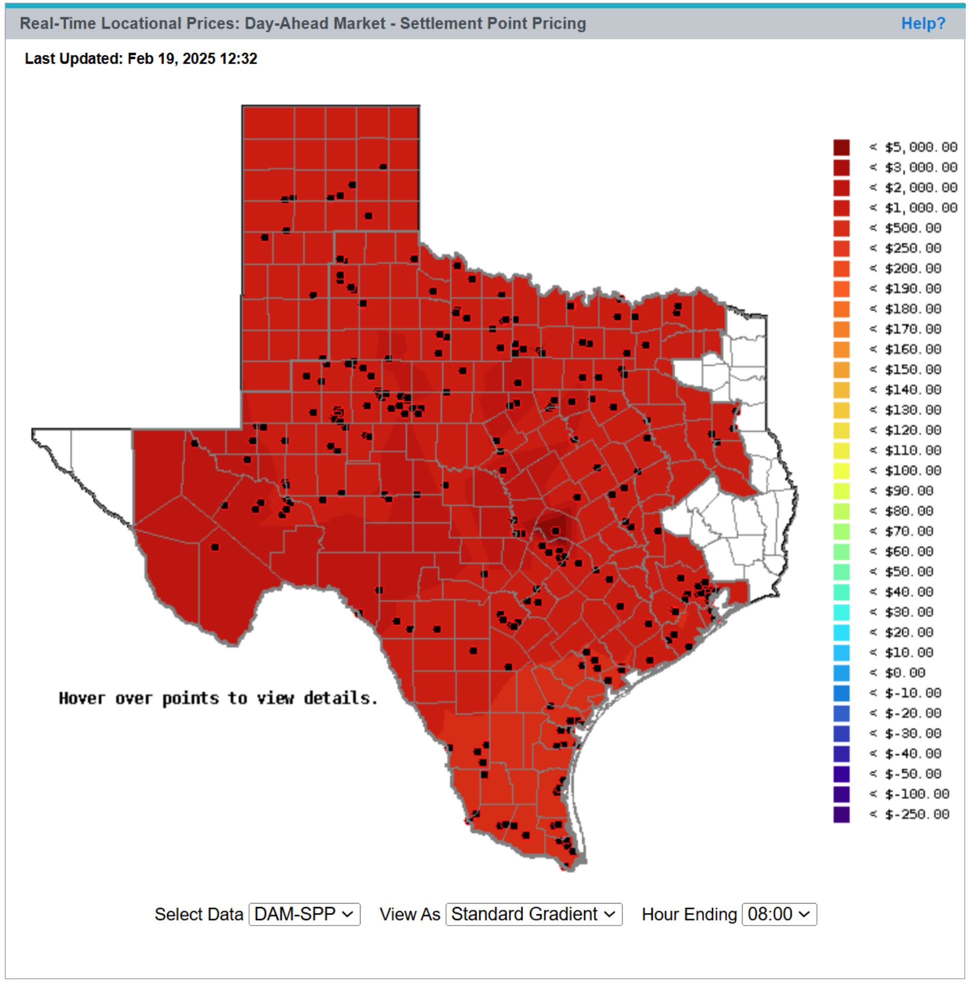
The source for much of this material "Analytic Research Foundations for the Next-Generation Electric Grid" (Chapter 2), The National Academies Press, 2016 (free download available)

Electricity Markets Common Features

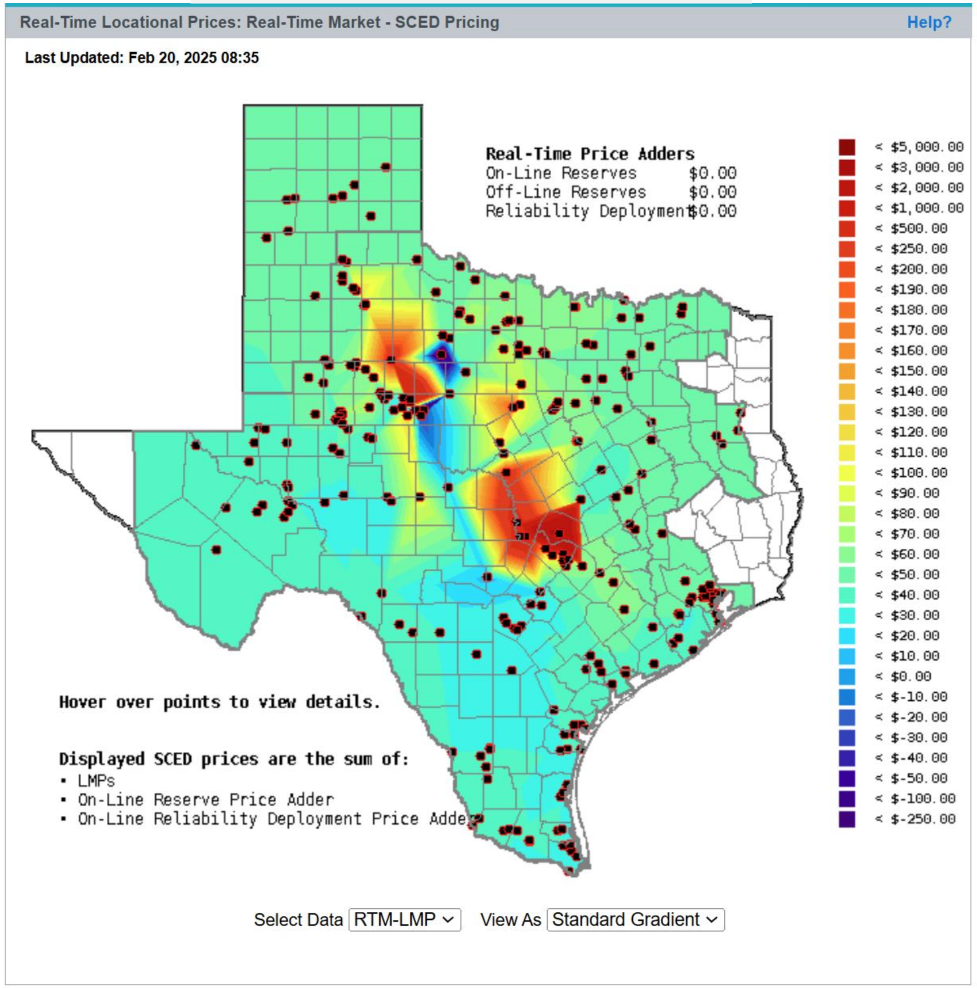
- Pricing is done using locational marginal prices, determined by an SCOPF
  - Most markets include a marginal losses component
- LMP markets are designed to send transparent price signals so people can make short and long-term decisions
  - Generators are free to offer their electricity at whatever price they desire; they do not have to reveal their "true" costs
  - Most of the times markets work as planned (competitive prices)
  - During times of shortages (scarcity) there are limits on LMPs; ERCOT's had been $9000/MWh prior to Uri; now it is $5000/MWh
  - Markets are run by independent system operators (ISOs)

ERCOT Feb 20, 2025 LMPs

Day Ahead Market



Real-Time Market

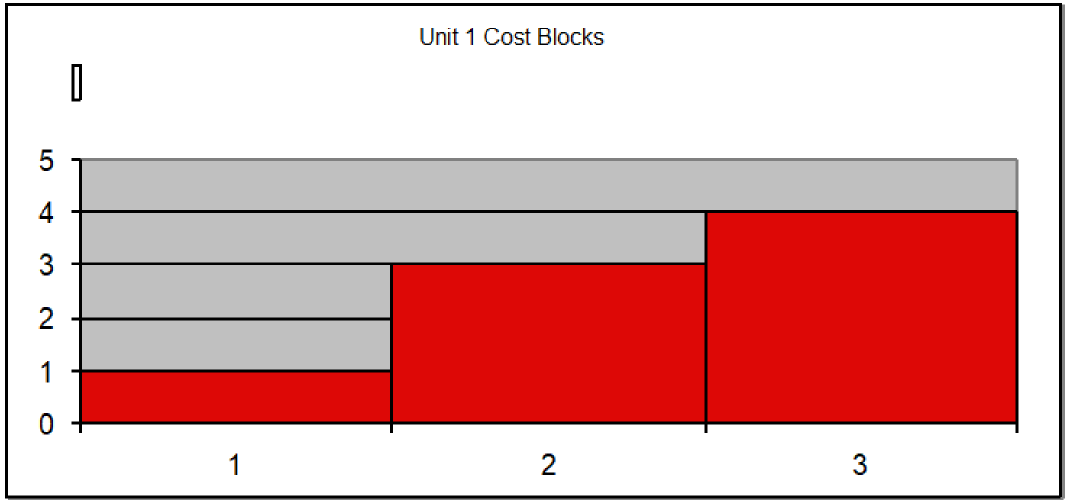


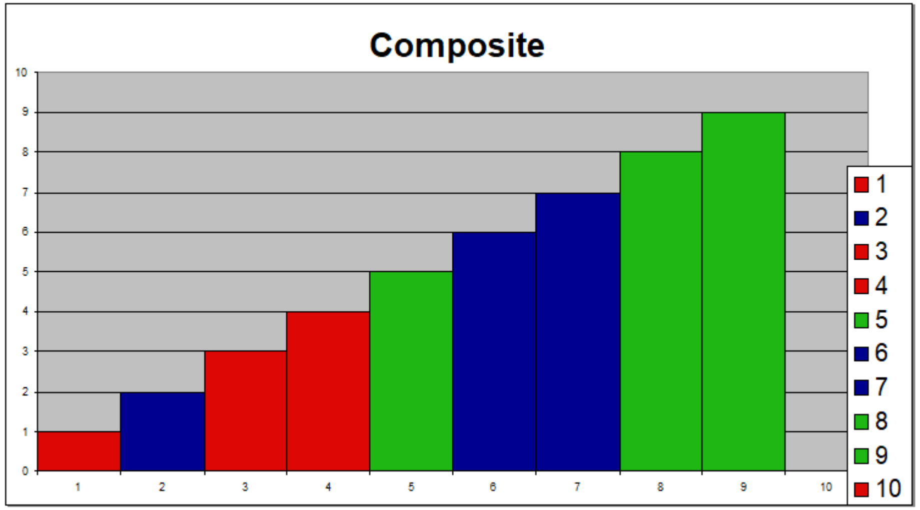
LMP Energy Markets

- In an LMP energy market the generation is paid the LMP at the bus, and the loads pay the LMP at the bus
  - This is done in both the day ahead market and in the real-time market (which makes up the differences between actual and the day ahead)
- The generator surplus (profit) is the difference between the LMP and the actual cost of generation
- Generators that offer too high are not selected to run, and hence make no profit
- A key decision for the generation owners is what values to offer

Generator Offers

- Generator offers are given in piecewise linear curves; that is, a fixed \$/MWh for so much power for a time period
- In the absence of constraints (congestion) the ISO would just select the lowest offers to meet the anticipated load
- Actual dispatch is determined using an SCOPF





General Guidelines

- Generators with high fixed costs and low operating costs (e.g., wind, solar, nuclear) benefit from running many hours
  - Usually they should submit offers close to their marginal costs
  - Wind (and some others) receive a production tax credit (PTC) for their first ten years of operation
    - $23/MWh for systems starting construction before 1/1/2017; $18/MWh 2017, $14/MWh in 2018, $10/MWh in 2019; It was suppose to end in 2019, but was extended in 12/2019 through 2020 at $15MWh; then it got extended through the end of 2021 at $18/MWh
    - On 8/16/22 then President Biden signed the Inflation Reduction Act of 2022 that extended the PTC through at least 2024; then it got broadened to clean energy facilities with details from the IRS issued on Jan 15, 2025; what will happen with the new administration isn't yet known
  - Generators with low fixed costs and high operating cost can do fine operating fewer hours (at higher prices)

Trading Electricity Using Auctions

- In its simplest form, an auction is a mechanism of allocating scarce goods based upon competition
  - a seller wishes to obtain as much money as possible, and a buyer wants to pay as little as necessary.
- An auction is usually considered efficient if resources accrue to those who value them most highly
- Auctions can be either one-sided with a single monopolist seller/buyer or a double auction with multiple parties in each category
  - bid to buy, offer to sell
- Most people's experience is with one-side auctions with one seller and multiple buyers

Auctions, cont.

- Electricity markets can be one-sided, with the ISO functioning as a monopolist buyer, while multiple generating companies make offers to sell their generation, or two-sided with load participation
- Auctions provide mechanisms for participants to reveal their true costs while satisfying their desires to buy low and/or sell high.
- Auctions differ on the price participants receive and the information they see along the way

Types of Single-Sided Auctions with Multiple Buyers, One Seller

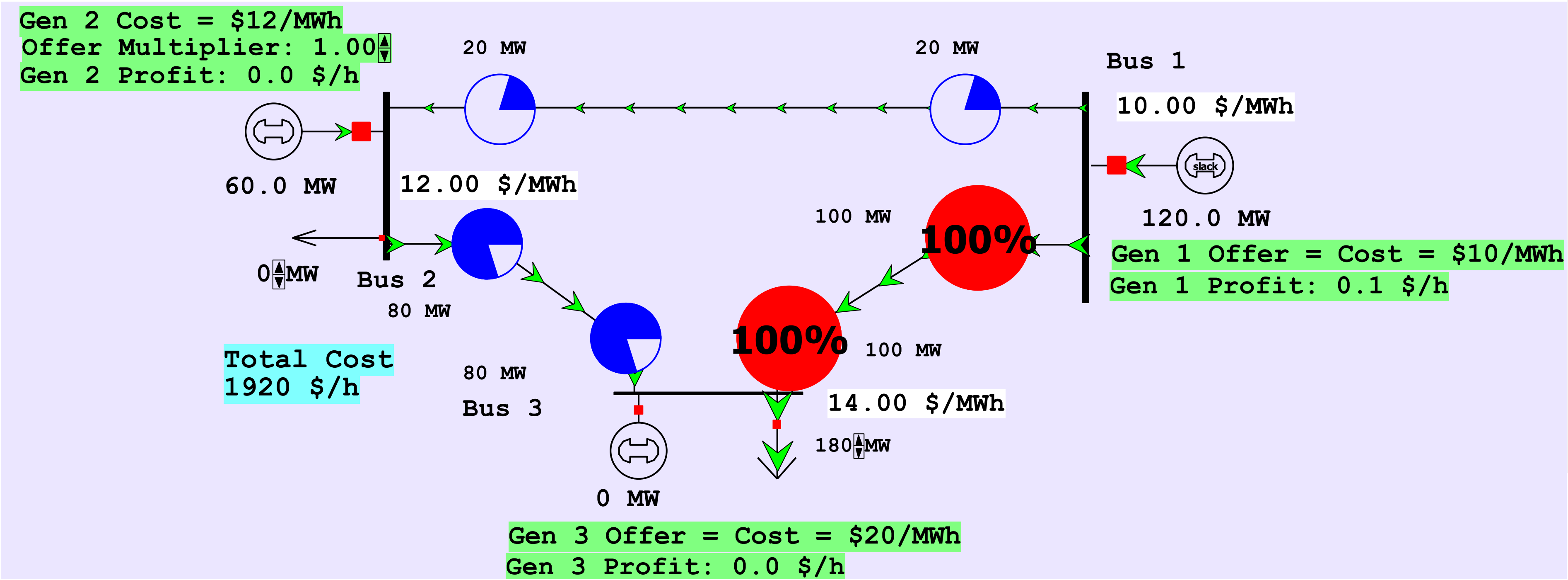
- Simultaneous auctions
  - English (ascending price to buy)
  - Dutch (descending price to buy)
- Sealed-bid auctions (all participants submit offers simultaneously)
  - First price sealed bid (pay highest price if one, discriminatory prices if multiple)
  - Vickrey (uniform second price) (pay the second highest price if one, all pay highest losing price if many); this approach gives people incentive to bid their true value

Uniform Price Auctions: Multiple Sellers, One Buyer

- Uniform price auctions are sealed offer auctions in which sellers make simultaneous decisions (done when submitting offers).
- Generators are paid the last accepted offer
- Provides incentive to offer at marginal cost since higher values cause offers to be rejected
  - reigning price should match marginal cost
- Price caps are needed to prevent prices from rising up to infinity during shortages
- Some generators offering above their marginal costs are needed to cover their fixed costs

What to Offer Example

- Below example shows 3 generator case, in which the bus 2 generator can vary its offer to maximize profit



Note, this example makes the unrealistic assumption that the other generators do not vary their offers in response

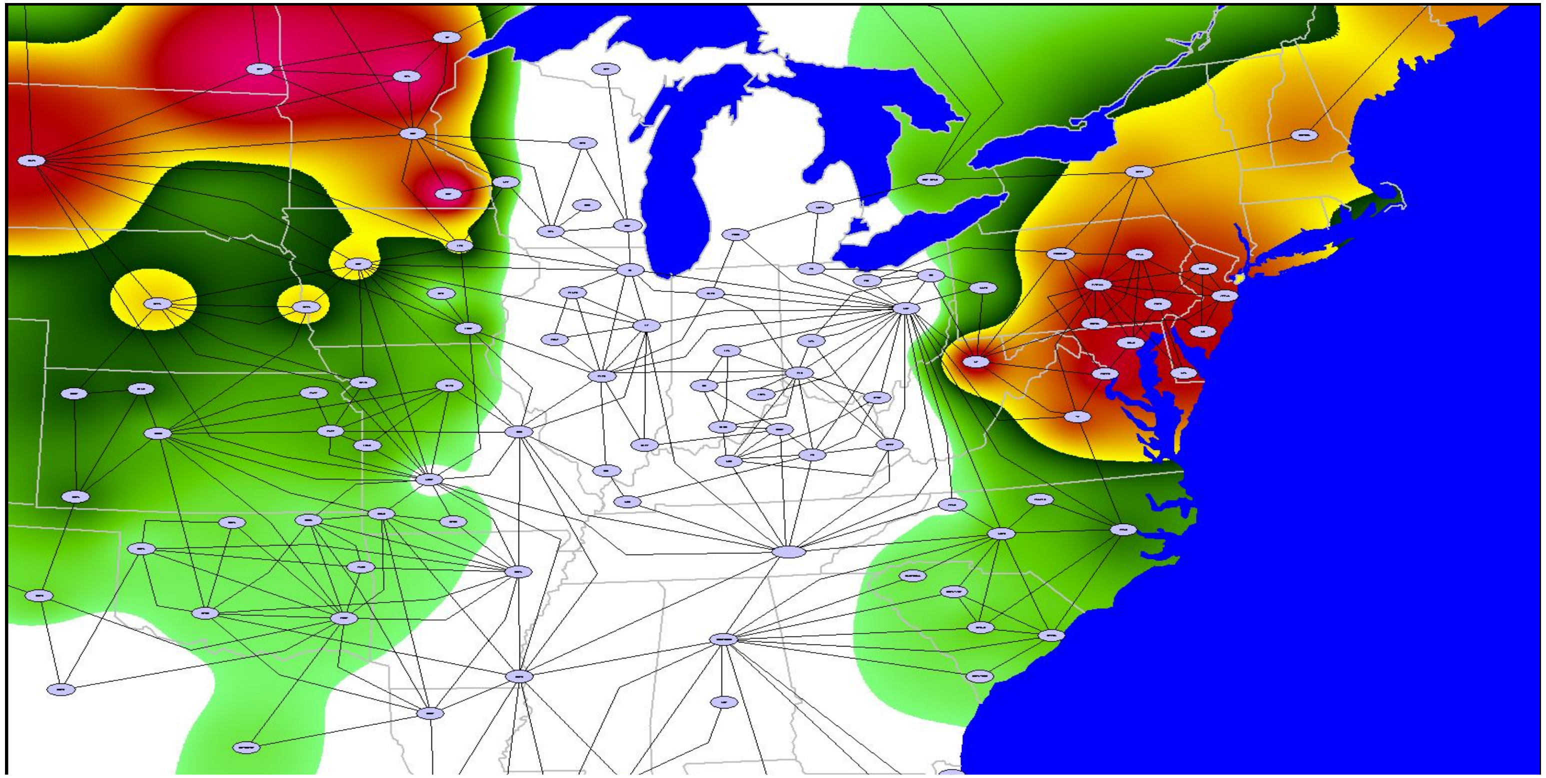
Horizontal Market Power

- One issue is whether a particular group of generators has market power
- Market power is the antithesis of competition
  - It is the ability of a particular group of sellers to maintain prices above competitive levels, usually by withholding supply
- The extreme case is a single supplier of a product (i.e., a monopoly)
- In the short run what a monopolistic producer can charge depends upon the price elasticity of the demand
- Sometimes market power can result in decreased prices in the long-term by quickening the entry of new players or new innovation

Market Power and Scarcity Rents

- A generator owner exercises market power when it is unwilling to make energy available at a price that is equal to that unit's variable cost of production, even thought there is currently unloaded generation capacity (i.e., there is no scarcity).
- Scarcity rents occur when the level of electric demand is such that there is little, if any, unused capacity
- Scarcity rents are used to recover fixed costs
- No market power is required to earn scarcity rents
  - a corn farmer earns scarcity rents when the price of corn exceeds the marginal cost of supply
- High prices do not necessarily indicate market power; there may just be a scarcity

June 1998 Heat Storm: Two Constraints Caused a Price Spike

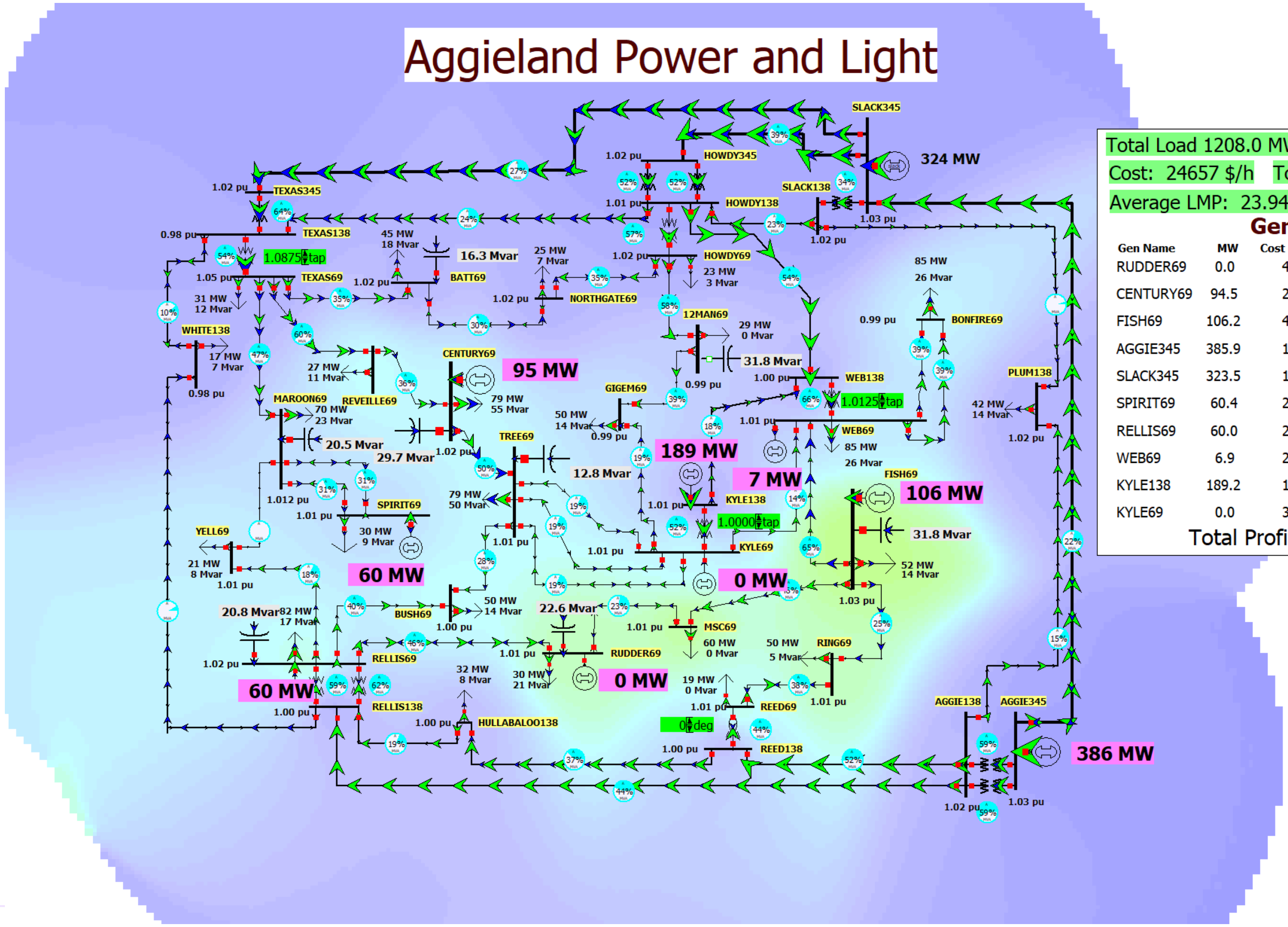


Price of electricity in Central Illinois went to $7500 per MWh!

Contoured areas could NOT sell into Midwest because of constraints on a line in Northern Wisconsin and on a transformer in Ohio

37 Bus Profit Maximization Example

- To try maximizing profits, open the previous lab case and change the cost multiplier for one or more generators



Total Load 1208.0 MW Load Multiplier 0.85
Cost: 24657 $/h Total Losses: 18.01 MW
Average LMP: 23.94 $/MWh

Generator Values

Gen Name	MW	Cost ($/MWh)	Cost Multiplier	LMP ($/MWh)	Profit $/hr
RUDDER69	0.0	42.0	1.00	35.82	0 $/h
CENTURY69	94.5	25.0	1.20	30.00	473 $/h
FISH69	106.2	40.0	1.00	40.00	0 $/h
AGGIE345	385.9	15.0	1.00	15.00	-0 $/h
SLACK345	323.5	16.0	1.00	16.00	-0 $/h
SPIRIT69	60.4	25.0	1.00	25.00	0 $/h
RELLIS69	60.0	25.0	1.00	32.28	437 $/h
WEB69	6.9	28.0	1.00	28.00	0 $/h
KYLE138	189.2	18.0	1.00	18.00	0 $/h
KYLE69	0.0	32.0	1.00	29.52	0 $/h

Total Profit: 910 $/h

Example Generator Supply Curves

Figure 3-1 Real-time and day-ahead hourly supply curves: January through September, 2023 and 2024

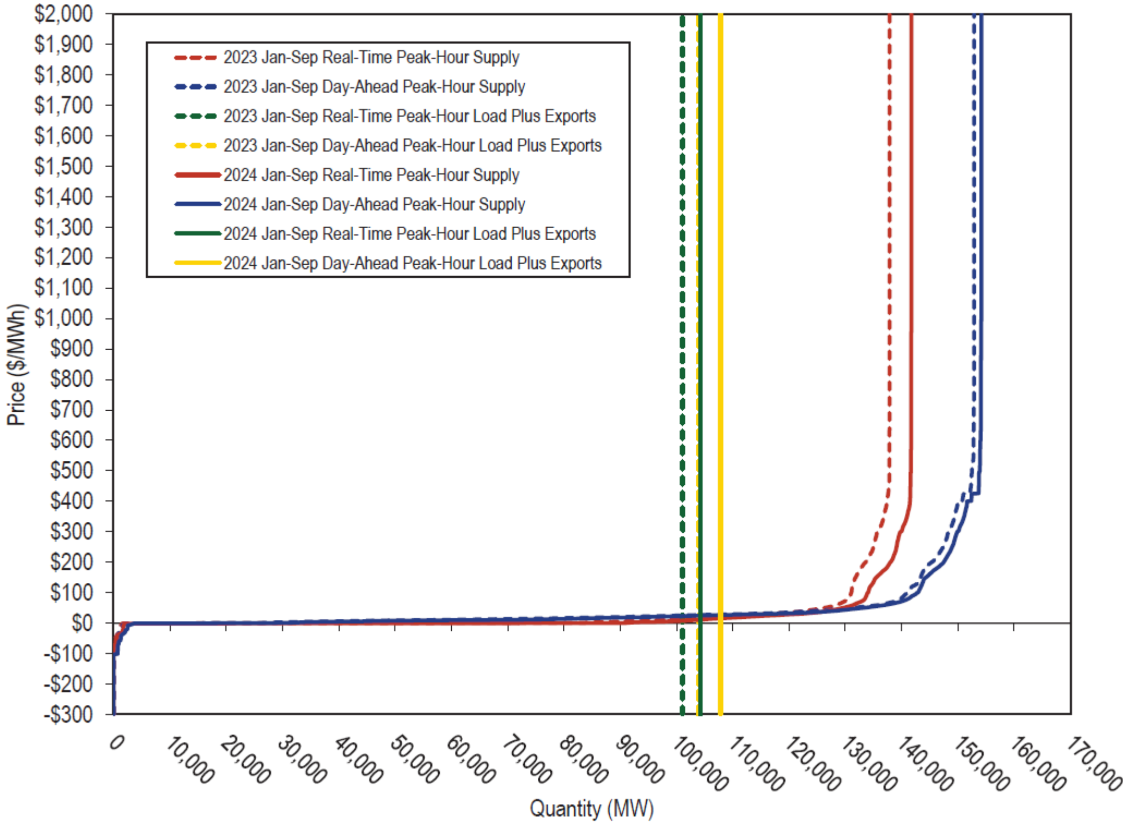


Figure 3-2 Typical dispatch range of supply curves

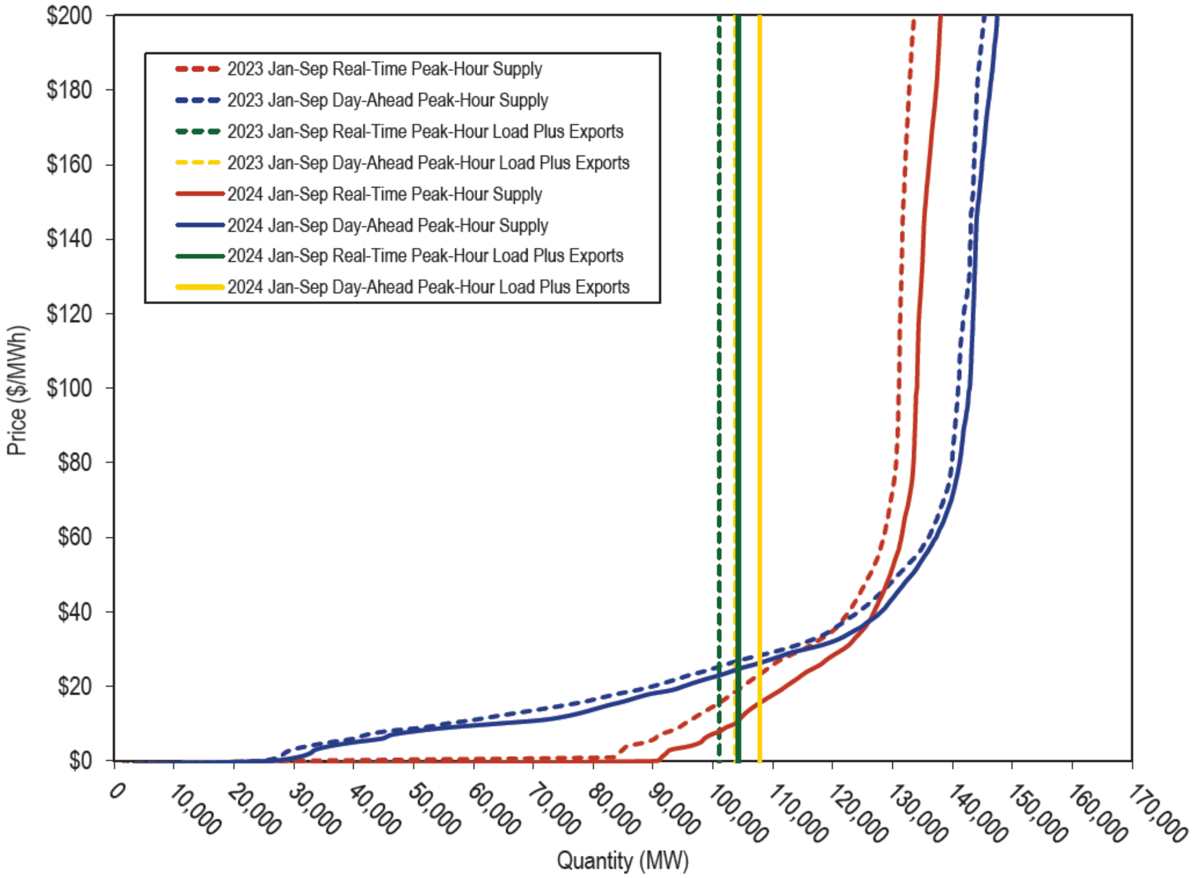


Image source: State of the Market Report for PJM, November 2024

Symptoms of Market Power

- Economic theory tells us that in a market with perfect competition, prices should be equal to the marginal cost to supply the product
- Therefore prices above marginal cost can indicate market power
- Justification: Let the amount of product = q, price = p, the supply cost = C(s), and Profit = P=q*p – C(s)

Let p = price, q = quantity, $C(q)$ = production cost; define profit $P = p \times q - C(q)$

Maximum profit is determined by $\frac{\partial P}{\partial q} = p + \frac{\partial p}{\partial q} q - \frac{\partial C(q)}{\partial q} = 0$

If a producer's offer does not affect the price then $\frac{\partial p}{\partial q} = 0$

Hence with no market power $p = \frac{\partial C(q)}{\partial q}$

Market Power Analysis

- In general market power analysis requires three steps
  - Identify relevant product or service (e.g., non-firm energy, capacity)
  - Identify relevant geographic market
    - Challenge in electric grids is the market can change with transmission system loading
  - Evaluate market concentration
    - One general measure of market power is the Herfindahl-Hirshman Index (HHI)

$$HHI = \sum_{i=1}^{N} q_i^2$$

where N is the number of participants and

q_i is the percentage market share

HHI Examples

- For a monopoly the HHI = 10,000
- If N=4, q_1=40%, q_2=25%, q_3=25%, q_4=10%, then HHI = 2950
- DOJ/FTC standards, adopted by FERC in 1992 for merger analysis
  - HHI below 1000 is considered to represent an unconcentrated market
  - anything above 1800 is considered concentrated
  - values were updated in 2010 to < 1500 for unconcentrated, and > 2500 highly concentrated, but 2024 guidelines seem to go with 1800 for highly concentrated

www.justice.gov/atr/herfindahl-hirschman-index

HHI Examples

- A company with 15 GW of generation seeks to merge with a company with 5 GW of generation in an 80 GW market. Assuming the new company is the largest in the market, what is the largest possible value for the new HHI?
  - The new company would have 25% market share. Since it is the largest, the highest HHI would be if there were three other companies almost as large (say close to 25% each). So the HHI in this case would be $4 \times 25^2 = 2500$. Of course if there are lots of other small companies it would be substantially less.

Collusion and Price Fixing

- Sherman Antitrust Act of 1890 attempts to prevent the artificial rising of prices by restriction of trade or supply
  - Goal is to preserve a competitive marketplace and prevent consumers from abuses
  - An "innocent monopoly" is allowed, but trying to artificially maintain that status is not; an innocent monopoly is where a company has achieved a monopoly position solely through its superior skills, innovation or market efficiency
- Agreements between competitors to tamper with prices (price fixing) could be a Sherman Act violation
- Competitors often need to collaborate but cannot collude (which is defined as acting together in secret to achieve an illegal purpose)
  –

Profit Optimization in Markets

- When studying markets we'd like to determine an equilibrium point with the assumption each player is trying to maximize their profit
- This is called the Nash Equilibrium, which has the following definition:
  - An individual looks at what its opponents are presently doing
  - The individual's best response to its opponents' behavior is to continue its present behavior
  - This is true for ALL individuals in the market
- The 2001 movie "A Beautiful Mind" is about John Nash's Life

Nash Equilibrium Example

- Consider a two player game, where each player has three choices. The table summaries the payoff for each player (player 1, player 2). The Nash equilibrium is shown in red.
- A Nash equilibrium requires players have mutually correct assumptions.

Player 2

Player 1

	l	m	r
U	8,3	0,4	3,8
M	4,0	5,5	4,0
R	3,5	0,4	5,3

Nash Equilibrium and the Prisoner's Dilemma

- Two prisoners are being interrogated simultaneously. If they betray their fellow criminal then they will get a lighter sentence, unless both of them betray each other. Then both serve a long sentence. If neither talks then the sentences will be lighter.

	Don't Betray	Betray
Don't Betray	2,2	0,3
Betray	3,0	1,1

Here a higher number is better, but the Nash Equilibrium is actually worse for both

Nash Equilibrium in Which a Mixed Strategy is Best

- Consider the Nash Equilibrium for the game paper, scissors & rock. This game has no Nash Equilibrium, indicating that a mixed strategy is best

Player 2

Player 1

	Paper	Scissors	Rock
Paper	0,0	-10,10	10,-10
Scissors	10,-10	0,0	-10,10
Rock	-10,10	10,-10	0,0