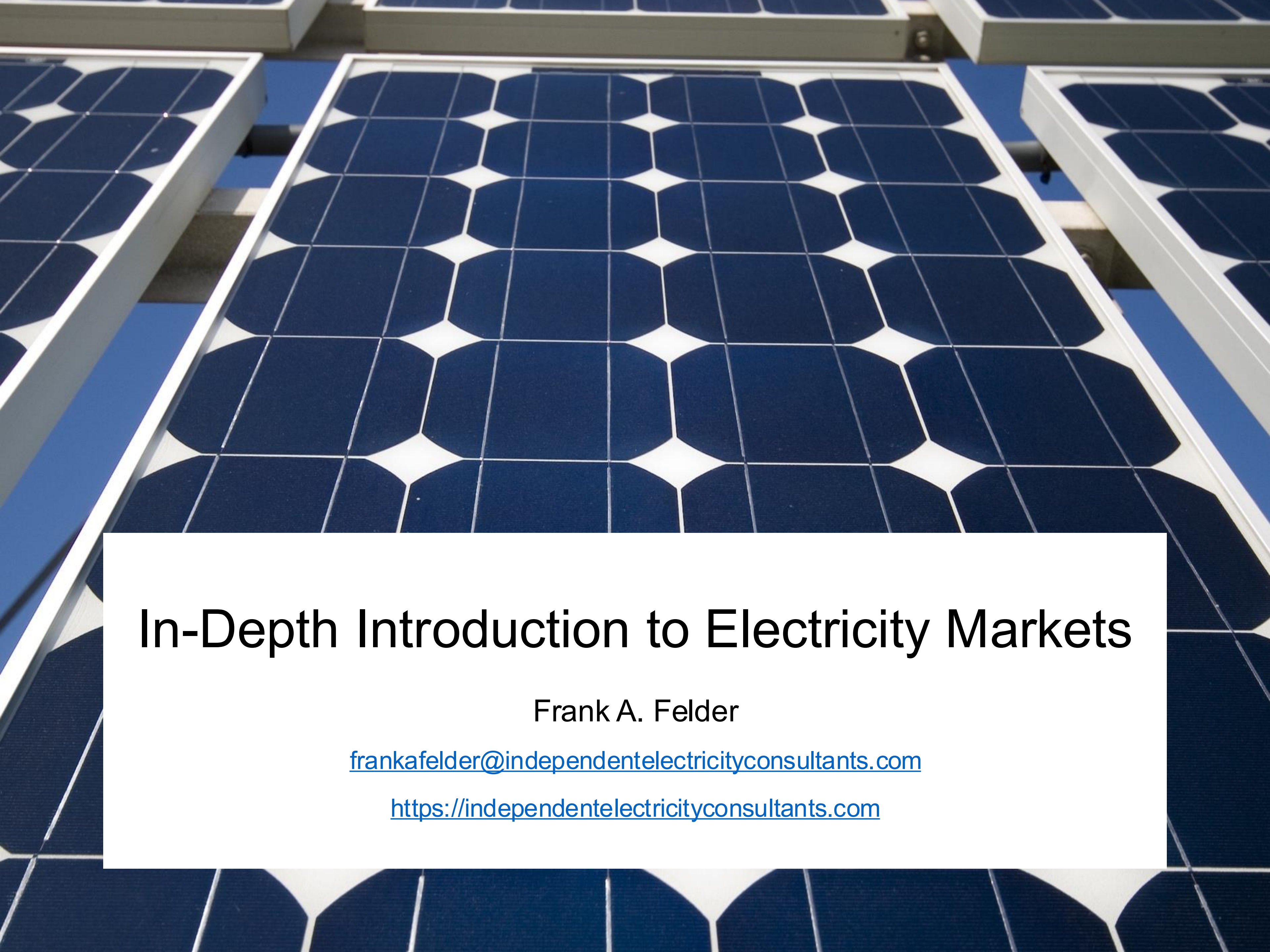


In-Depth Introduction to Electricity Markets

Frank A. Felder

frankafelder@independentelectricityconsultants.com

https://independentelectricityconsultants.com

DECEMBER 2025 TRAINING

- Dec. 2: Introduction to the Electricity Sector, 9:30-12:30
- Dec. 3: Power System Fundamentals, 9:30-12:30
- Dec. 10: Electricity Markets, 9:30-12:30
- Dec. 11: Political, Regulatory and Business Context, 9:30-12:30

- Dec. 2: Trump Administration Electricity Policy Update, 2-3 pm
- Dec. 10: Quiz Bowl, 4-5 pm

Gatineau & Virtual

New and Expanded Topics for In-depth Session

In The News
Trump Administration policies and the electricity sector
Data centers: large loads and business opportunities
Geothermal, nuclear
Locational marginal emissions
Business model and strategies for independent power producers
And much more!

2025 Training slides available at
https://www.independentelectricityconsultants.com/training-presentations

MAJOR THEMES

Successful analyses – whether engineering, economic, legal/regulatory or business – requires an integrated knowledge of the electric industry

Electricity markets are highly regulated and only cover about a third of the supply chain

The U.S. has two major types of electricity markets, although important variations exist within each of these market types

The U.S. has a multi-jurisdictional system that regulates different and overlapping parts of the industry

The industry is responding to major new trends; that being said, it is subject to substantial inertia. In the U.S. these trends are:

- Substantial load growth including data centers and generation shortages
- Integrating variable renewable resources, although with pushback from the Trump Administration
- Out-of-market funding for clean energy at the state level
- Transmission expansion with increased federal role
- Smart grid and virtual power plants
- Expanding nuclear power

Seminar Agenda

Session 1: Introduction to the Electricity Sector

9:30-9:45

Introduction, Logistics, Course Overview

9:45-12:30

Introduction to the Electricity Sector

- Big Picture
- For folks new or relatively new to the electricity sector

Session 2: Power System Fundamentals

9:30-9:45

Course Recap

9:45-12:30

Power System Fundamentals to Understand Electricity Markets

- The characteristics of how power systems work and how they influence electricity market design

There will be a 15-minute break half-way through each session

Seminar Agenda

Session 3: Electricity Markets

9:30-9:45

Review of Previous Sessions

Questions

9:45-12:30

US RTO/ISO Electricity Markets and Comparisons to Other Electricity Markets

Session 4: Political, Regulatory and Business Context

9:30-9:45

Course Recap

9:45-12:30

Electricity Regulatory Policies, Emerging Trends, and Business Strategies

There will be a 15-minute break half-way through each session

Letters of attendance for continuing education are available upon request
Email me at: frankafelder@independentelectricityconsultants.com

ADDITIONAL SESSIONS

I. Tuesday, Dec. 2, 2-3 pm: Trump Administration Electricity Policy Update

Policy update on Trump Administration's activities in the electricity sector, with a focus on the recent U.S. Department of Energy Advanced Notice of Proposed Rulemaking on Integrating Large Loads

Discussion-driven and Q&A-based format

II. Wednesday, Dec. 10, 4-5 pm: Quiz Bowl

2 Rounds, 15-20 minutes each

- Round 1: In Depth Introduction to Electricity Markets
- Round 2: Transmission planning, power system optimization, Western Electricity Markets, Market Power and Mitigation

Looking for 2 to 4 teams of 2-4 members per team

CONTACT ME! (in person and/or via email: frankafelder@independentelectricityconsultants.com)

Session 1
Introduction to the Electricity Sector

IN THE NEWS

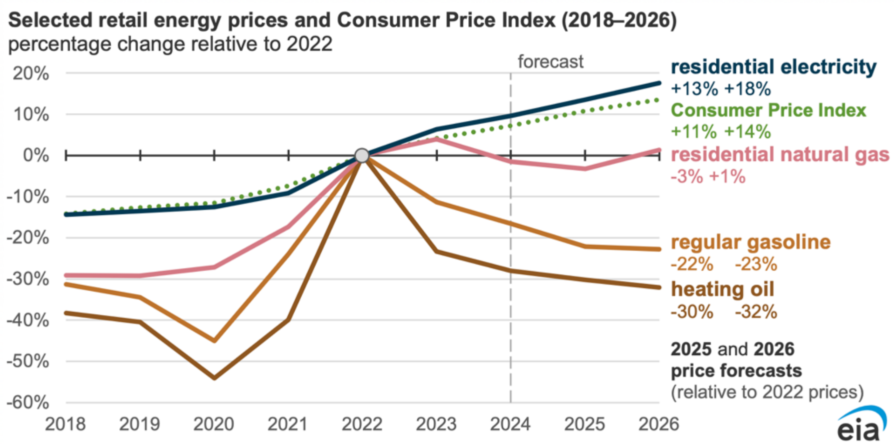
AI Data Centers Are Sending Power Bills Soaring

Wholesale electricity costs as much as 267% more than it did five years ago in areas near data centers. That's being passed on to customers.

Bloomberg Technology, Sept. 29, 2025, https://www.bloomberg.com/graphics/2025-ai-data-centers-electricity-prices/?embedded-checkout=true

MAY 14, 2025

U.S. electricity prices continue steady increase



Data source: U.S. Energy Information Administration, *Short-Term Energy Outlook*, May 2025
Data values: Energy Prices

https://www.eia.gov/todayinenergy/detail.php?id=65284

UTILITY DIVE | Deep Dive | Opinion | Library | Events | Press Releases | Topics

DOE large load interconnection proposal sparks federal-state jurisdiction concerns

State regulators, lawmakers and ratepayer advocates voiced alarm over the department's interconnection proposal, while the Data Center Coalition offered qualified support.

Published Nov. 24, 2025

https://www.utilitydive.com/news/doe-large-load-interconnection-ferc-naruc/806278/

Trump's DOE may soon force more coal plants to stay open

Colorado coal plants are likely to face DOE orders to keep running past planned closure dates, even as the costs of keeping an old Michigan plant open pile up.

By Jeff St. John
12 November 2025

Canary Media, https://www.canarymedia.com/articles/fossil-fuels/trump-colorado-coal-stay-open-orders

Share Print Download Save

AI is fueling high demand for compute power, spurring companies to invest billions of dollars in infrastructure. But with future demand uncertain, investors will need to make calculated decisions.

https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/the-cost-of-compute-a-7-trillion-dollar-race-to-scale-data-centers

POWER SECTOR OVERVIEW

Motivation: What is the power system, its major components, and why is it undergoing fundamental change?

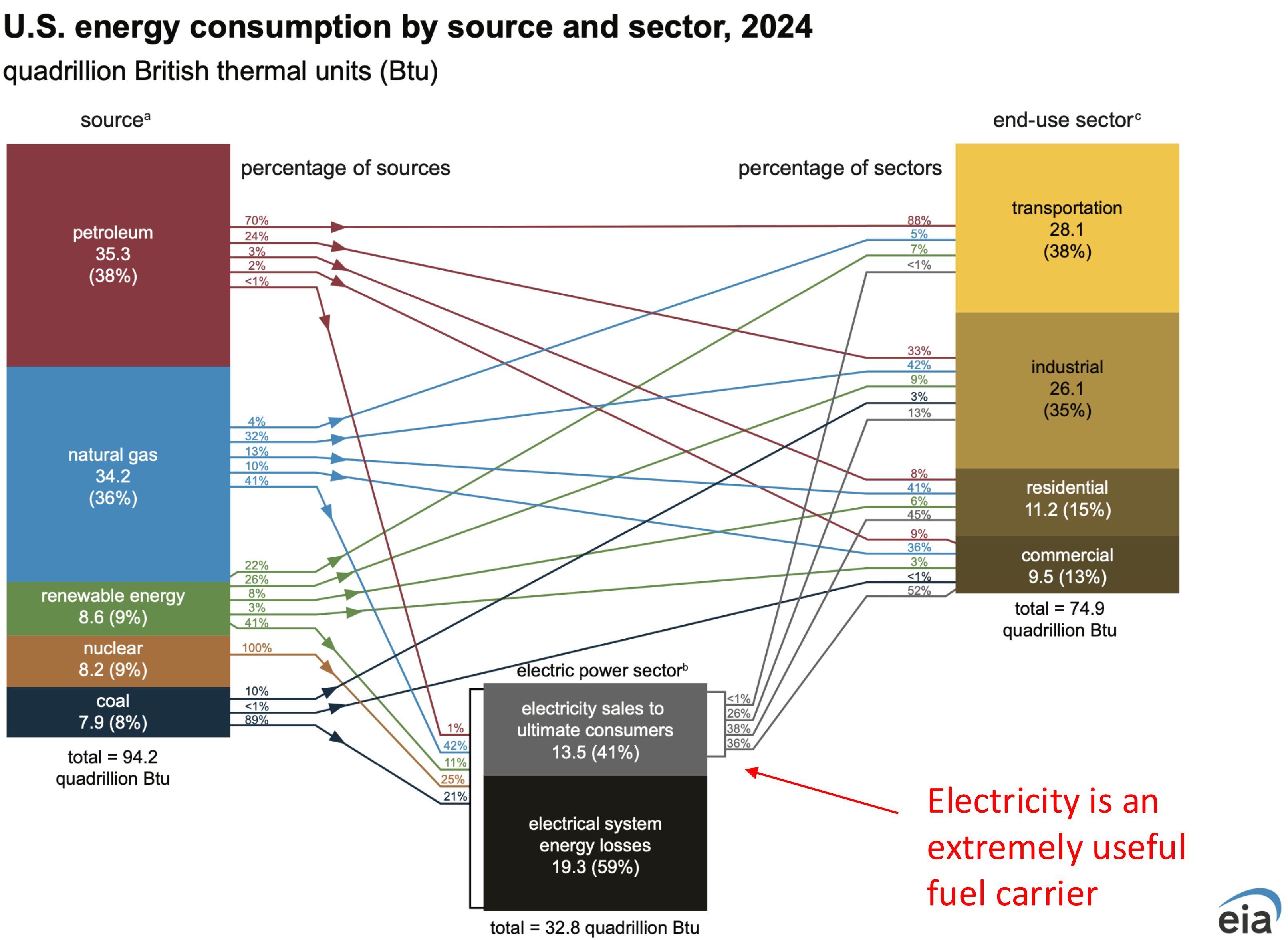
Key Questions:

- What are generation, transmission, distribution, and load?
- What are the roles of economic regulation and markets in the power sector?
- What are the different physical and economic characteristics of generation?
- Why and how is the electric power system changing?

Take Aways:

- The power sector is influenced by technology, economics, business strategies, and public policy
- The sector is fundamentally changing and expanding due to the energy transition

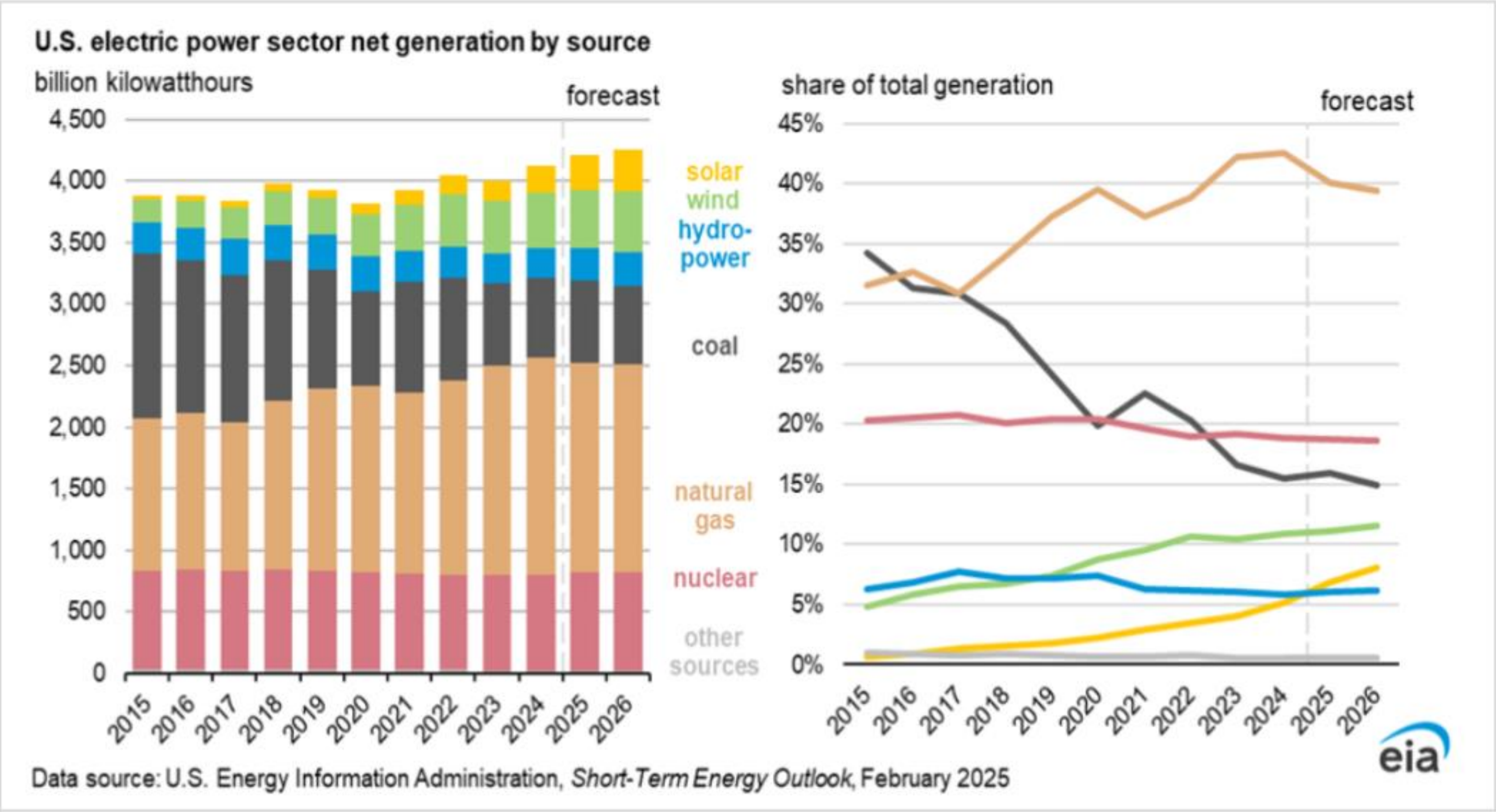
*Many slides include references and the final slides list additional ones



Electricity is an extremely useful fuel carrier

https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy_spaghettichart_2024.pdf

US ELECTRICITY GENERATION BY FUEL SOURCE



Natural gas is displacing coal
Wind & solar PV are increasing substantially

https://www.eia.gov/outlooks/steo/report/elec_coal_renew.php

US GRID (approximate numbers as of 2024)

12,000 power plants greater than 1 MW
1,250,000 MW of generation capacity
412,000 MW of generation under development
55,000 substations
500,000 miles of high-voltage lines
5,500,000 miles of local distribution lines
Serves 160 million customers (meters)

- AC power allows for very high voltages, which enables the transfer of electricity over long distances with minimal losses
- AC power is generally not controlled, i.e., power from a particular generation unit is not directed to a particular customer, although technologies exist to do so (flexible AC (FACT) devices)

Key Takeaway: power systems are massive and very capital intensive

https://ifp.org/how-to-save-americas-transmission-system/

SUPPLY CHAIN

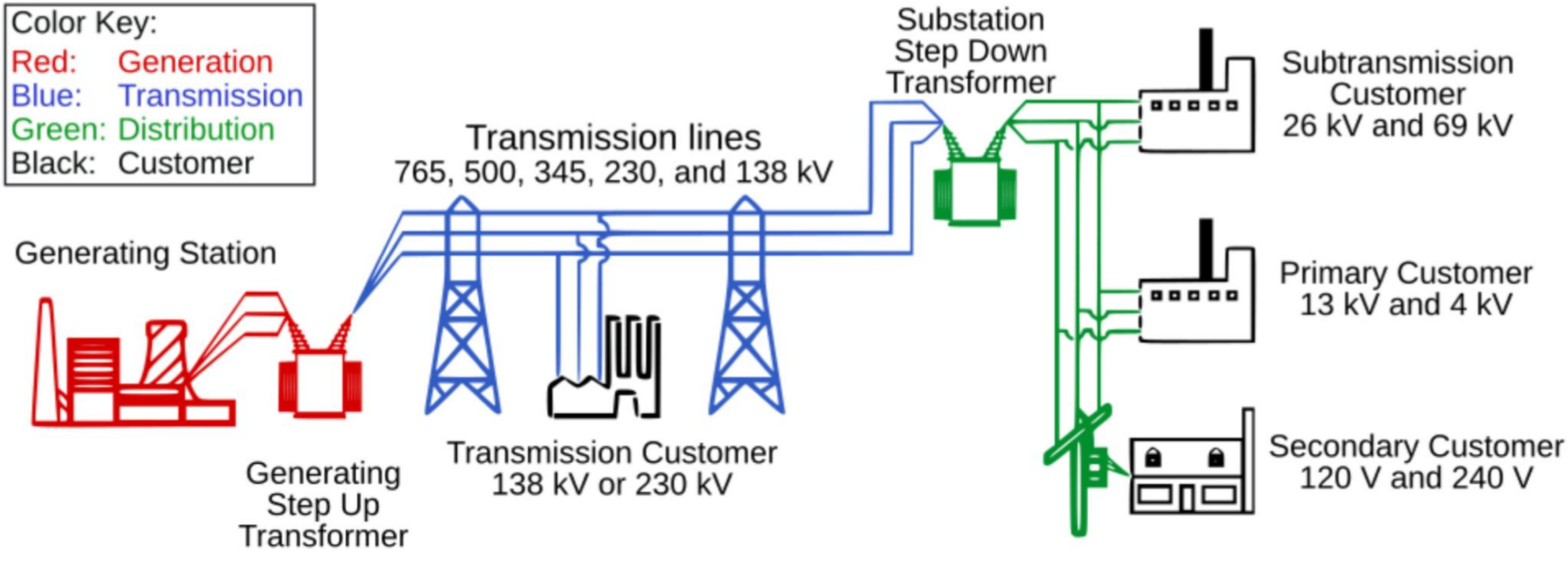
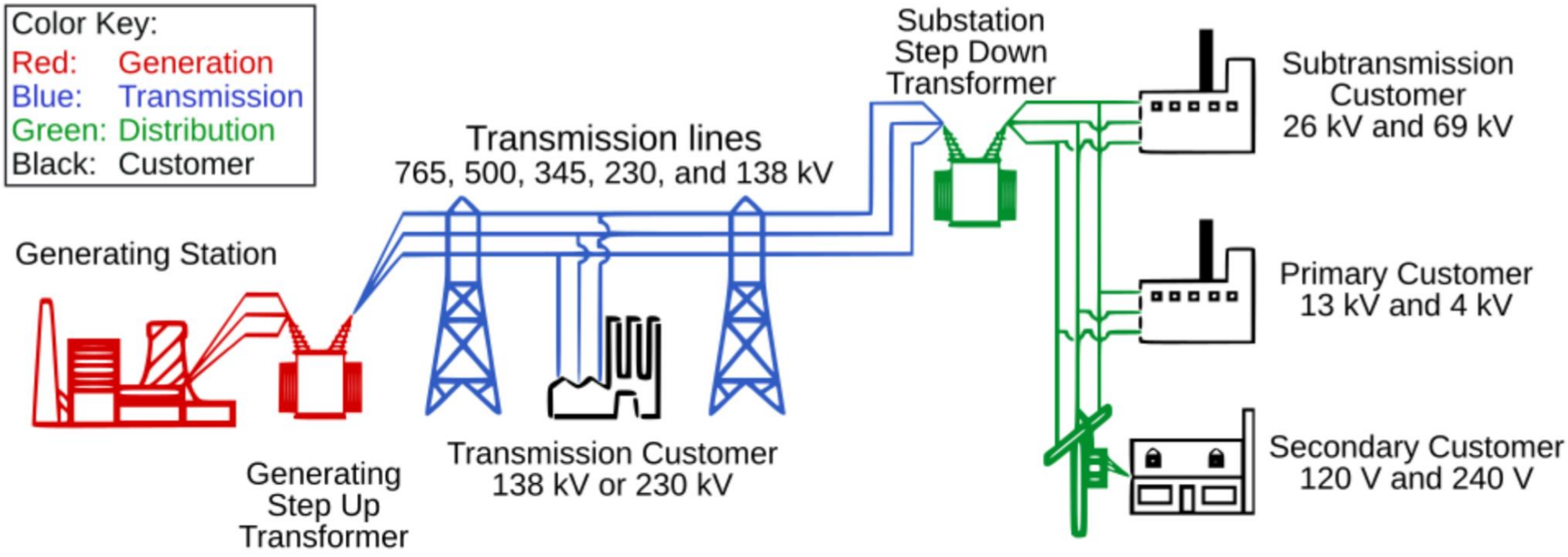


Figure from the U.S.-Canadian Power System Outage Task Force final report on the 2003 Blackout, p. 5.

- This figure does not capture the *meshed network* of the transmission system
- Distribution systems are typically *radial (linear)* outside of urban areas

REGULATORY AND MARKET STRUCTURE

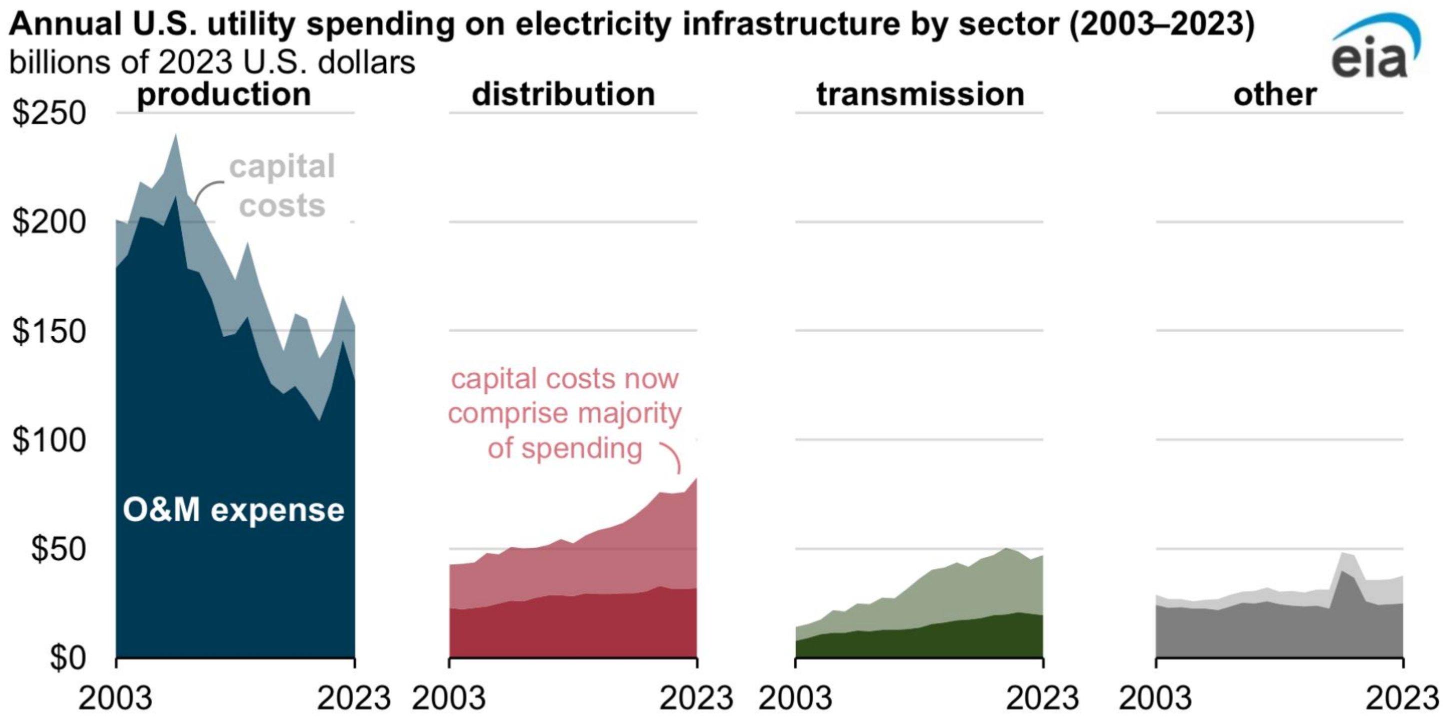


U.S.-Canadian Power System Outage Task Force final report on the 2003 Blackout, p. 5.

- Generation – either market based or economically regulated (e.g., cost of service)
- Transmission – economically regulated
- Distribution – economically regulated
- Load – either market based (if there is a wholesale market) or economically regulated)

- US Federal-State Jurisdictional Boundary at transmission-distribution connection

U.S. ELECTRICITY SUPPLY CHAIN EXPENDITURES



Data source: U.S. Energy Information Administration and Federal Energy Regulatory Commission (FERC) Financial Reports, as accessed by Ventyx Velocity Suite
Note: O&M=operation and maintenance https://www.eia.gov/todayinenergy/detail.php?id=63724

Note: These are the most recent US gov't issued numbers

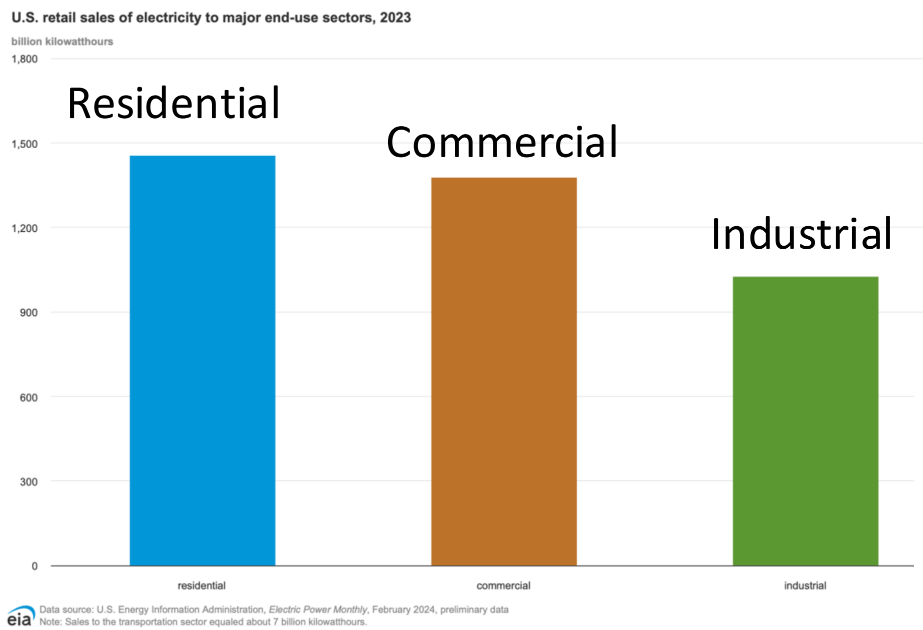
Electric utilities will invest more than $1.1T by 2030 to meet demand growth: EEI

The electric utility sector's capital expenditures "are higher than any other sector in the U.S. economy," Edison Electric Institute President and CEO Drew Maloney said.

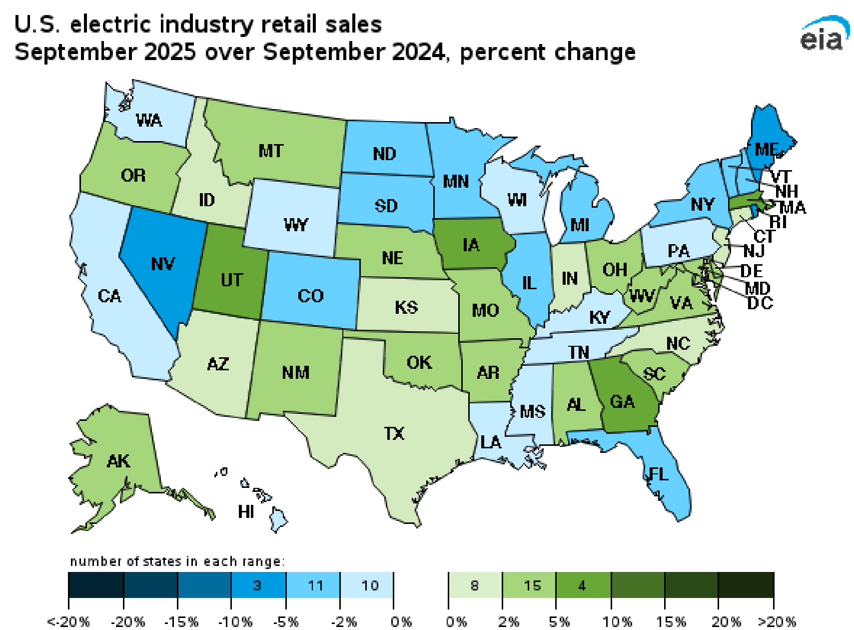
Published July 23, 2025

Utility Dive, https://www.utilitydive.com/news/electric-utilities-will-invest-more-than-11t-by-2030-to-meet-demand-growt/753783/

U.S. ELECTRICITY SALES BY CUSTOMER CLASS



https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php



https://www.eia.gov/electricity/monthly/update/end-use.php

Retail sales by customer class can vary substantially by region

Residential and commercial are approximately equal.

Industrial is expected to increase substantially due to data centers.

TIMELINE

Transmission Construction:
3-10 years

Generation Construction:
2-10 years

Planned Generation and Transmission Maintenance:
1-3 years

Unit commitment:
12 hours ahead for the next 24 hour day

Economic Dispatch:
Every 5 minutes but planned for 6 hours ahead

Time

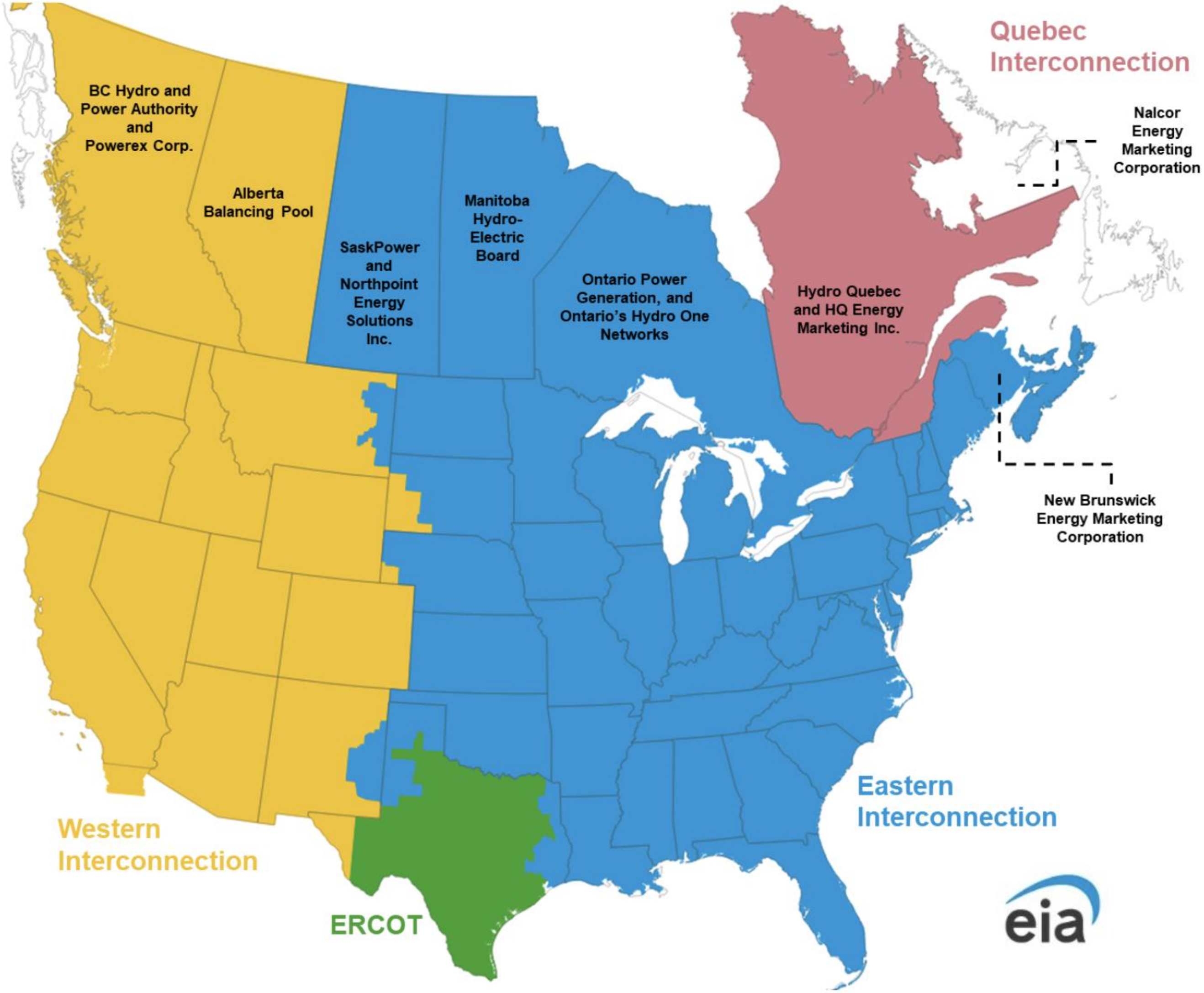
Build | Maintain | Schedule | Operate | Real Time

Note: diagram not drawn to scale

Electricity time scale covers fractions of a second to decades

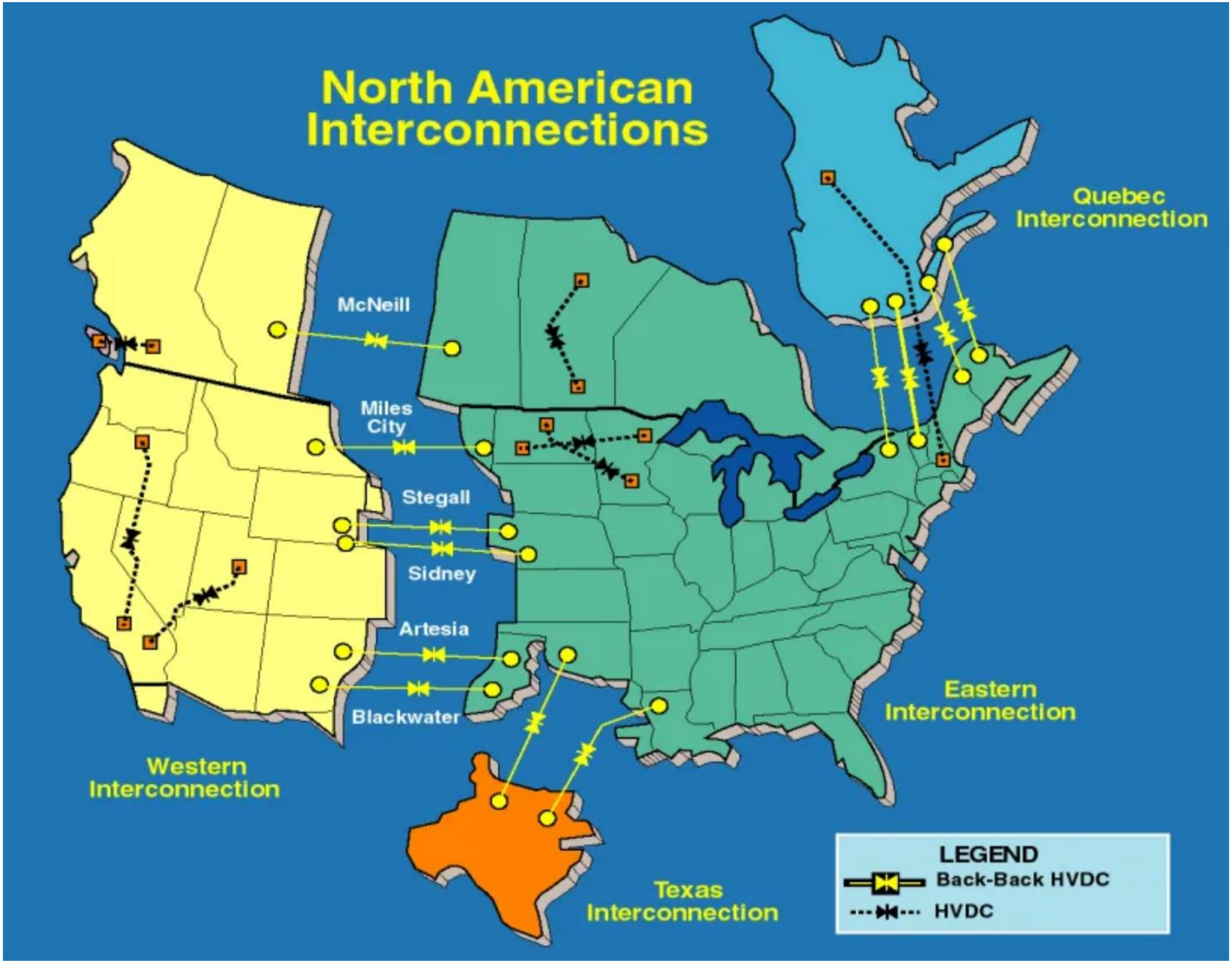
See https://ifp.org/how-to-save-americas-transmission-system/ for Transmission construction timelines and data

North American selected electricity power producers, trade entities, and interconnections (as of Nov 2024)



Data source: The North American Electric Reliability Corporation and Canadian Energy Regulator
Note: ERCOT=Electric Reliability Council of Texas

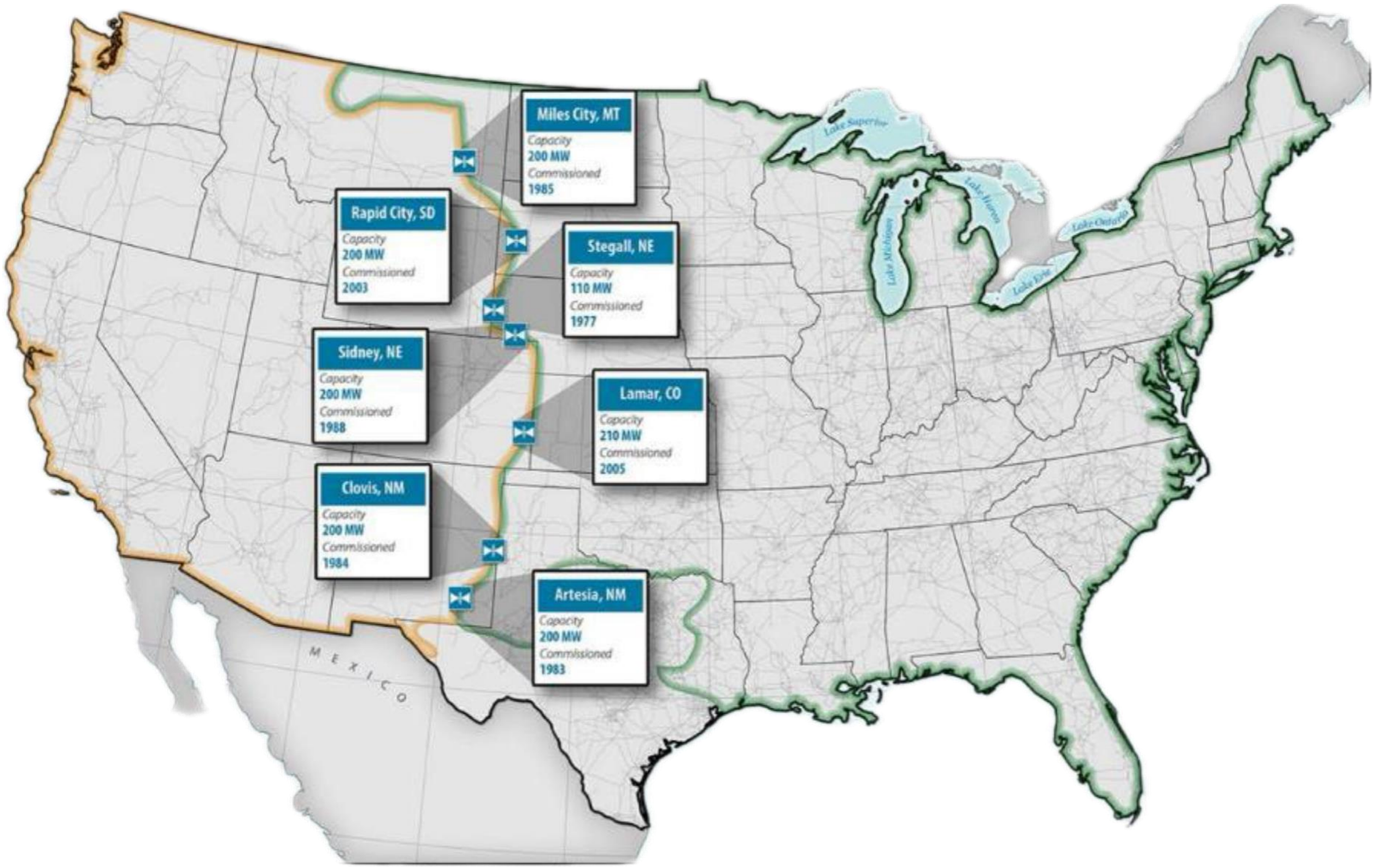
https://www.eia.gov/todayinenergy/detail.php?id=63684



https://jasondoering.substack.com/p/the-grids-org-chart

May not include all interconnections

US EAST-WEST DIRECT CURRENT (DC) TIES



https://www.google.com/search?client=safari&rls=en&q=Map+of+U.S.+Transmission+System+and+B2B+HVDC+Ties&ie=UTF-8&oe=UTF-8#vhid=OtKmYvrPwPGnjM&vssid=_jXYvZ5STOOWf5NoPi62PgQQ_45

RELIABILITY ORGANIZATIONS

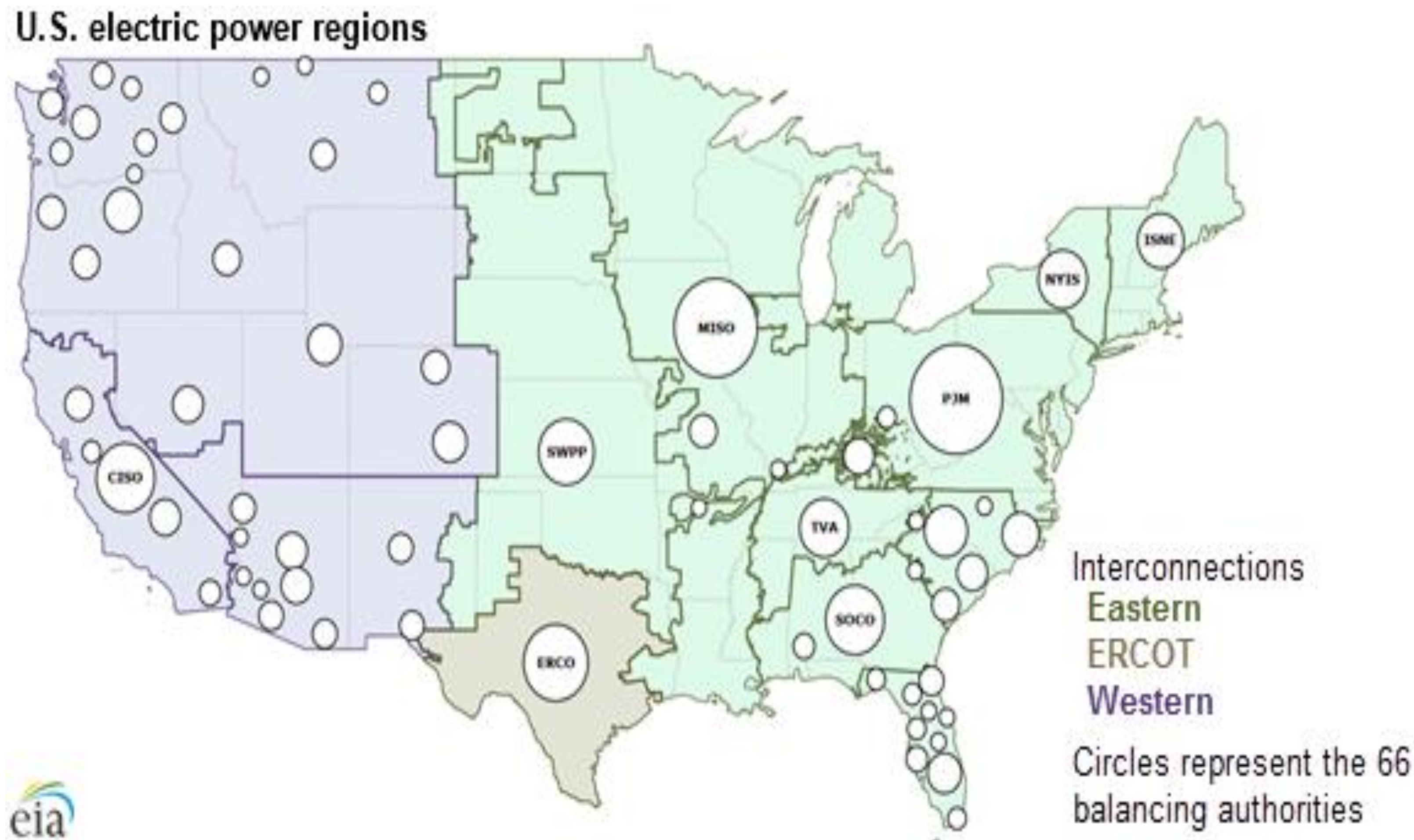
NERC (North American Electric Reliability Corporation), NERC Regional Reliability Councils, Reliability Coordinators, Regional Transmission Organizations (RTOs), and Independent System Operators (ISOs) have various roles in operations and planning

- The basic operational organizations are control areas/balancing authorities: an electrical region that regulates its generation to balance load and maintain planned interchange schedules with other control areas and assists in controlling the frequency of the interconnected system
- Control Areas/balancing authorities are interconnected to form grids
- Reliability Coordinator is the entity that is the highest level of authority, oversees multiple control areas/balancing authorities, is responsible for the reliable operation of the Bulk Electric System, has the **Wide Area view of the Bulk Electric System**, and has the operating tools, processes, procedures, and authority to prevent or mitigate emergency operating situations in both next-day analysis and real-time operations

NERC RELIABILITY COORDINATORS

https://www.nerc.com/programs/bulk-power-system-awareness/reliability-coordinators

CONTROL AREAS/BALANCING AUTHORITIES

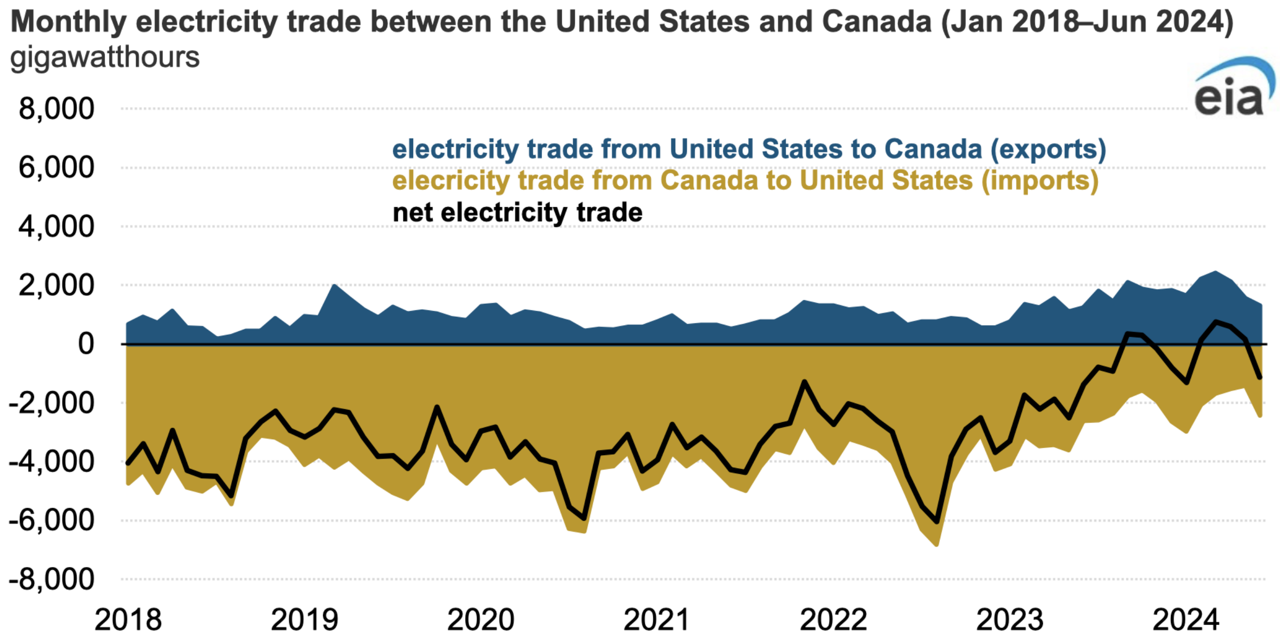


https://www.eia.gov/todayinenergy/detail.php?id=27152

NOVEMBER 12, 2024

U.S. electricity exports to Canada have increased since September 2023

Updated March 6, 2025 to correct the labels in a figure.



https://www.eia.gov/todayinenergy/detail.php?id=63684

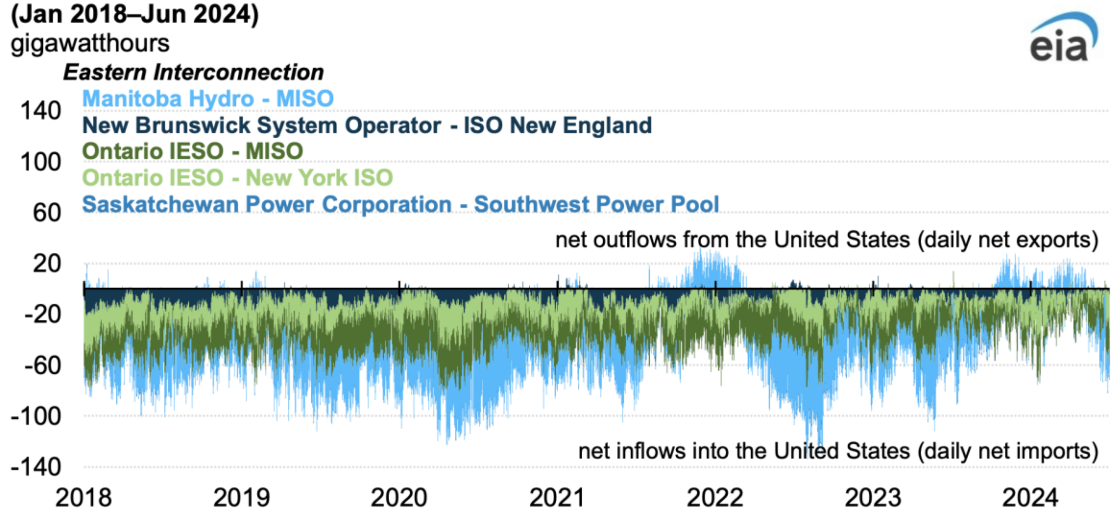
Data source: U.S. Energy Information Administration, Form EIA-111, *Quarterly Electricity Imports and Exports Report*

- Electricity imports and exports play a critical role in ensuring the reliability of the electricity systems in Canadian provinces and U.S. states.
- All of Canada's electricity trade is with the U.S. In 2024, Canada exported 35.7 Terawatt hours (TWh) of electricity, valued at $3.1 billion.
- Canada imported 20.9 TWh of electricity, valued at $1.2 billion in 2024. [10]

https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2025/market-snapshot-overview-of-2024-canada-us-energy-trade.html

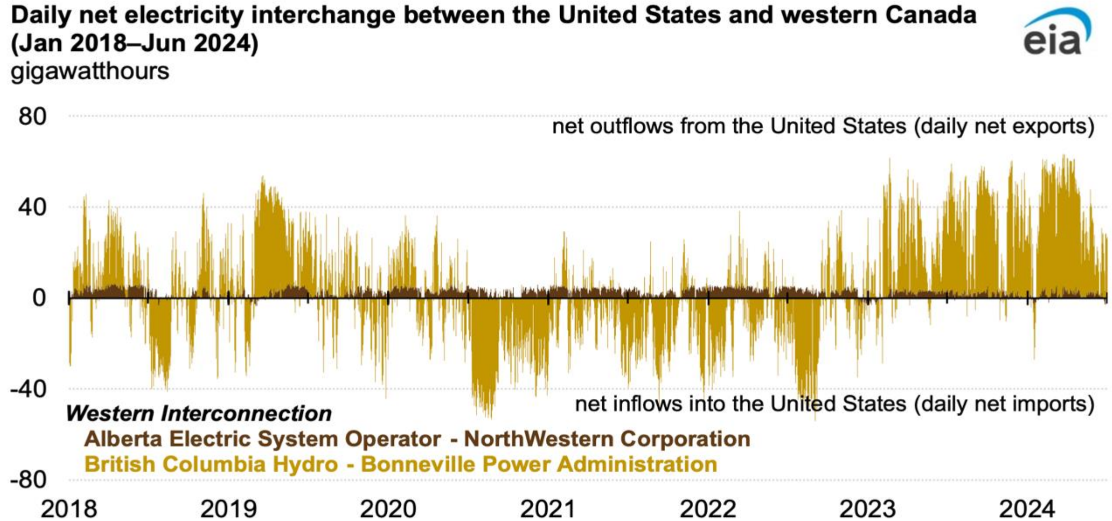
Daily exchanges are highly variable

Daily net electricity interchange between the United States and the eastern Canadian grid (Jan 2018–Jun 2024)
gigawatthours



Data source: U.S. Energy Information Administration, Form EIA-930, *Daily Balancing Authority Operations Report*
Note: The net values represent the interchange from a U.S. balancing authority to a Canadian balancing authority. Values are reported by U.S. balancing authorities. Negative interchange values indicate net inflows into the United States, and positive interchange values indicate net outflows from the United States. EIA's interchange data only account for balancing authorities bordering Canada. Electricity imports and exports occur simultaneously in both directions between various states in the United States and Canadian provinces.

Daily net electricity interchange between the United States and western Canada (Jan 2018–Jun 2024)
gigawatthours



Data source: U.S. Energy Information Administration, Form EIA-930, *Daily Balancing Authority Operations Report*
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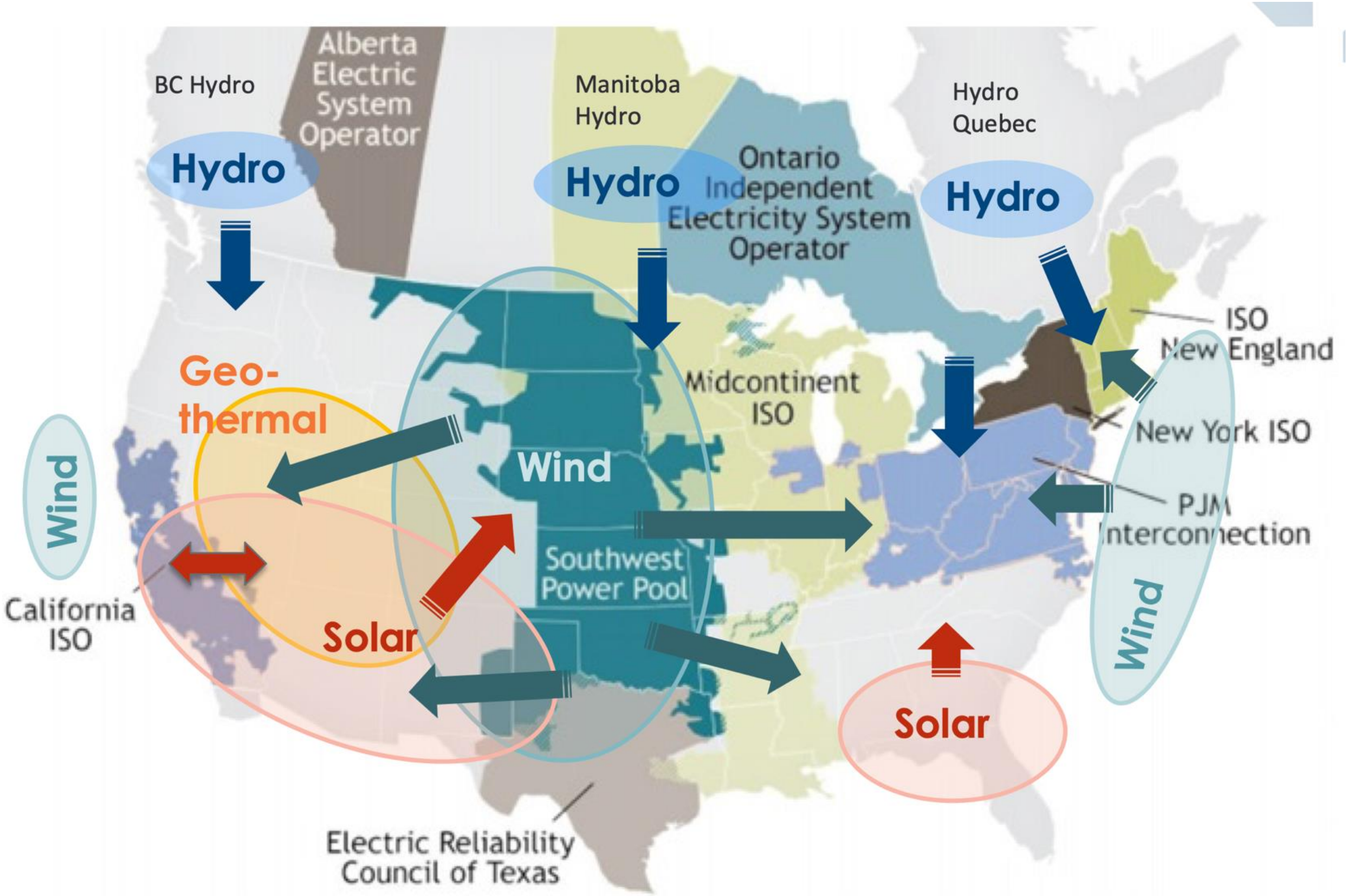
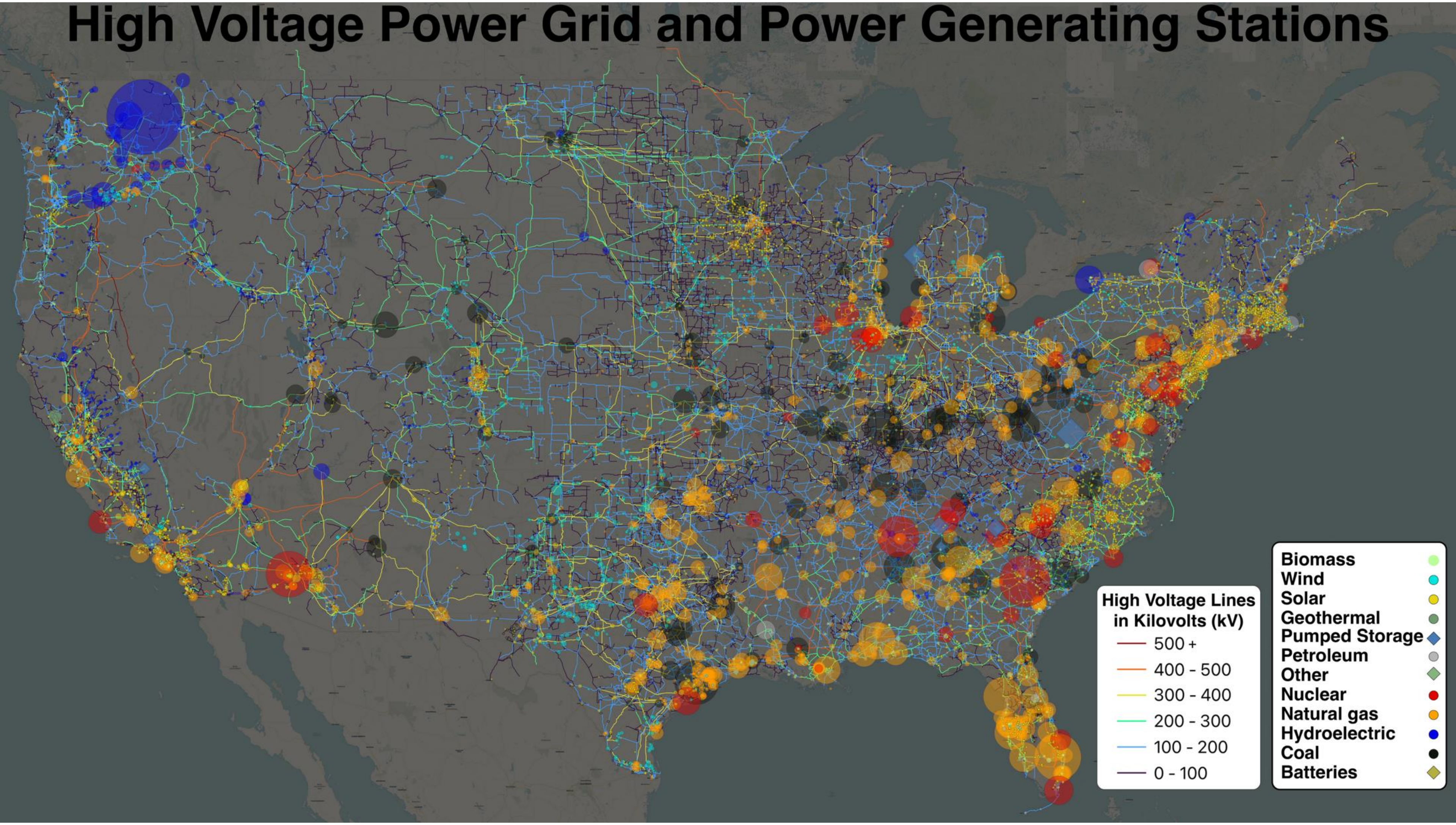
https://www.eia.gov/todayinenergy/detail.php?id=63684

LOCATION OF EMERGING GENERATION RESOURCES IN NORTH AMERICA

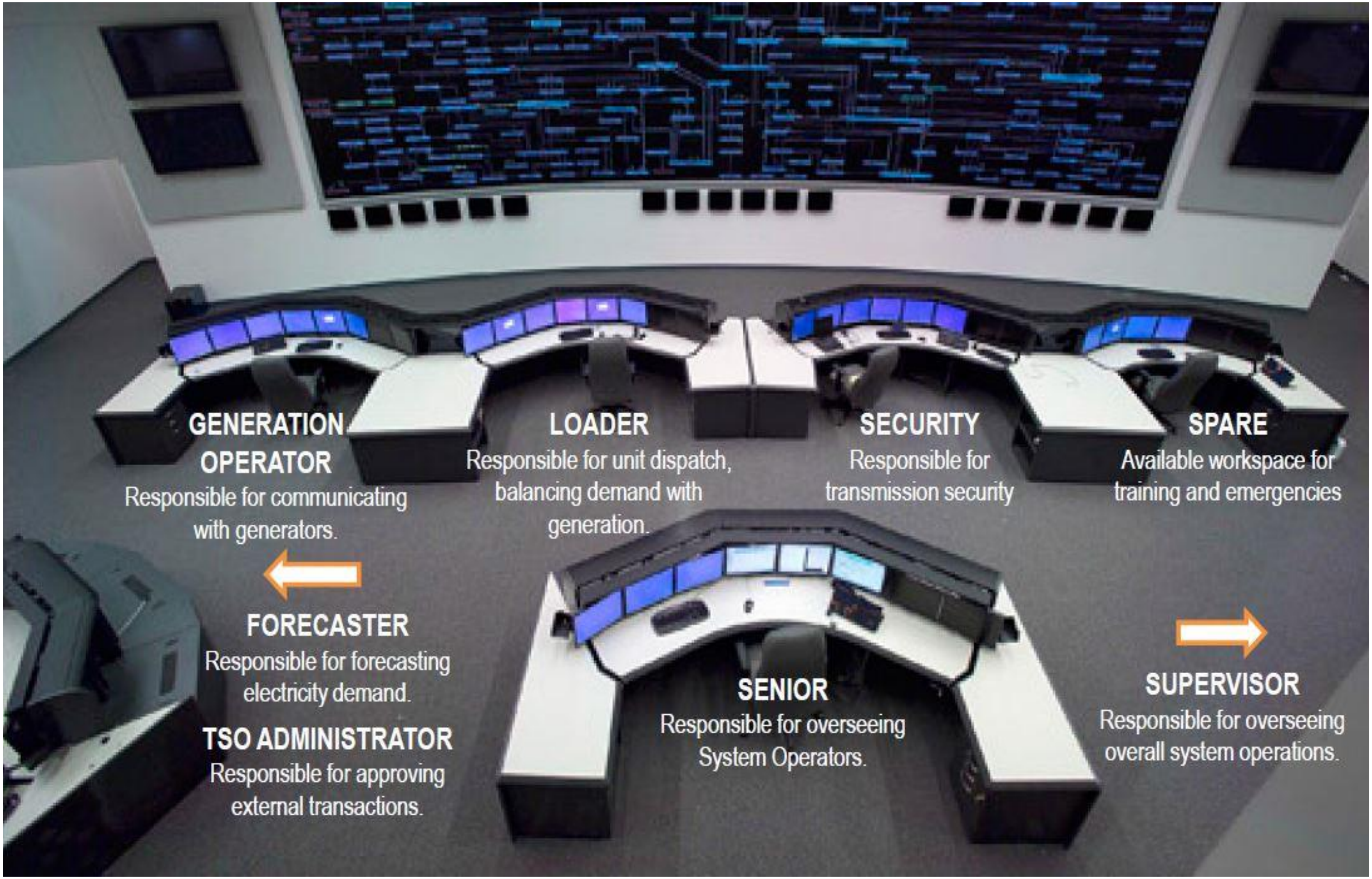


Brattle, 2021, https://www.brattle.com/wp-content/uploads/2021/10/Transmission-Investment-Needs-and-Challenges.pdf



https://commons.wikimedia.org/wiki/File:High_voltage_power_grid_of_the_United_States.webp#/media/File:Electrical_grid_and_power_plants.webp

CONTROL ROOM



GENERATION

Multiple types of generation units to address demand variations:

- Baseload (e.g., nuclear, coal, natural gas combined cycle (CC)) – run 24x7
- Intermediate (e.g., natural gas CC) – run much of the time
- Peaking (e.g., natural gas combustion turbine (CT), diesel generator) – run infrequently
- Centralized (e.g., nuclear, coal, natural gas), large scale (e.g., solar, wind) and distributive generation (e.g., solar panels, backup power)

Tradeoffs

- Capital and fixed costs vs. operating costs, which are primarily driven by fuel costs and heat rate
- Lower operating costs vs. operational flexibility (e.g., start up time, ramp rate)
- Cleaner but intermittent vs. dirtier and dispatchable
- Storage options are becoming less expensive (e.g., pumped storage, hydro reservoirs, batteries, etc.)

GENERATION HEAT RATES

Engineering Efficiency for Thermal Units

Heat Rate = Btu/kWh *Note Btu = British Thermal Unit*

- Inverse measure of efficiency: the higher the heat rate the less efficient
- Coal plants: 9,000 - 11,000 Btu/kWh
- Natural gas combined cycles: 6-8,000 Btu/kWh
- Peaking units: 12,000 and greater Btu/kWh

Startup Time - the amount of time to warm up a unit so that it can operate

Ramp Rate (MW/minute) - how fast a unit can alter its output

Economic Efficiency

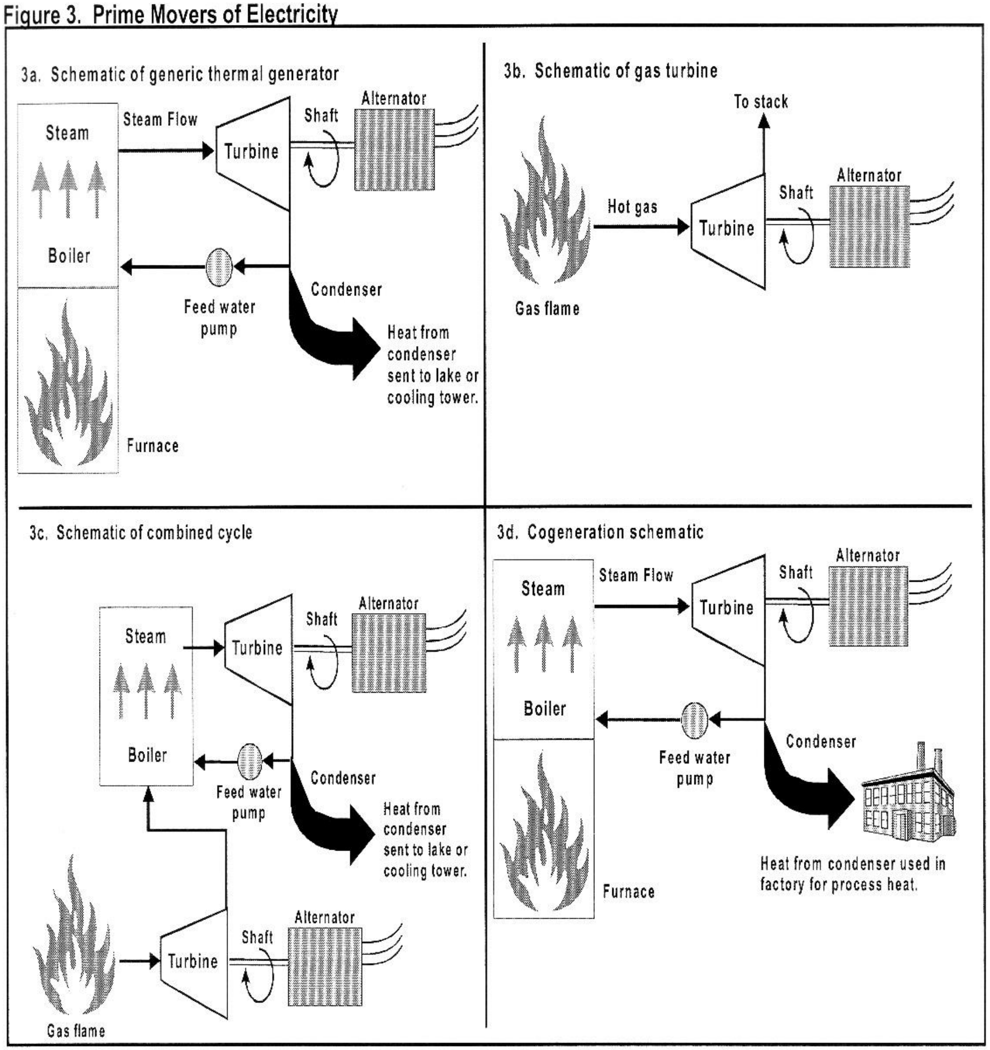
Private Economic Cost:

Heat Rate (Btu/kWh) * Fuel Cost ($/Btu) = Cost ($/kWh)

Social Economic Cost:

Heat Rate (Btu/kWh) * (Fuel + Environmental Cost ($/Btu)) = Cost ($/kWh)

GENERATION



Source: R. Baldick, "Introduction to Electric Power Systems for Legal and Regulatory Professionals," Course Materials, The University of Texas at Austin (1999).

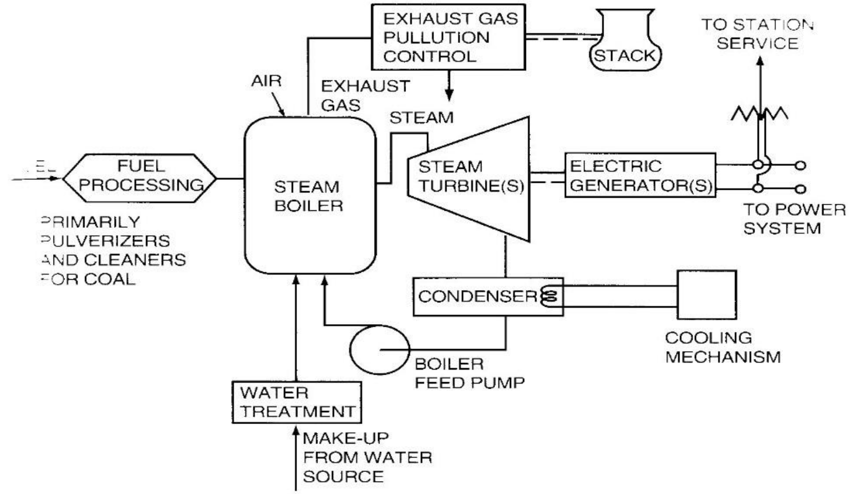
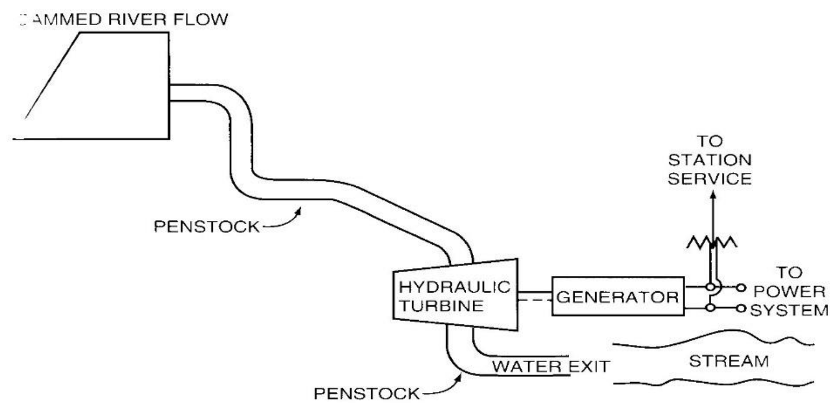


Figure 5.2. Schematic of conventional fossil steam power plant.

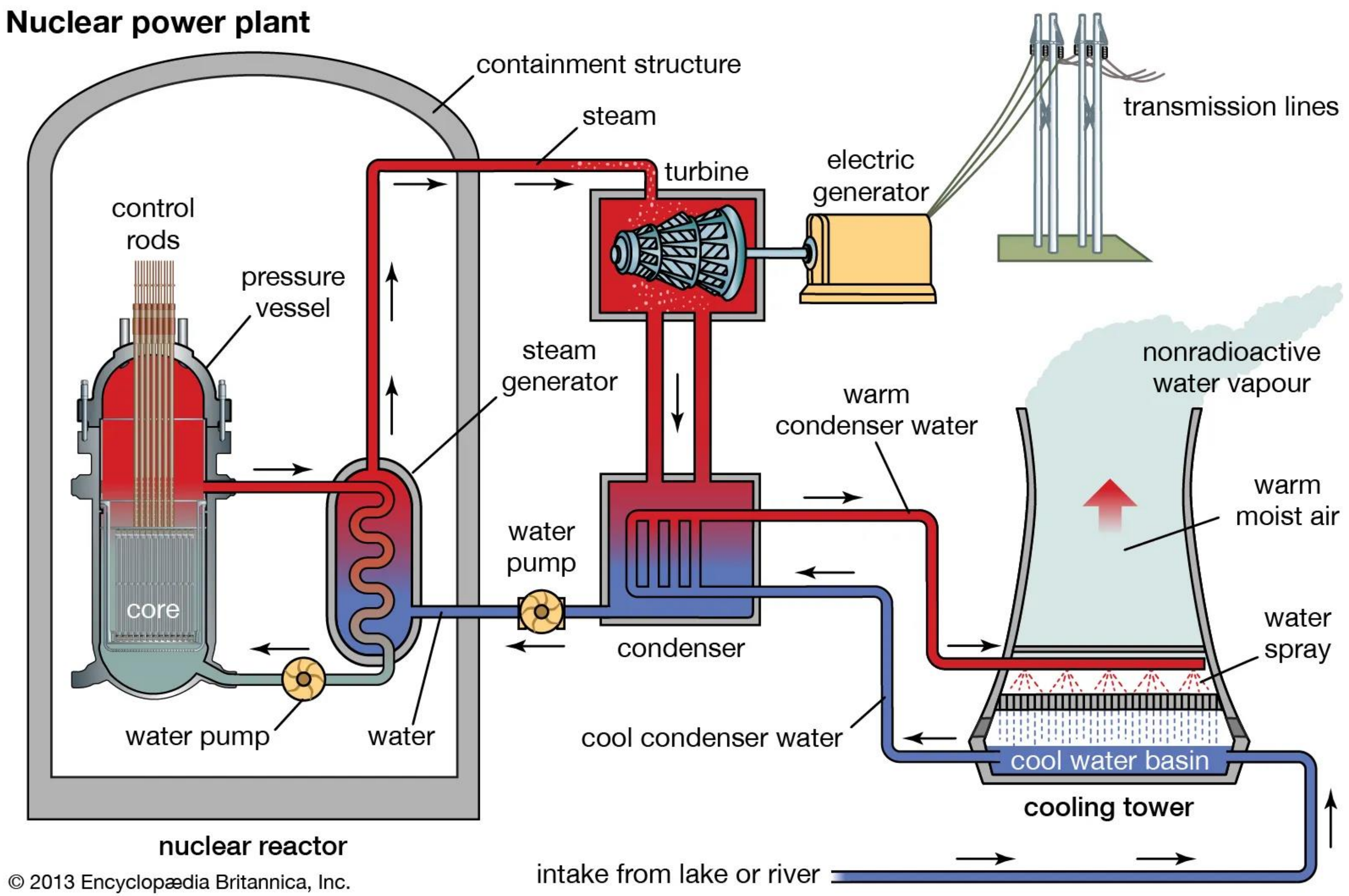


J. Casazza and F. Delea, Understanding Electric Power Systems: An Overview of the Technology and the Marketplace, IEEE Press, 2003 p. 61.

COMBINED CYCLE GENERATION

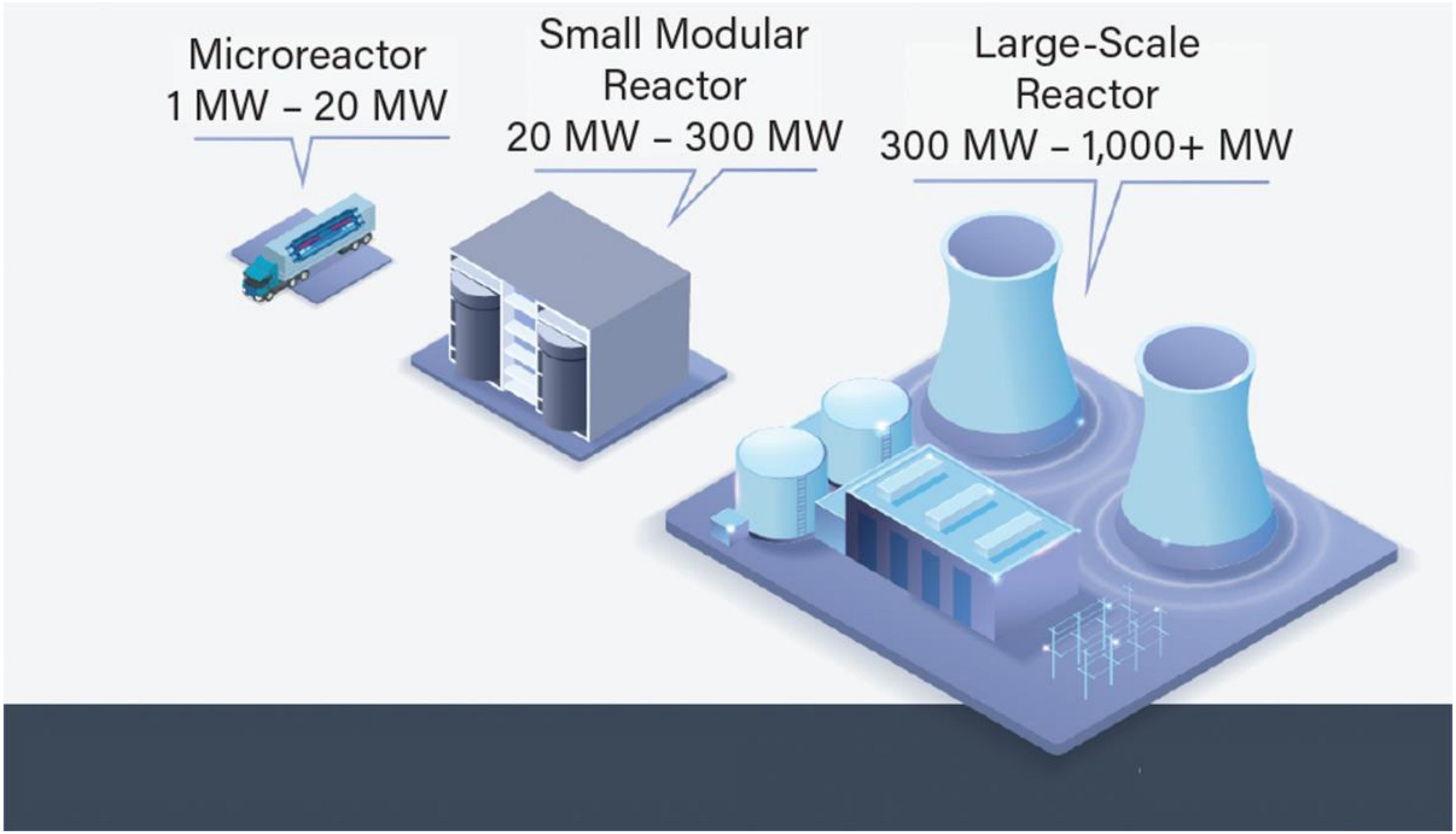
https://www.youtube.com/watch?v=qG7SlVfAuPA

NUCLEAR POWER – LARGE SCALE



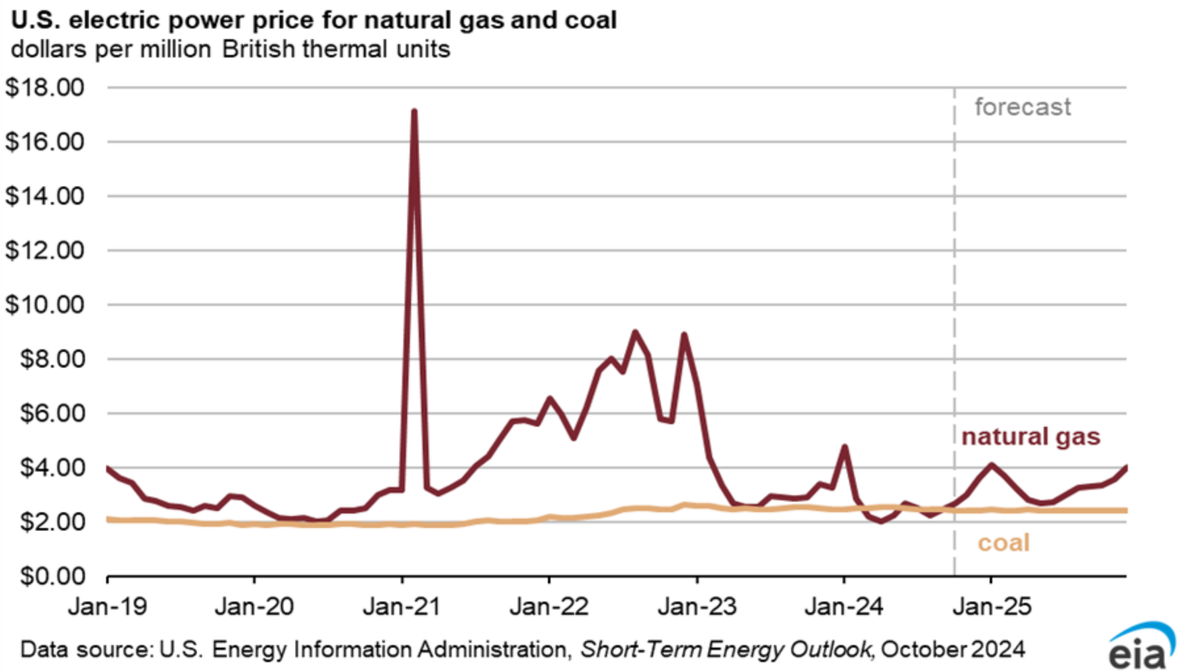
https://www.britannica.com/technology/nuclear-power

NUCLEAR POWER – SMALL MODULAR REACTORS (SMRS) & MICROREACTORS



https://www.aiche.org/resources/publications/cep/2022/april/advances-very-small-modular-nuclear-reactors

US COAL AND NATURAL GAS PRICES



https://www.eia.gov/outlooks/steo/report/elec_coal_renew.php

Commentary Commodities

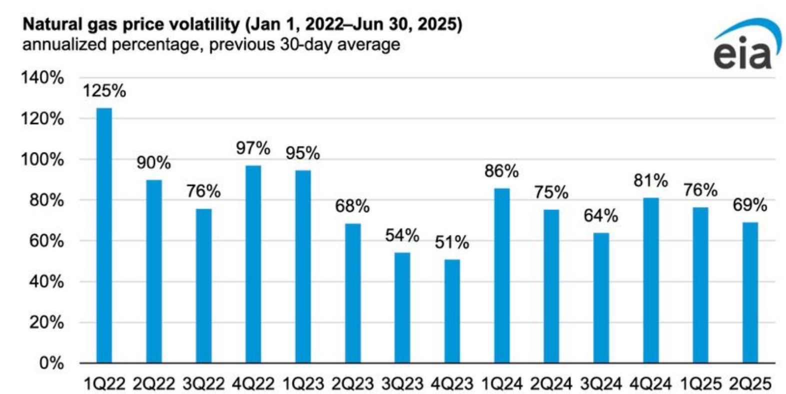
Don't expect Ukraine peace deal to alter Europe's gas gameplan

Ron Bousso

https://www.reuters.com/markets/commodities/dont-expect-ukraine-peace-deal-alter-europes-gas-gameplan-2025-11-26/

JULY 24, 2025

Natural gas price volatility fell over the first half of 2025



Data source: Bloomberg L.P.
Note: Annualized percentage, a widely used trading measure of price volatility, is the standard deviation for the previous quarter of daily changes in the Henry Hub front-month futures price multiplied by the square root of 252 (number of trading days in a year) multiplied by 100. Percentages are averages for that period. 1Q25=first quarter of 2025

https://www.eia.gov/todayinenergy/detail.php?id=65784

CAPACITY FACTORS

- Capacity is the ability of a generation unit to produce energy

- Energy is the amount that the unit produces

  E.g., a 100 MW unit that produces 500,000 MWh of energy has a capacity factor of:

  500,000 MWh/[100 MW * 8760] = 0.57 = 57%
  (Note: 8760 is the number of hours in a non-leap-year year)

- Compare a 1,000 MW nuclear power plant with a 90% capacity factor to a 1,000 MW wind farm with a 30% capacity factor with 1,000 MW of Photo Voltaic (PV) with a 15% capacity factor

- At the retail level, usage is measured in kW and kWh

- At the wholesale level, usage is measured in MW and MWh

1,000 kWh = 1 MWh	1,000 kW = 1 MW
1,000 MWh = 1 GWh	1,000 MW = 1 GW

ELECTRICITY UNITS

	Country-level Generation/Supply	Wholesale Generation/Supply	Retail Demand/Load
Capacity (Size)	GW - gigawatt	MW - megawatt	kW - kilowatt
Energy (Usage)	GWh – gigawatt-hour	MWh – megawatt-hour	kWh – kilowatt-hour
Price/Cost		$/MW or $/MW-year $/MWh	$/kW or $/kW-day $/kWh

James Watt - 30 January 1736 – 25 August 1819) was a Scottish inventor, mechanical engineer, and chemist who improved on Thomas Newcomen's 1712 Newcomen steam engine with his Watt steam engine in 1776, which was fundamental to the changes brought by the Industrial Revolution in both his native Great Britain and the rest of the world.

https://en.wikipedia.org/wiki/James_Watt

CAPACITY FACTORS OF US ELECTRICITY SOURCES

Yearly Capacity Factors

Year/Month	Geothermal		Hydroelectric		Nuclear		Other Biomass		Other Fossil Gas		Solar				Wind	
											Photovoltaic		Thermal			
	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor	Time Adjusted Capacity (MW)	Capacity Factor
Annual Data																
2014	2,513.3	72.0%	79,582.8	37.2%	98,569.3	91.7%	5,114.6	62.7%	1,994.0	54.0%	6,555.6	25.6%	1,445.3	18.3%	60,587.8	34.0%
2015	2,523.0	71.9%	79,650.8	35.7%	98,614.6	92.3%	5,104.5	62.6%	2,527.7	60.8%	9,521.6	25.5%	1,697.3	21.7%	67,106.2	32.2%
2016	2,516.6	71.6%	79,806.0	38.2%	99,364.8	92.3%	5,099.5	62.7%	2,458.8	64.8%	14,161.4	25.0%	1,757.9	22.1%	74,162.7	34.5%
2017	2,460.4	73.2%	79,698.8	43.0%	99,619.5	92.3%	5,125.6	61.8%	2,375.8	62.8%	21,940.9	25.6%	1,757.9	21.8%	83,355.6	34.6%
2018	2,391.5	76.0%	79,771.9	41.9%	99,605.2	92.5%	5,059.0	61.8%	2,543.9	65.4%	27,143.3	25.1%	1,757.9	23.6%	89,228.5	34.6%
2019	2,535.2	69.6%	79,838.0	41.2%	98,836.7	93.4%	4,786.5	62.5%	2,504.1	67.4%	31,840.8	24.3%	1,758.1	21.2%	97,564.8	34.4%
2020	2,561.5	69.1%	79,810.4	40.7%	97,238.3	92.4%	4,653.8	62.5%	2,275.2	64.6%	39,458.1	24.2%	1,747.9	20.6%	107,387.7	35.3%
2021	2,588.5	69.8%	79,878.4	36.0%	95,802.7	92.8%	4,490.4	63.2%	1,902.5	60.9%	51,219.7	24.4%	1,629.0	20.5%	123,757.1	34.4%
2022	2,616.0	69.0%	80,054.5	36.3%	94,969.9	92.7%	4,402.5	60.2%	1,716.0	61.6%	64,501.0	24.4%	1,480.0	23.1%	136,669.4	35.9%
2023	2,670.6	69.4%	79,982.5	35.0%	95,065.2	93.0%	4,162.6	60.4%	1,871.6	53.8%	77,130.8	23.2%	1,480.0	22.1%	143,443.5	33.2%

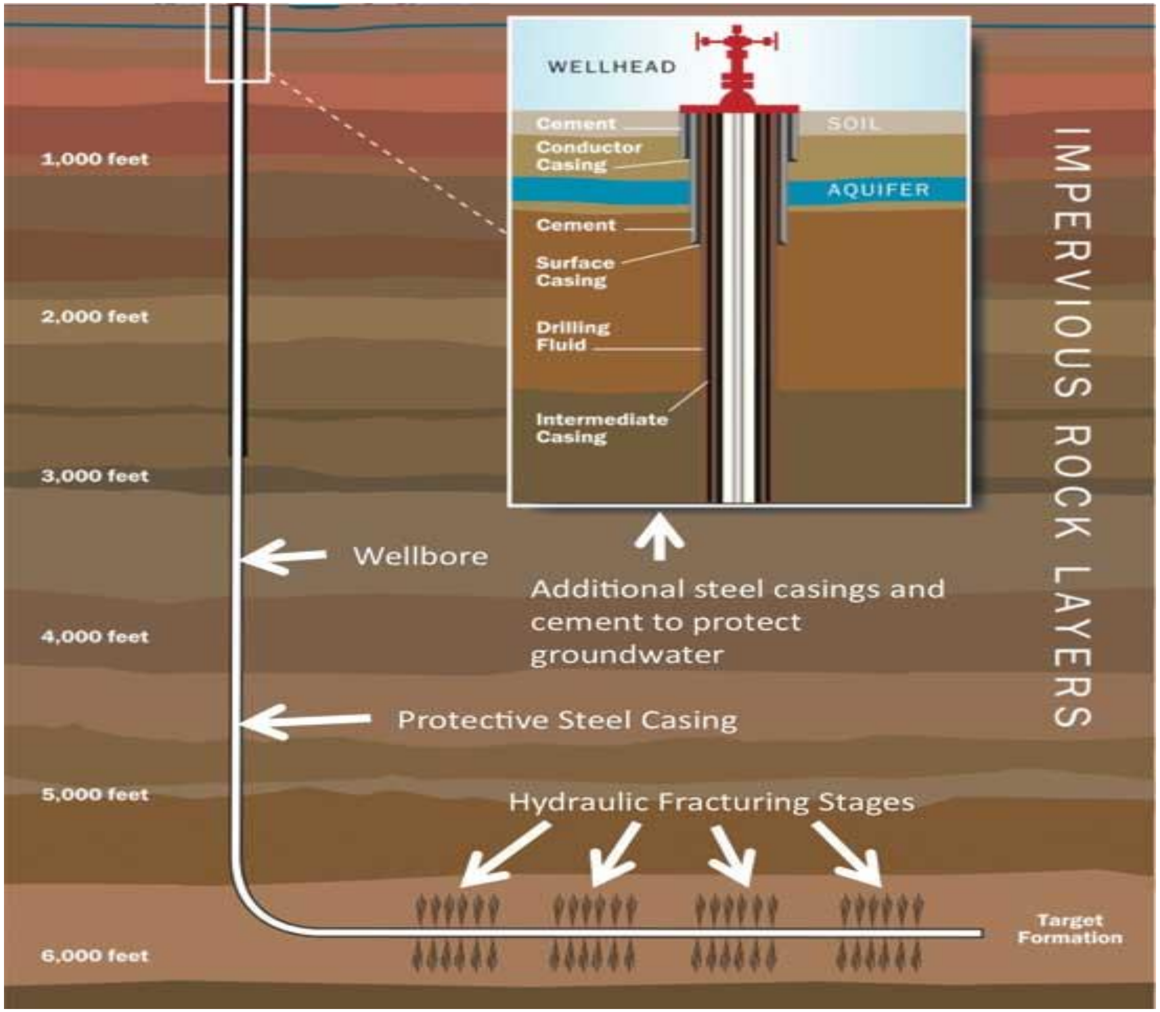
2023 Monthly Capacity Factors

Year 2023	Geothermal TAC (MW)	Geothermal CF	Hydroelectric TAC (MW)	Hydroelectric CF	Nuclear TAC (MW)	Nuclear CF	Other Biomass TAC (MW)	Other Biomass CF	Other Fossil Gas TAC (MW)	Other Fossil Gas CF	Solar PV TAC (MW)	Solar PV CF	Solar Thermal TAC (MW)	Solar Thermal CF	Wind TAC (MW)	Wind CF
January	2,657.6	71.2%	79,971.6	38.2%	94,598.2	100.7%	4,259.7	60.5%	1,896.8	48.4%	71,639.2	14.2%	1,480.0	7.7%	140,883.2	36.3%
February	2,657.6	72.4%	79,989.6	37.1%	94,598.2	95.7%	4,158.1	59.6%	1,896.8	54.3%	72,849.9	18.6%	1,480.0	10.9%	141,532.3	43.1%
March	2,623.3	73.2%	79,989.6	35.9%	94,598.2	89.3%	4,158.1	58.3%	1,866.8	54.7%	73,402.2	21.5%	1,480.0	14.0%	142,245.7	40.6%
April	2,623.3	70.6%	80,007.4	34.4%	94,598.2	83.2%	4,158.1	55.5%	1,866.8	54.7%	73,948.2	26.8%	1,480.0	27.8%	142,659.5	41.2%
May	2,684.3	66.9%	79,978.4	46.5%	94,598.2	86.9%	4,158.1	61.0%	1,866.8	51.1%	74,880.6	29.5%	1,480.0	27.4%	142,976.1	30.0%
June	2,684.3	66.5%	79,979.8	37.5%	94,598.2	95.2%	4,158.1	62.3%	1,866.8	54.1%	75,981.9	30.9%	1,480.0	34.6%	143,730.8	26.4%
July	2,684.3	64.6%	79,979.8	36.9%	94,598.2	99.1%	4,159.4	61.9%	1,866.8	57.0%	77,601.9	30.9%	1,480.0	35.0%	143,730.8	25.9%
August	2,671.8	63.1%	79,979.8	35.8%	95,712.2	97.9%	4,155.4	61.3%	1,866.8	56.4%	78,928.8	28.7%	1,480.0	28.3%	144,230.3	26.2%
Sept	2,671.8	67.4%	79,977.0	29.4%	95,712.2	95.1%	4,155.4	58.0%	1,866.8	52.9%	79,648.0	25.6%	1,480.0	27.7%	144,334.3	27.1%
October	2,695.8	70.4%	79,974.9	26.3%	95,712.2	86.3%	4,147.2	59.4%	1,866.8	51.2%	80,606.0	22.0%	1,480.0	26.1%	144,417.5	33.1%
November	2,695.8	73.7%	79,979.5	29.6%	95,712.2	90.3%	4,148.8	61.7%	1,866.8	54.0%	82,386.8	16.7%	1,480.0	15.7%	145,235.0	34.6%
December	2,695.8	72.9%	79,983.6	32.1%	95,712.2	96.7%	4,133.2	64.5%	1,866.8	56.4%	83,392.8	13.5%	1,480.0	9.9%	145,232.0	34.6%

https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b

NORTH AMERICAN NATURAL GAS RESOURCES

SHALE NATURAL GAS & FRACKING



Fracking is a method of extracting oil and natural gas from rock formations

U.S. Liquefied Natural Gas (LNG) Terminals

North America liquefied natural gas export facilities, existing and under construction (2016–2027)

eia

Data source: U.S. Energy Information Administration, *Liquefaction Capacity File*, and trade press
Note: Bcf/d=billion cubic feet per day. Map current as of October 2023.

U.S. Department of Energy Reverses Biden LNG Pause, Restores Trump Energy Dominance Agenda

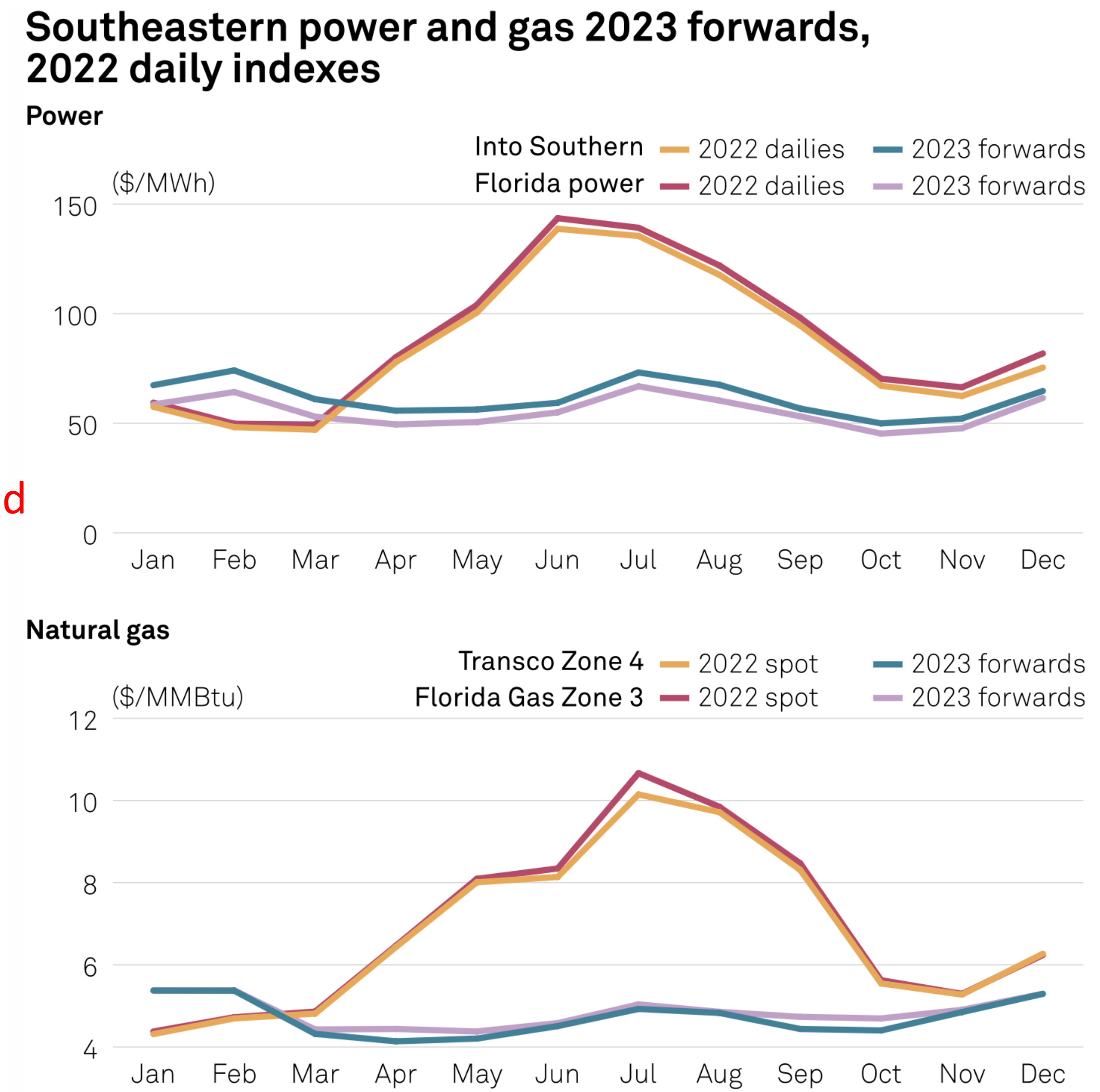
The U.S. Department of Energy, effective today, is ending the Liquefied Natural Gas pause, and returning to regular order.

Energy.gov

January 21, 2025

https://www.energy.gov/articles/us-department-energy-reverses-biden-lng-pause-restores-trump-energy-dominance-agenda

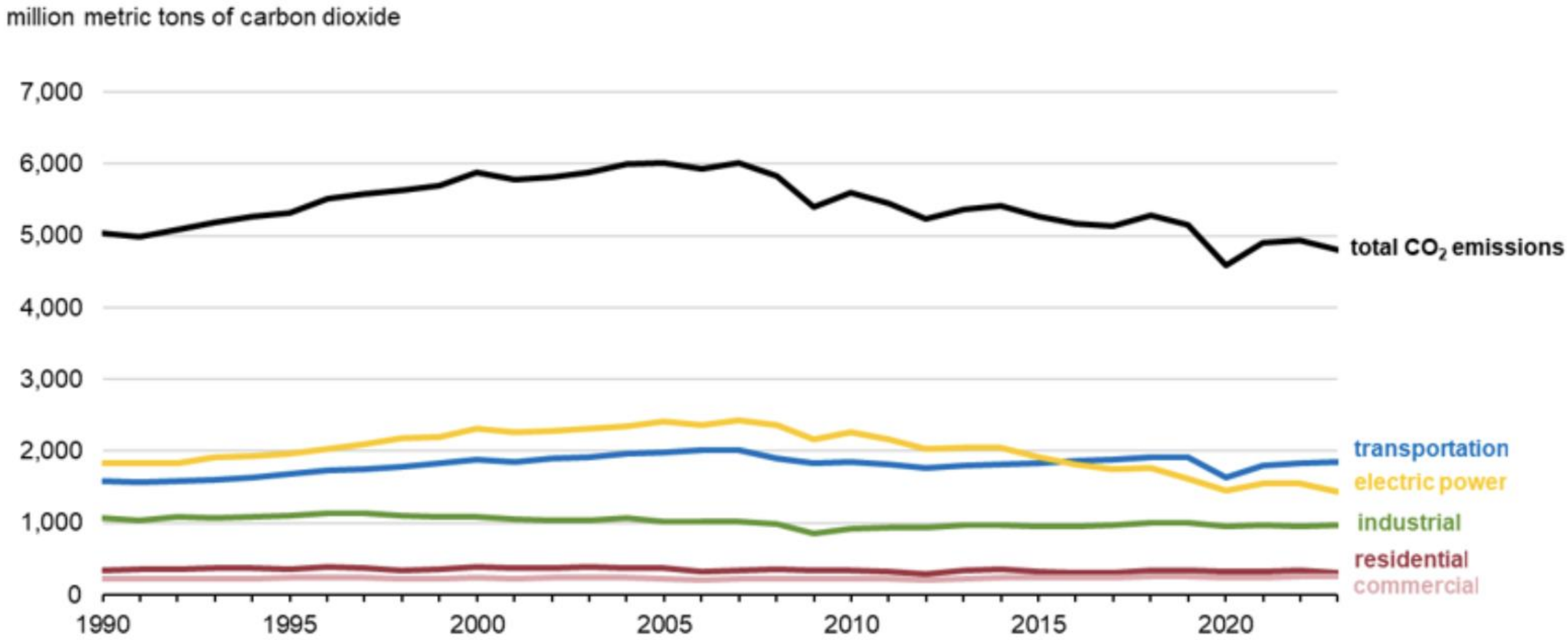
Electricity & Natural Gas Prices are Highly Positively Correlated



Notes: All power day-ahead indexes and forwards are on-peak. Day-ahead indexes are for delivery through Dec. 29. Forwards as of Dec. 28, 2022.
Source: S&P Global Commodity Insights

https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/122922-southeast-us-power-markets-face-big-changes-in-2023-as-forwards-indicate-weaker-prices

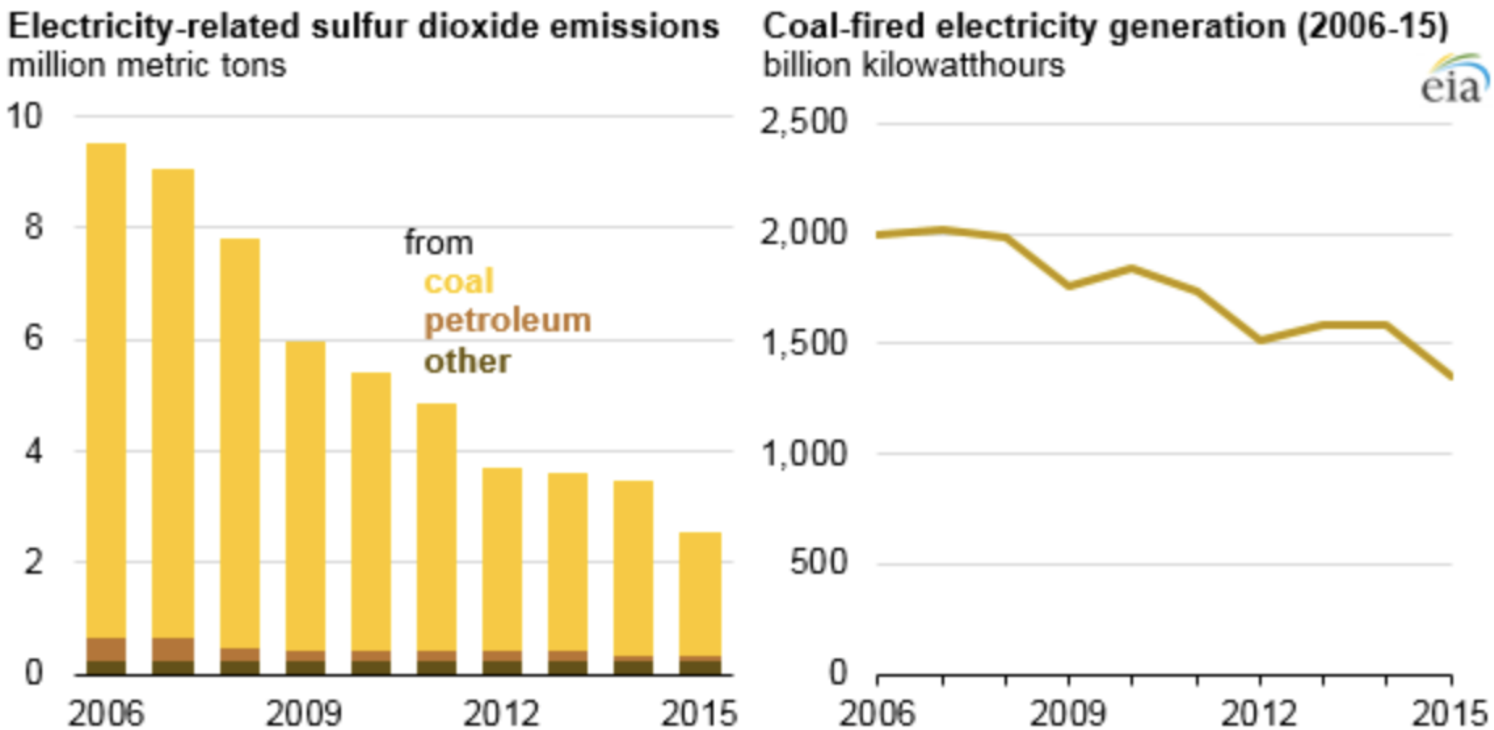
Figure 1. U.S. energy-related CO_2 emissions by sector, 1990–2023



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, March 2024, Tables 11.1–11.6

https://www.eia.gov/environment/emissions/carbon/

Sulfur dioxide emissions from U.S. power plants have fallen faster than coal generation

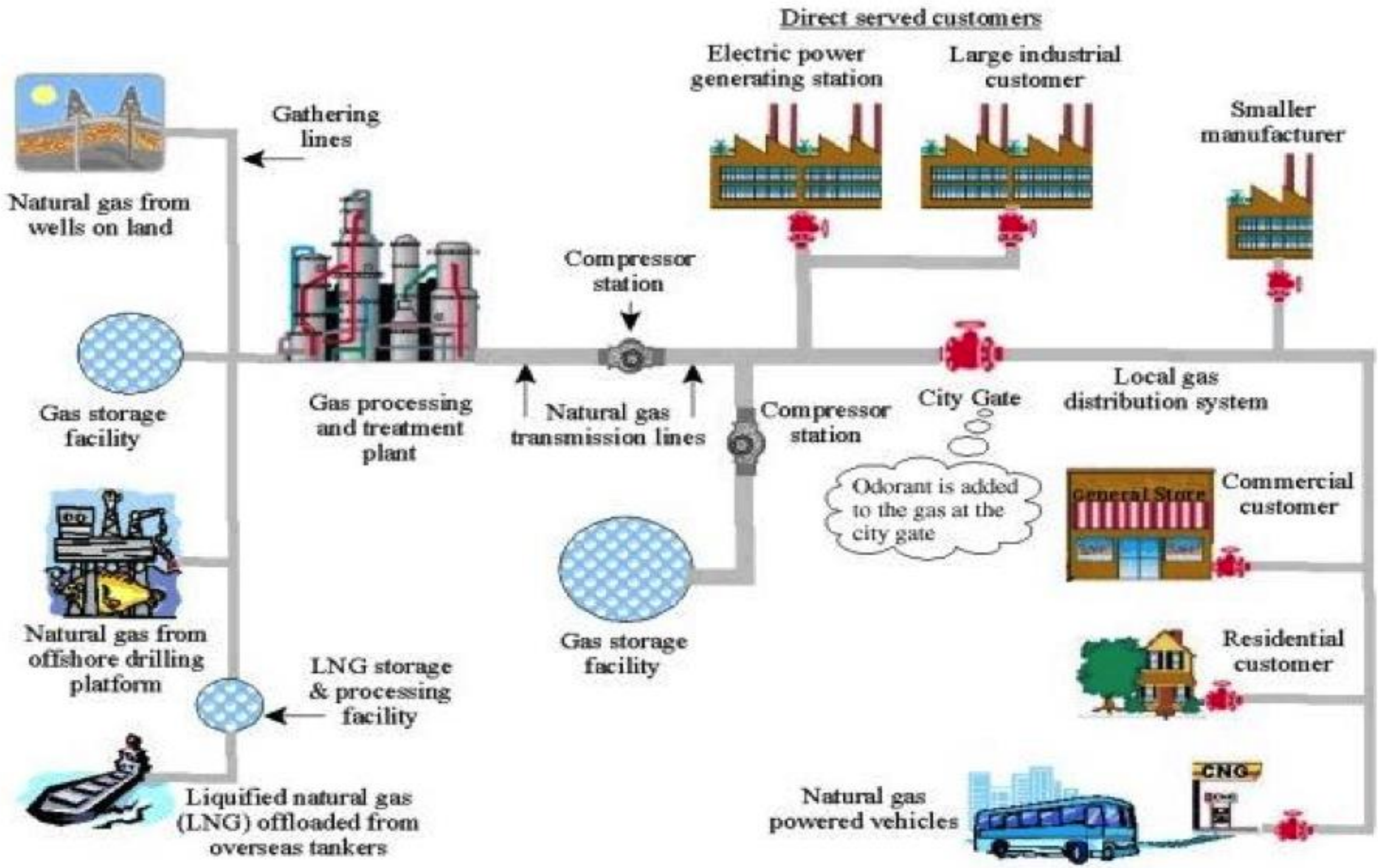


Source: U.S. Energy Information Administration, *Electric Power Annual*

Sulfur dioxide (SO2) emissions produced in the generation of electricity at power plants in the United States declined by 73% from 2006 to 2015, a much larger reduction than the 32% decrease in coal-fired electricity generation over that period. From 2014 to 2015, the most recent year with complete power plant emissions data, SO2 emissions fell 26%—the largest annual drop in percentage terms in the previous decade. Nearly all electricity-related SO2 emissions are associated with coal-fired generation.

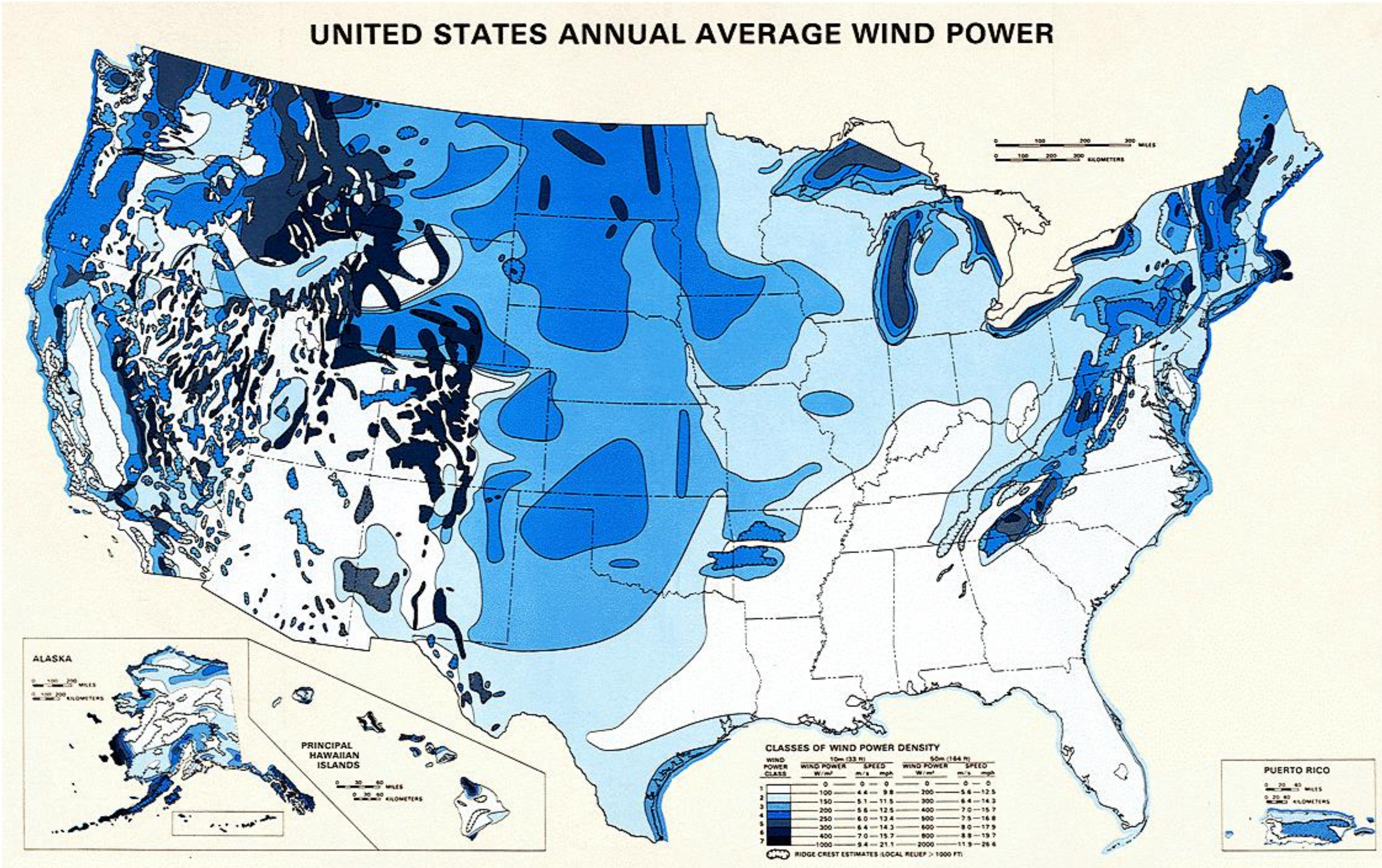
https://www.eia.gov/todayinenergy/detail.php?id=29812

GAS-ELECTRICITY INTERDEPENDENCE

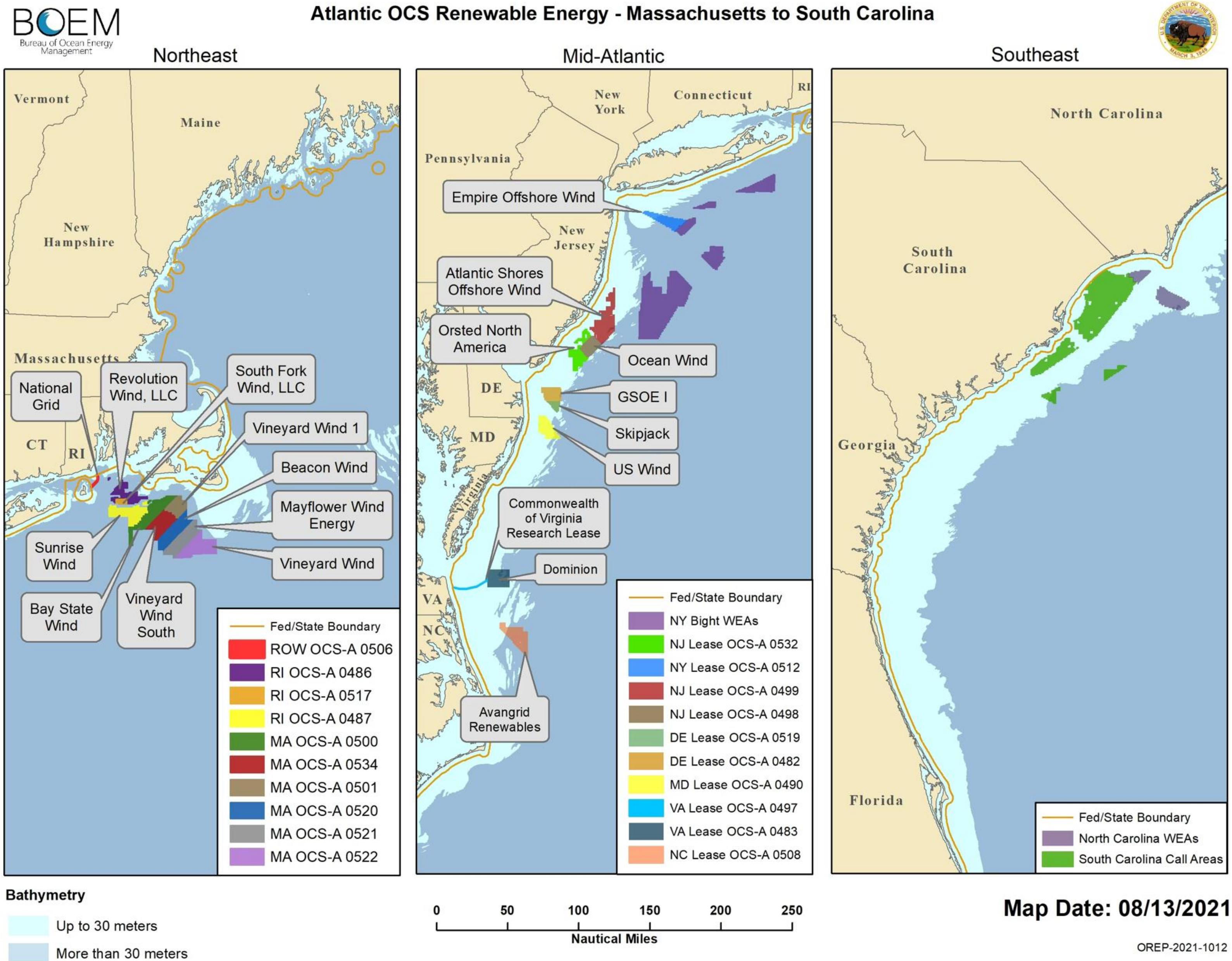


Natural gas disruption or extreme cold weather can severely impact electricity reliability and prices

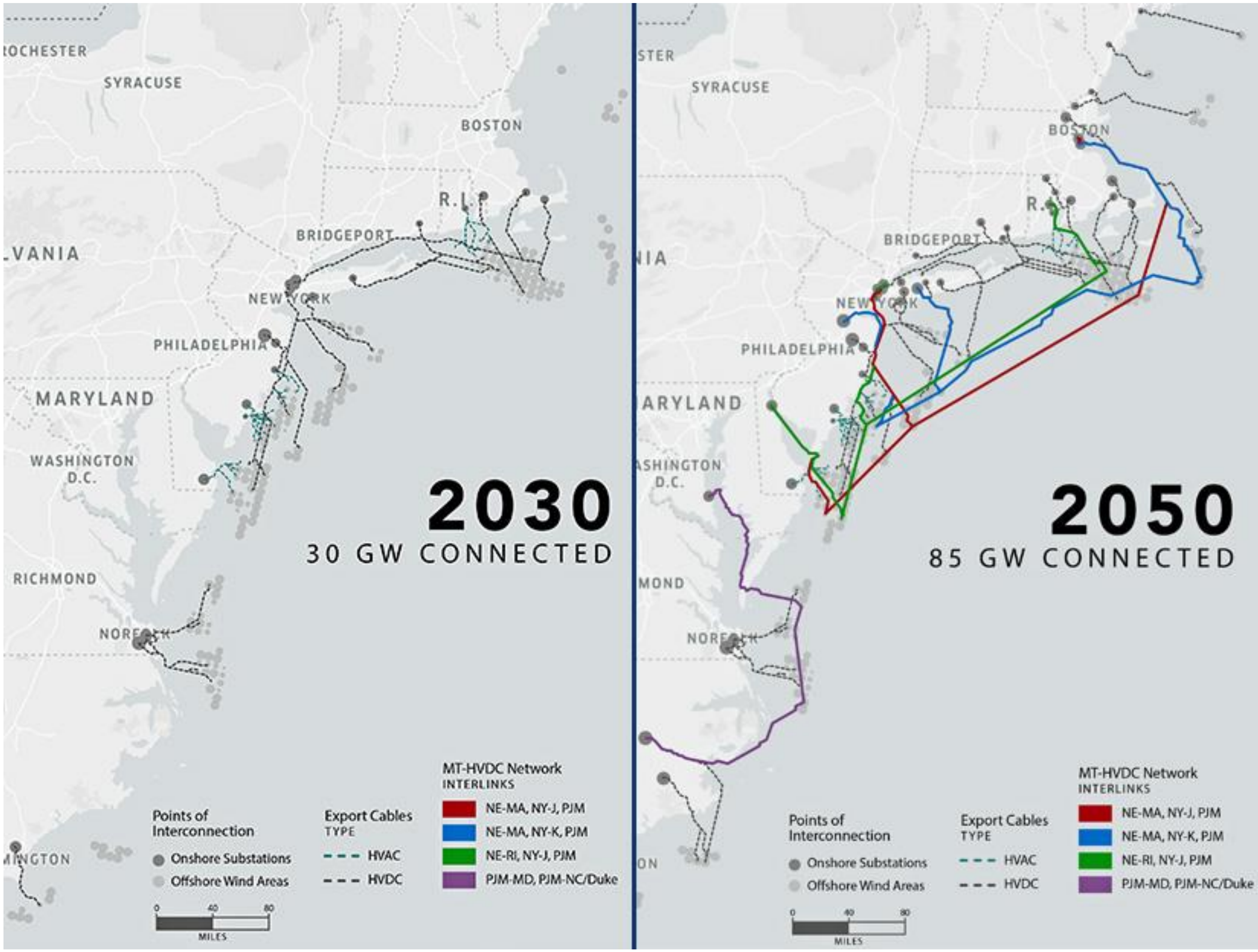
US WIND RESOURCES



Atlantic OCS Renewable Energy - Massachusetts to South Carolina



EAST COST OFFSHORE WIND POWER



TRUMP OFFSHORE & ON SHORE WIND ACTIONS

PRESIDENTIAL ACTIONS

TEMPORARY WITHDRAWAL OF ALL AREAS ON THE OUTER CONTINENTAL SHELF FROM OFFSHORE WIND LEASING AND REVIEW OF THE FEDERAL GOVERNMENT'S LEASING AND PERMITTING PRACTICES FOR WIND PROJECTS

January 20, 2025

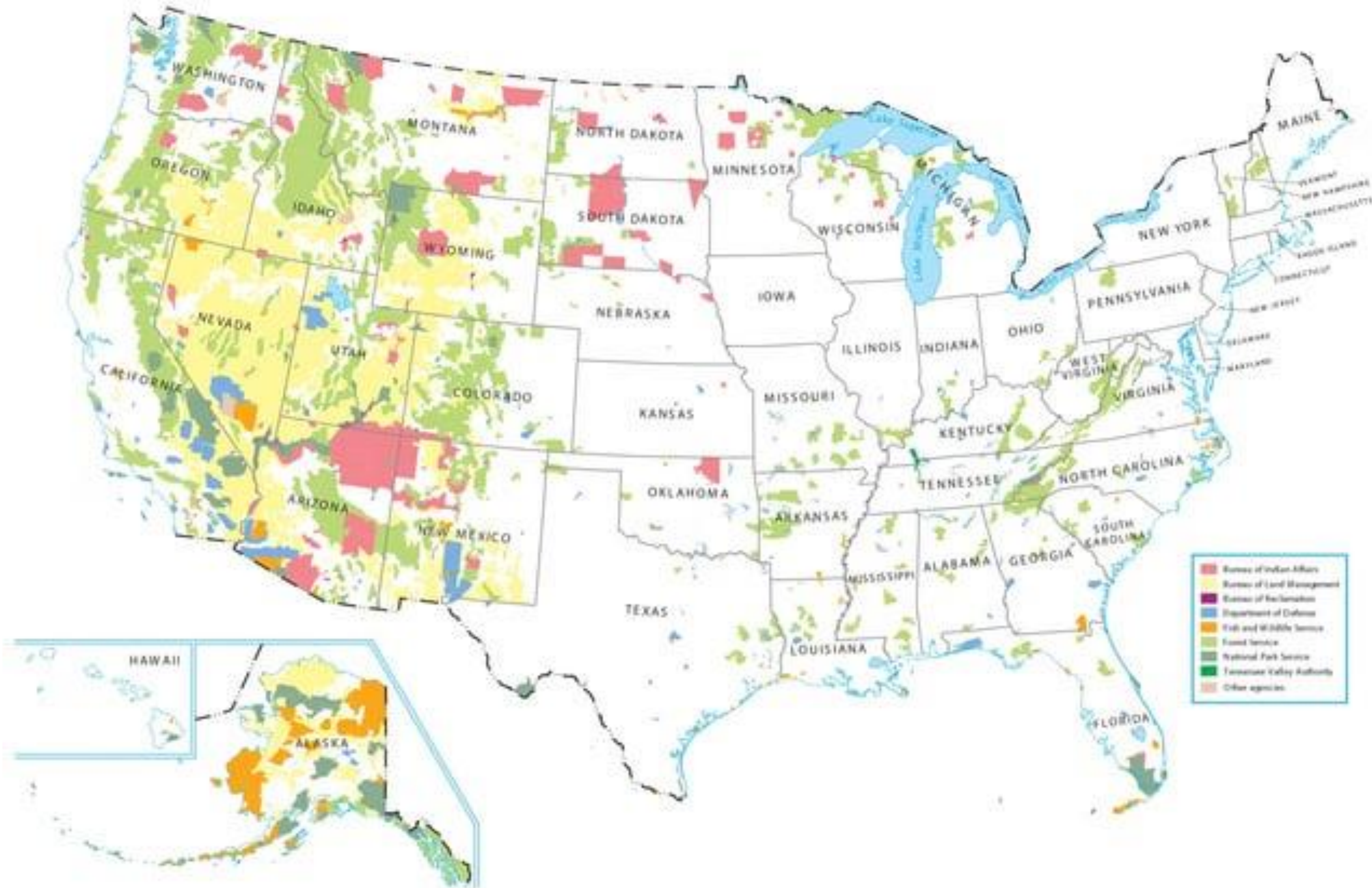
https://www.whitehouse.gov/presidential-actions/2025/01/temporary-withdrawal-of-all-areas-on-the-outer-continental-shelf-from-offshore-wind-leasing-and-review-of-the-federal-governments-leasing-and-permitting-practices-for-wind-projects/

Moratorium on New or Renewed Federal Actions for Onshore and Offshore Wind Projects, Pending Federal Review

The Memorandum[1] orders relevant federal agencies to not issue new or renewed approvals, rights of way, permits, leases or loans for onshore or offshore wind projects pending the completion of a comprehensive federal review of federal wind leasing and permitting practices. The Memorandum orders a multi-federal agency review of onshore and offshore wind projects that could impact the fate of such projects.[2]

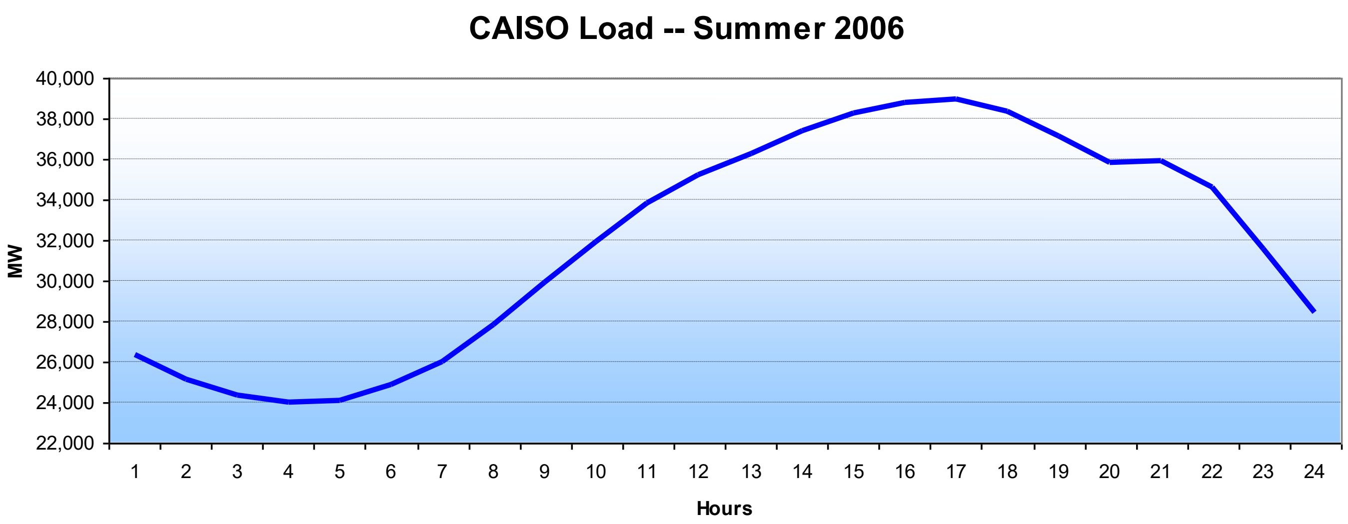
https://www.whitecase.com/insight-alert/trump-orders-moratorium-federal-actions-wind-projects-and-withdrawal-new-or-renewed

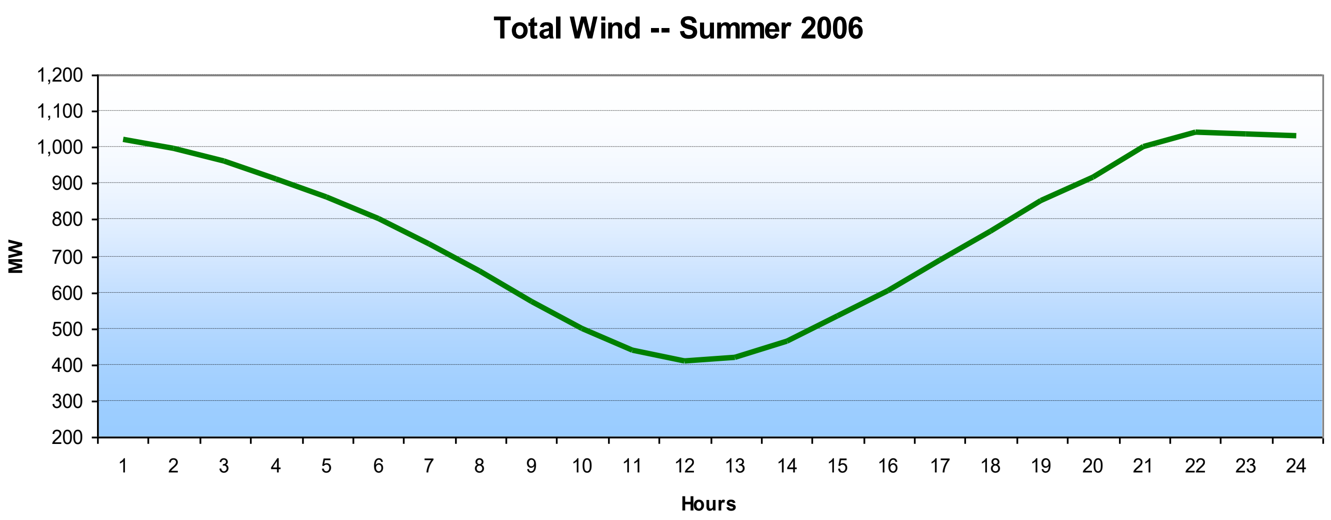
U.S. FEDERAL LANDS



https://www.reddit.com/r/neoliberal/comments/151o35d/what_should_the_united_states_government_do_with/?rdt=33357

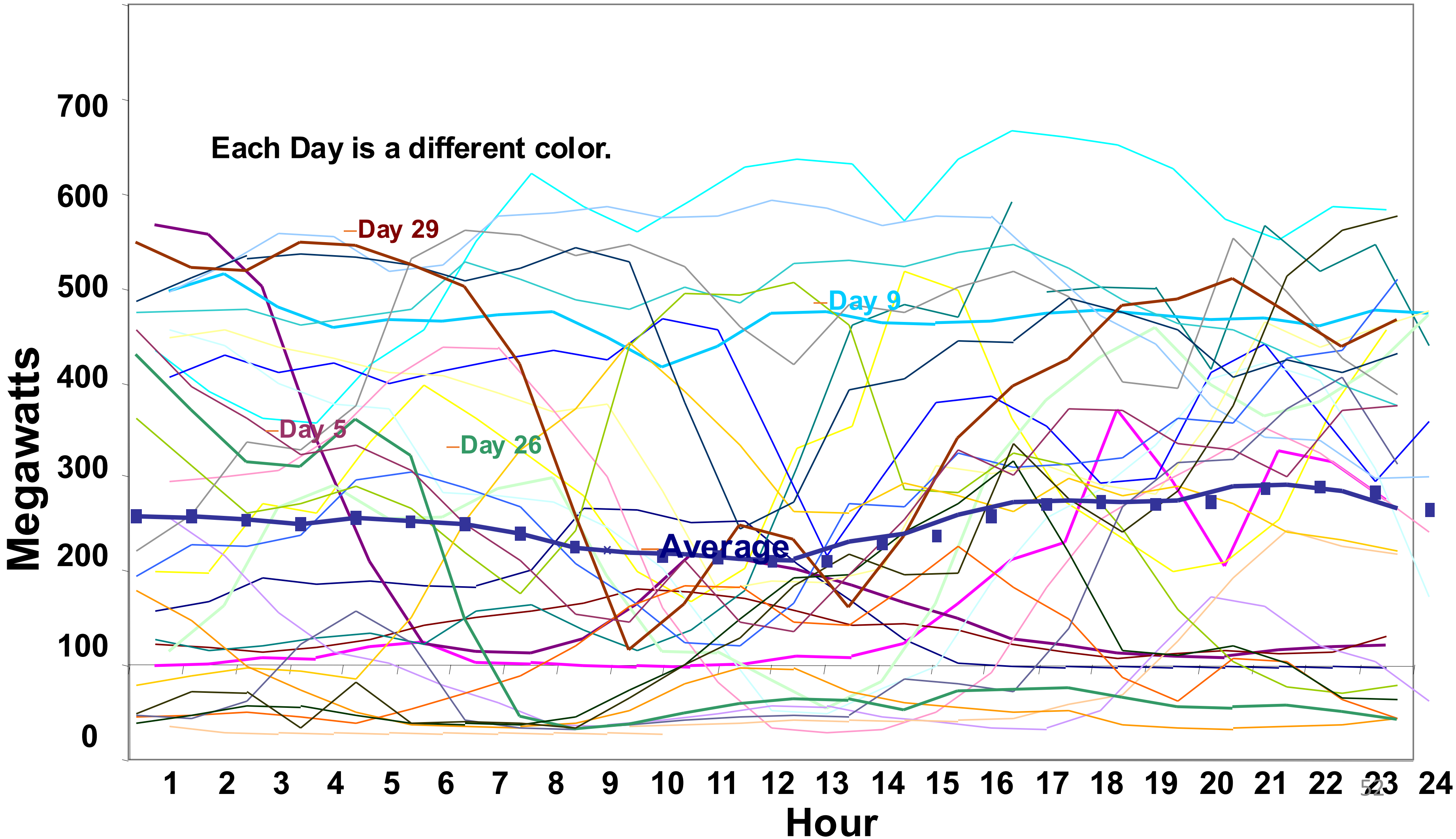
WIND AVAILABILITY



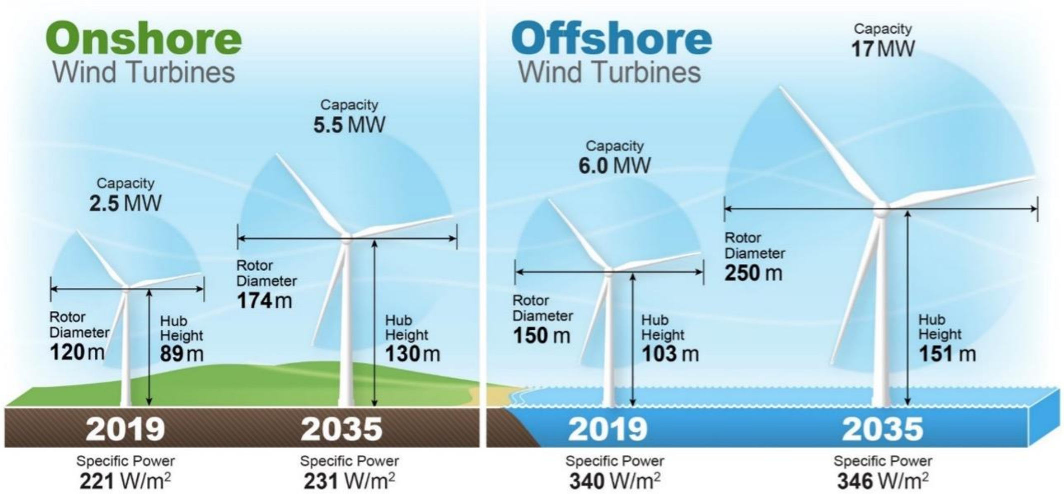


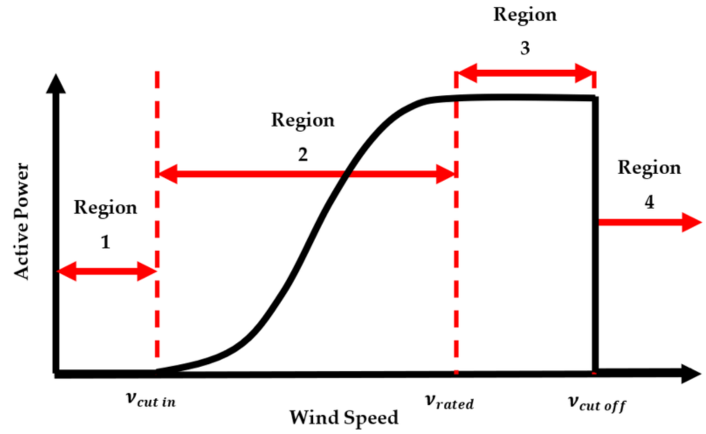
WIND VARIABILITY

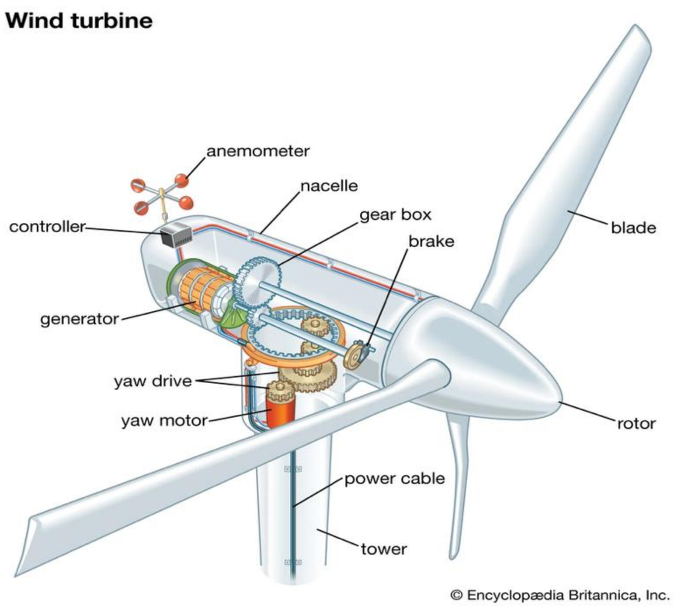
The average for April 2005 is smooth, but the day-to-day variability is great, showing the importance of improved forecasting tools and telemetry to the operating floor.

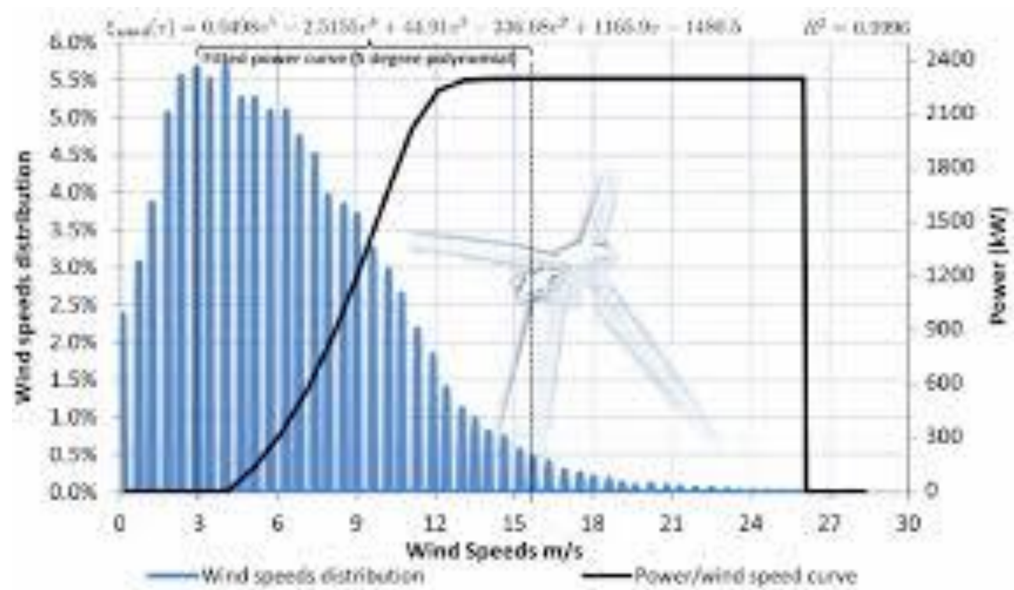


WIND TURBINES

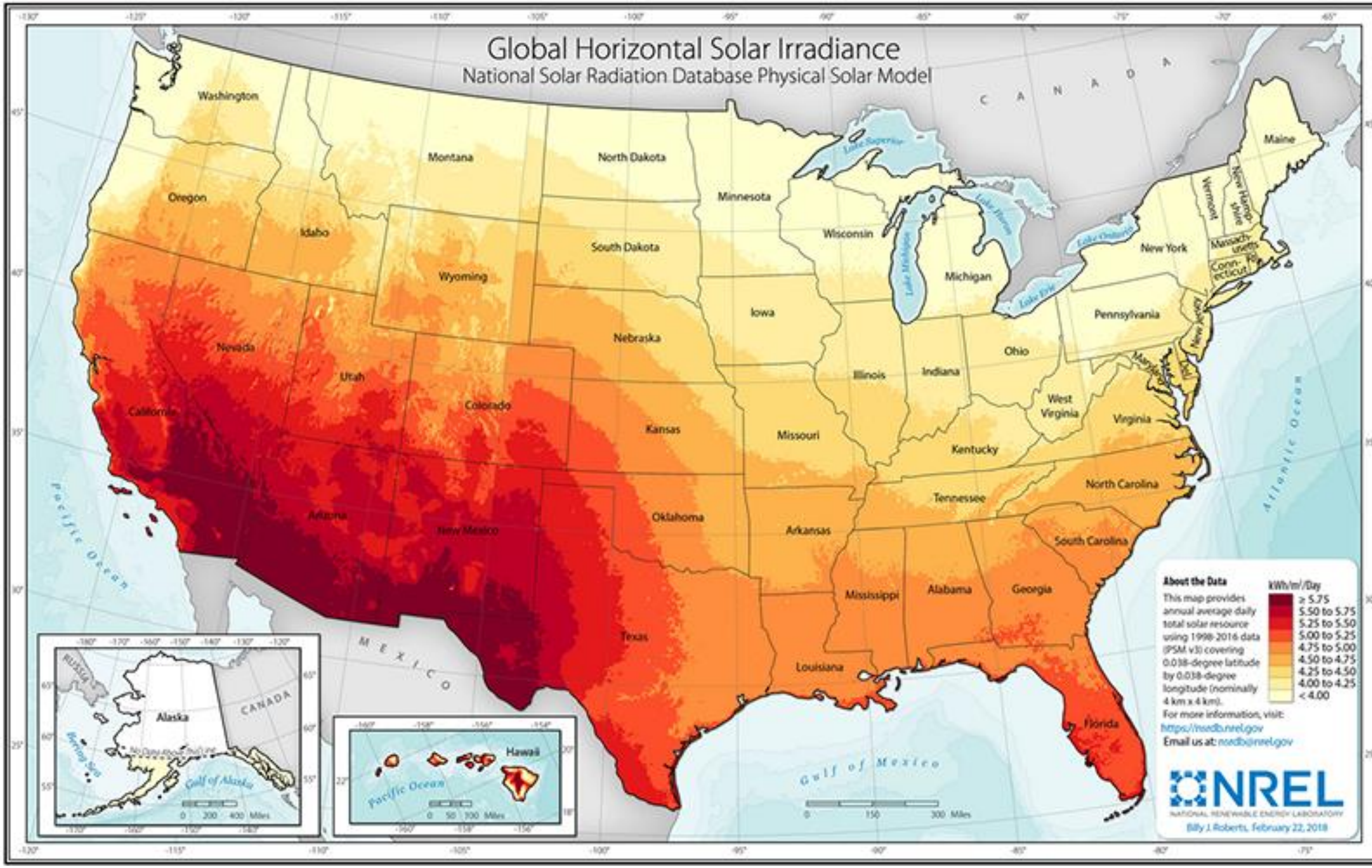








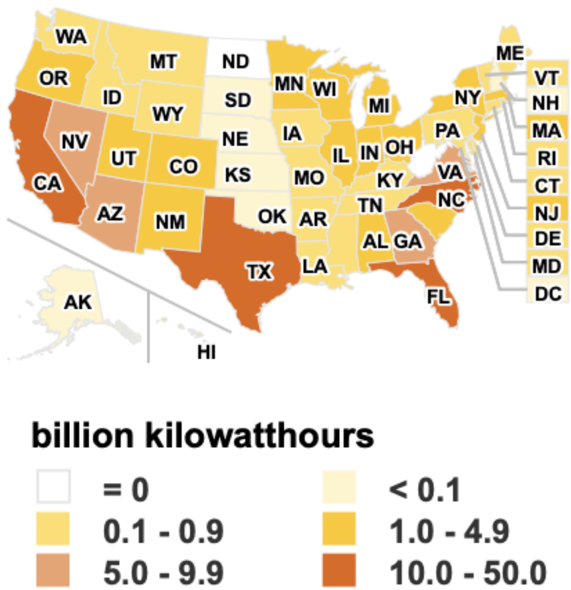
U.S. SOLAR AVAILABILITY



https://www.eia.gov/energyexplained/solar/where-solar-is-found.php

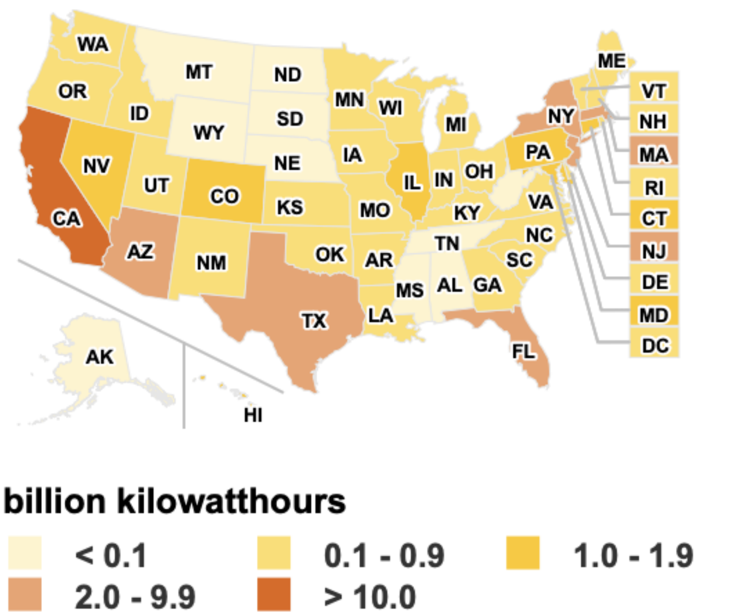
SOLAR GENERATION BY STATE

Utility-scale solar electricity generation by state in 2023



Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2024, preliminary data
Note: Includes solar photovoltaic and solar thermal-electric power plants with at least 1 megawatt of alternating current electricity generation capacity.

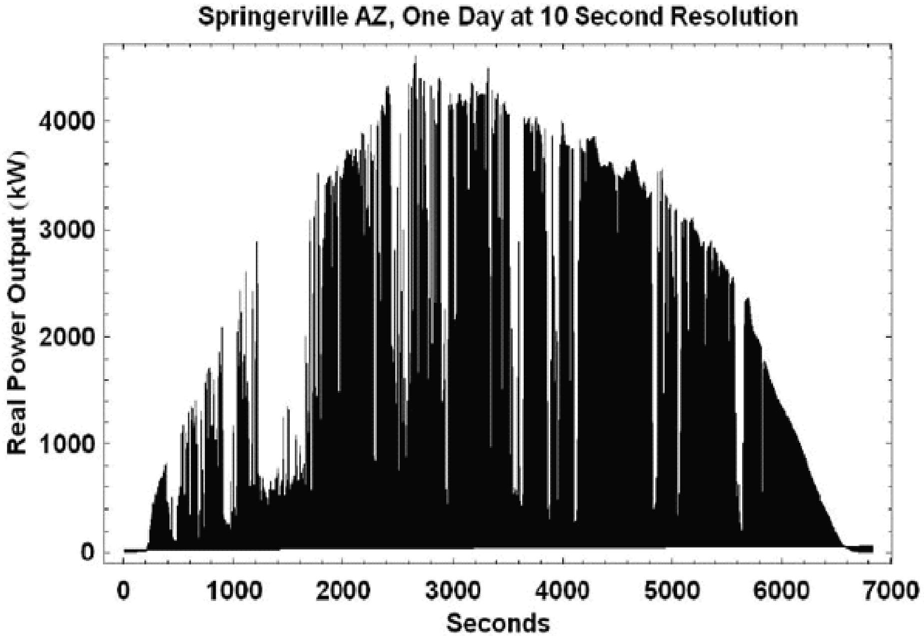
Small-scale solar photovoltaic electricity generation by state in 2023

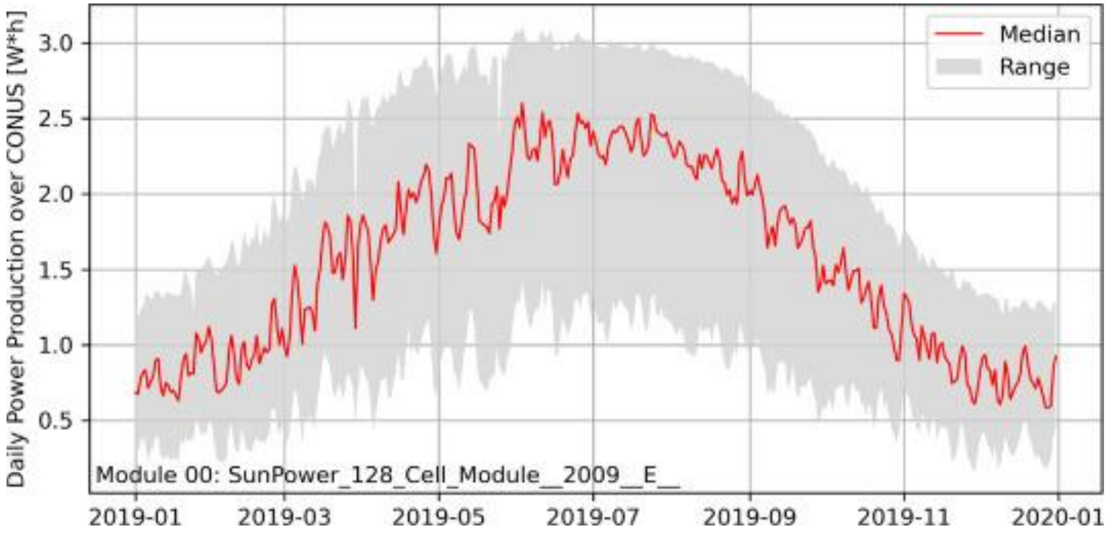


Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2024, preliminary data
Note: Small-scale plants have less than 1 megawatt of alternating current electricity generation capacity.

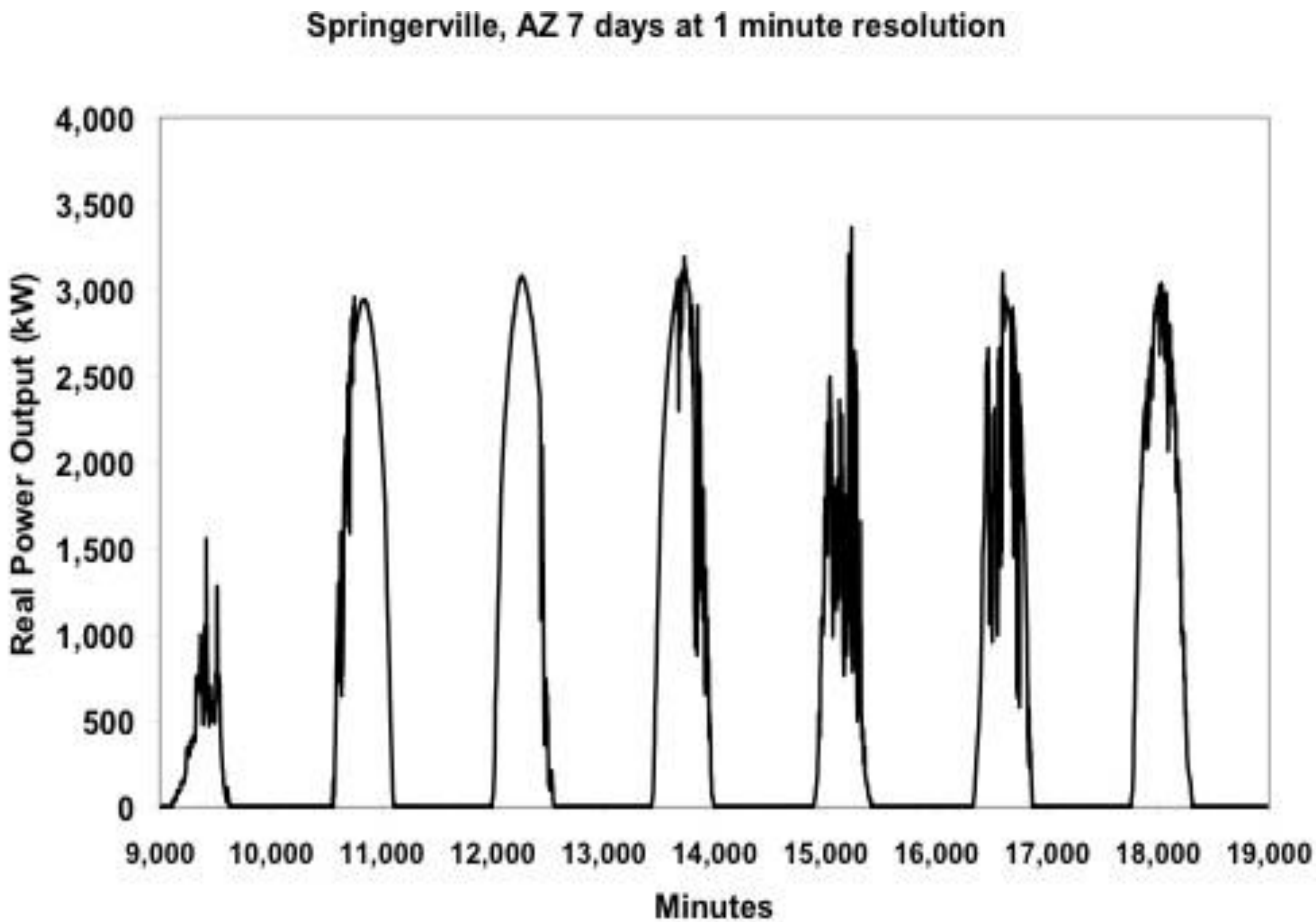
https://www.eia.gov/energyexplained/solar/where-solar-is-found.php

SOLAR VARIABILITY

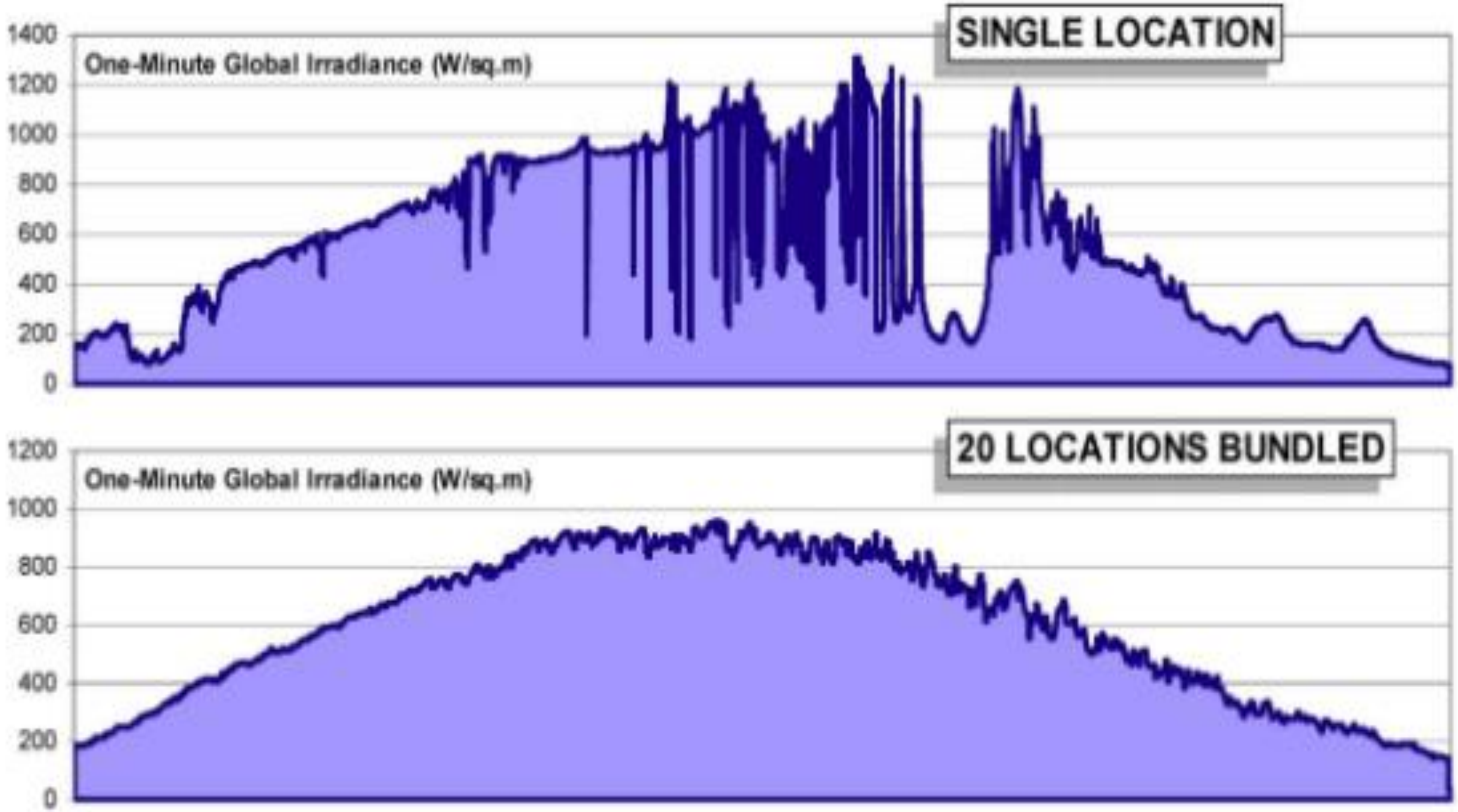




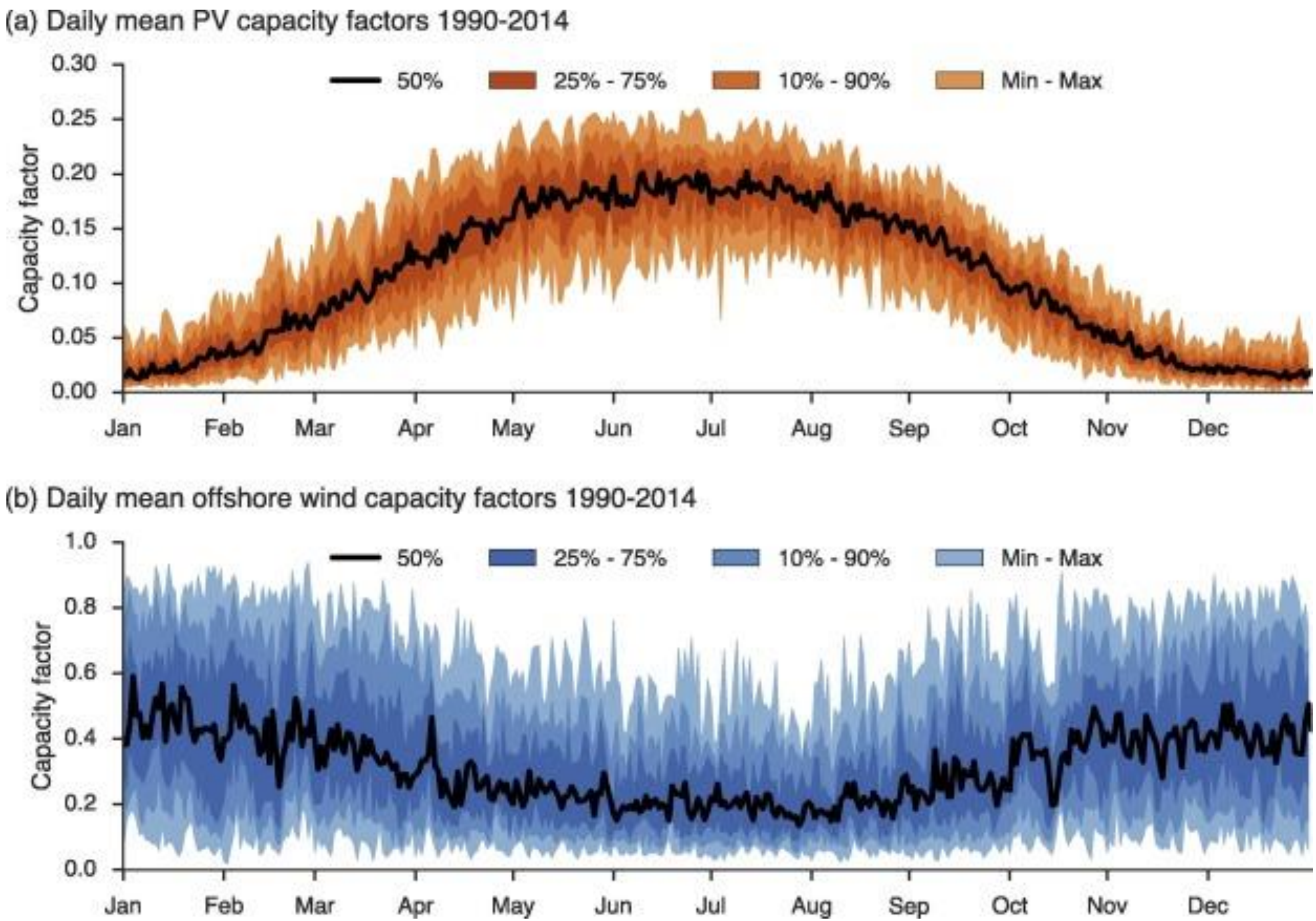
SOLAR VARIABILITY



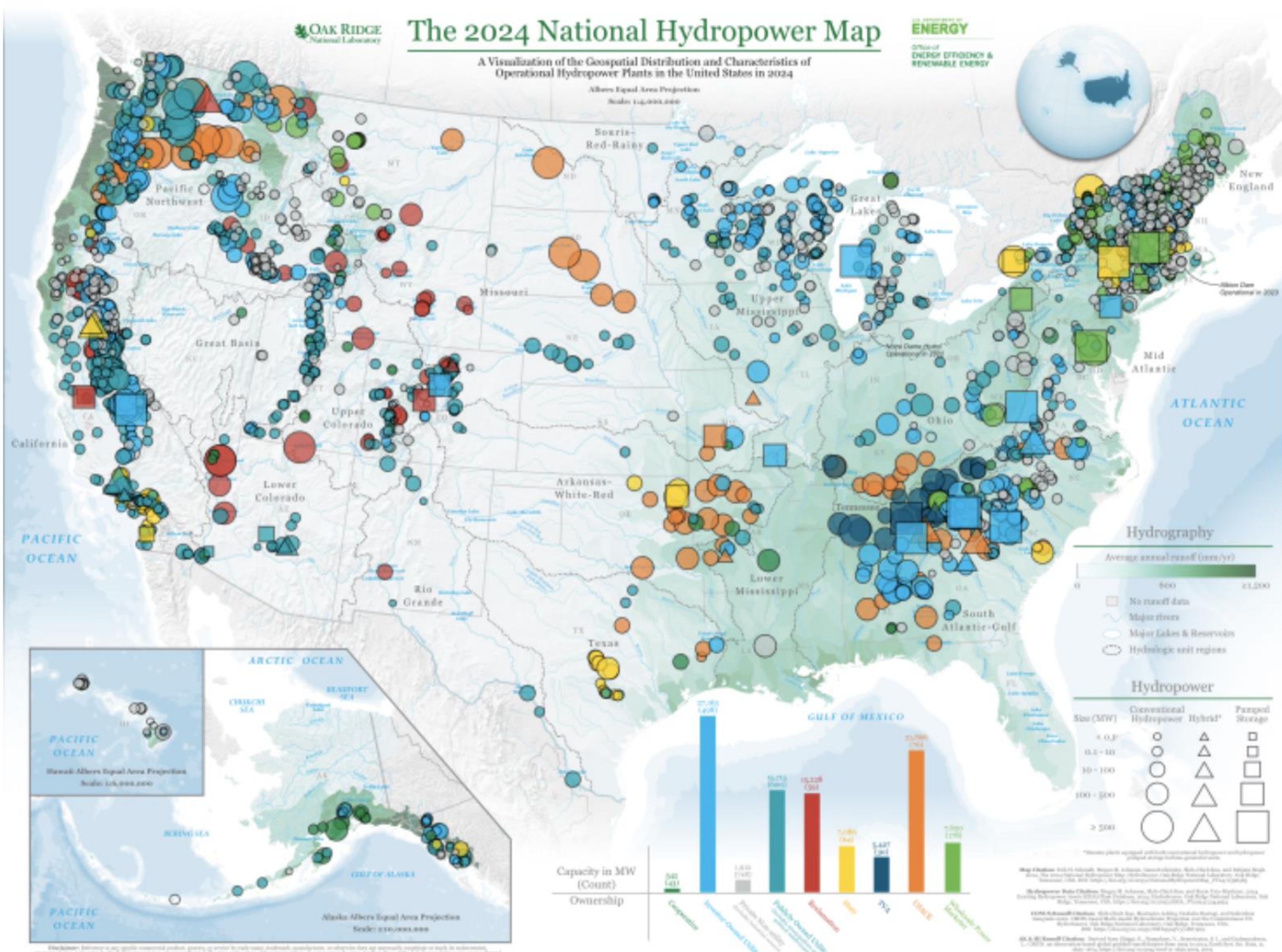
SOLAR VARIABILITY



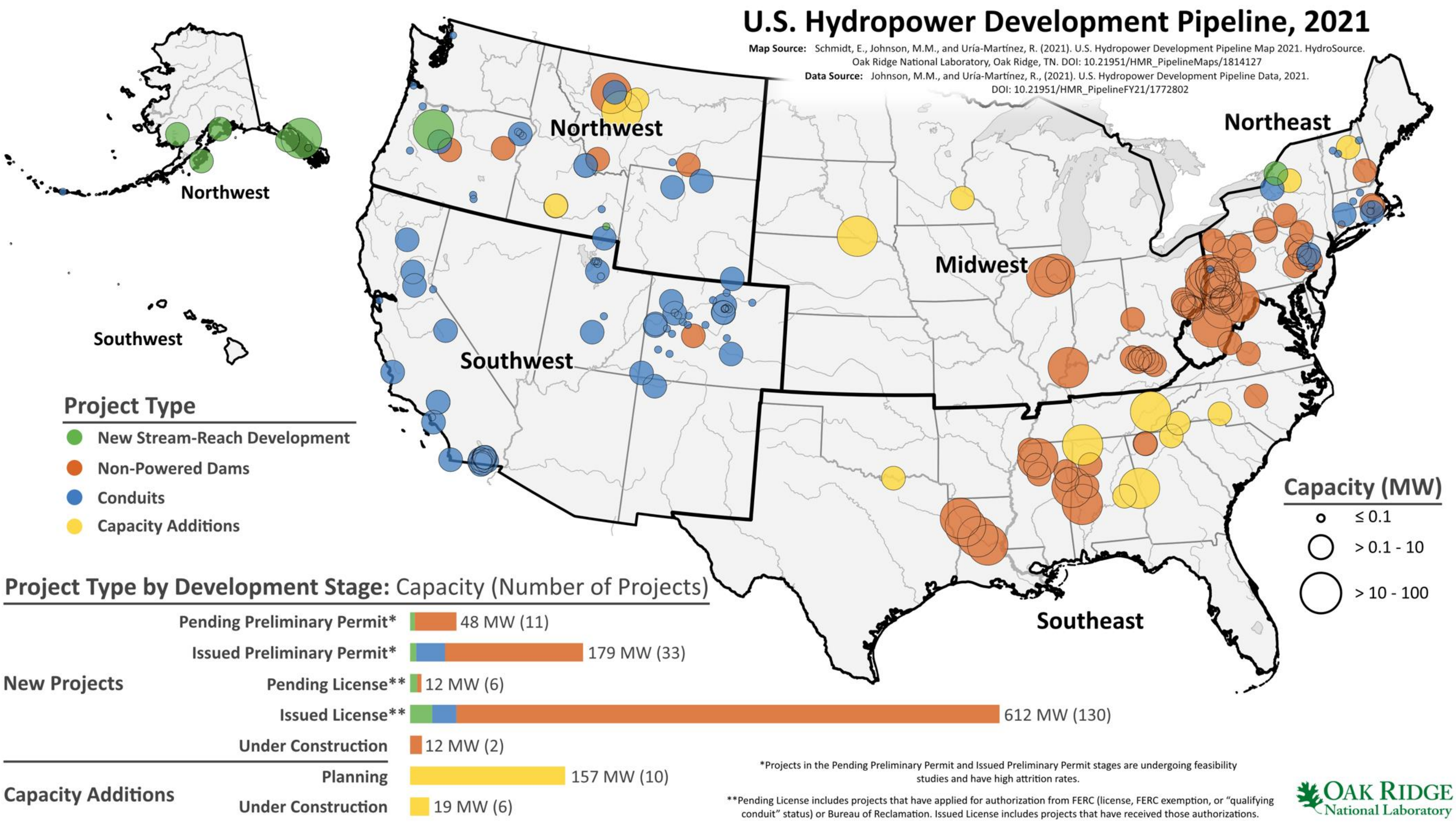
WIND & SOLAR CORRELATION



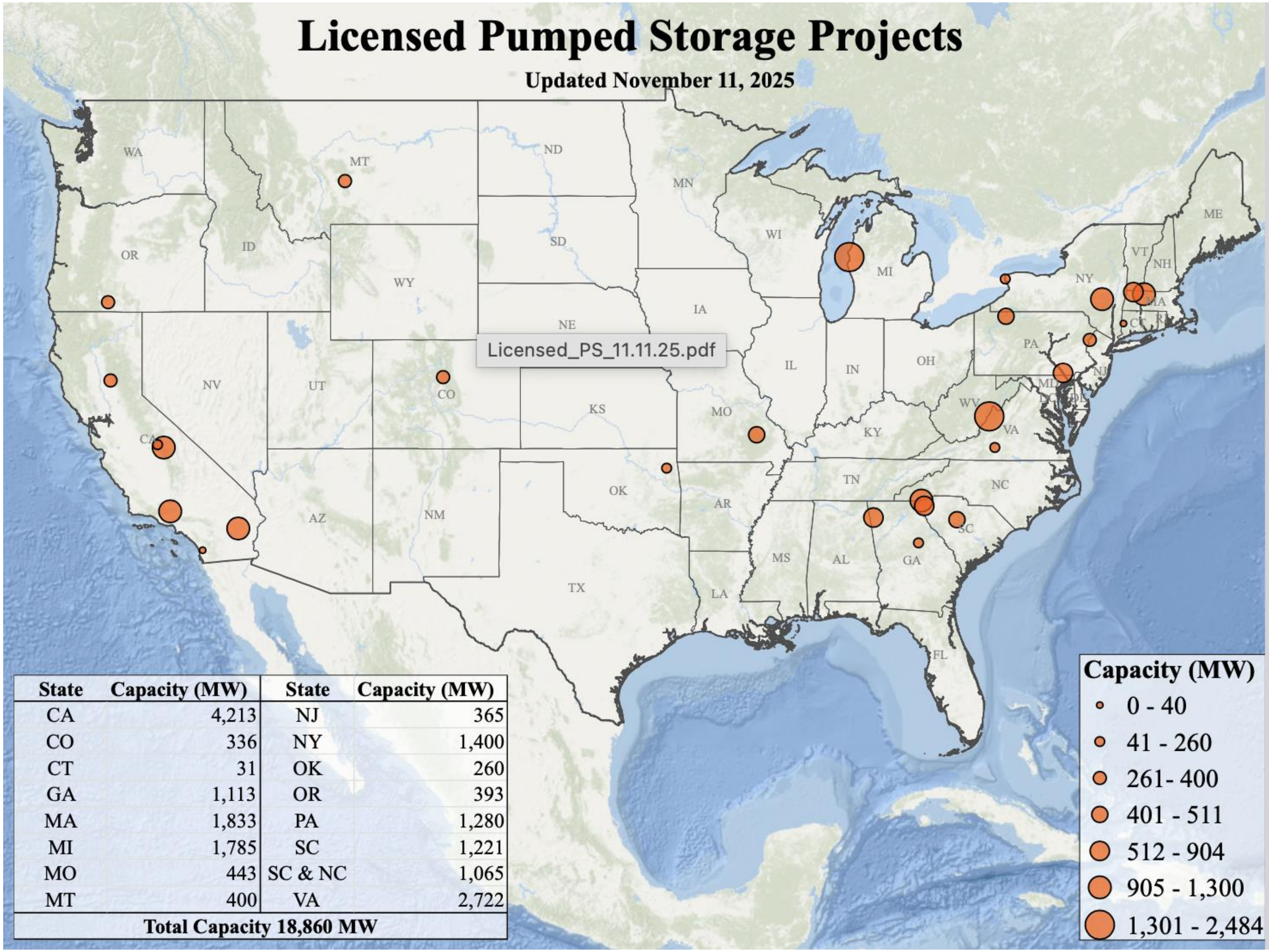
https://www.sciencedirect.com/science/article/pii/S0306261917302775



https://hydrosource.ornl.gov/data/maps/2024-national-hydropower-map/



https://hydrosource.ornl.gov/map/map-us-hydropower-development-pipeline-2021

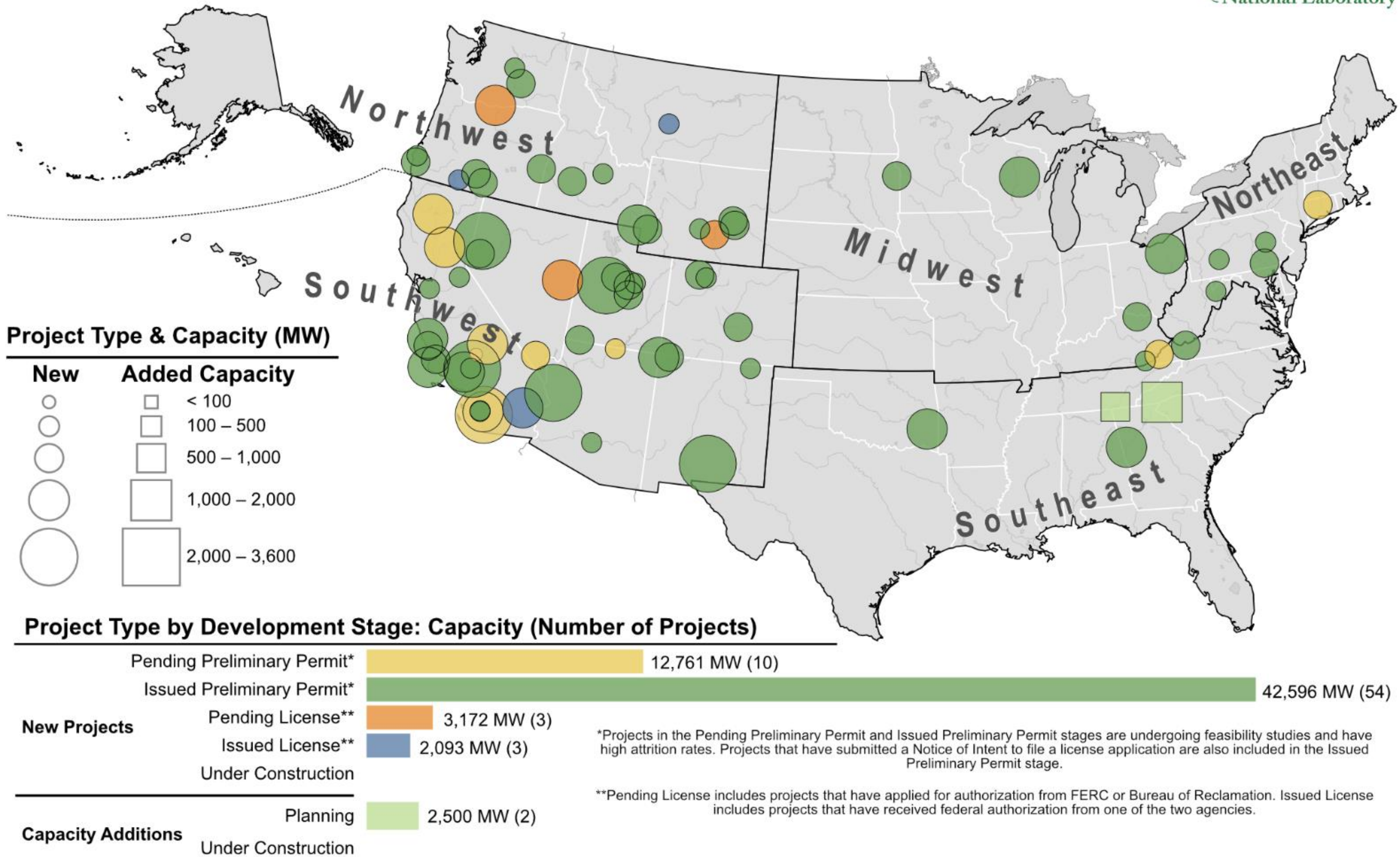


State	Capacity (MW)	State	Capacity (MW)
CA	4,213	NJ	365
CO	336	NY	1,400
CT	31	OK	260
GA	1,113	OR	393
MA	1,833	PA	1,280
MI	1,785	SC	1,221
MO	443	SC & NC	1,065
MT	400	VA	2,722
Total Capacity 18,860 MW			

https://www.ferc.gov/media/licensed-pumped-storage-projects-map-1

U.S. Pumped Storage Hydropower Development Pipeline, 2025

OAK RIDGE National Laboratory

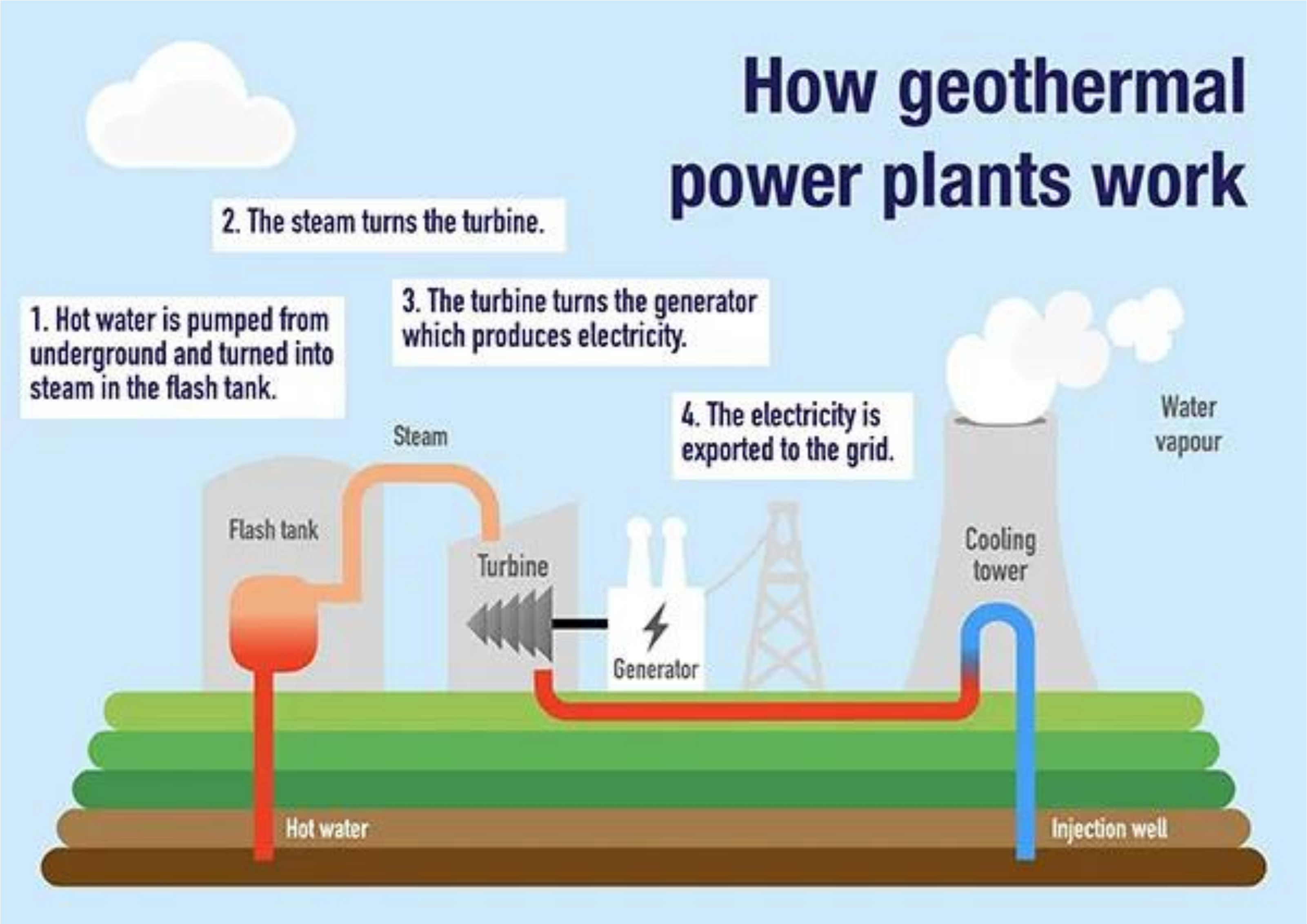


Map Source: Erik H. Schmidt, Megan M. Johnson and Rocio Uría-Martínez. 2025. U.S. Pumped Storage Hydropower Development Pipeline, 2025. [Map]. HydroSource. Oak Ridge National Laboratory. Oak Ridge, Tennessee, USA. DOI: 10.21951/HMR_PipelineMaps/2569210

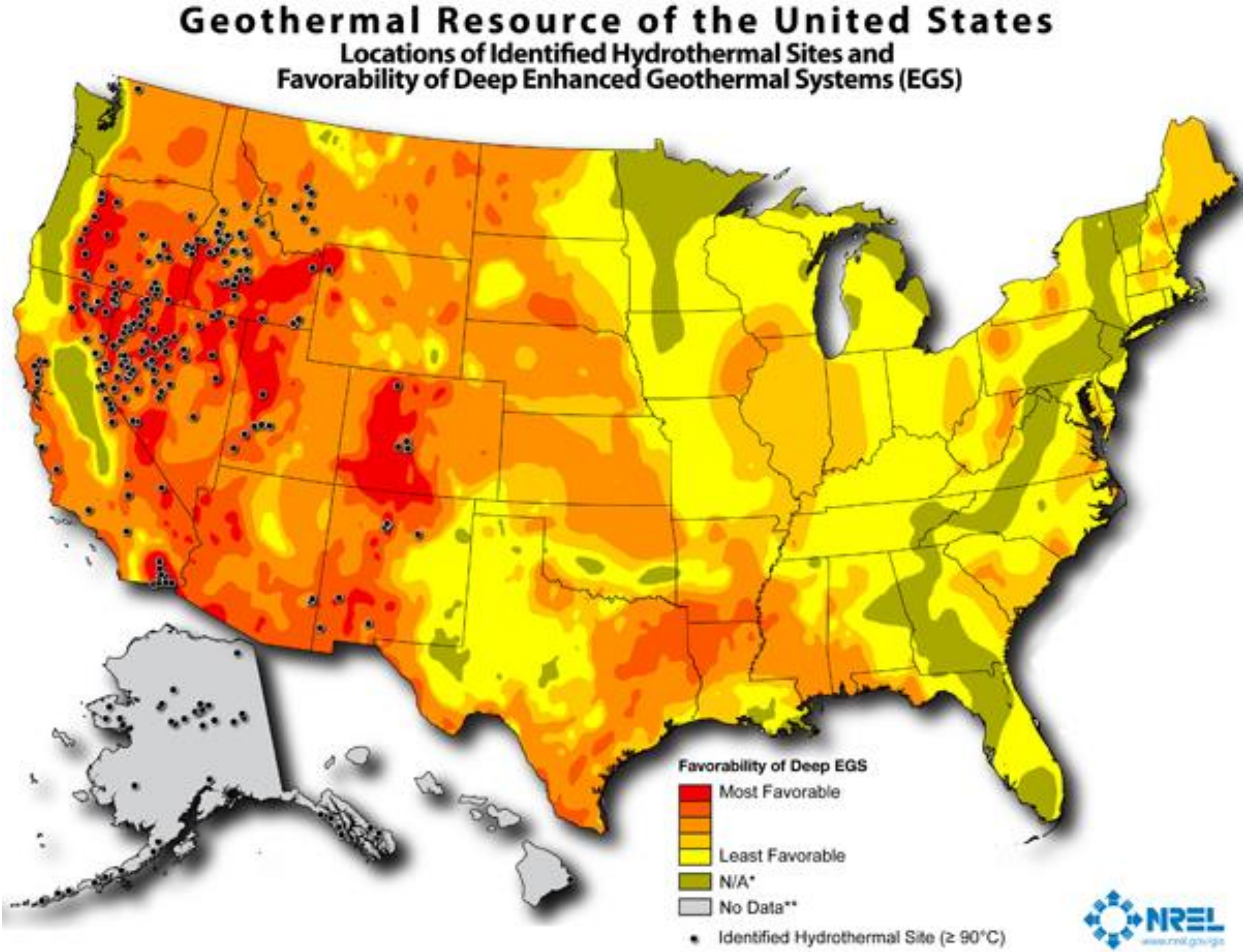
Data Source: Johnson, M.M., and Uría-Martínez, R., (2025). U.S. Hydropower Development Pipeline Data, 2025. HydroSource. Oak Ridge National Laboratory. Oak Ridge, Tennessee, USA. DOI: 10.21951/HMR_PipelineFY25/2563167

https://hydrosource.ornl.gov/data/maps/map-us-psh-development-pipeline-2025/

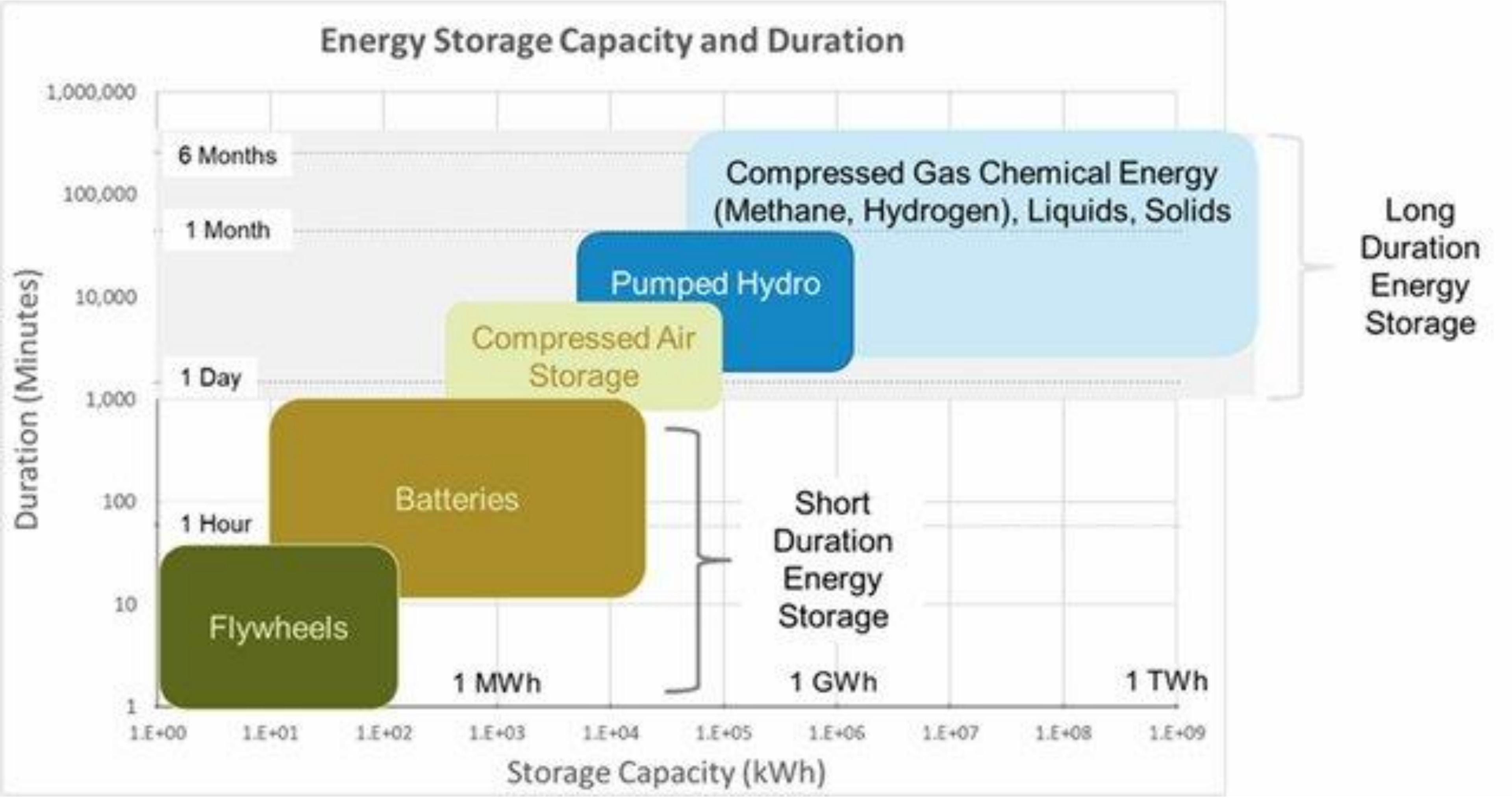
GEOTHERMAL POWER PLANTS



https://amigoenergy.com/blog/understanding-geothermal-energy/



https://www.eia.gov/todayinenergy/detail.php?id=3970

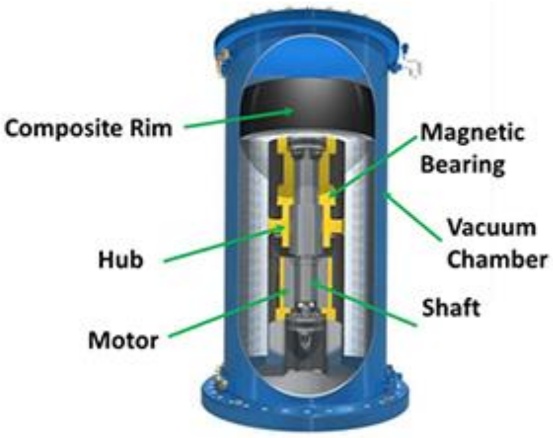


https://www.researchgate.net/publication/358700260_Long-Duration_Utility-Scale_Energy_Storage/figures?lo=1

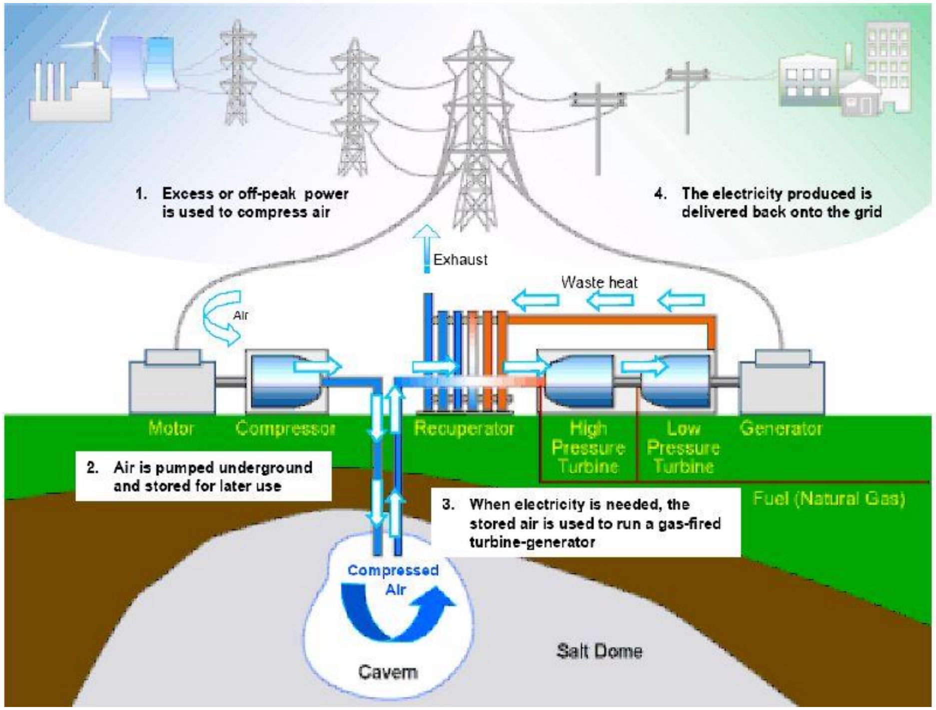
U.S. Department of Energy defines long-duration energy storage as capable of delivering electricity for 10 or more hours

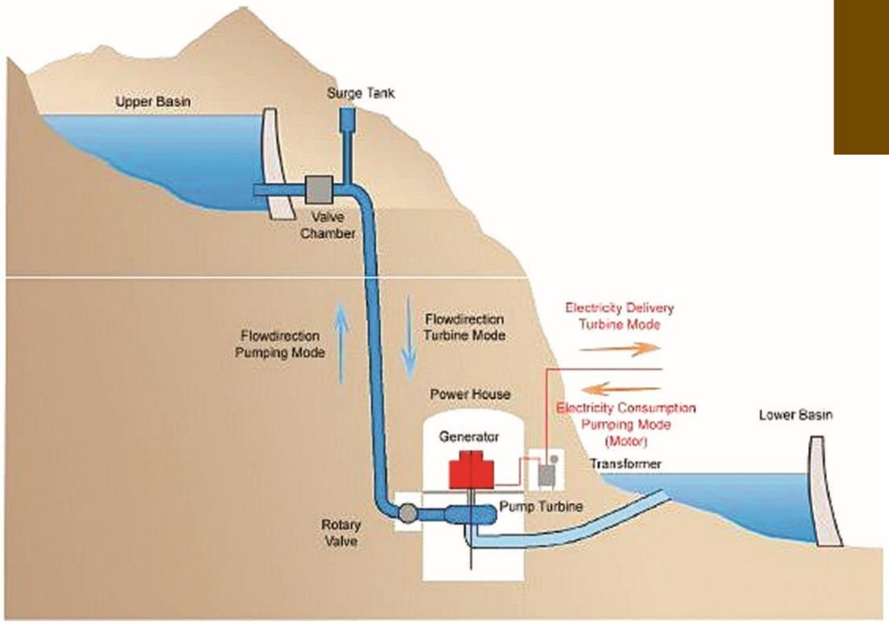
https://www.energy.gov/oced/long-duration-energy-storage

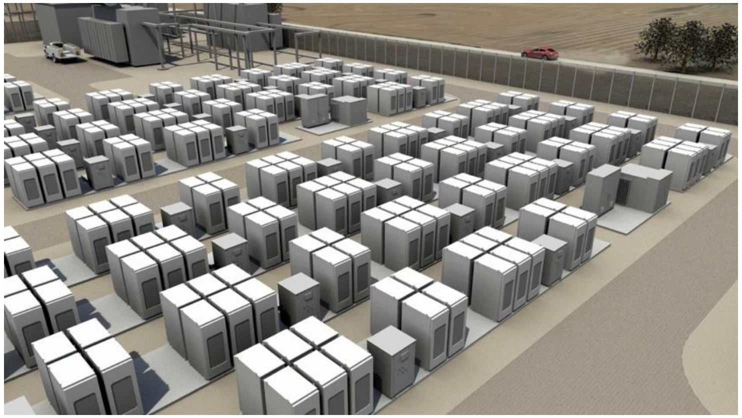
SOLUTIONS TO INTERMITTENCY



Source: Beacon Power, LLC







LONG DURATION ENERGY STORAGE

NON-EXHAUSTIVE – HYDROGEN AND HYBRID LONG DURATION STORAGE EXCLUDE

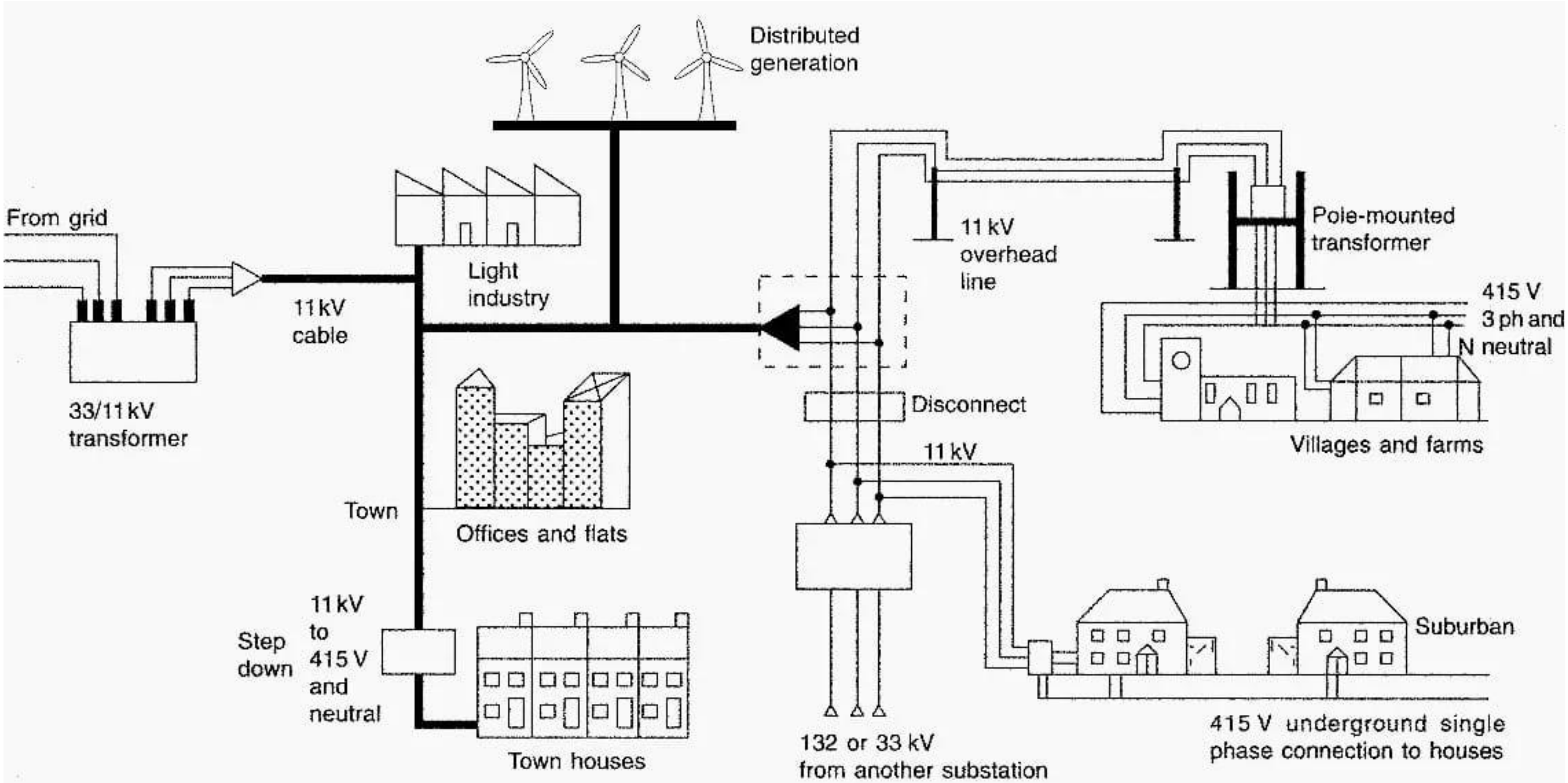
△ Faces geologic constraints[4] · ■ Not enough public datapoints to obtain a reliable value · Less Desirable → More Desirable

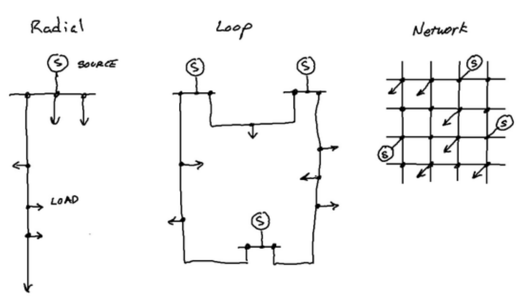
Inter-day · Can function as both · Multi-day/week

Duration	Energy storage form	Technology	Nominal duration, hrs	LCOS[5], \$/MWh	Min. deployment size, MW	Average RTE, %	TRL
Inter-day	Mechanical	Traditional pumped hydro (PSH) △	0–15	70–170	200 – 400	70–80	9
		Novel pumped hydro (PSH)	0–15	70–170	10–100	50–80	5-8
		Gravity-based △	0–15	90–120	20–1,000	70–90	6-8
		Compressed air (CAES) △	6–24	80–150	200–500	40–70	7-9
		Liquid air (LAES) [1]	10–25	175–300	50–100	40–70	6-9
		Liquid CO2 [1]	4–24	50–60	10–500	70–80	4-6
Multi-day / week	Thermal	Sensible heat (e.g., molten salts, rock material, concrete) [2]	10-200[2]	300	10–500	55–90	6-9
		Latent heat (e.g., aluminum alloy)	25–100	300	10–100	20–50	3-5
		Thermochemical heat (e.g., zeolites, silica gel)	XX	XX	XX	XX	XX
	Electrochemical	Aqueous electrolyte flow batteries	25–100	100-140	10–100	50–80	4-9
		Metal anode batteries	50–200	100	10–100	40–70	4-9
		Hybrid flow battery, with liquid electrolyte and metal anode (some are Inter-day) [2,3]	8–50[2]	XX	>100	55–75	4-9

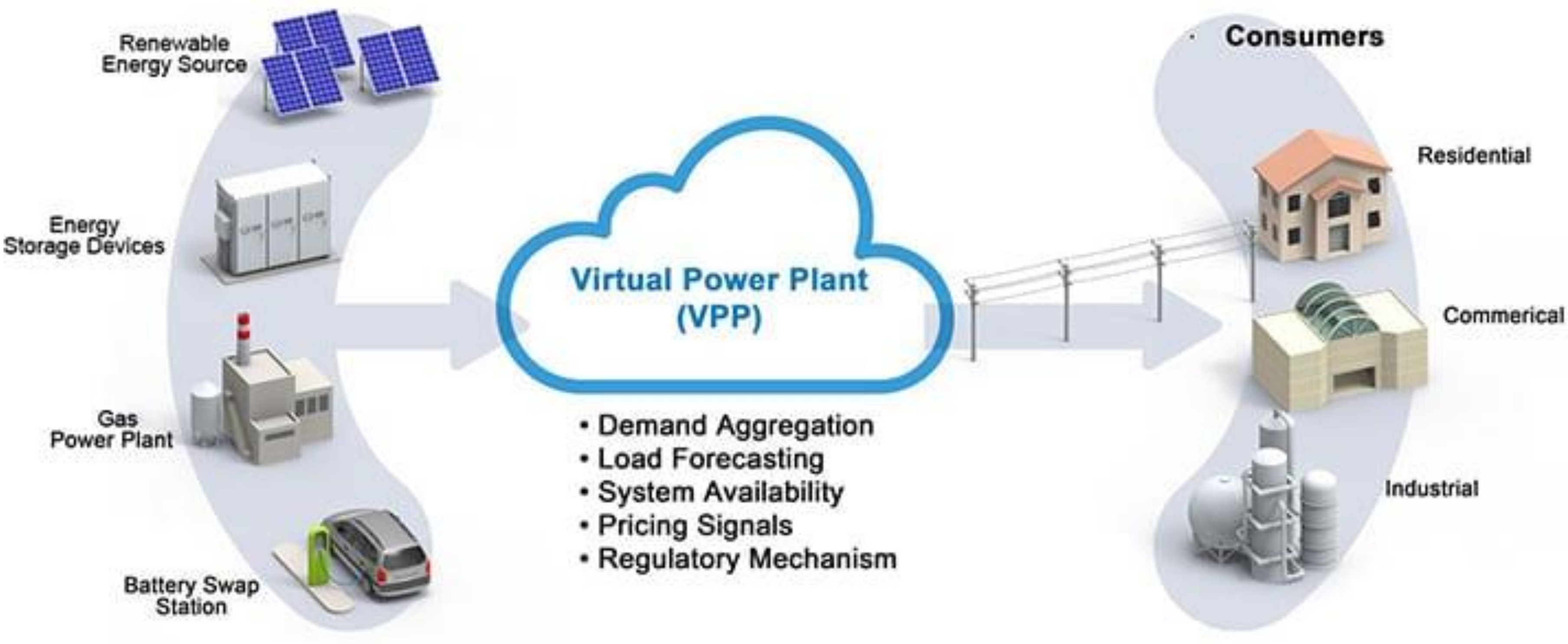
https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-LDES-vPUB-0329-update.pdf

DISTRIBUTION SYSTEM





VIRTUAL POWER PLANTS



What is being Electrified?

Transportation

- Public Charging Stations
- Electric Vehicles
- Fleet Electrification

Residential

- In-Home Charging Stations
- Air-source Heat Pumps
- Lawn maintenance equipment (mower, trimmer, hedger, blower, etc.)

Aviation

- Pushbacks
- Belt Loaders
- Baggage Tugs

Commercial and Industrial

- Heat recovery chillers
- Replace pneumatic equipment with electric
- Install induction furnaces for non-ferrous metal melting

Heavy Duty Off-Road

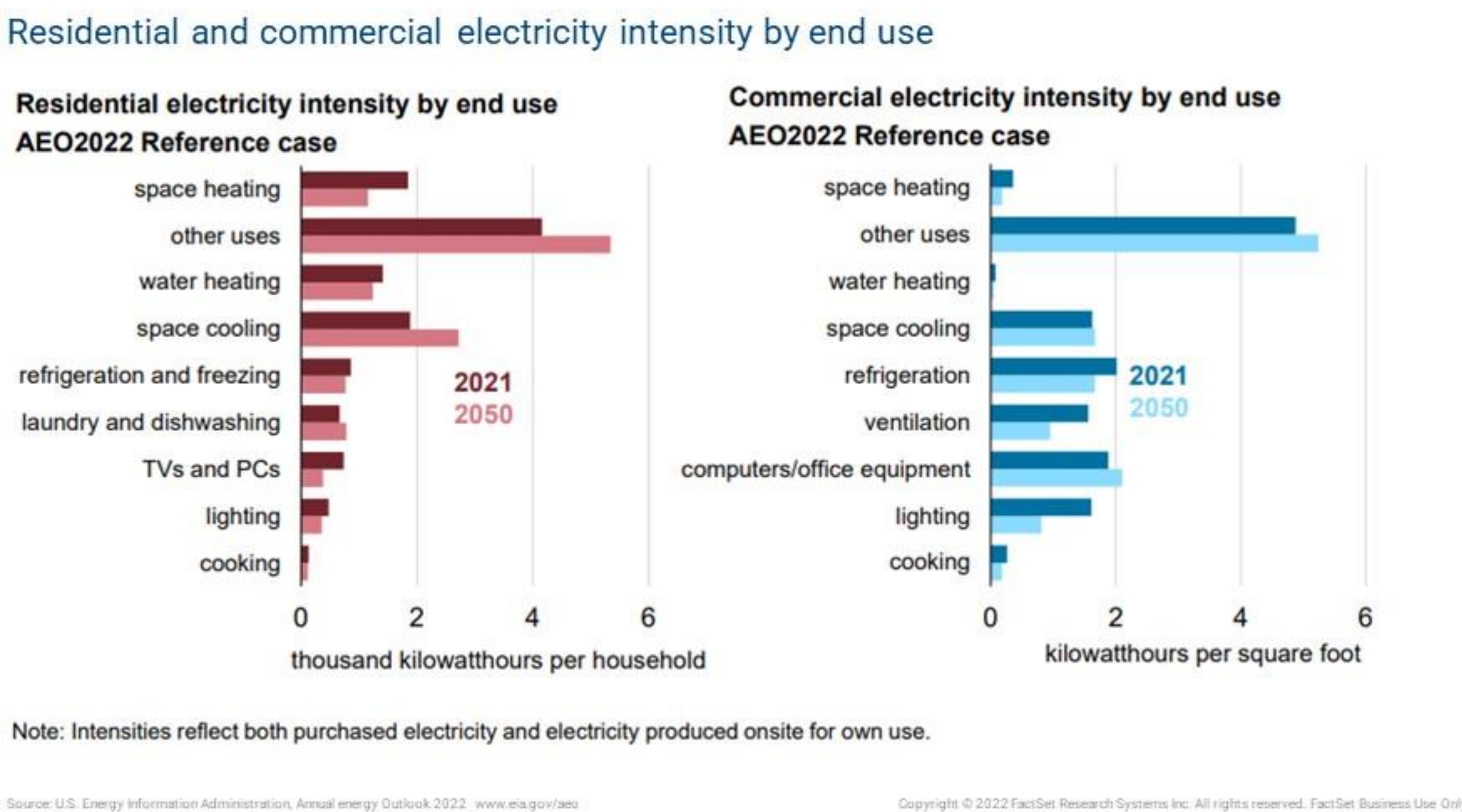
- Replace propane/gas forklifts with electric
- Eliminate Truck Stop idling
- Convert rail yard cargo handling equipment to electric

Agriculture

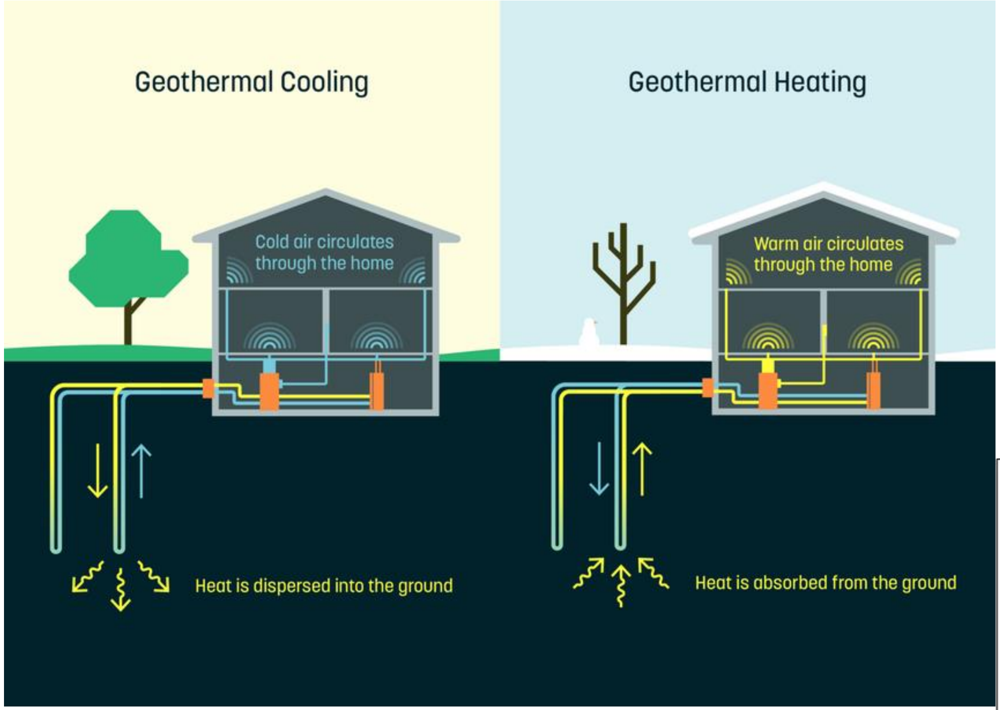
- Retrofit Diesel Irrigation Pumps to Electric
- Indoor agriculture (controlled lighting, and space-conditioning)
- Infrared drying and peeling of vegetables

https://www.wtsenergy.com/glossary/electrification/

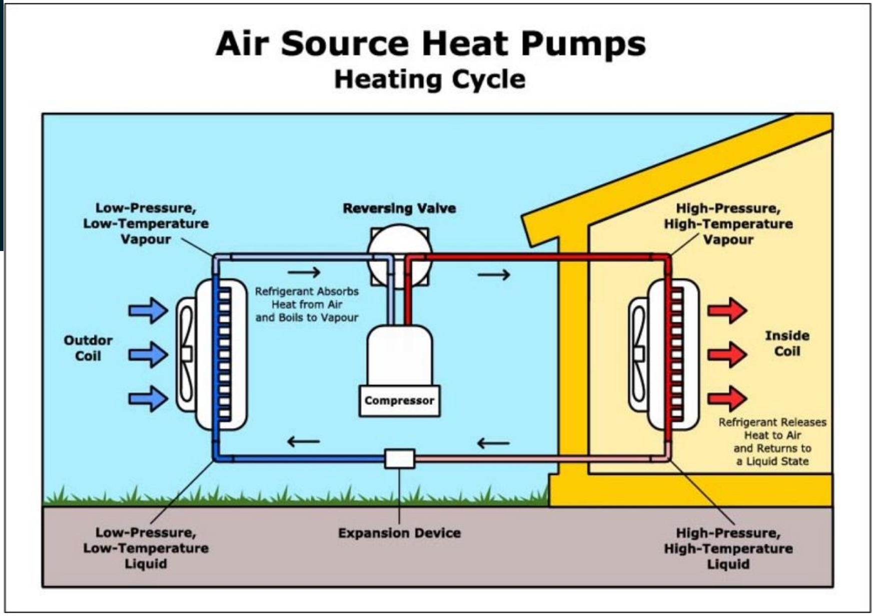
END USES OF ELECTRICITY



HEAT PUMPS



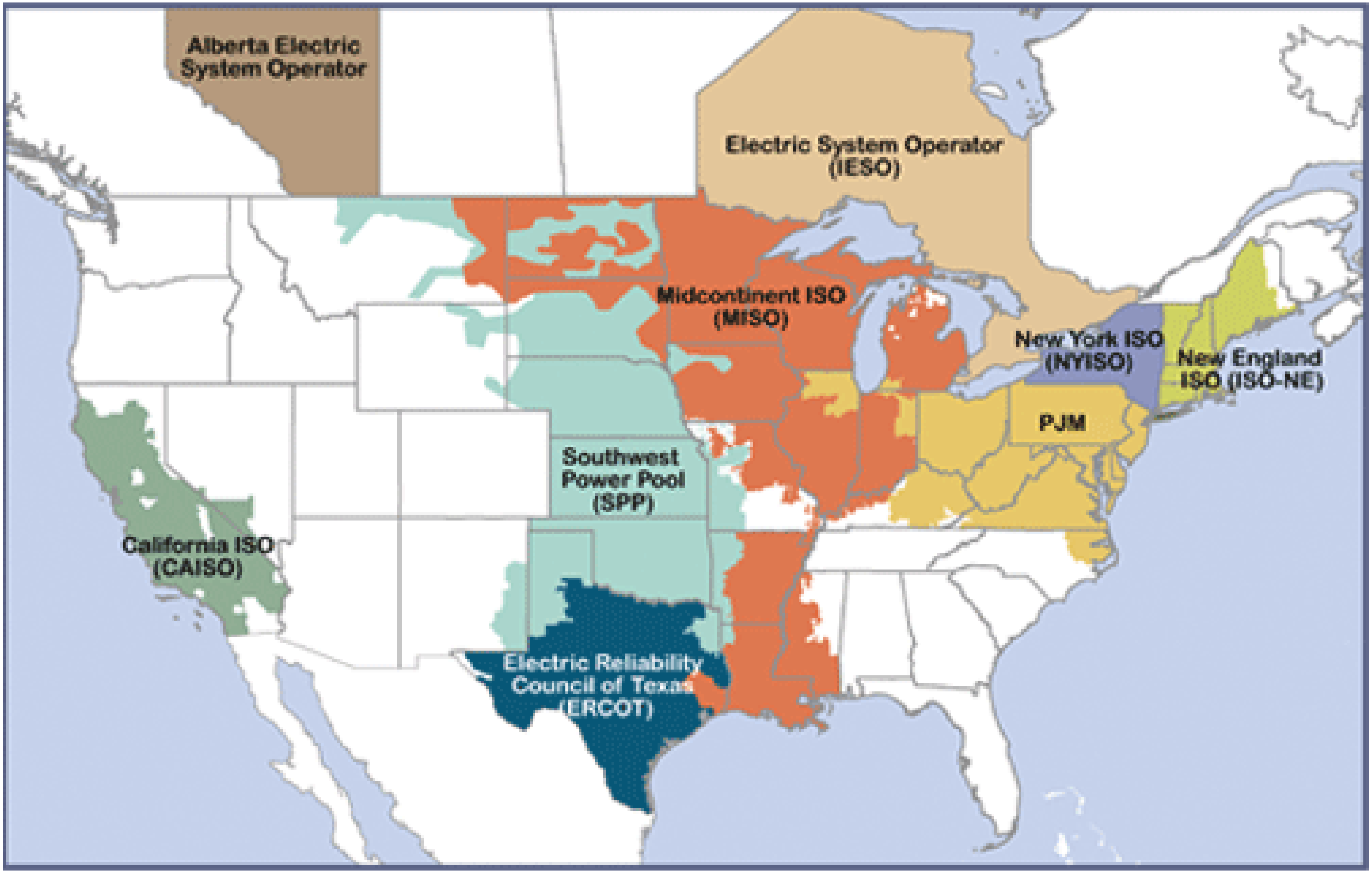
https://rmi.org/clean-energy-101-geothermal-heat-pumps/



https://www.energy.gov/energysaver/air-source-heat-pumps

Can provide both heating and cooling

REGIONAL TRANSMISSION ORGANIZATION (RTO)/INDEPENDENT SYSTEM OPERATOR (ISO)



KNOWLEDGE SELF-CHECK

1. Approximately how much of total energy usage involves electricity?
2. Why is electricity such a good carrier of energy?
3. What is meant by increased electrification and why is that considered necessary?
4. What are the major components of the electric power system?
5. What are the different ways to produce electricity?
6. Why do different types of generation units have different capacity factors?
7. What does dispatchability mean?
8. What are the emerging trends in the electricity sector?
9. What are the major technological and policy trends affecting the electric power system?

TERMINOLOGY AND ABBREVIATIONS CHECK

- IPPs
- ESCO/Load Aggregators
- LSEs
- GenCo
- TransCo
- RTO/ISO
- PUC/PSC
- FERC
- Utilities
- Capacity
- Energy

Session 2
Power System Fundamentals

POWER SYSTEM OVERVIEW

Motivation: Understanding the physics of power systems to understand electricity markets

Key Questions:

- What is meant by loop flows or parallel flows?
- What is dispatch and unit commitment?
- What ancillary services are needed to operate the grid?
- In reliability analysis, what is the difference between adequacy and security/operational reliability?

Take Aways:

- The intuition and importance of loop flows (aka power flows, parallel flows)
- The wide variation in system conditions that the system operates under
- Two different engineering frameworks are used to analyze power systems (deterministic and probabilistic)
- The interaction between different electricity markets and among electricity markets and air emissions and renewable markets

*Many slides include references and the final slide lists additional ones

LOOP FLOWS

KIRCHHOFF'S CURRENT AND VOLTAGE LAWS

- The amount of current entering a node equals the amount exiting
- The voltage change around a complete circuit is zero

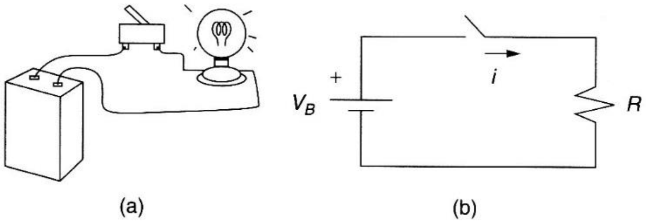
OHM'S LAW

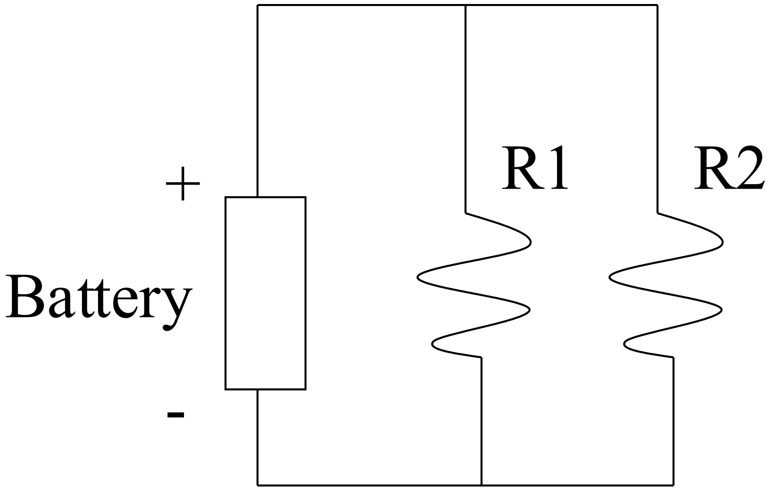
- V = IR

  V is voltage (Volts)

  I is current (Amps)

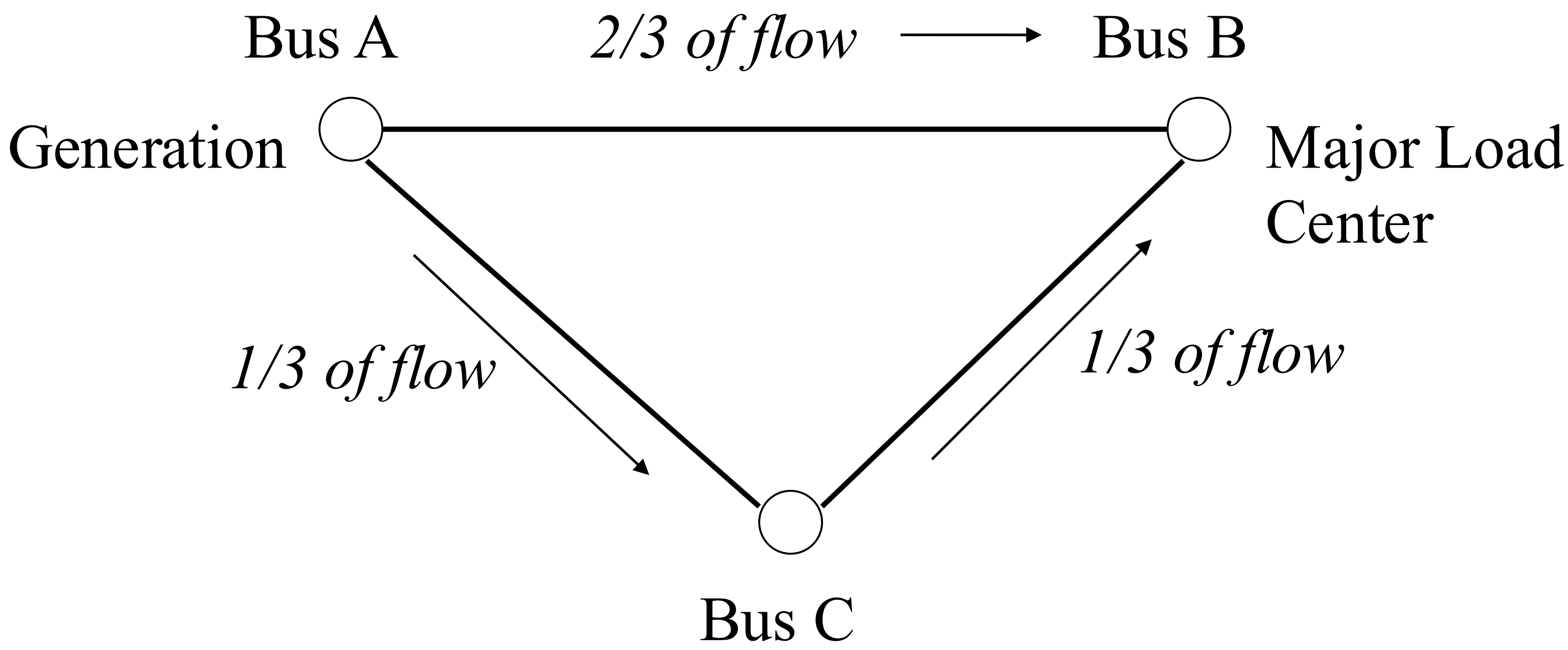
  R is resistances (Ohms)





R1 and R2 are resistors, e.g., light bulbs in a flashlight

LOOP FLOWS



Assume each transmission line has the same impedance (which is not true in practice)

Flows on each transmission line may be limited for a variety of reasons

Nodes = Buses = Locations

LEAST COST OBJECTIVE

Objective

Plan and operate the bulk power system so that it satisfies system loads and engineering criteria at the least cost

- Power flow analysis determines the current and voltages on a power system
- Optimal power flow (OPF) determines the least cost dispatch to satisfy system loads and engineering criteria

Dispatch Problem (every 5 minutes)

Minimize cost of serving electric energy demand subject to:

- Demand = Supply
- Transmission/reliability constraints:

  Thermal limits: prevent damage to transmission components

  Stability: keeping generation units in synchronism

  Voltage: maintain voltage within acceptable limits

  Frequency: maintain frequency within acceptable limits

  Contingency: ability to withstand the failure of components (ability to withstand the failure of 1 contingency is called "n-1")

DISPATCH SOLUTION

Dispatch Problem solution:

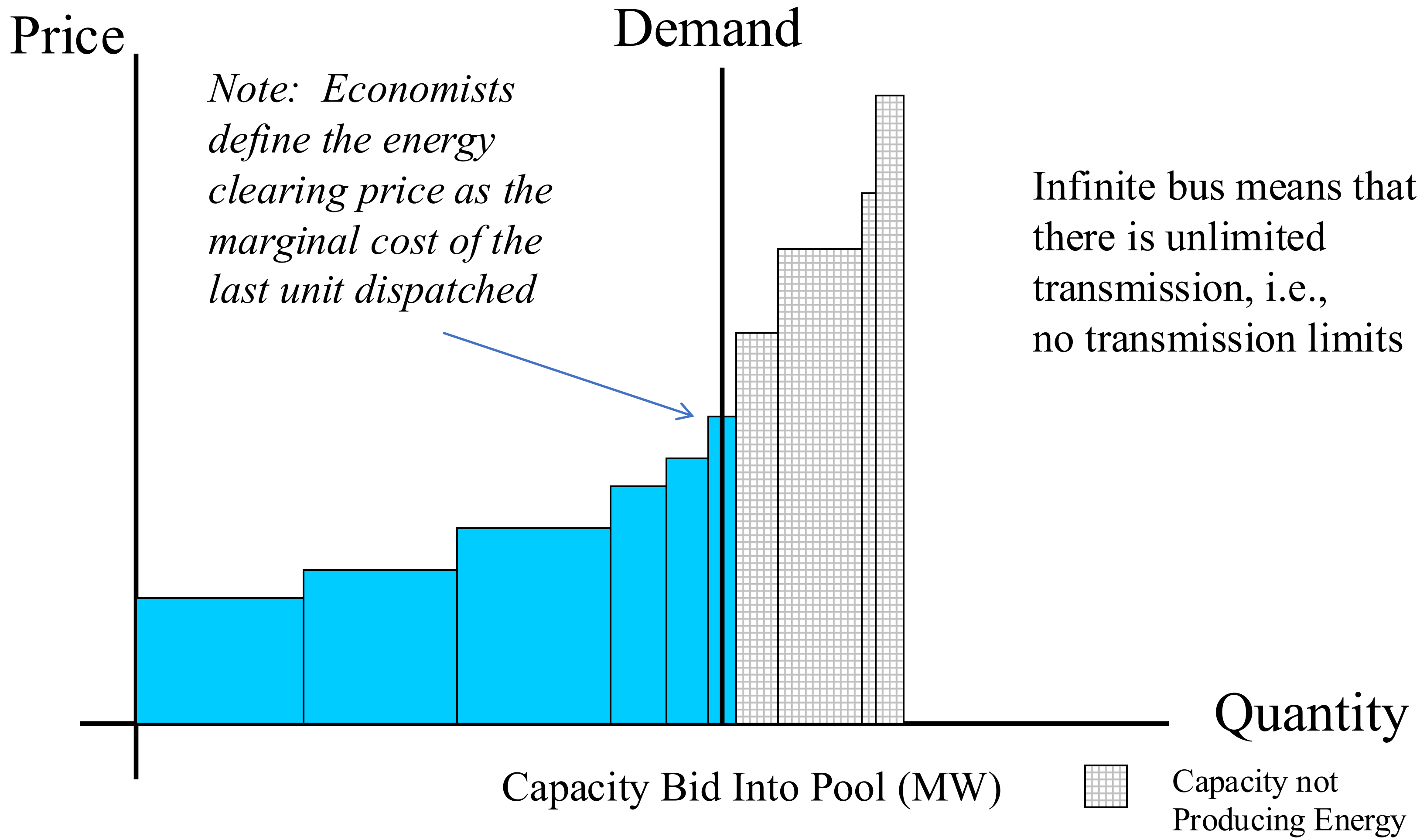
For each time period (e.g., five minutes), a list of generation output for each generator is produced

For each time period, a list is produced of prices at each node that reflects the marginal cost of serving one more MWh at that node for that time period

Nodal price (t) = marginal fuel cost + variable maintenance cost + transmission constraints + transmission losses

Nodal price = Locational Prices = Locational Marginal Prices (LMPs)

INFINITE BUS SOLUTION (NO TRANSMISSION CONSTRAINTS)



Infinite bus means that there is unlimited transmission, i.e., no transmission limits

This stacking from inexpensive to more expensive is referred to as *merit order dispatch*

LOOP FLOW PROBLEM

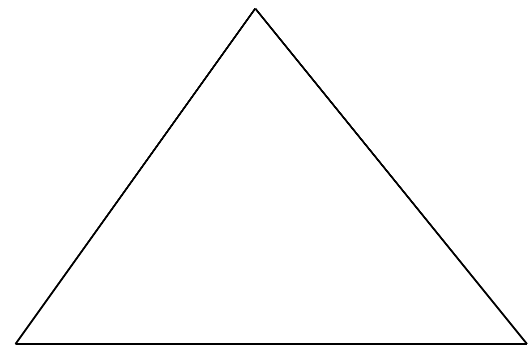
<u>No Transmission Constraints</u>

3 Bus Example
- Lines have identical impedances
- No transmission losses

What is the least-cost dispatch?
- Without any transmission constraint?

=> Solution
- G1: Dispatched 0 MW
- G2: Dispatched 150 MW

G1 Max Output = 90 MW at $50/MWh



G2 Max Output = 150 MW at $30/MWh

Load= 150 MW

LOOP FLOW PROBLEM

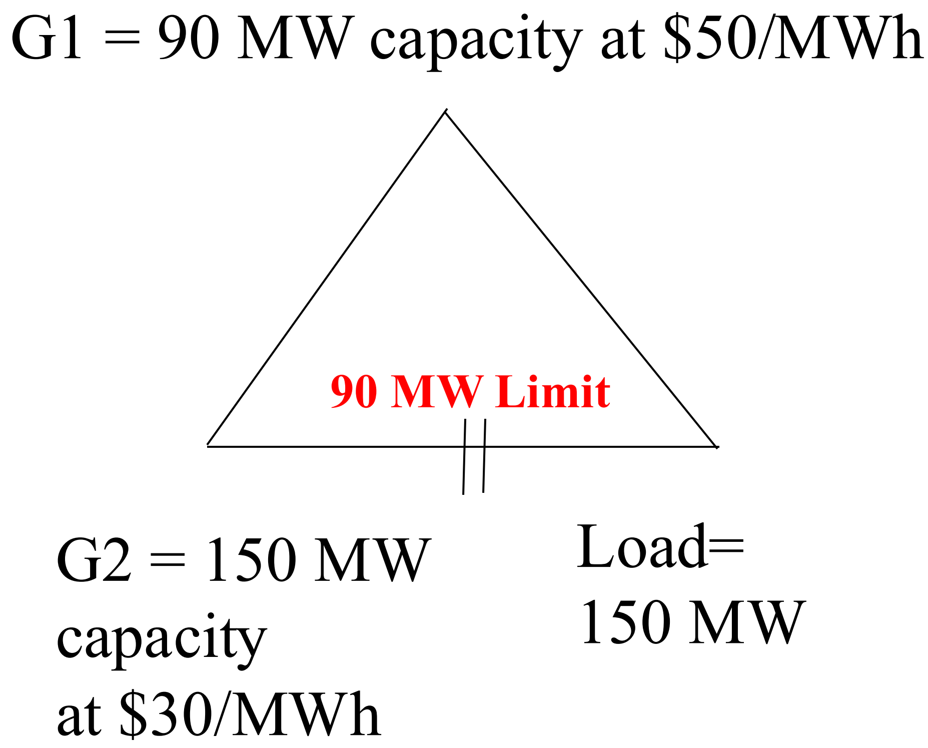
<u>Transmission Constraint</u>

3 Bus Example

- Lines have identical impedances
- No transmission losses

What is the least-cost dispatch?

- With a 90 MW transmission constraint



LOOP FLOW SOLUTION

3 Bus Example

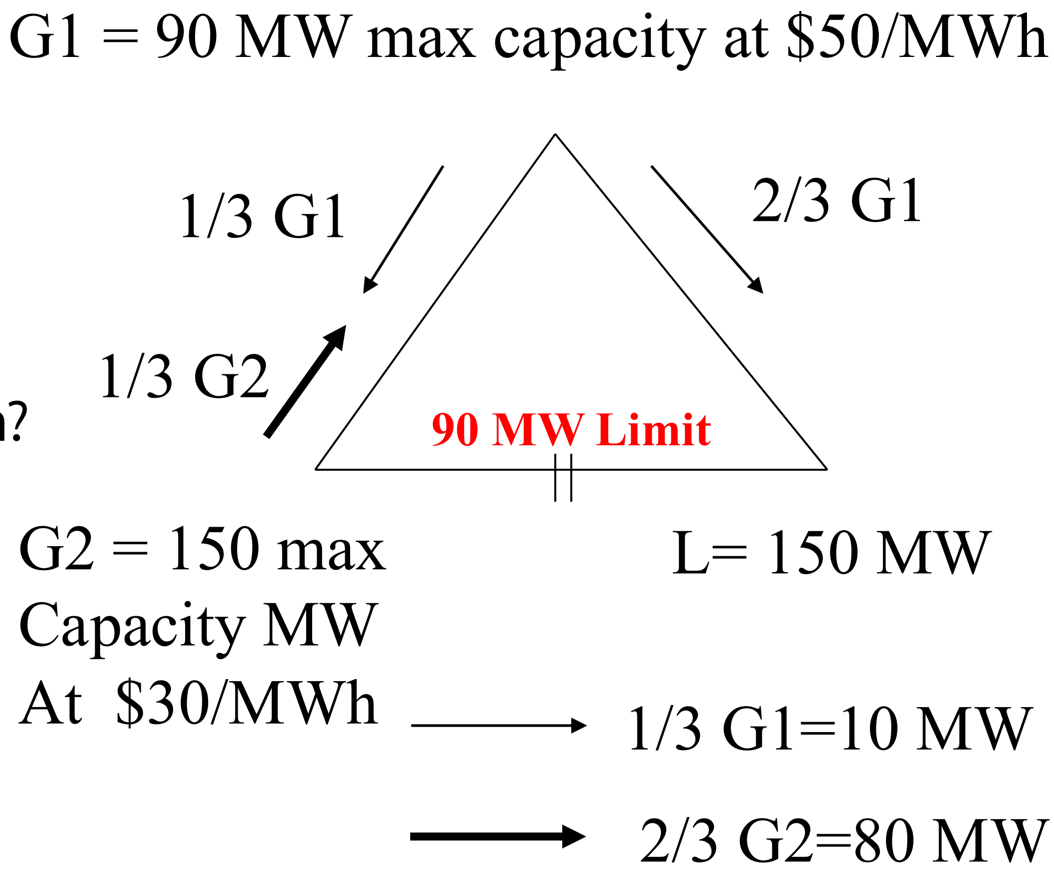
- Lines have identical impedances
- No transmission losses

What is the least-cost dispatch?

- With a 90 MW transmission constraint

=> Solution

- G1: 30 MW
- G2: 120 MW
- G1+G2 = 150 MW = Load



TRANSMISSION EXPANSION

Reconductor existing lines

Add new transmission lines

Add capacitors

Add power system stabilizers

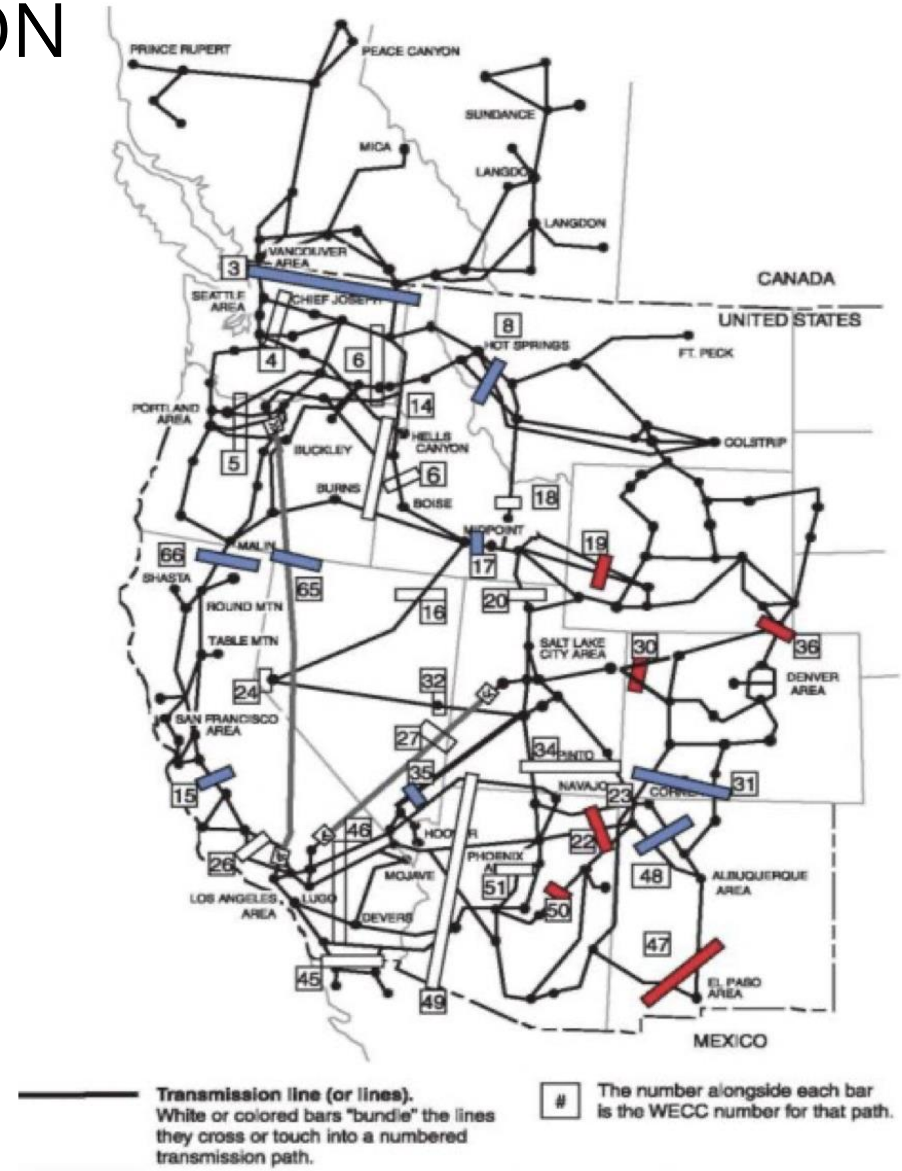
Add FACTS (aka phase angle regulators)

Add SPS – Special Protection Systems

Add HVDC link in parallel with existing AC system

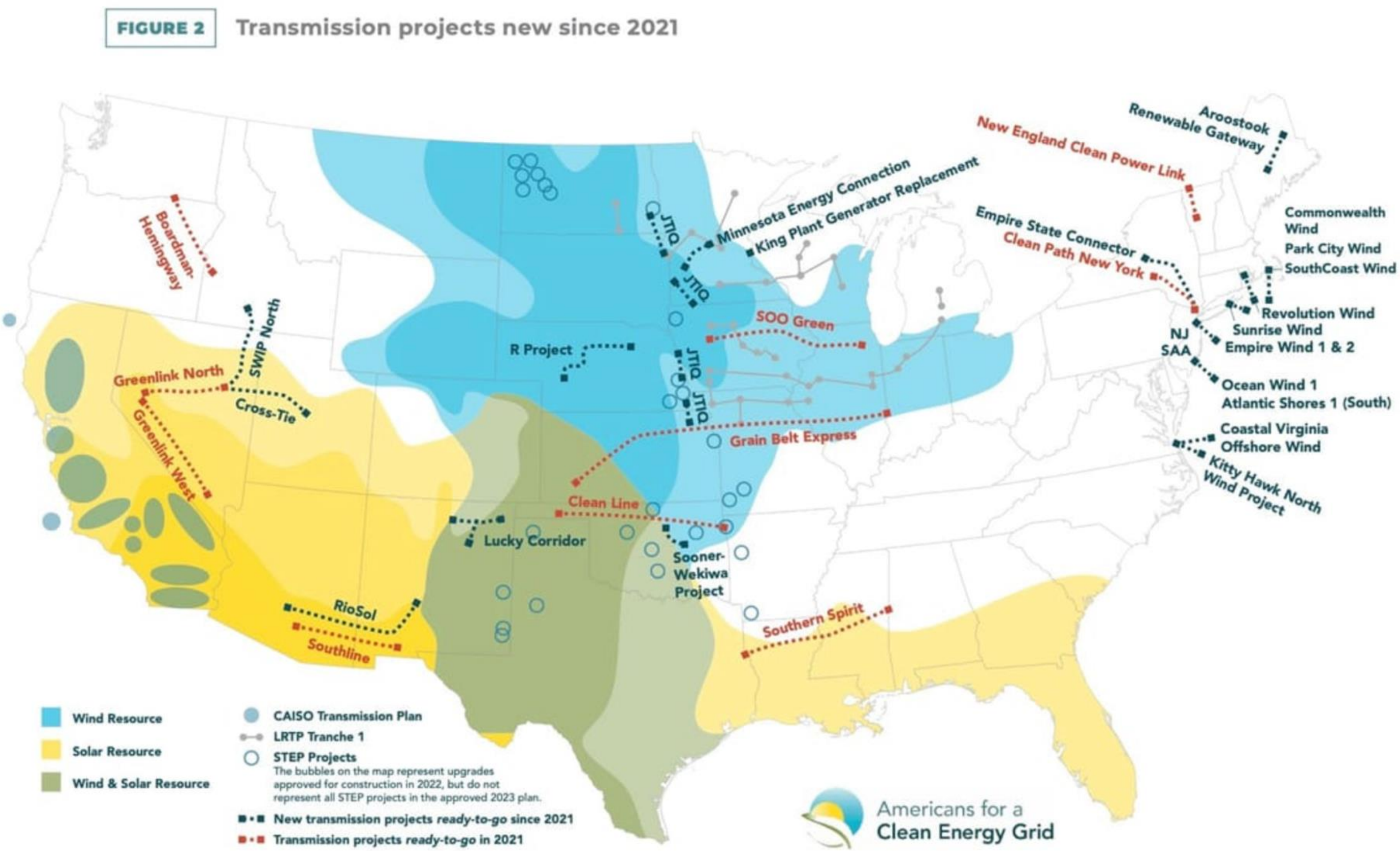
Raise the transmission towers to accommodate more sag

Grid-enhancing Technologies (GETs)



Source: Western Electricity Coordinating Council (WECC). See also: https://www.wecc.org/Reliability/TAS_PathReports_Combined_FINAL.pdf.

U.S. TRANSMISSION EXPANSION



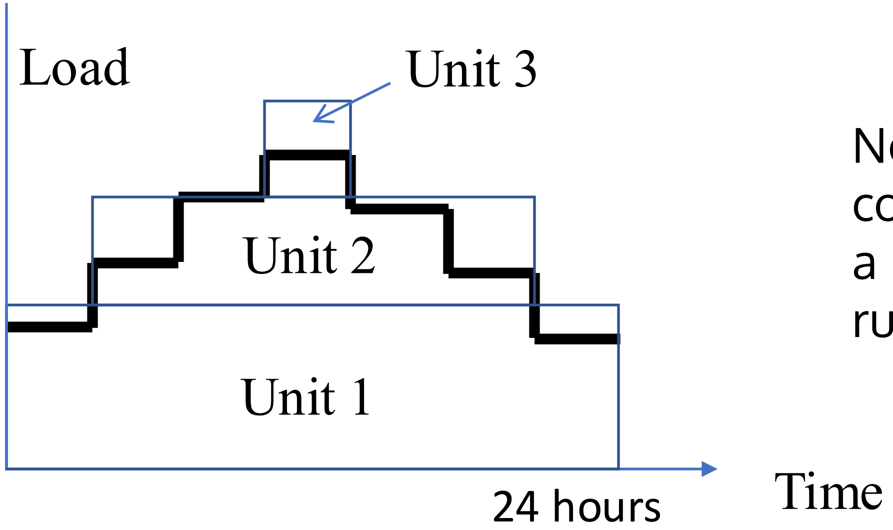
UNIT COMMITMENT

<u>Unit Commitment:</u> Minimize start-up, no-load, and running costs subject to meeting load reliably & the constraints of generation units (size, start-up time, ramp rates, min. run times, min. down times, etc.) over 24 hours.

The solution to this optimization is not only the output level of individual generation units but which units to commit.

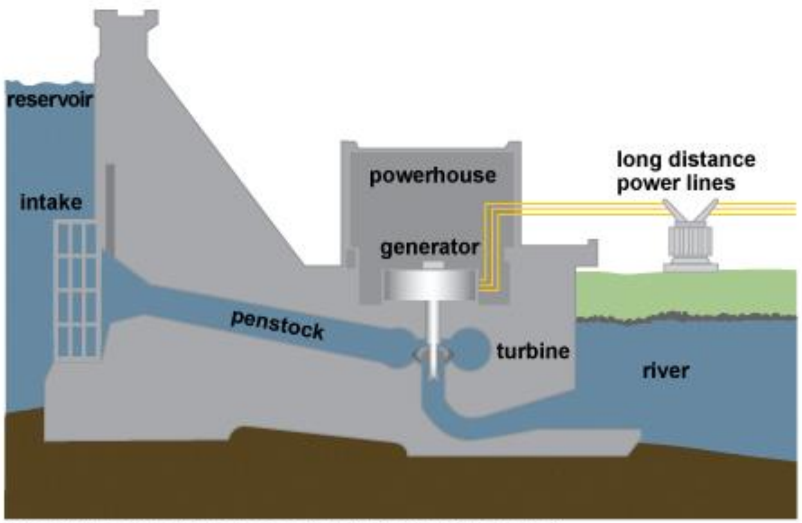
<u>Dispatch:</u> Minimize no-load and running costs subject to meeting load reliably & the constraints of the generation units (size and ramp rates) over 5 minutes.

The solution to this optimization problem is the output level of individual generation units; solved every 5 minutes.

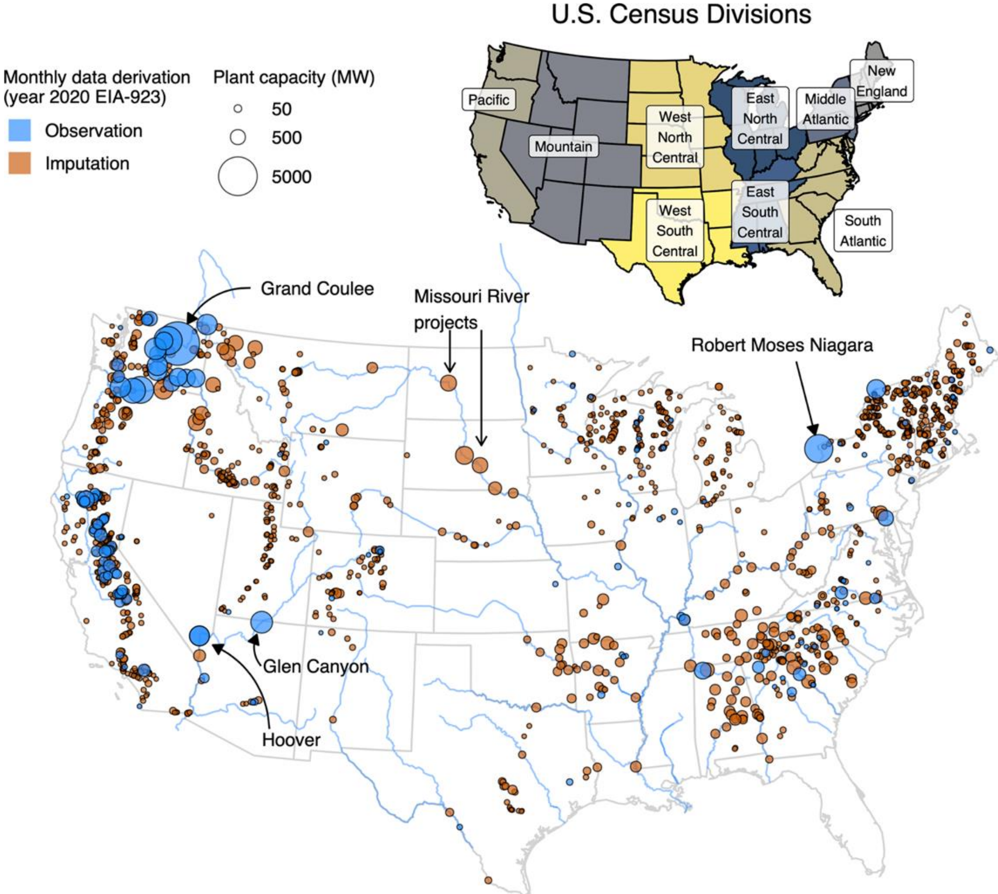


Note: Unit commitment is much more complicated than dispatching and requires a more sophisticated algorithm and longer run time.

HYDROELECTRIC SCHEDULING

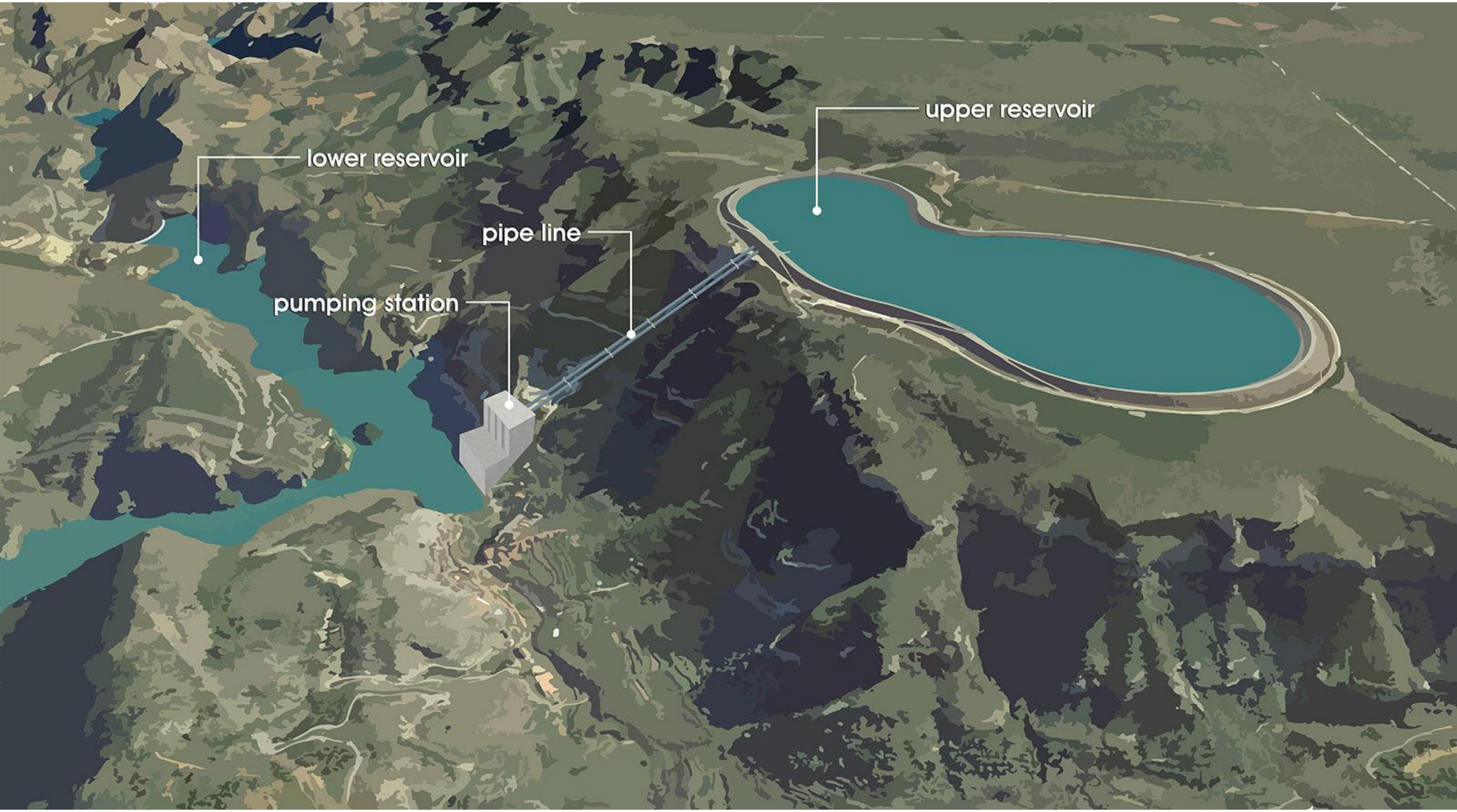


Source: Adapted from the Tennessee Valley Authority (public domain)

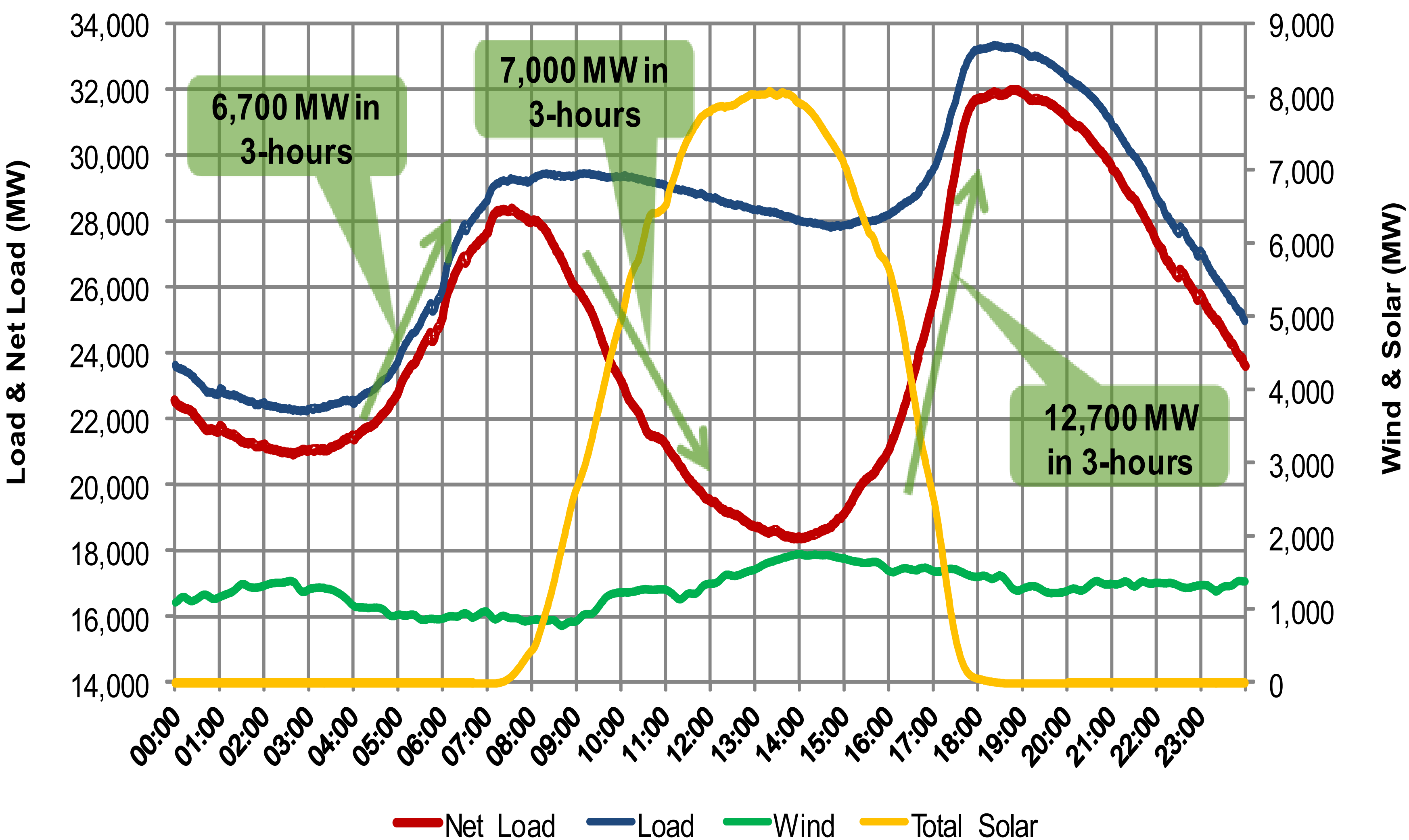


- Upstream plans affect downstream
- Different time periods for scheduling, seasonal, daily
- Hydro unit constraints: recreational, flooding, irrigation, fishing, waterway navigation

PUMP STORAGE



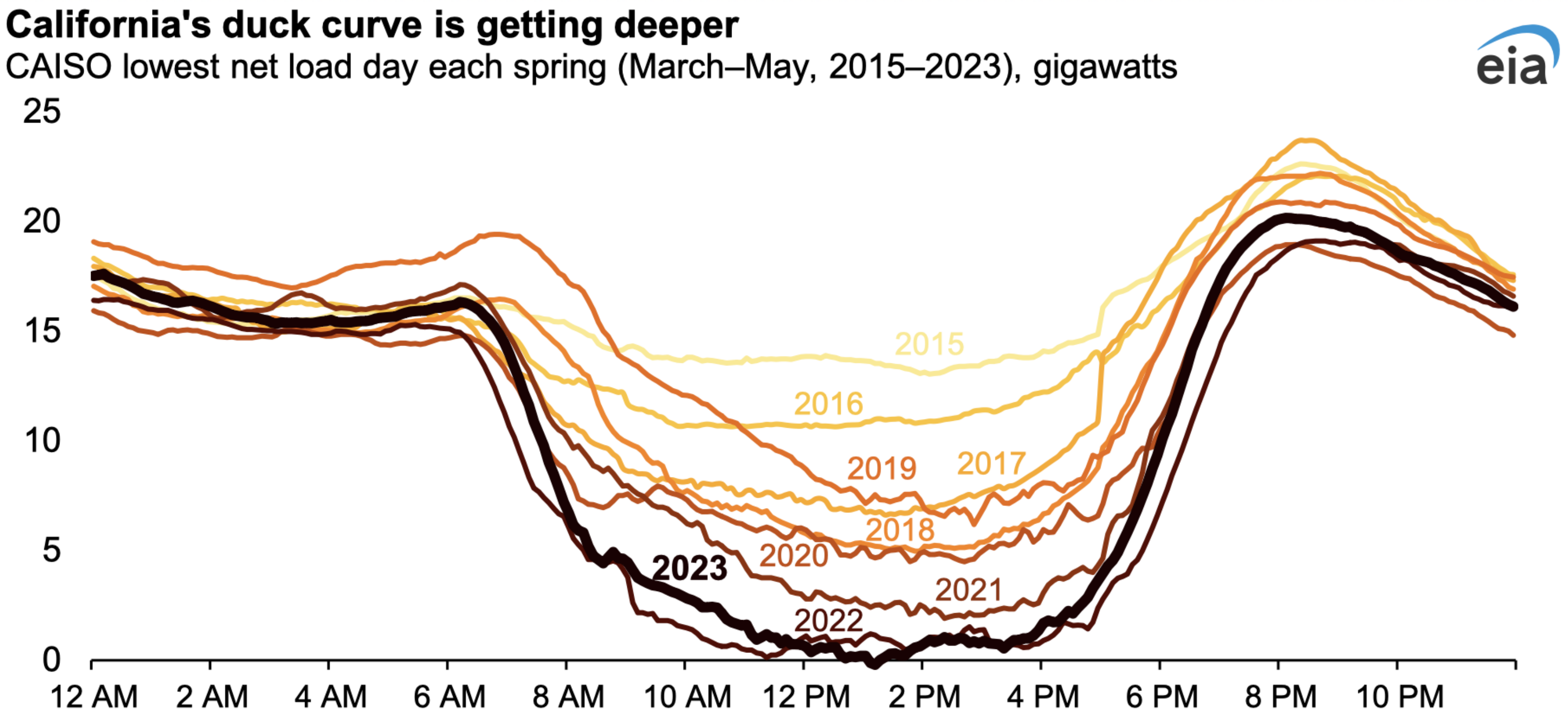
“DUCK DIAGRAM”



“DUCK DIAGRAM” AND NET LOAD

JUNE 21, 2023

As solar capacity grows, duck curves are getting deeper in California



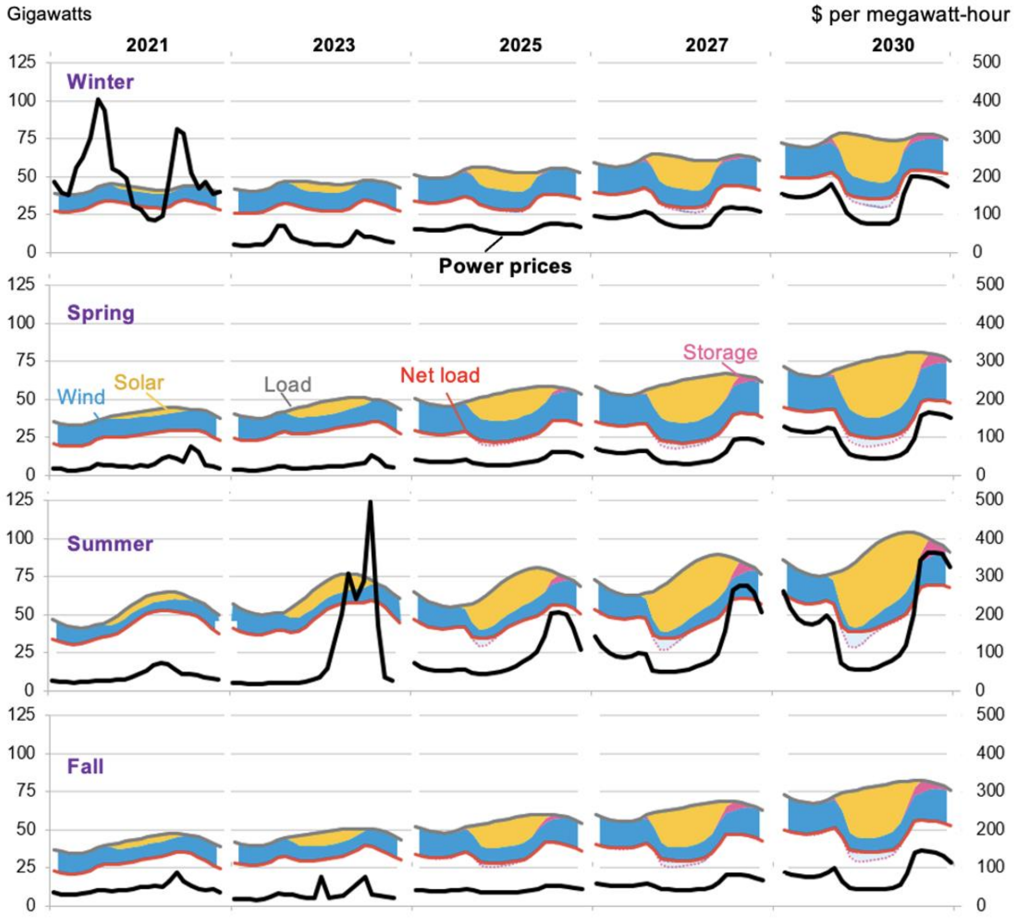
Data source: California Independent System Operator (CAISO)

https://www.eia.gov/todayinenergy/detail.php?id=56880

ERCOT DUCK CURVE AND PRICES

Solar Is Shaping Hourly Dynamics in Texas

Select average hourly load and renewables output in Ercot



Source: BloombergNEF

Note: Power price forecast is average across weather years for North Hub. Net load is defined as load minus generation from renewables and batteries. It represents the level of output required from thermal generation and is a major factor in determining power prices. Net load is before Bitcoin mines' price-responsive behavior. Winter 2021 had record power prices due to Winter Storm Uri in February 2021, when prices were $9,000 per megawatt-hour for multiple days. Ercot is the Electric Reliability Council of Texas.

https://about.bnef.com/blog/texas-tug-of-war-grid-juggles-solar-boom-and-power-hungry-data-centers/

Table 1a. Estimated capacity-weighted[a] levelized cost of electricity (LCOE) and levelized cost of storage (LCOS) for new resources entering service in 2027 (2021 dollars per megawatthour)

Plant type	Capacity factor (percent)	Levelized capital cost	Levelized fixed O&M[b]	Levelized variable cost	Levelized transmission cost	Total system LCOE or LCOS	Levelized tax credit[c]	Total LCOE or LCOS including tax credit
Dispatchable technologies								
Ultra-supercritical coal	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Combined cycle	87%	$8.56	$1.68	$25.80	$1.01	$37.05	*NA*	$37.05
Advanced nuclear	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Geothermal	90%	$21.80	$15.20	$1.21	$1.40	$39.61	-$2.18	$37.43
Biomass	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Resource-constrained technologies								
Wind, onshore	43%	$27.45	$7.44	$0.00	$2.91	$37.80	*NA*	$37.80
Wind, offshore	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Solar, standalone[d]	29%	$26.35	$6.34	$0.00	$3.41	$36.09	-$2.64	$33.46
Solar, hybrid[d,e]	26%	$39.12	$15.00	$0.00	$4.51	$58.62	-$3.91	$54.71
Hydroelectric[e]	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Capacity resource technologies								
Combustion turbine	10%	$55.55	$8.37	$49.93	$10.00	$123.84	*NA*	$123.84
Battery storage	10%	$64.74	$29.64	$18.92	$11.54	$124.84	$0.00	$124.84

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022*

[a] The capacity-weighted average is the average levelized cost per technology, weighted by the new capacity coming online in each region. We base the capacity additions for each region on additions from 2025 to 2027. Technologies for which capacity additions are not expected do not have a capacity-weighted average and are marked as *NB*, or *not built*.

[b] O&M = operations and maintenance

[c] The tax credit component is based on targeted federal tax credits such as the Production Tax Credit (PTC) or Investment Tax Credit (ITC) available for some technologies. It reflects tax credits available only for plants entering service in 2027 and the substantial phaseout of both the PTC and ITC as scheduled under current law. Technologies not eligible for PTC or ITC are indicated as *NA,* or *not available*. The results are based on a regional model, and state or local incentives are not included in LCOE and LCOS calculations. See text box on page 2 for details on how the tax credits are represented in the model.

[d] Technology is assumed to be photovoltaic (PV) with single-axis tracking. The solar hybrid system is a single-axis PV system coupled with a four-hour battery storage system. Costs are expressed in terms of net AC (alternating current) power available to the grid for the installed capacity.

[e] As modeled, we assume that hydroelectric and hybrid solar PV generating assets have seasonal and diurnal storage, respectively, so that they can be dispatched within a season or a day, but overall operation is limited by resource availablility by site and season for hydroelectric and by daytime for hybrid solar PV.

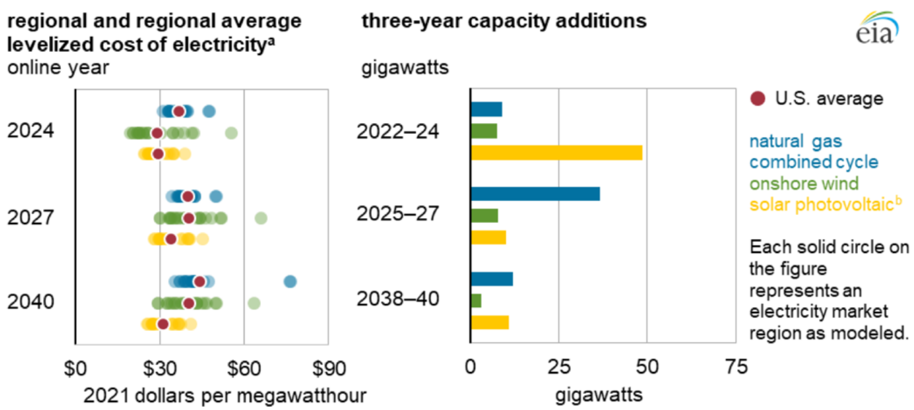
https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

LEVELIZED COST OF ELECTRICITY LIMITATIONS

Levelized Cost of Electricity (LCOE) does **NOT**:

- Include non-market costs, such as environmental costs
- Reflect the risks of its various components, e.g., nuclear power plant construction risk, carbon pricing for coal plants, natural gas fuel price risk
- Account for revenues: different technologies produce at different times garnering different prices for their output
- Account for engineering characteristics such as dispatchability, intermittency, etc.
- LCOE depends heavily on the assumed capacity factor

Figure 1. Levelized cost of electricity (with applicable tax subsidies) by region and total incremental capacity additions for selected generating technologies entering into service in 2024, 2027, and 2040



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022*

[a] Levelized cost includes tax credits available for plants entering service during the projection period.
[b] Technology is assumed to be photovoltaic with single-axis tracking. Costs are expressed in terms of net AC (alternating current) power available to the grid for the installed capacity.

https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

TAXONOMY OF COSTS

<table>
<tr><th></th><th>Private Cost</th><th>Taxpayer Cost</th><th>Societal Cost</th></tr>
<tr><td>Capital Cost
One-time, fixed cost
e.g., power plant cost</td><td rowspan="3">Paid by investor and who then try to recover from consumers</td><td>ITC
Investment tax credit</td><td rowspan="3">Environmental Costs
e.g., greenhouse gas emissions; air pollutants

Reliability/ Resiliency</td></tr>
<tr><td>Fixed Cost
Periodic cost that does not vary with output
e.g., replacement of a component</td><td>Tax deduction of maintenance costs</td></tr>
<tr><td>Variable Cost
Cost that varies with output
e.g., fuel cost</td><td>PTC
Production tax credit</td></tr>
</table>

ENERGY vs POWER

ENERGY is the amount of power delivered over time measured in Watt-hours (Wh) (analogous to distance traveled)

e.g., a 100W light bulb consumes 2,400 Wh (or 2.4 kWh) of energy in 24 hours

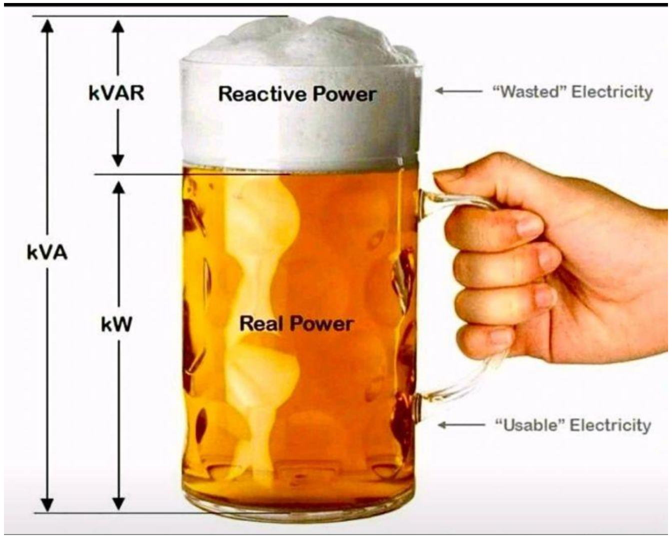
POWER is the rate at which energy is used or supplied (analogous to speed)

- Real Power has the units of watts and measures the strength of a supply source
- Reactive Power, measured in vars, is needed by wires and motors to enable energy conversion but provides no useful work

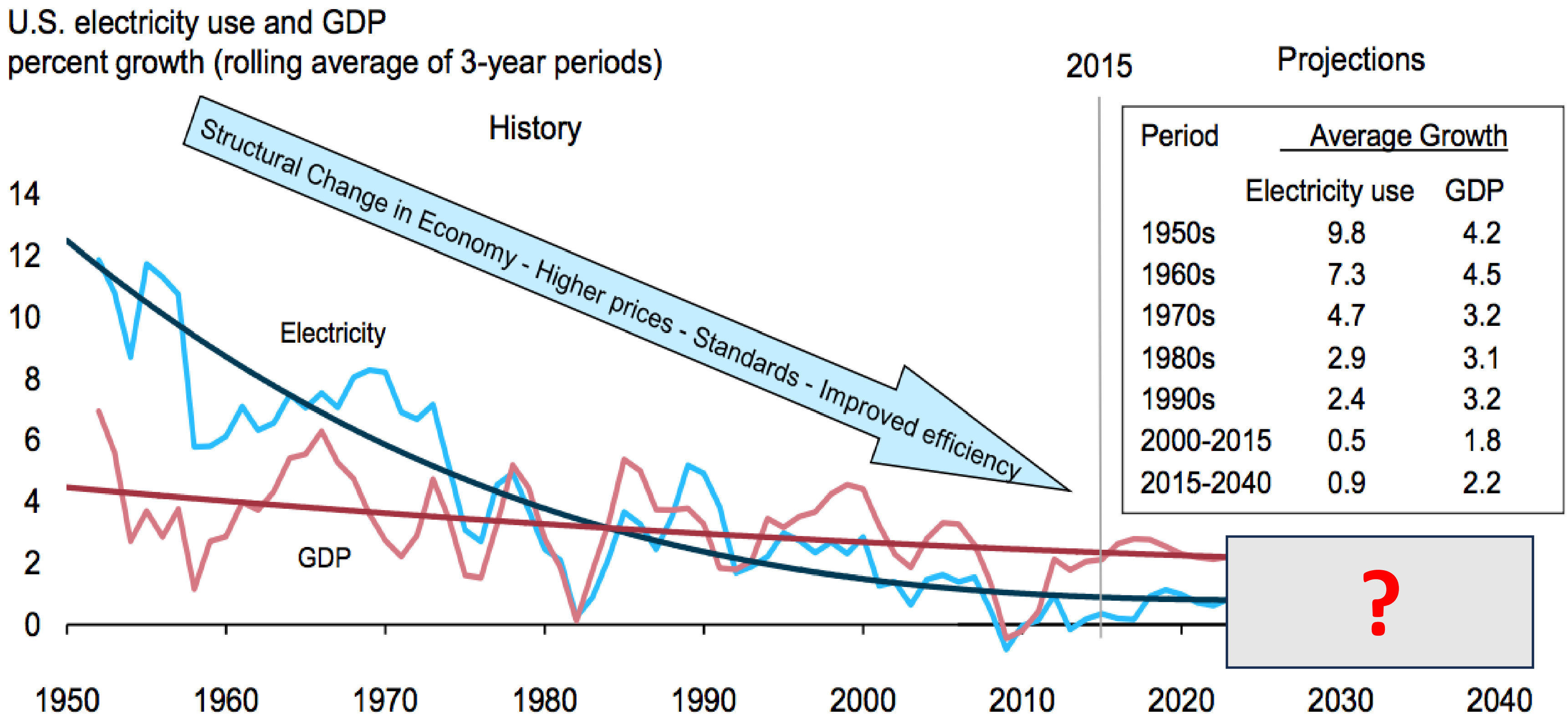
Insufficient reactive power was a contributing factor to the August 2003 blackout

Similar to a golfer who must hit the ball high in the air even though his goal is only to move the ball horizontally

See the FERC Staff Report (2005) *Principles for Efficient and Reliable Reactive Power Supply and Consumption*



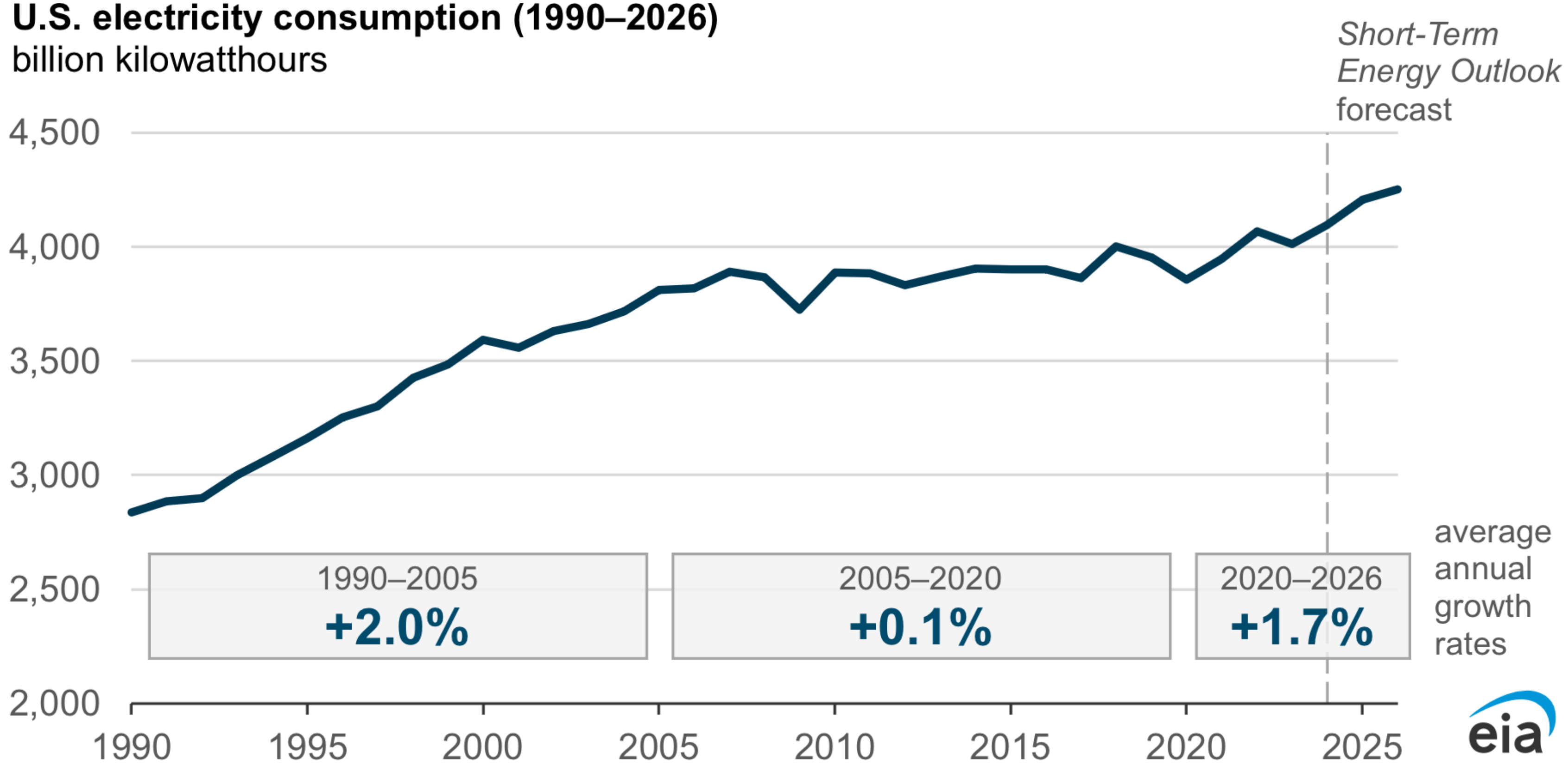
GDP & ELECTRICITY DEMAND GROWTH RATE



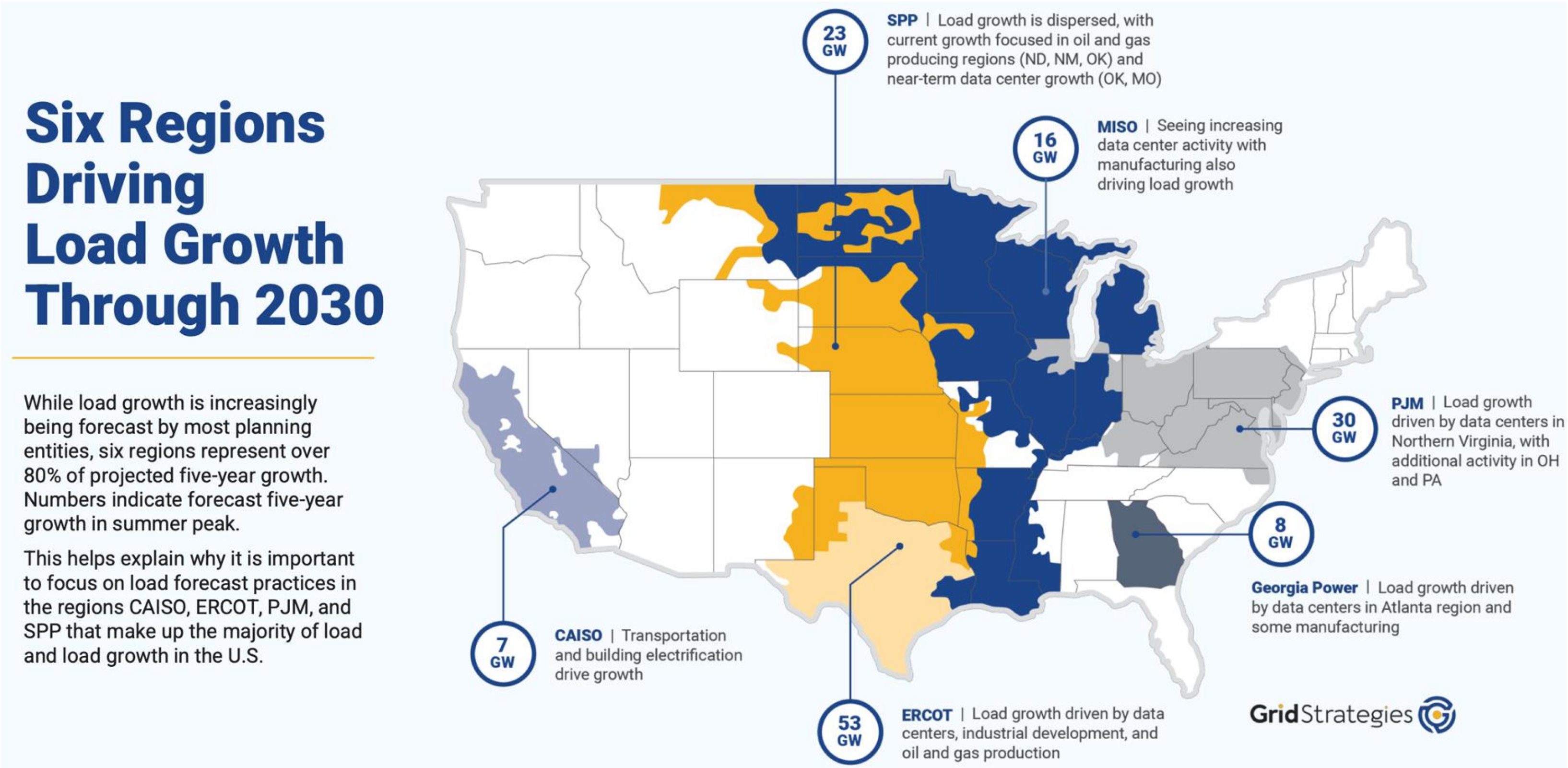
Source: EIA, Annual Energy Outlook 2016

Note: Very recent electricity demand growth rate projections are bullish!

After more than a decade of little change, U.S. electricity consumption is rising again



Data source: U.S. Energy Information Administration, *Monthly Energy Review* and *Short-Term Energy Outlook*, May 2025
Data values: Electricity Overview (history) and U.S. Electricity Industry Overview (forecast)

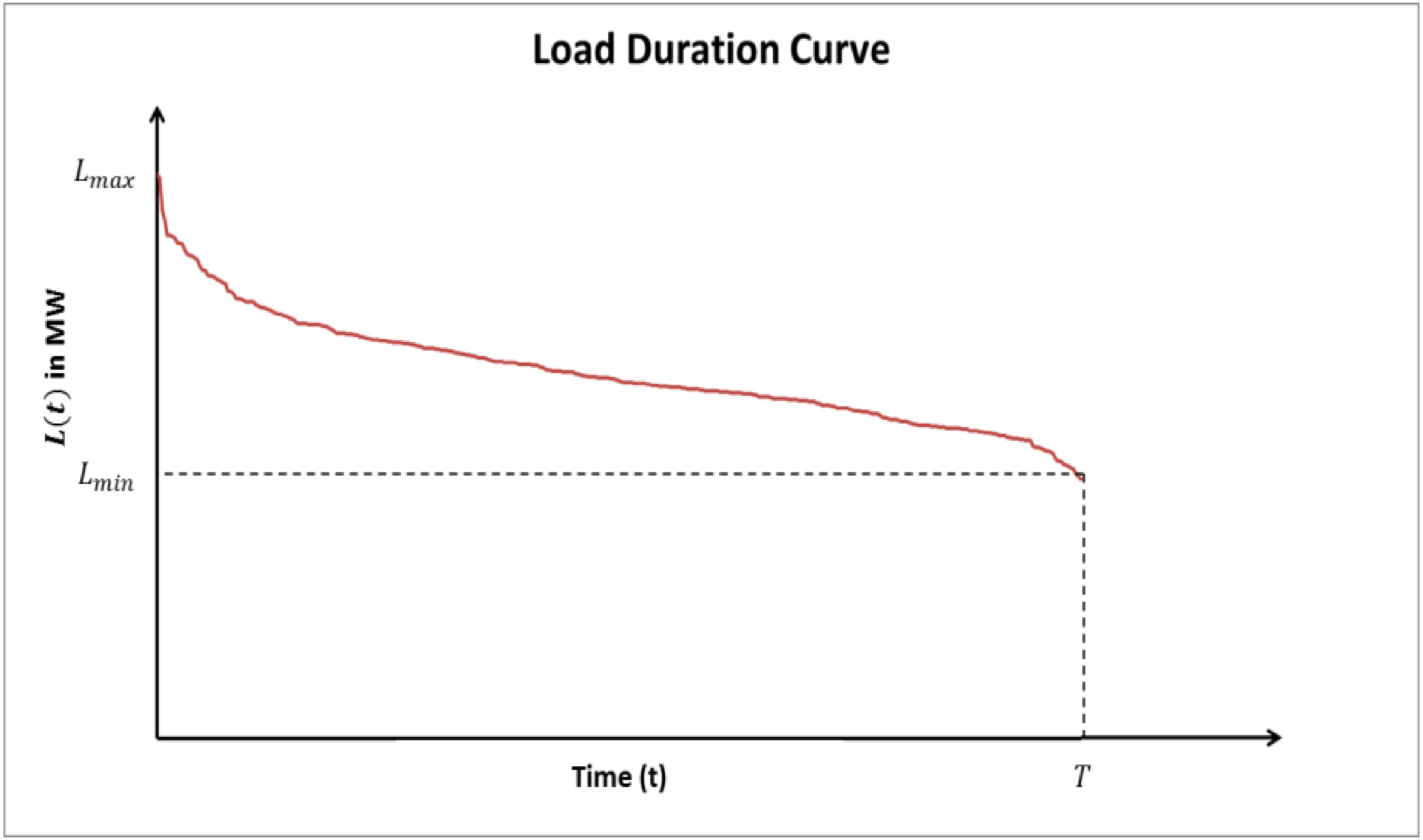


Grid Strategies, 2025, https://gridstrategiesllc.com/wp-content/uploads/Grid-Strategies-National-Load-Growth-Report-2025.pdf

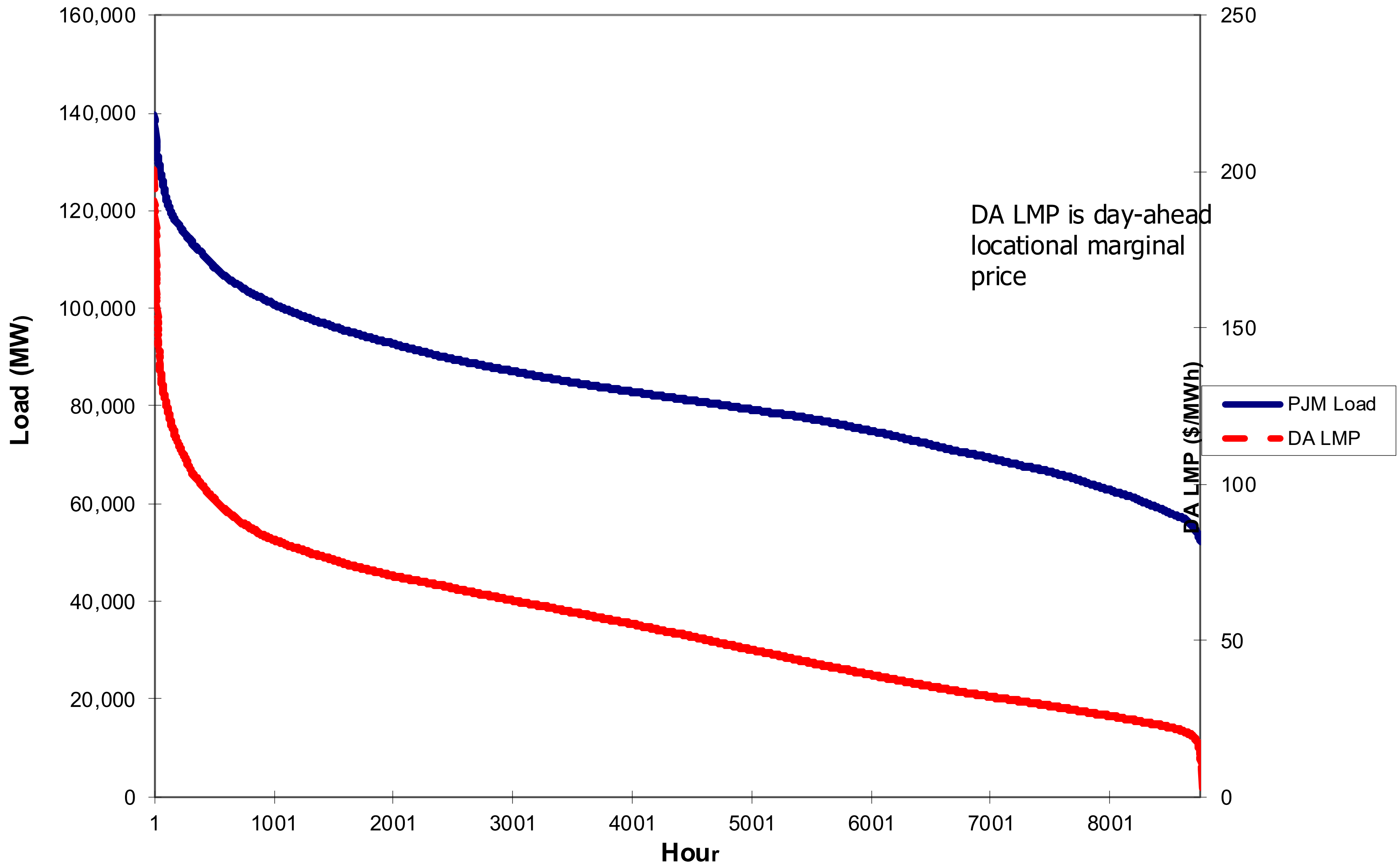
Powering the US Data Center Boom: Why Forecasting Can Be So Tricky

September 17, 2025 By **Ian Goldsmith** and **Zach Byrum** Cover Image by: Gerville / iStock https://www.wri.org/insights/us-data-centers-electricity-demand

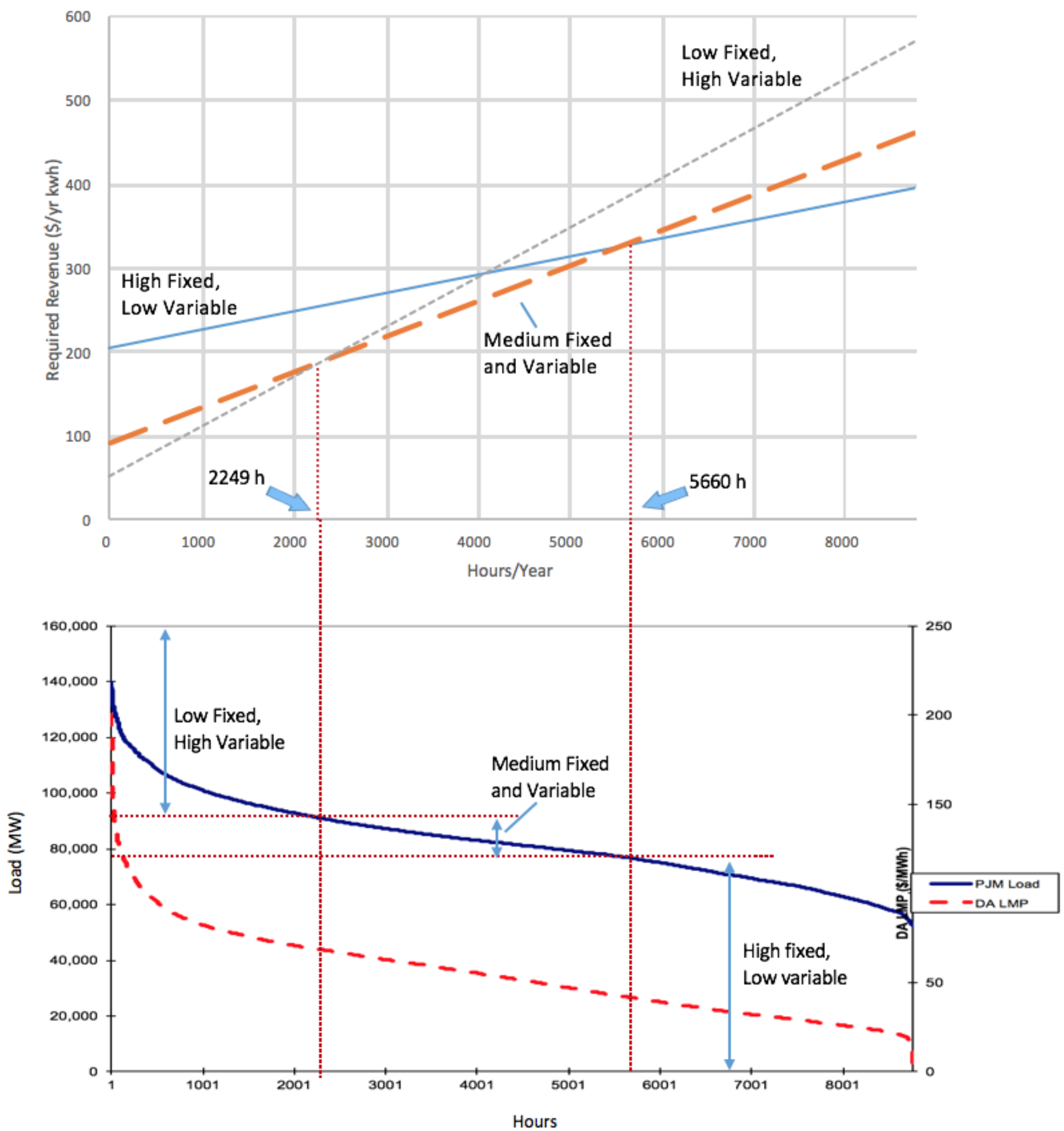
LOAD DURATION CURVE (LDC)



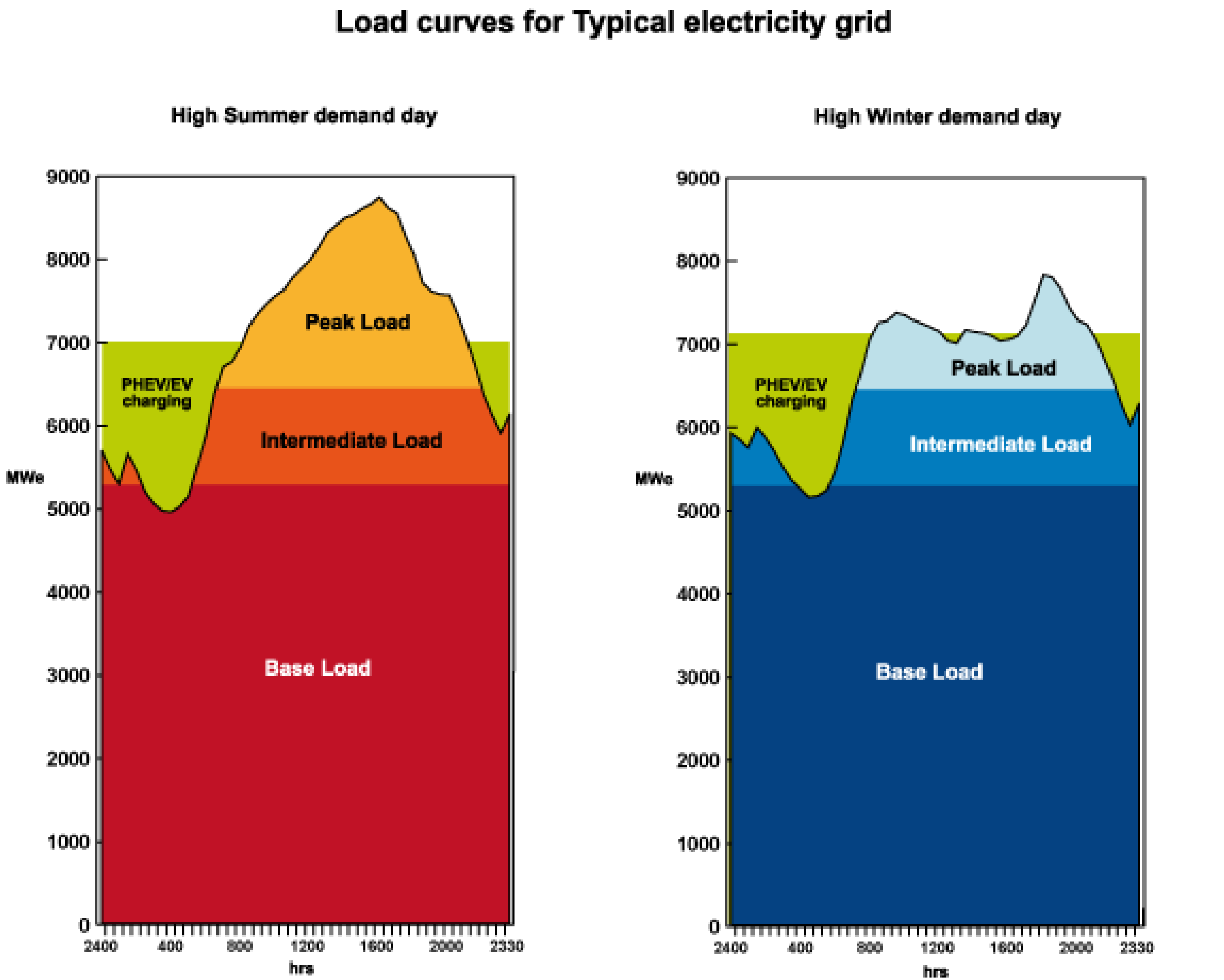
ANNUAL LOAD DURATION CURVE

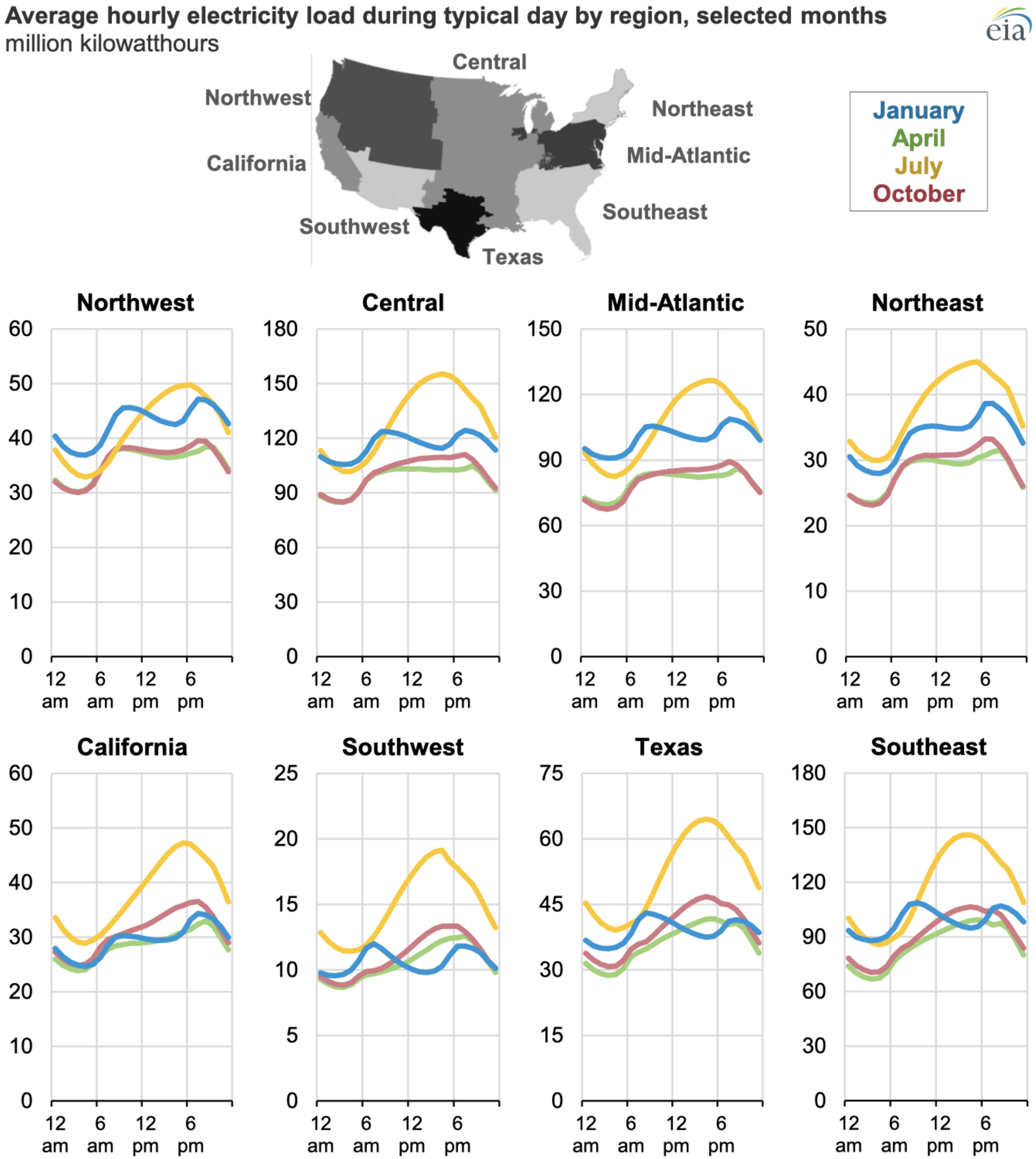


GENERATION INVESTMENT



WEEKLY ELECTRICITY DEMAND

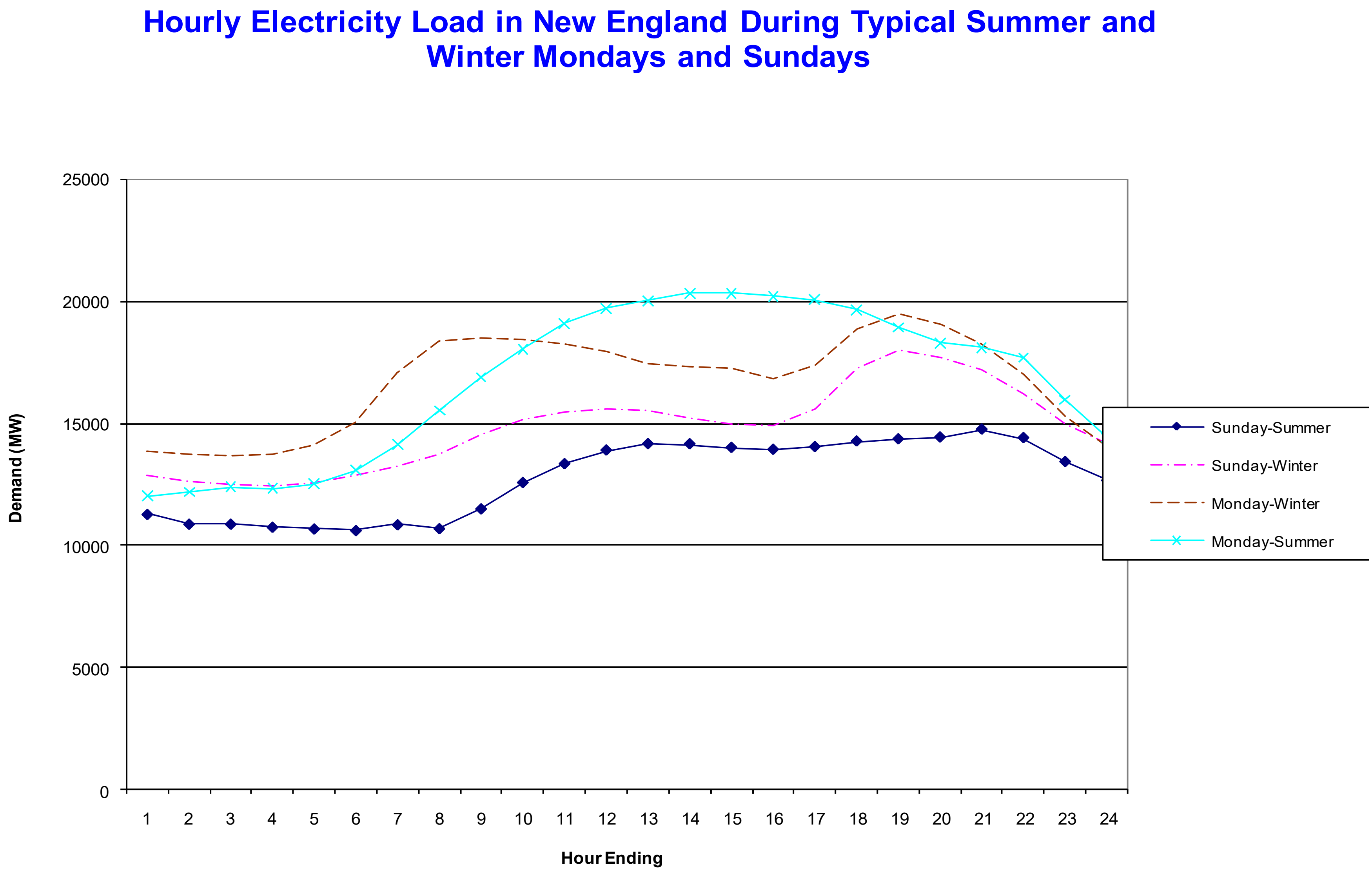




Source: U.S. Energy Information Administration, *U.S. Hourly Electric Grid Monitor*
Note: Hourly load shown is displayed for each region's local time zone.

https://www.eia.gov/todayinenergy/detail.php?id=42915

HOURLY ELECTRICITY DEMAND



POWER SYSTEM TERMINOLOGY

VOLTAGE (V) is equivalent to pressure in water or gas systems. Voltage in homes is typically 120 to 240 volts, whereas in cities it is around 12,000 volts

CIRCUIT refers to a delivery combination of a supply source with a voltage and conductors

LINES are the physical transmission and distribution conductors

BUSES, short for busbars, are points in the circuit where multiple lines, transformers, generators, and loads are connected

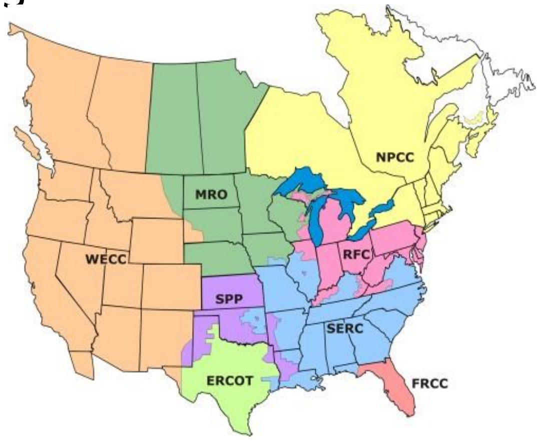
GRID refers to the interconnection of lines in a power system

BULK POWR SYSTEM refers to generation and transmission

NERC RELIABILITY CRITERIA

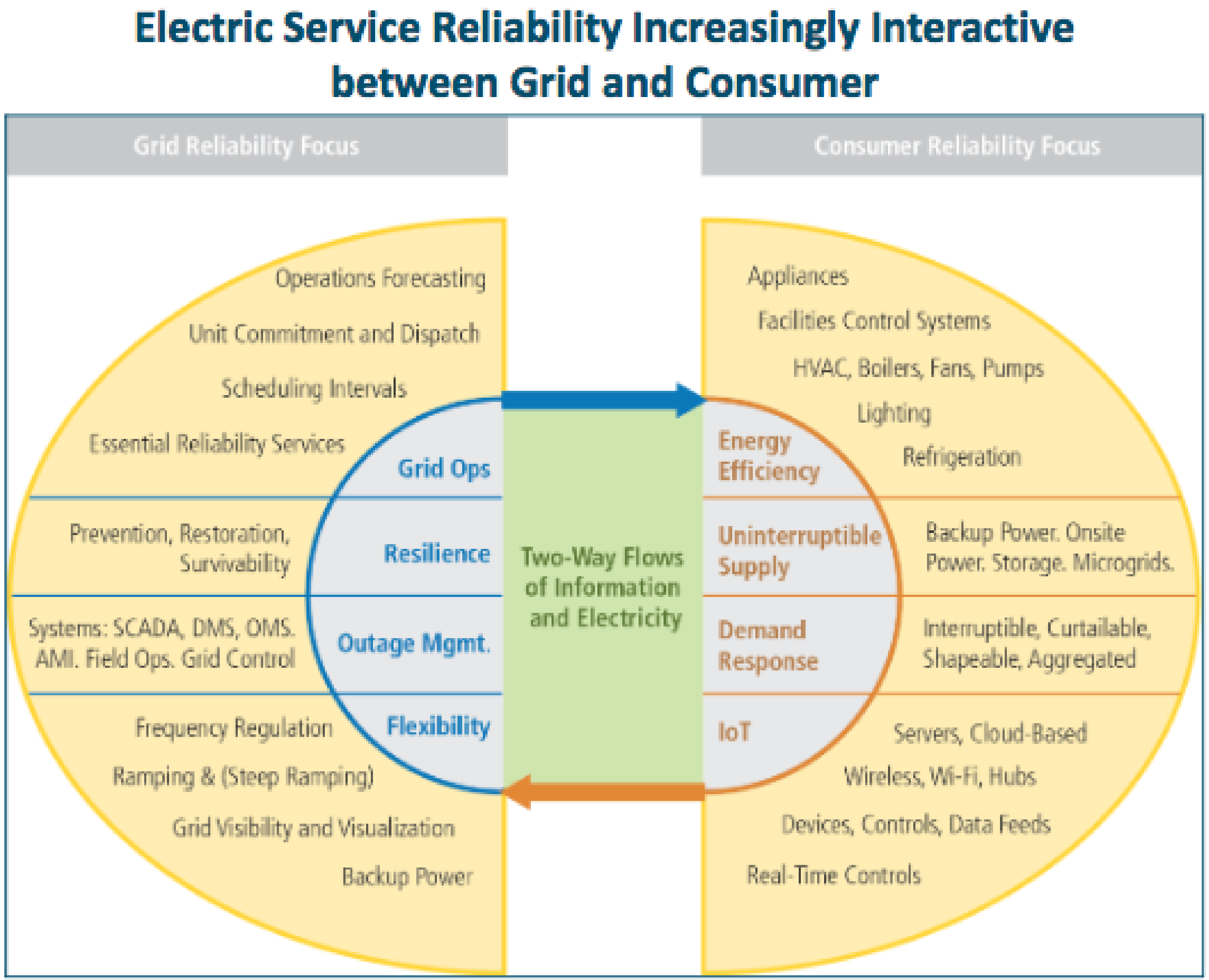
Recall that NERC (the North America Electric Reliability Corporation) sets the reliability standards that are adopted by the Federal Energy Regulatory Commission (FERC)

- The bulk electric systems shall be planned and operated to avoid widespread cascading interruptions of electricity supply for the types of contingency events normally encountered on electric systems (i.e., more probable contingencies)
- The bulk electric systems also must demonstrate the ability of its bulk electric system to withstand more severe contingencies
- The frequency of having to disconnect firm load should not exceed one time in ten years



NERC Regions

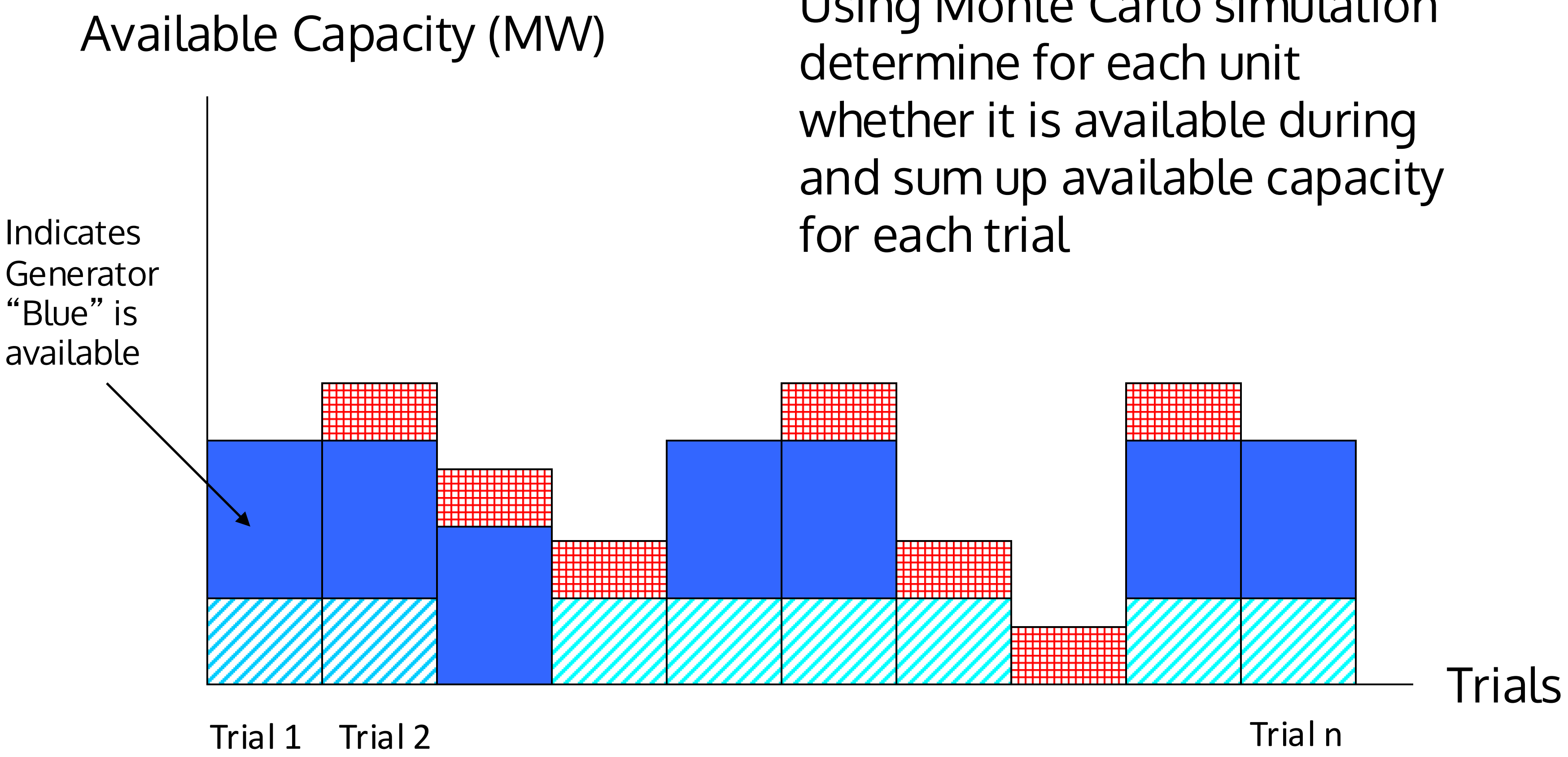
RELIABILITY

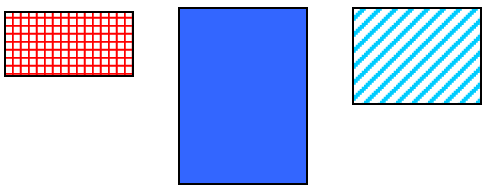


Source: Department of Energy, 2016

GENERATION CAPACITY ADEQUACY

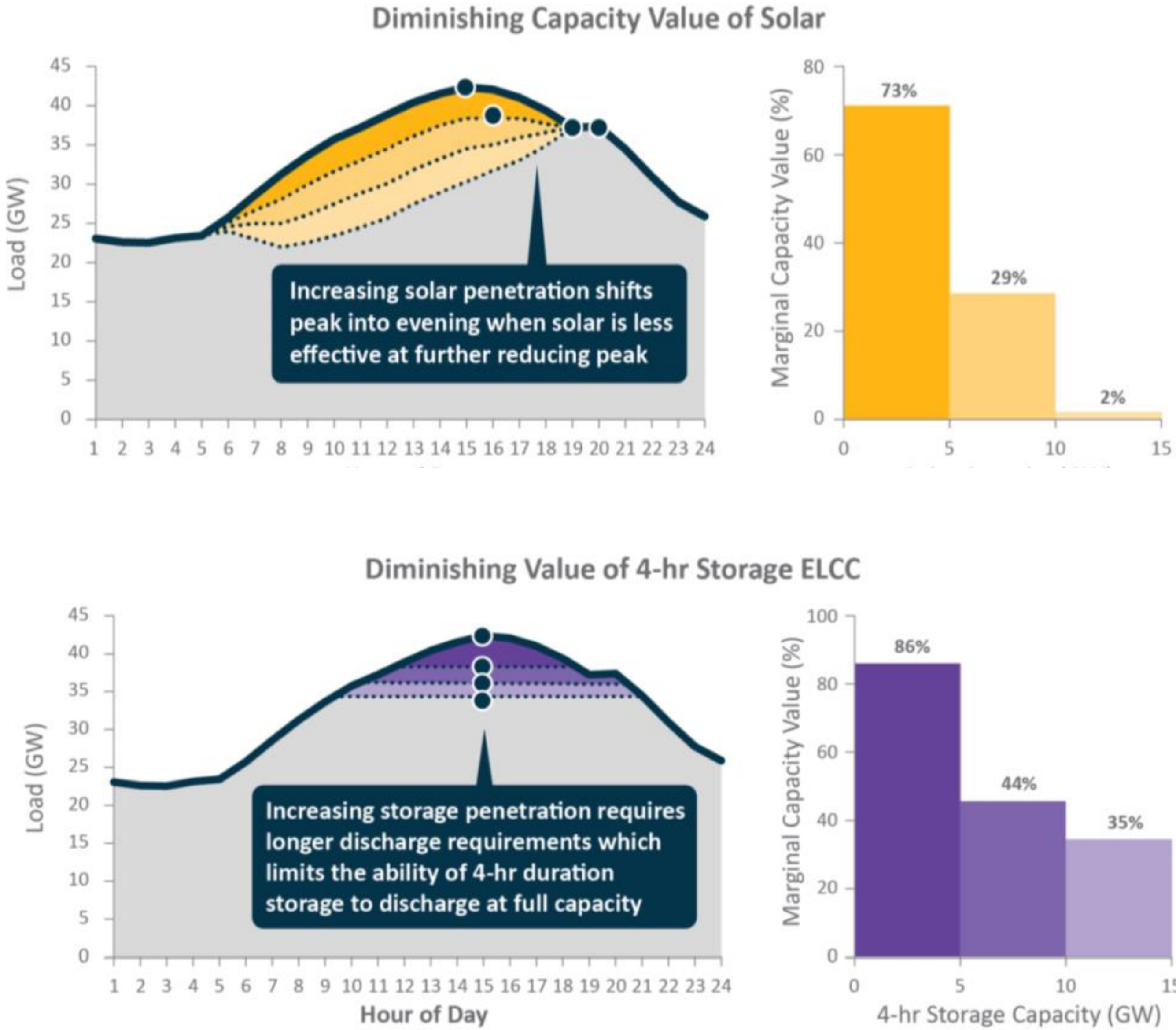
Using Monte Carlo simulation determine for each unit whether it is available during and sum up available capacity for each trial





Indicate 3 different generation unit and the height of each box is its total capacity in MW

EFFECTIVE LOAD CARRYING CAPABILITY (ELCC)

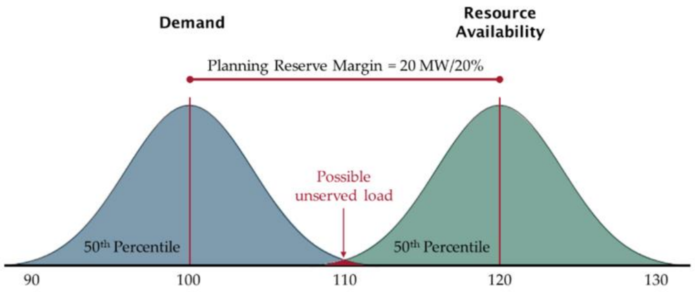


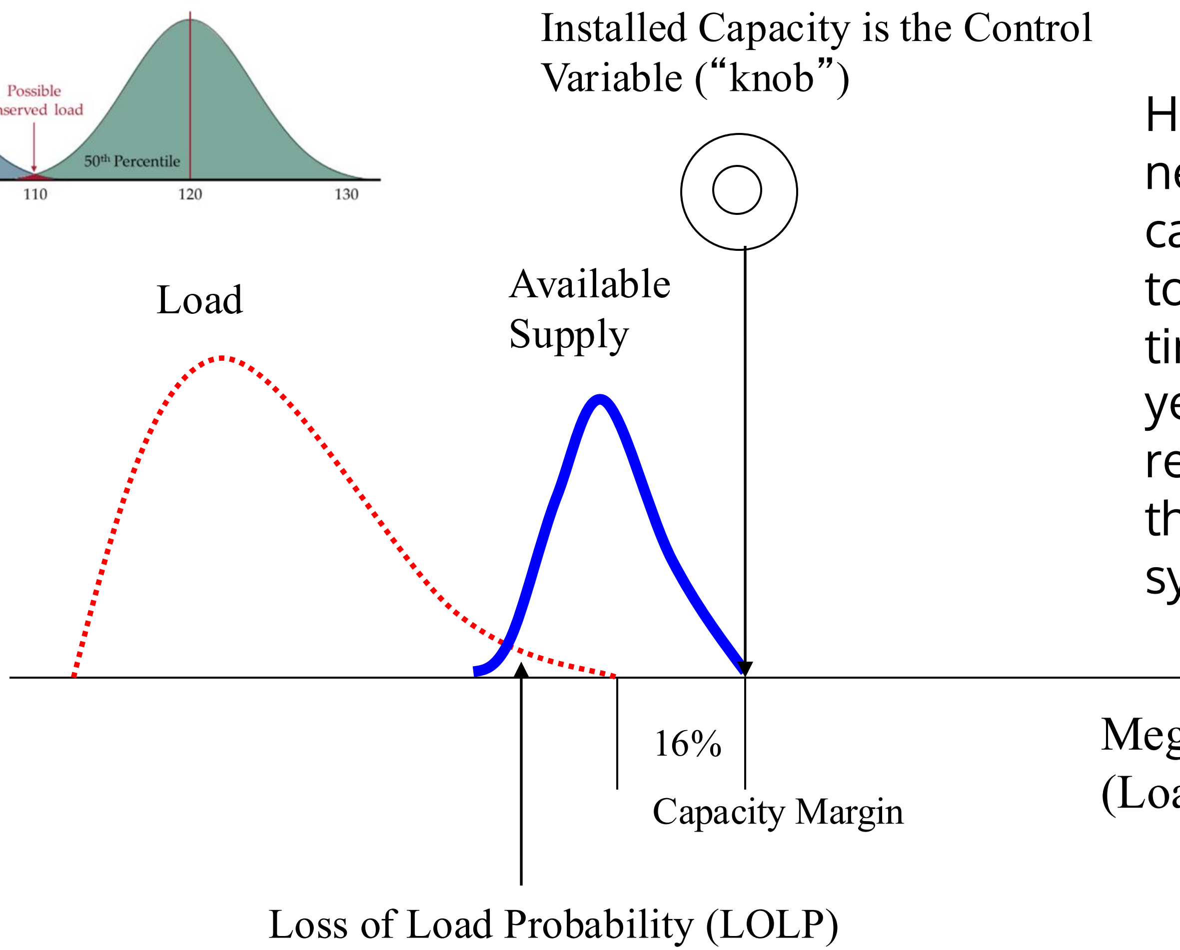
ELCC is the ability of a resource to produce electricity when needed for resource adequacy

MRI is marginal reliability impact is another way to determine the capacity value of a resource

GE, Evaluation of ELCC Methodology in the ISO-NE Footprint, Oct. 10, 2022

GENERATION CAPACITY ADEQUACY





Hydro systems need a lower capacity margin to obtain the 1-time-in-ten-year requirement than thermal systems

ANCILLARY SERVICES

Operating Reserves

- Ten-minute spinning reserves
- Ten-minute non-spinning reserves
- Thirty-minute reserves

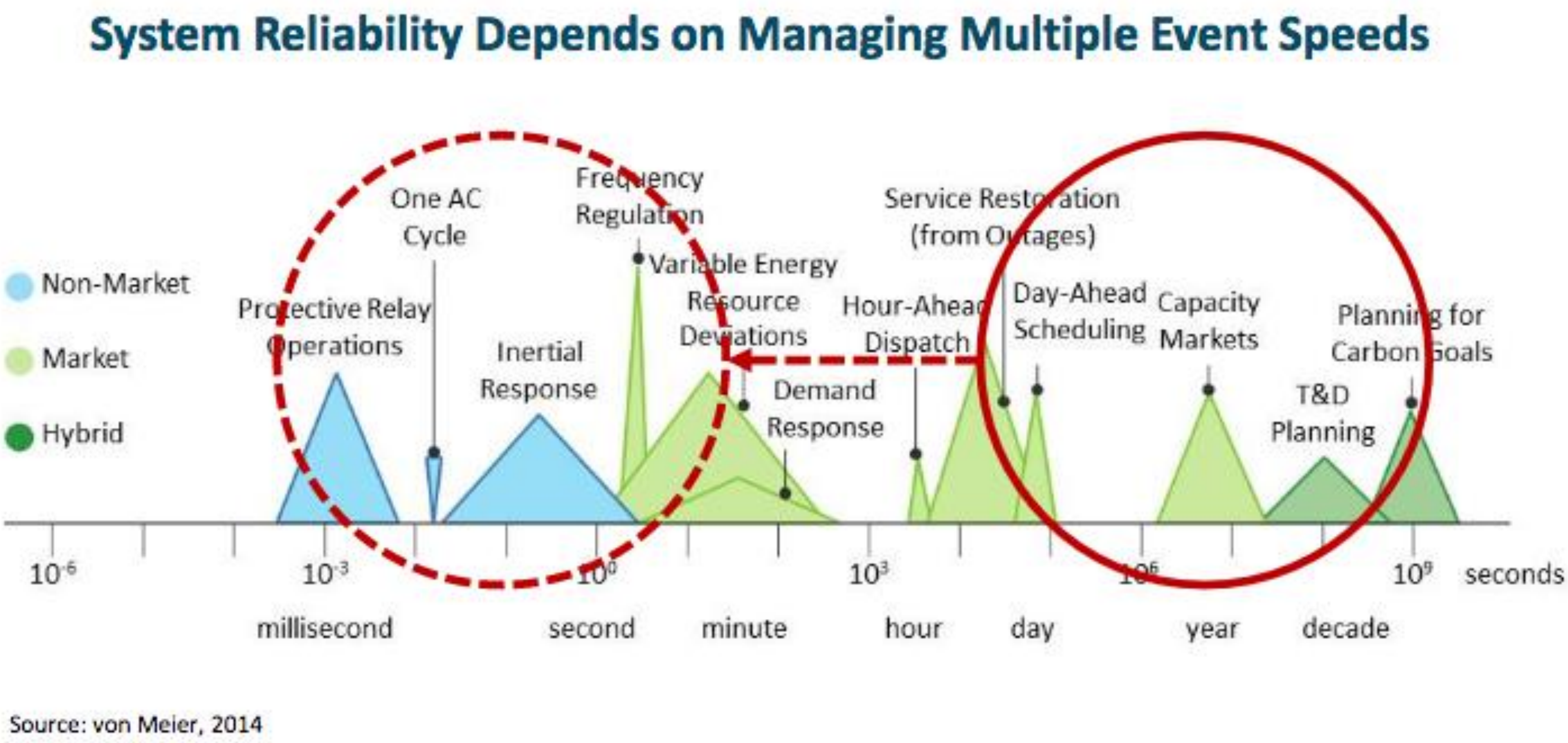
Typical reliability rule is to have sufficient operating reserves to cover 1.5 times the largest contingency or 1 times the largest and .5 times the second largest

Automatic Generation Control (AGC)

Black Start Service, Voltage Control (VARs) aka Reactive Power, …

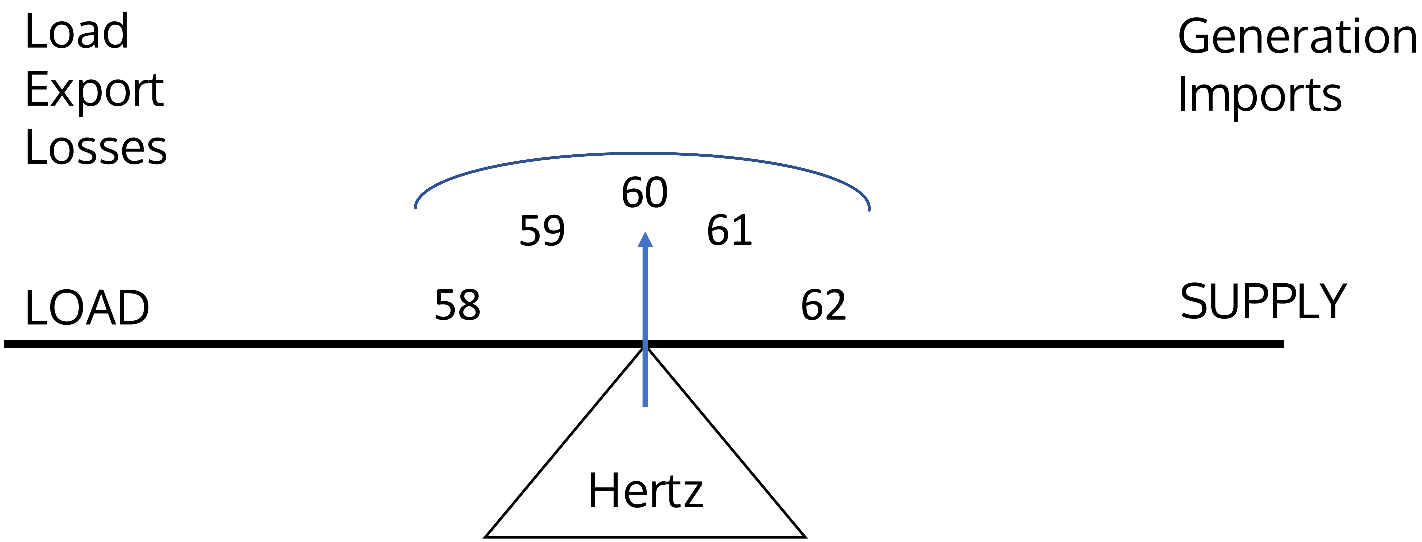
Problems arise when ancillary services are such that they interact with the energy market => need to consider opportunity costs

TIMELINE



http://energyoutlook.naseo.org/Data/Sites/13/media/presentations/Battershell--QER-1.2-Briefin.PDF

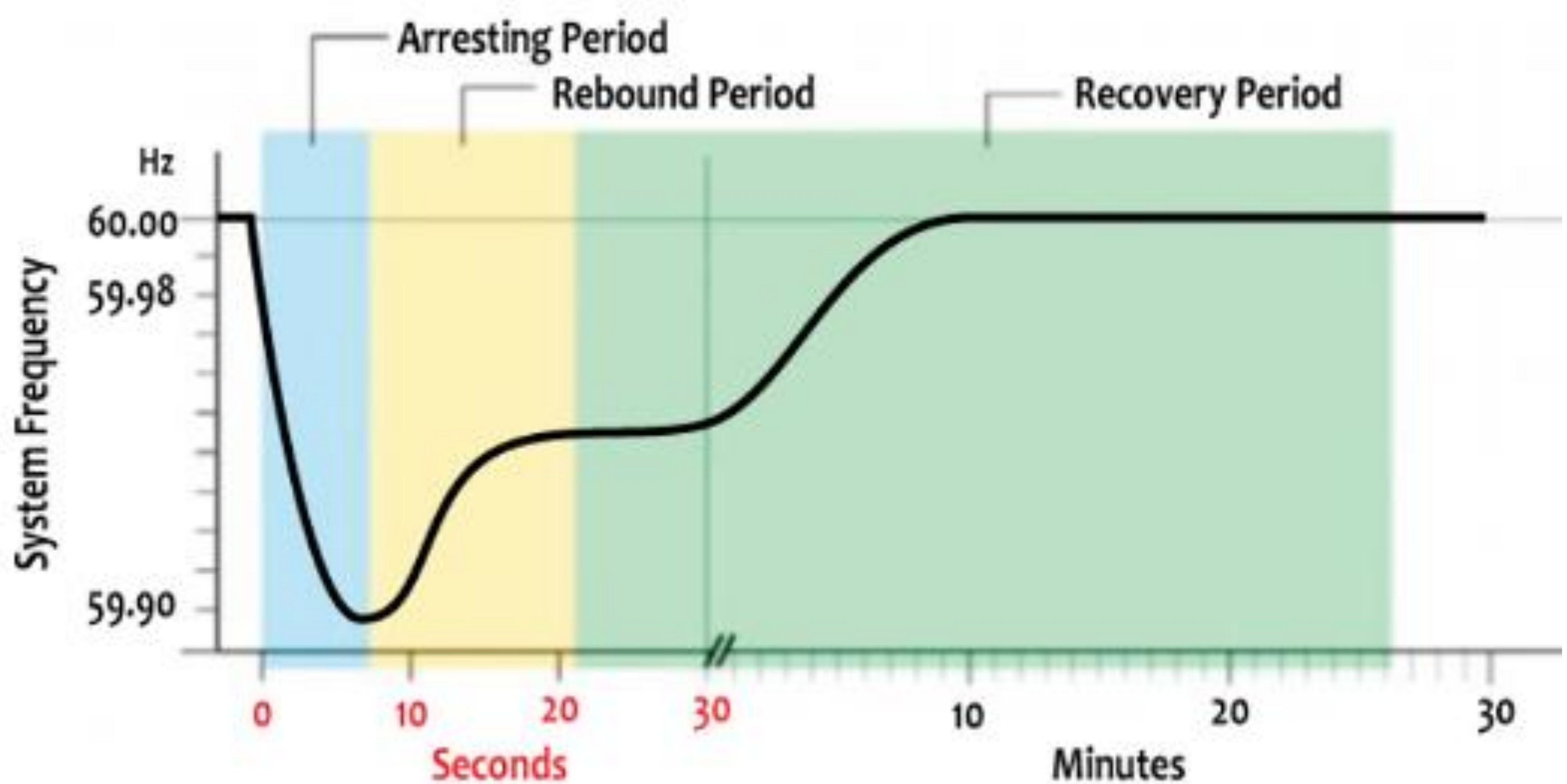
BALANCING SUPPLY & DEMAND



Load (demand) and supply must be in balance at (almost) all times

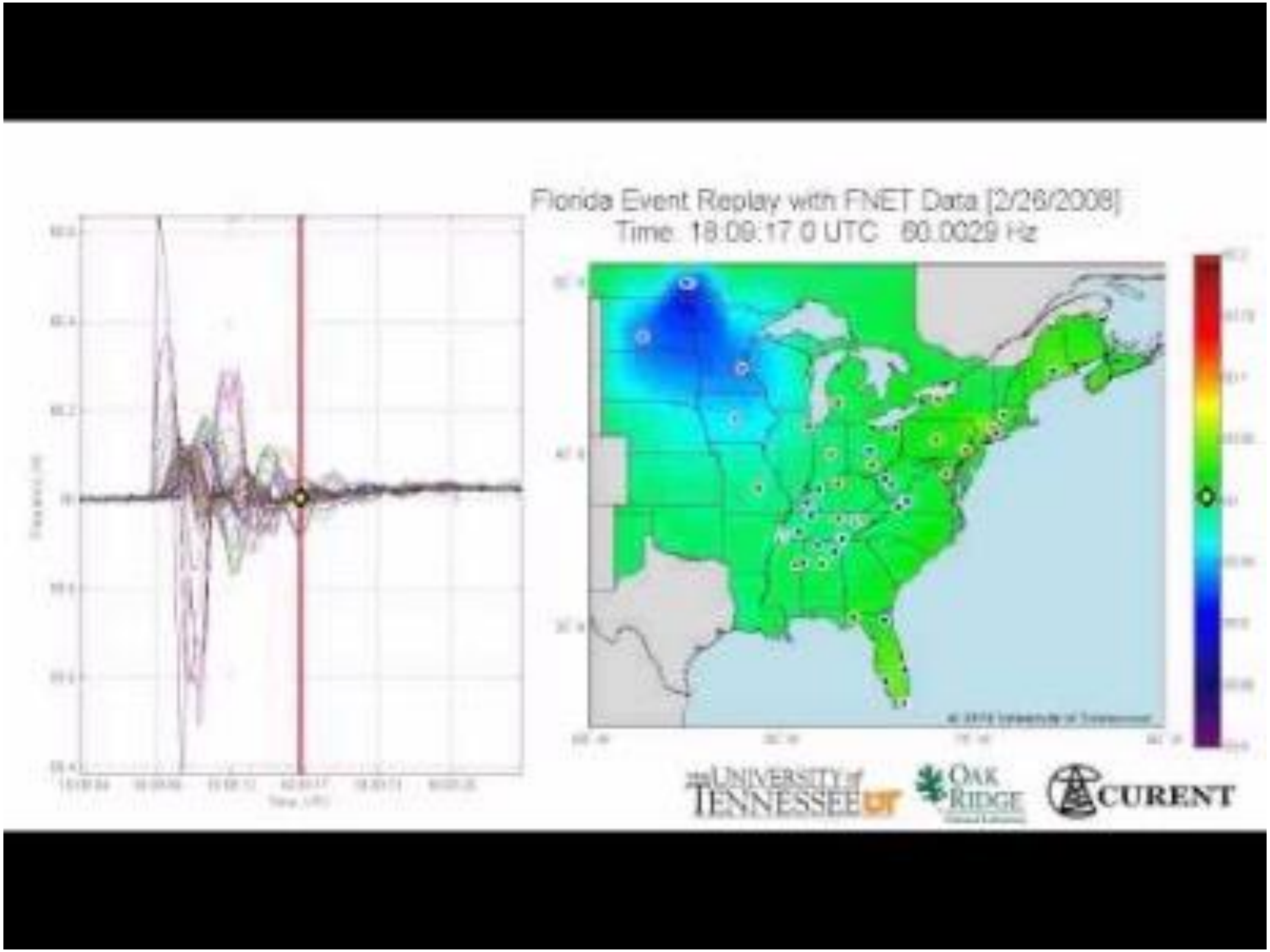
http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERS%20Abstract%20Report%20Final.pdf

BALANCING SUPPLY & DEMAND



http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERS%20Abstract%20Report%20Final.pdf

VIDEO OF POWER PLANT TRIPPING OFFLINE



https://www.youtube.com/watch?v=bdBB4byrZ6U

KNOWLEDGE SELF-CHECK

1. What is loop flow and why is it important in the planning and operations of power systems?
2. What is the dispatch problem and how is it different from the unit commitment problems?
3. How do generation investment and transmission development overlap?
4. What is the Duck Curve?
5. What is the load duration curve and why is it useful?
6. How does electricity demand change by day, week, season, and over longer periods of time?
7. How does NERC frame the reliability of the power system?
8. What is resource adequacy and how is it calculated?
9. What are the different types of ancillary services and why are they needed?
10. What happens if electricity supply and demand are not in balance?

TERMINOLOGY AND ABBREVIATIONS CHECK

- NERC
- Loop flow
- Parallel flow
- Dispatch
- FACTS
- SPS
- HVDC
- GETs
- LCOE
- Energy
- Power
- LDC
- AGC

Session 3:
Electricity Markets

ELECTRICITY MARKETS OVERVIEW

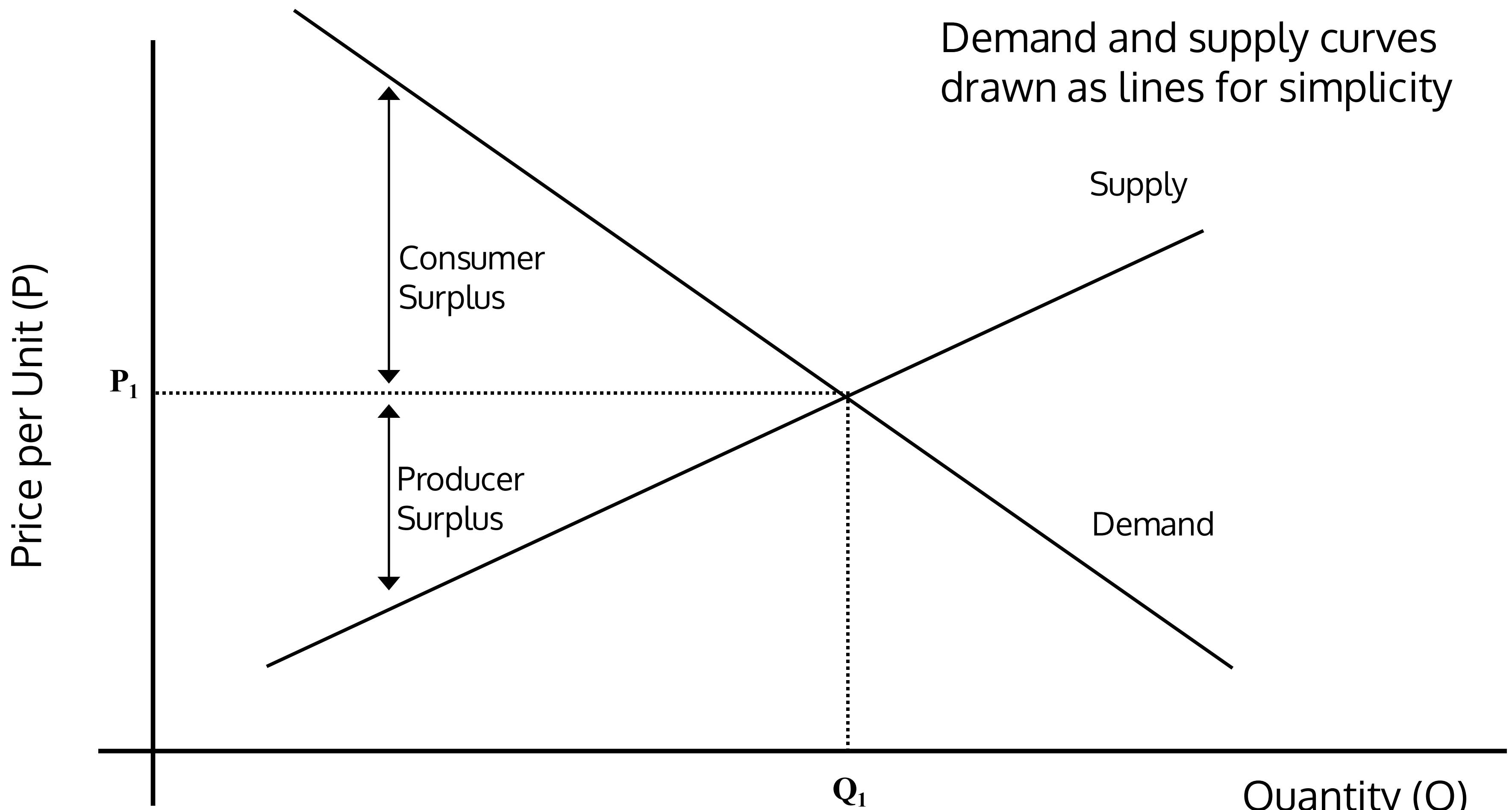
Topics

- Review of microeconomics
- Electricity markets in RTOs/ISOs
- Calculation of LMPs (Locational Marginal Prices)
- Multi-settlement (Day-Ahead (DA) and Real-Time (RT) energy markets)
- Bilateral energy markets
- Capacity markets
- Markets for emissions and renewable resources
- Market power

Key Questions

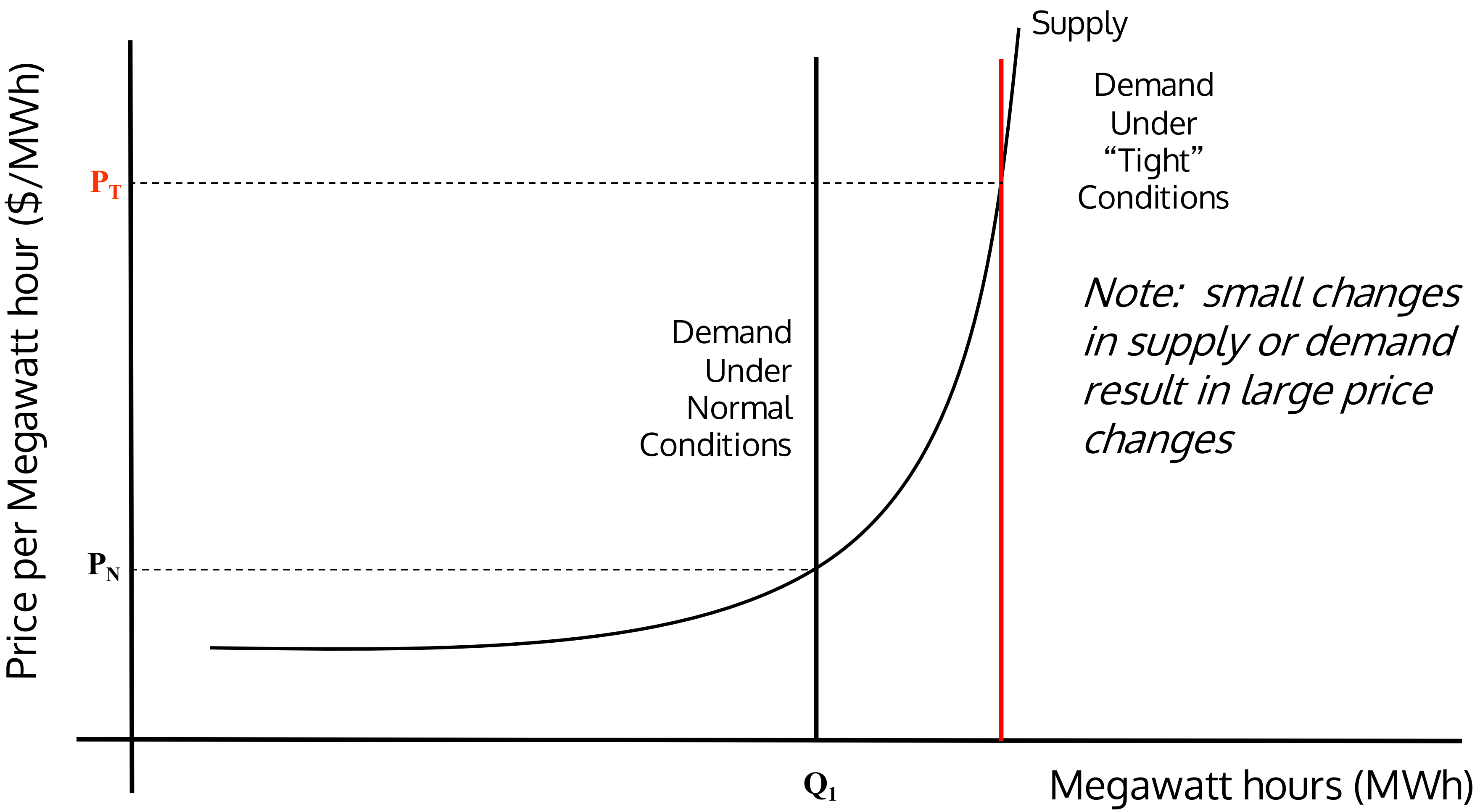
- Why is Locational Marginal Pricing necessary (LMPs)
- Why are prices based upon marginal costs not average costs?
- Why are there uniform clearing prices?
- Why are both day-ahead and real-time markets necessary?
- How is congestion risk managed?
- How are markets for emissions, renewables, and capacity related?
- Why are wholesale electricity markets susceptible to market power?

EFFICIENT PRICING - MICROECONOMICS



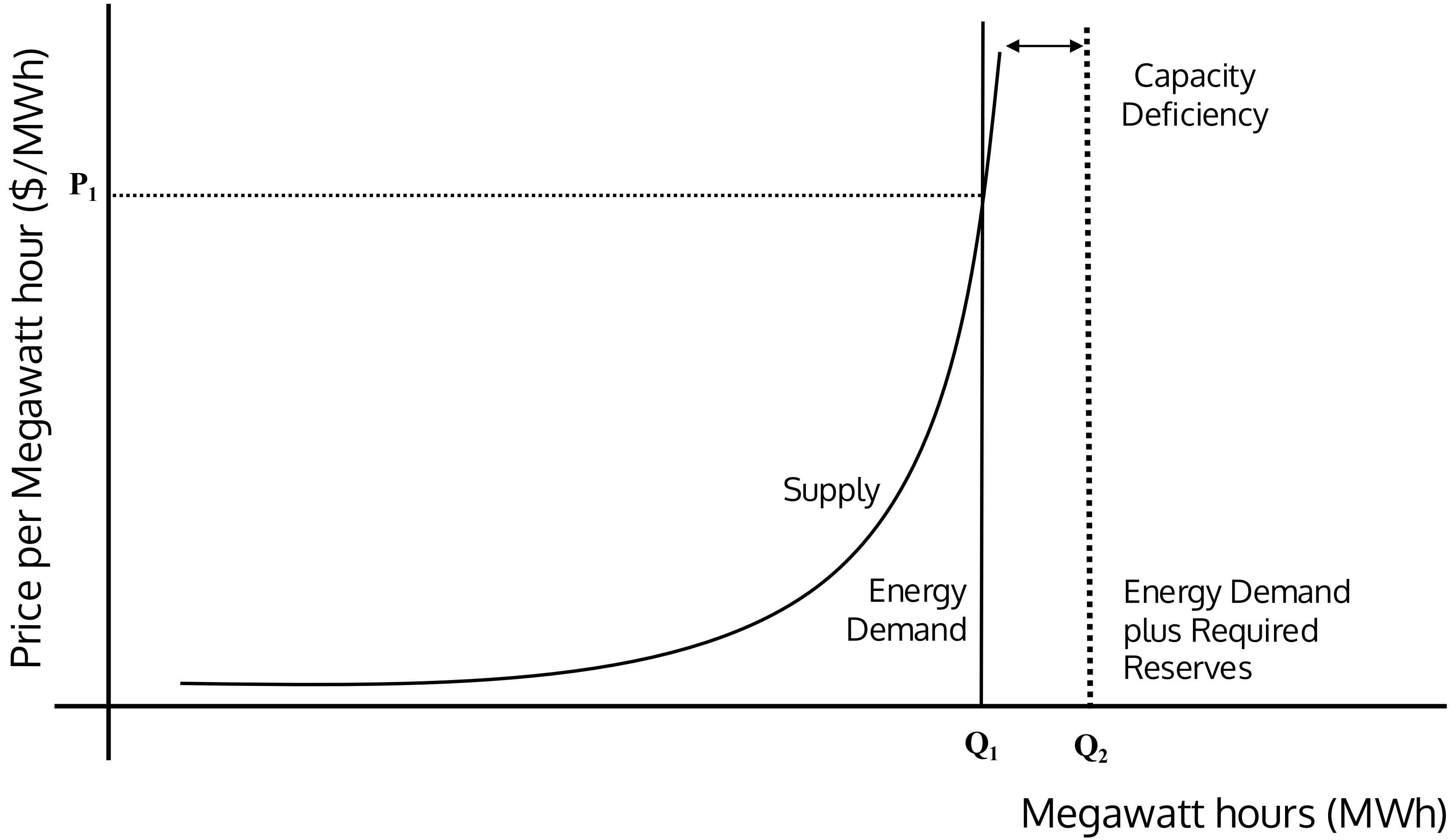
Social Welfare = Consumer Surplus + Producer Surplus

ELECTRICITY SUPPLY & DEMAND

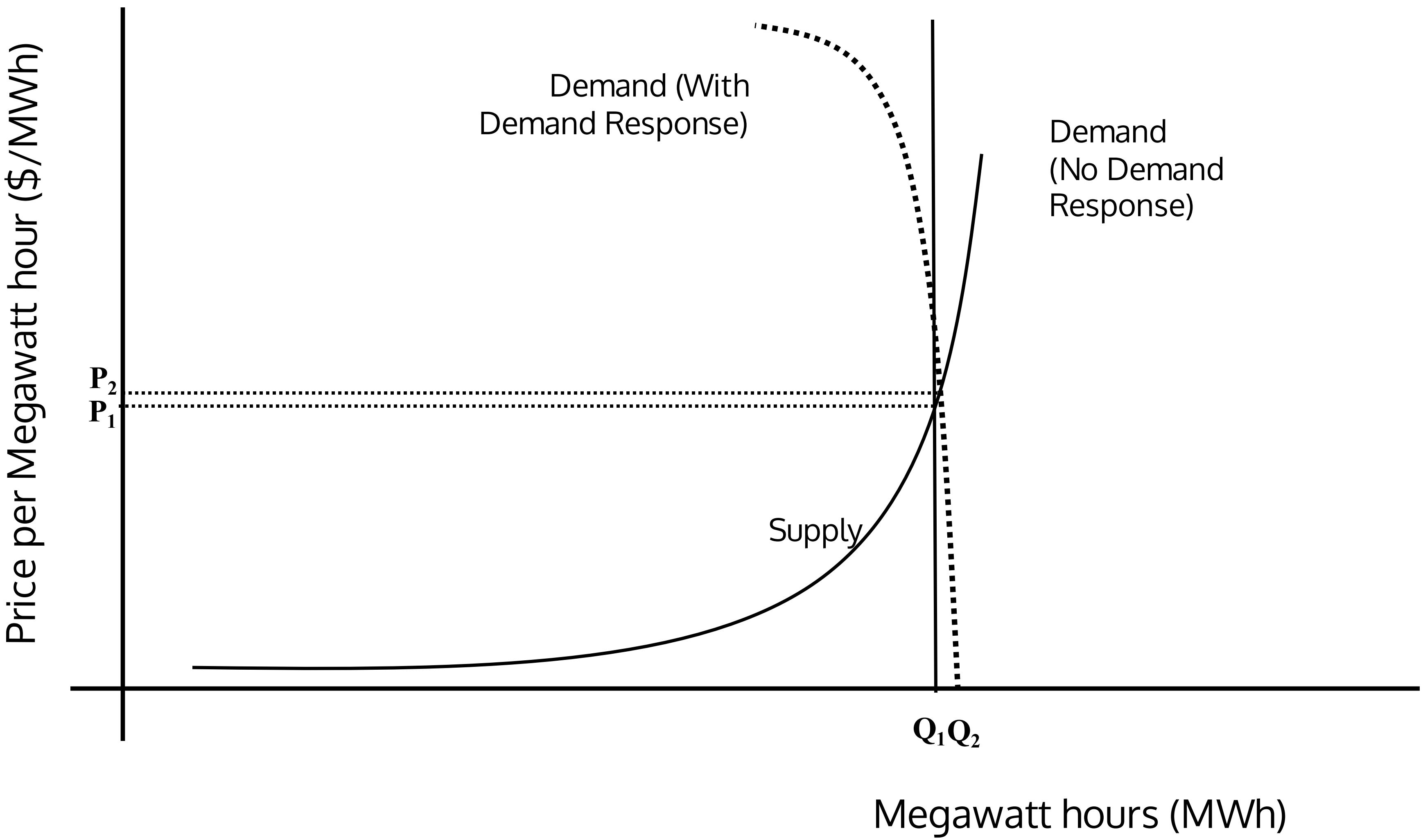


Sometimes the electricity supply curve is characterized as a "hockey stick"

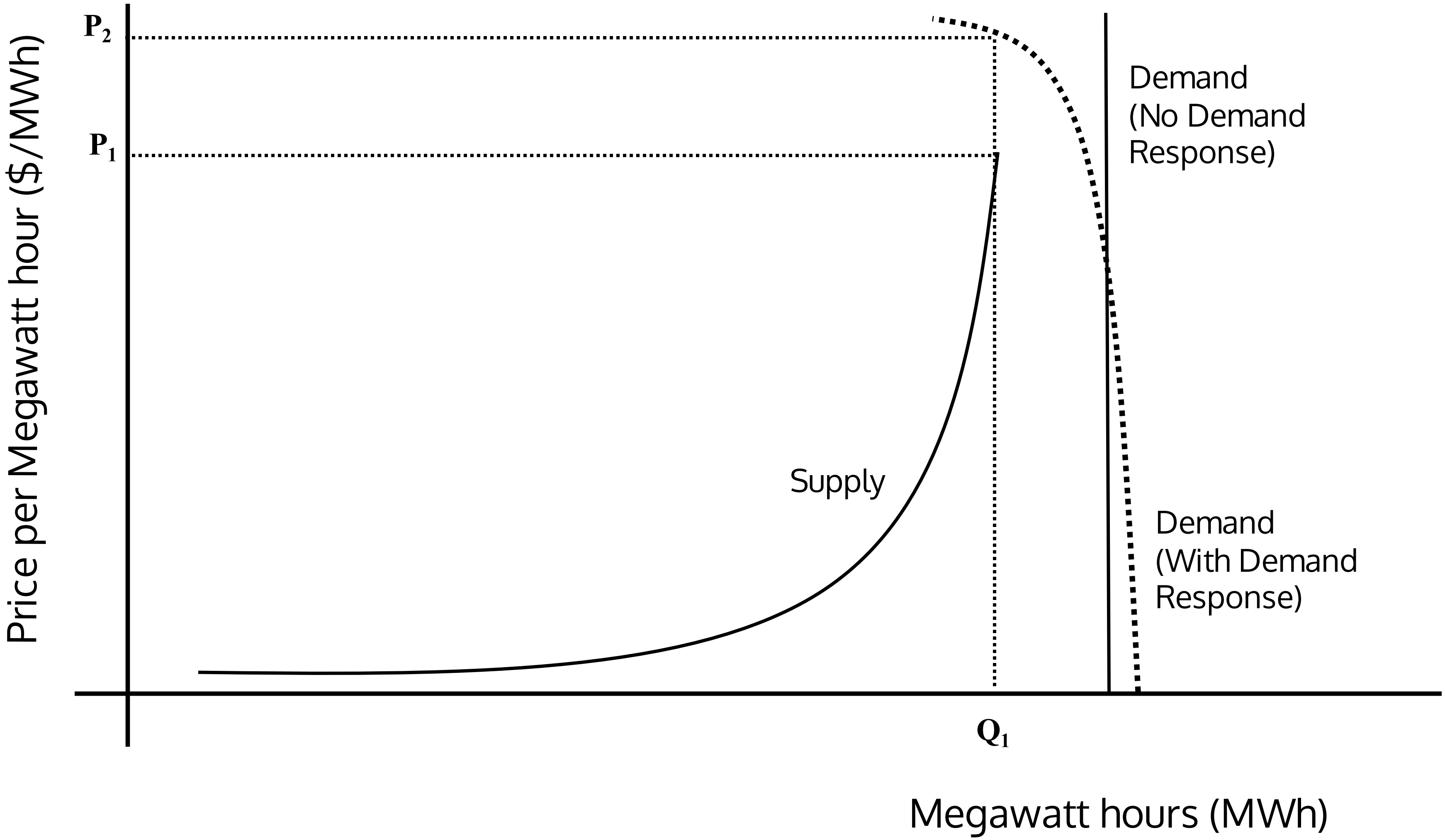
DEMAND PLUS RESERVES



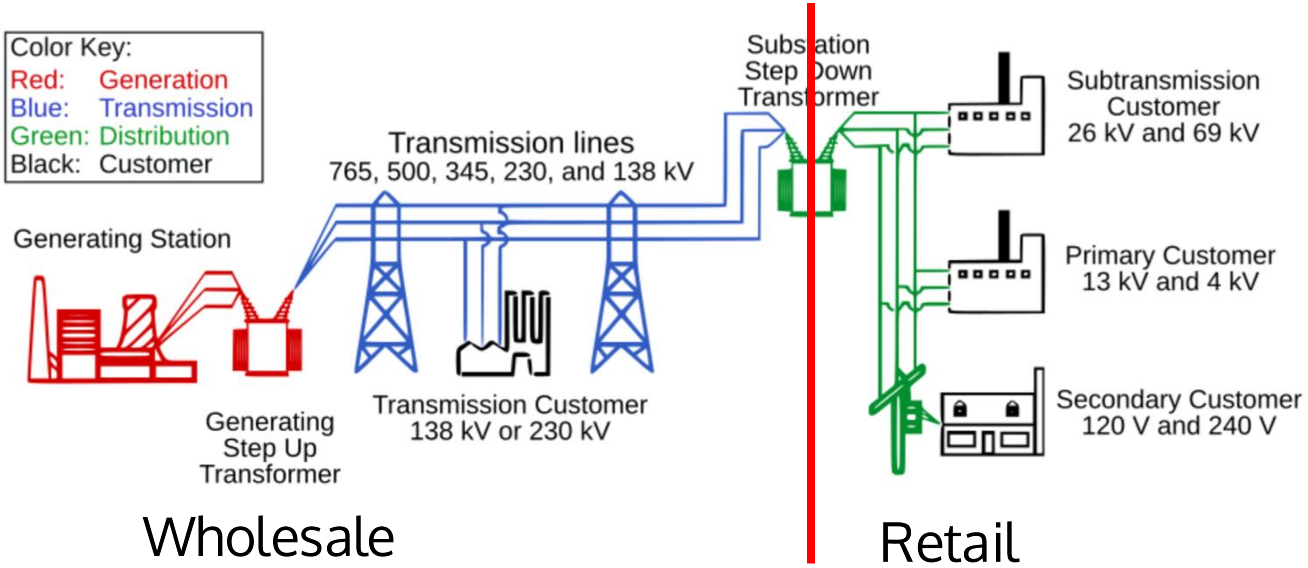
EFFICIENT PRICING DURING SURPLUS



EFFICIENT PRICING DURING SHORTAGES



WHOLESALE v. RETAIL ELECTRICITY MARKETS



Wholesale Products

- Energy ($/MWh)
- Capacity ($/(MW-day) or $/(kW-year)
- Demand response
- Ancillary services

Retail Products

- Wholesale commodity
- Renewable energy credits
- Fixed vs. variable pricing
- Green products
- Other discounts, points, etc.

Recall the US Federal-State Jurisdictional Split

RTO/ISO ELECTRICITY MARKETS

- Energy Markets

  Day-Ahead, needed for unit commitment problem (hourly, Locational Marginal Prices (LMPs) due to congestion)

  Real Time, needed to match actual operations to payments (5 minutes, locational marginal prices due to congestion)

- Transmission congestion (TCCs, FTRs, FCRs)

  Needed to manage congestion risk (difference between LMPs)

- Installed Capacity

  Needed to meet NERC's 1 time in 10 years criterion

- Operating Reserves, needed to meet n-1 criterion

  10 minute spinning reserves
  10 minute non-spinning reserves
  30 minute non-spinning reserves

LOCATIONAL MARGINAL PRICES

- Sets price equal to the incremental cost of delivering energy to each node or location on the system

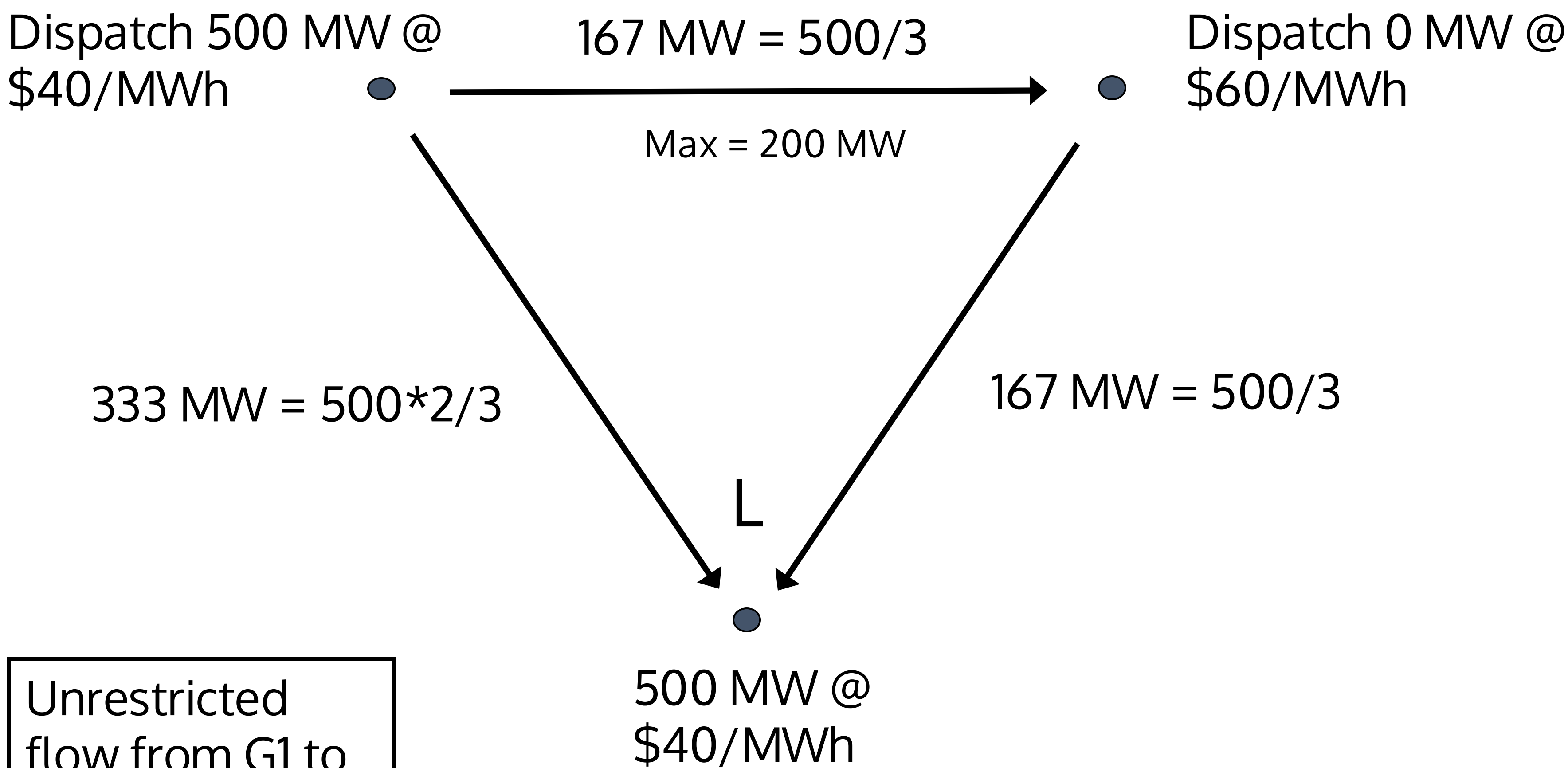
  NOTE: Prices are NOT set to average costs

- Absent binding transmission constraints, LMPs will generally equal the bid of the least-cost available resource
- With binding transmission constraints, LMPs will vary and may be less than, equal to, or greater than the bids of available resources
- Prices typically include transmission loss component in addition to energy and congestion components
- LMPs can be very volatile across time
- LMPs can diverge dramatically when transmission constraints bind
- LMPs may be negative, although this is infrequent

LMPs: NO BINDING CONSTRAINT

$0\ MW \leq G_1 \leq\ 1{,}000\ MW$

$0\ MW \leq G_2 \leq\ 1{,}000\ MW$



Unrestricted flow from G1 to L @ $40/MWh

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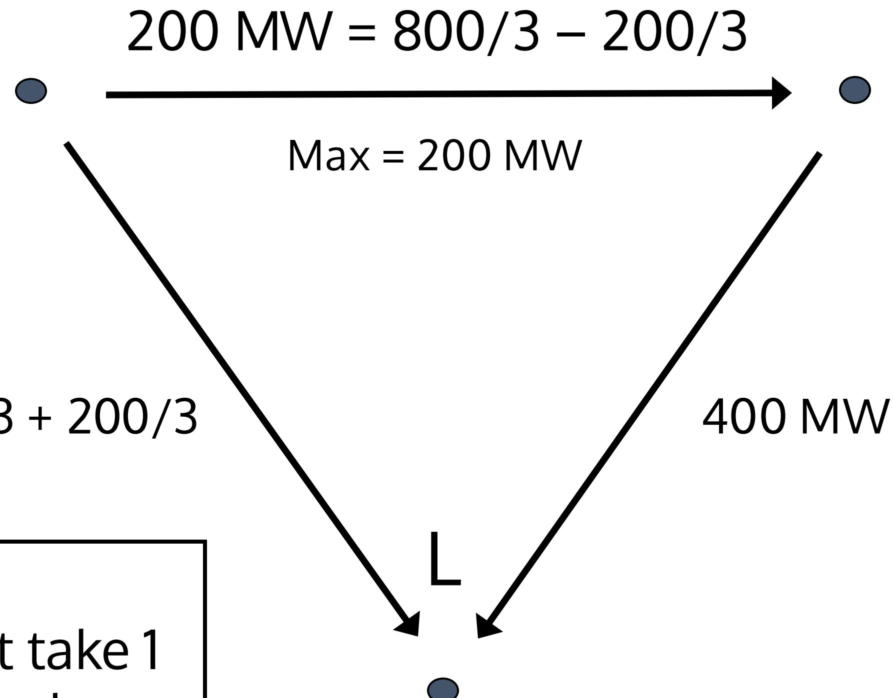
LMPs: BINDING CONSTRAINTS

G_1 Output

800 MW @
$40/MWh

G_2 Output

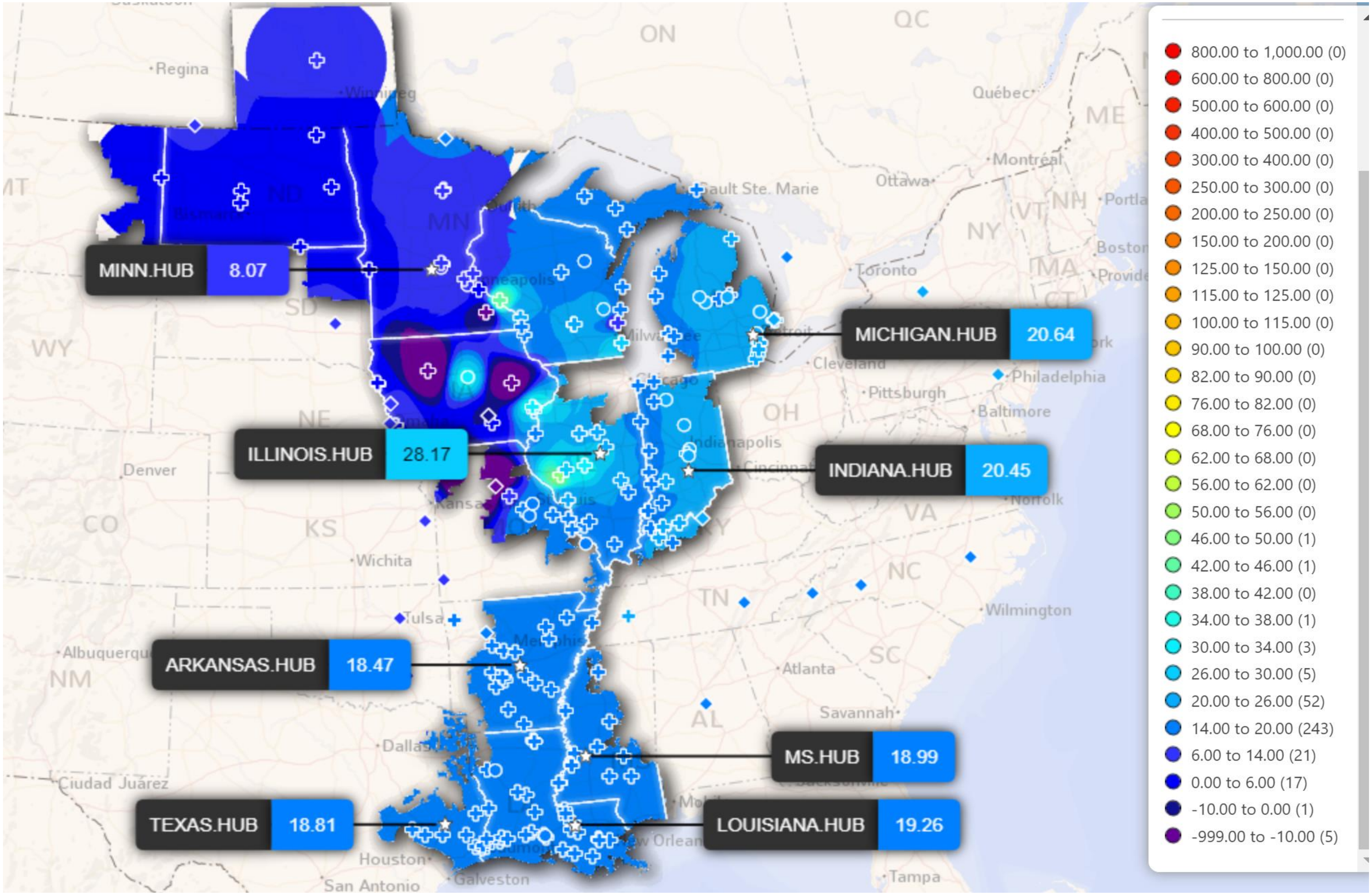
200 MW @
$60/MWh



1,000 MW @
$???/MWh

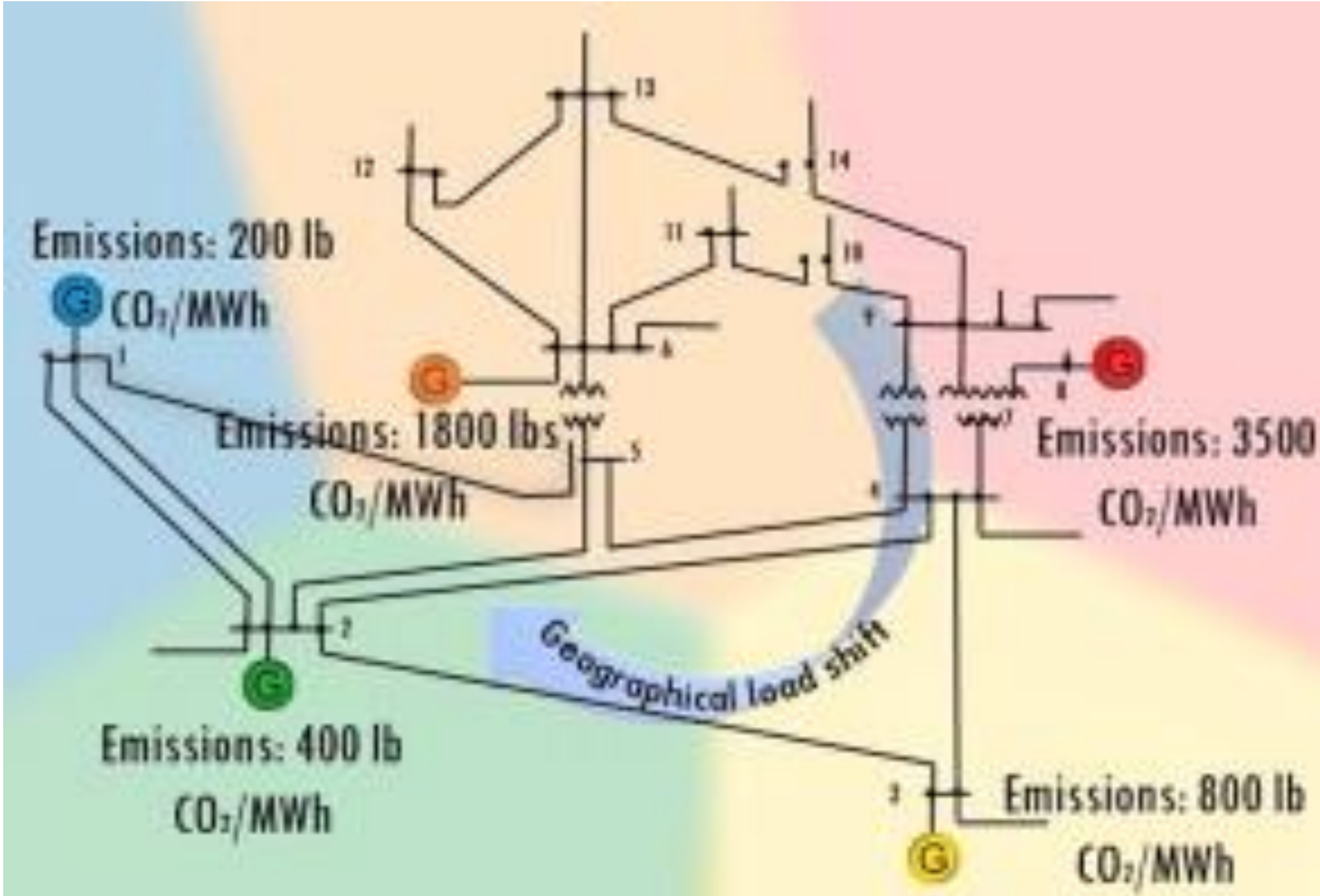
Due to 200 MW limitation, L must take 1 MW @ $60 for each MW @ $40 ⇒ P = $???/MWh

MISO LMPs CONTOUR MAP



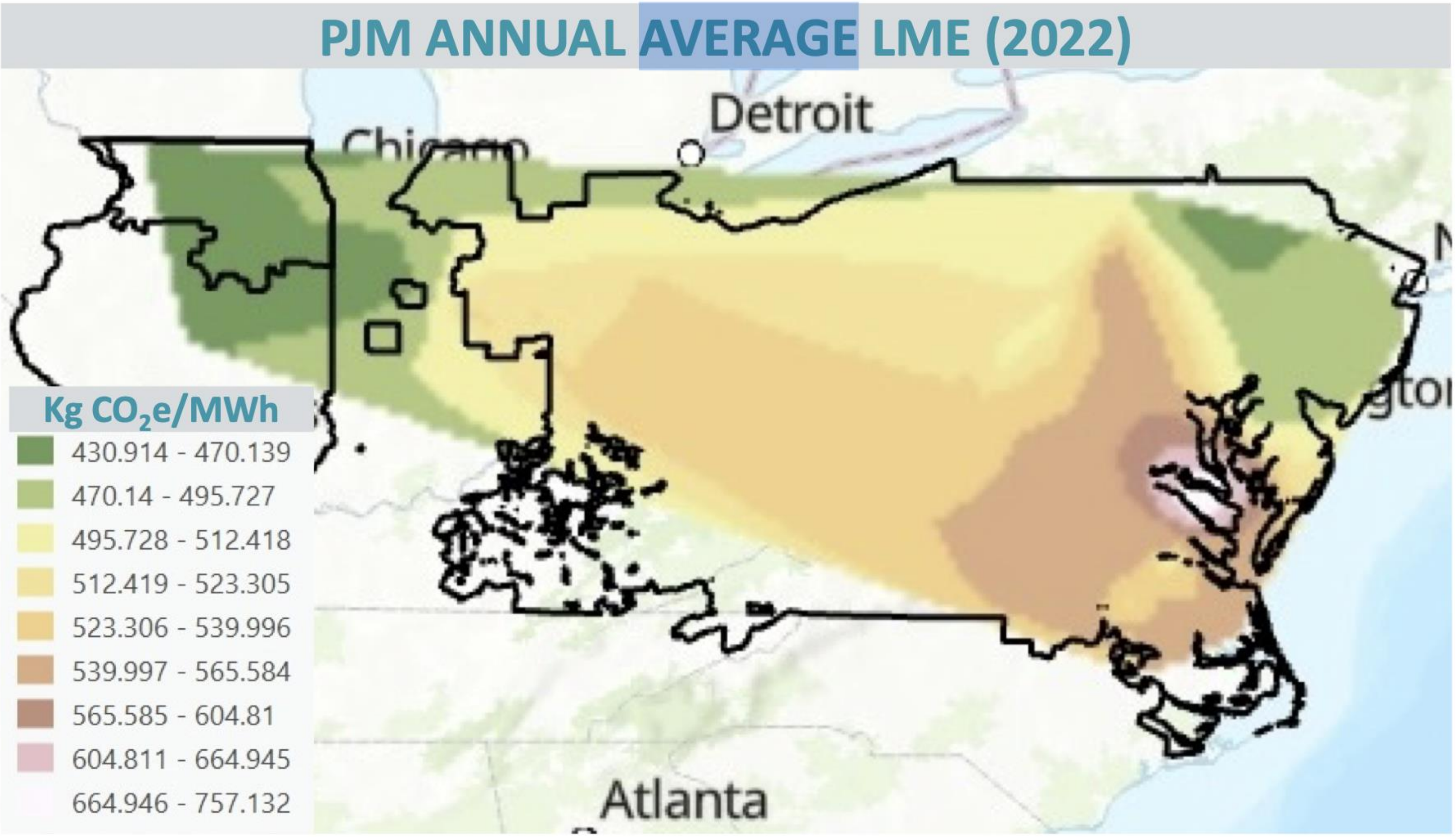
https://api.misoenergy.org/MISORTWD/lmpcontourmap.html

LOCATIONAL MARGINAL EMISSIONS



https://www.sciencedirect.com/science/article/abs/pii/S0306261913010611

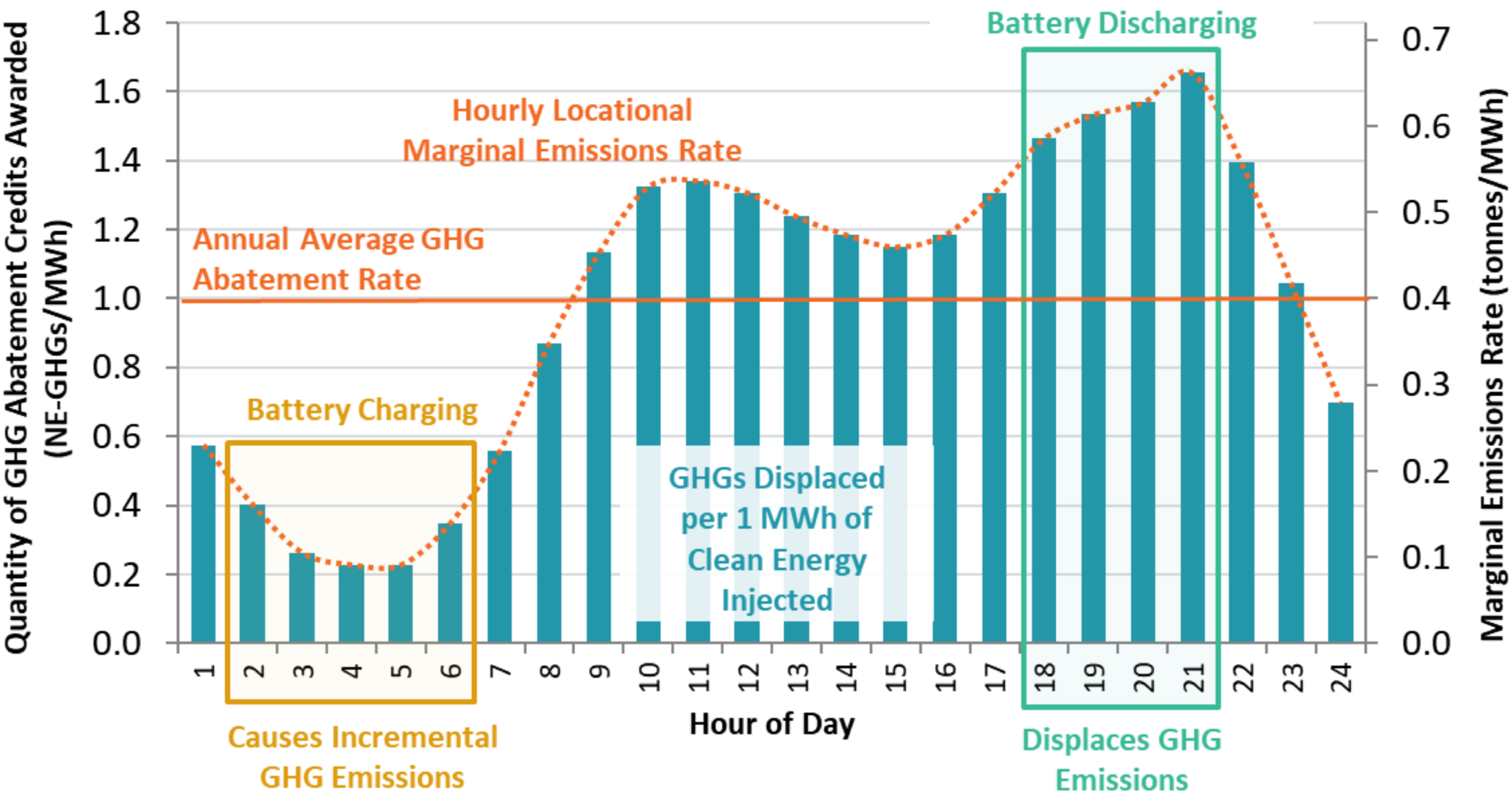
LOCATIONAL MARGINAL EMISSIONS – PJM DATA



Source: Contour map developed using interpolation from generation node data. Data from ReSurety LME data product, derived from PJM Interconnection 5-minute, nodal LME data.

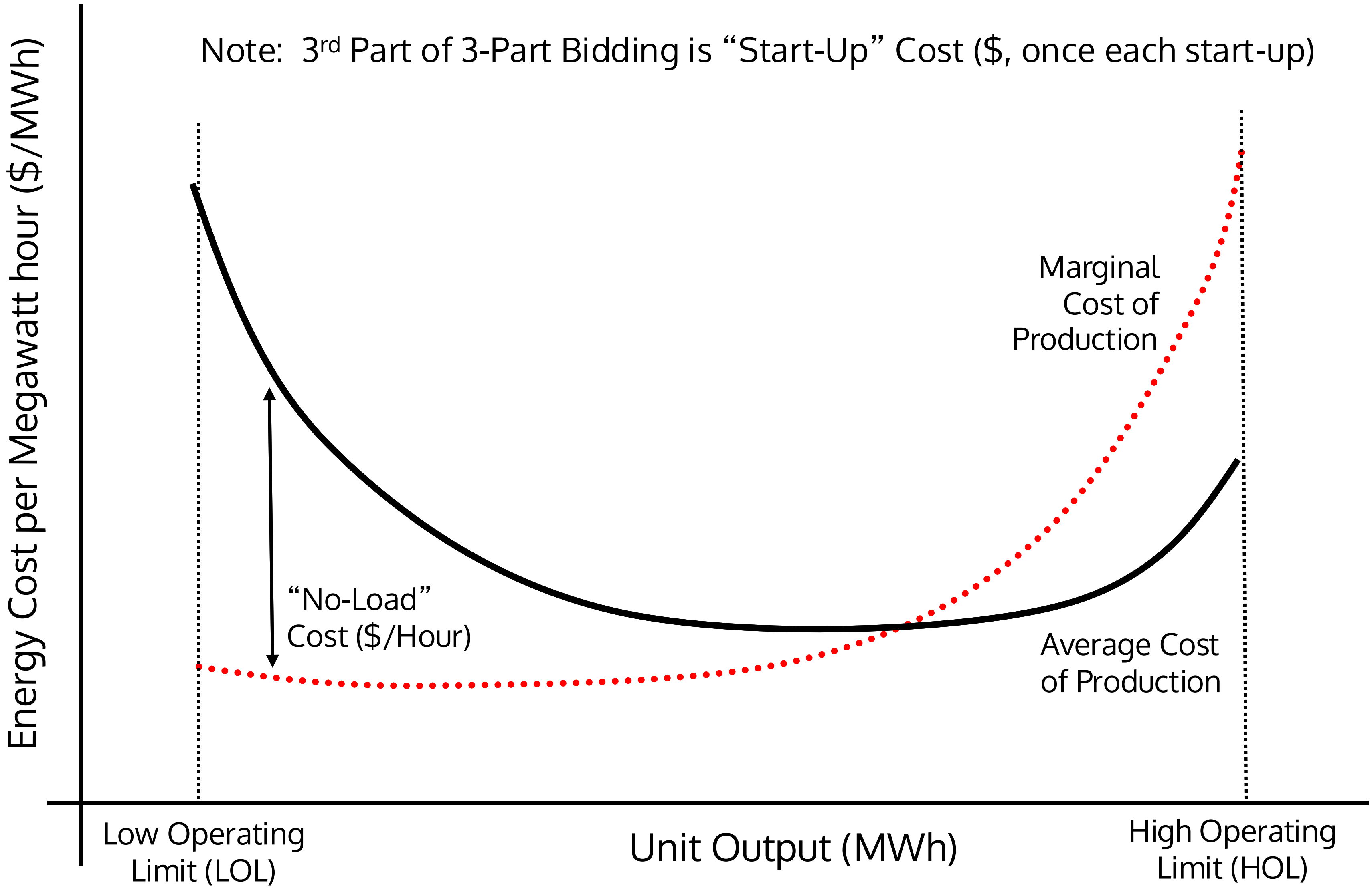
https://www.brattle.com/wp-content/uploads/2023/01/Locational-Marginal-Emissions.pdf

MARGINAL EMISSIONS OVER TIME



https://www.brattle.com/wp-content/uploads/2023/01/Locational-Marginal-Emissions.pdf

GENERATION UNIT COSTS



OFFERS & BIDS

- Generation Units

  A generation unit offers its start-up costs, running costs, and up to ten bid blocks over its operating range

  This is referred to as three-part bidding

- Demand

  Load Serving Entities (LSEs) submit bids in the form of demand curves

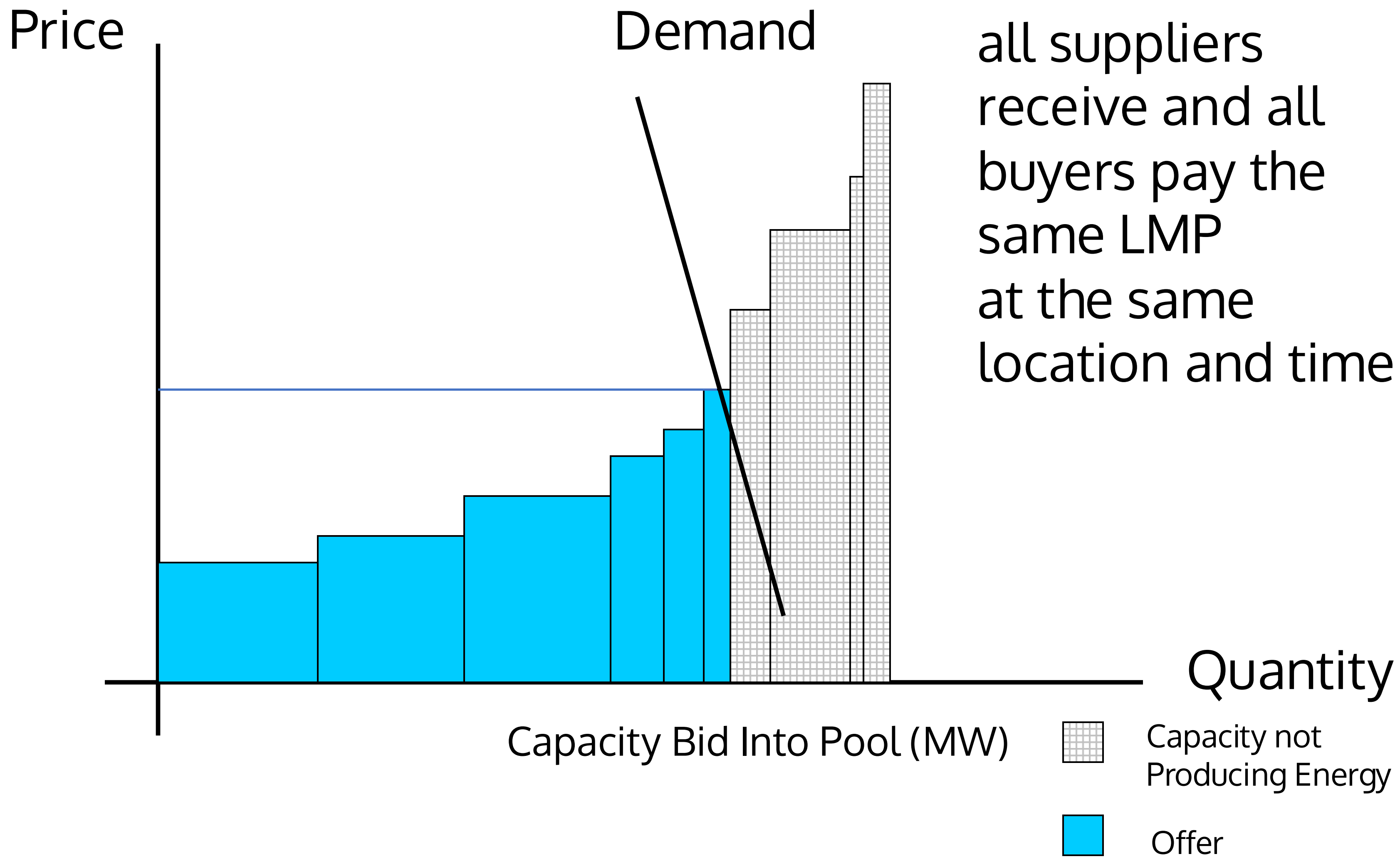
- Any Market Participant (Virtual Offers and Bids or Convergence Bidding)

  Submit offers and/or bids even if not planning to supply power or serve load

- ISOs

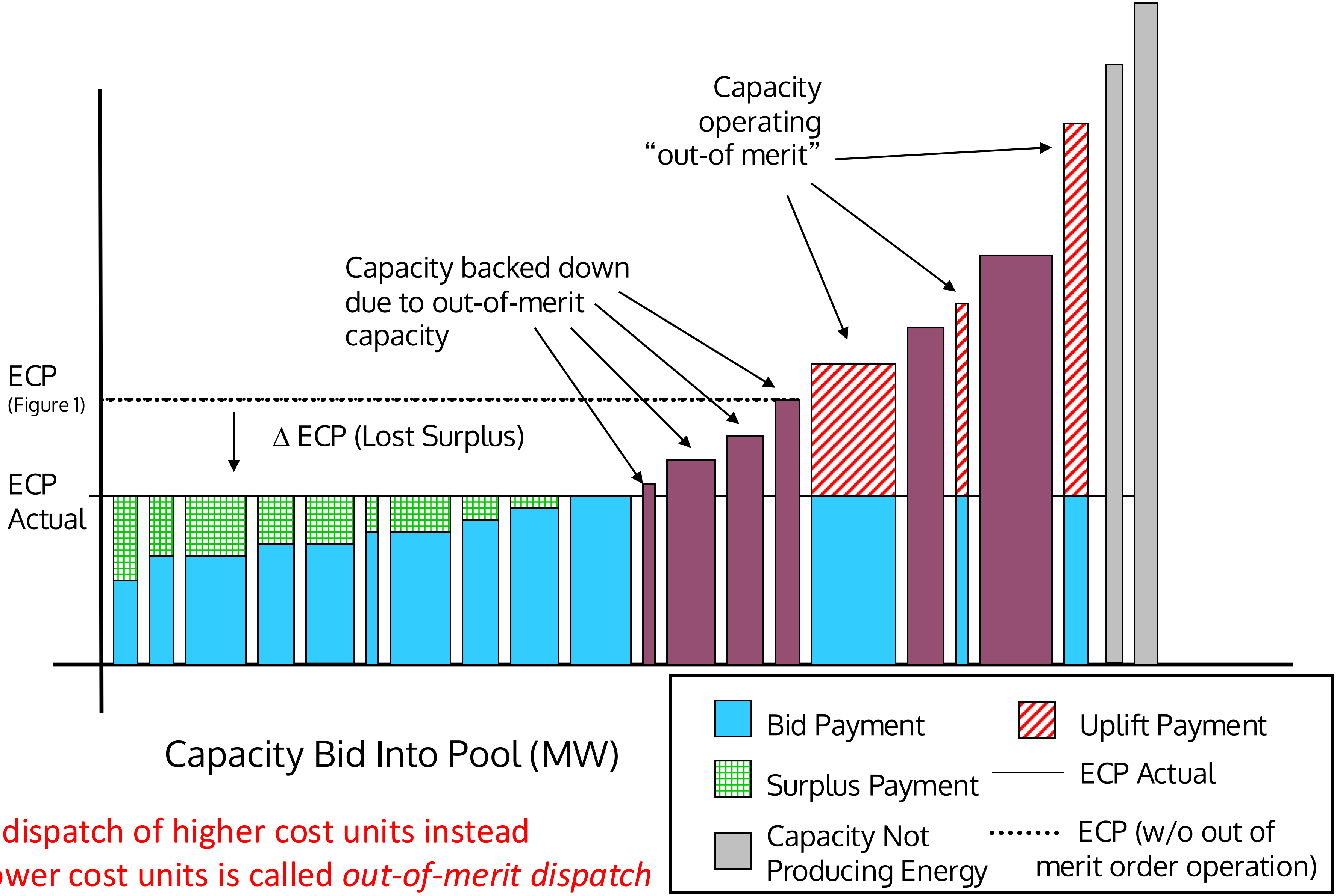
  ISOs clear offers and bids subject to security constrained unit commitment (day-ahead market) and dispatch (security constrained dispatch) using a uniform price clearing auction

UNIFORM AUCTION



Uniform auction means that all suppliers receive and all buyers pay the same LMP at the same location and time

WHY LMPs ARE NEEDED



The dispatch of higher cost units instead of lower cost units is called *out-of-merit dispatch*

ISO MULTI-SETTLEMENT

Day-ahead markets

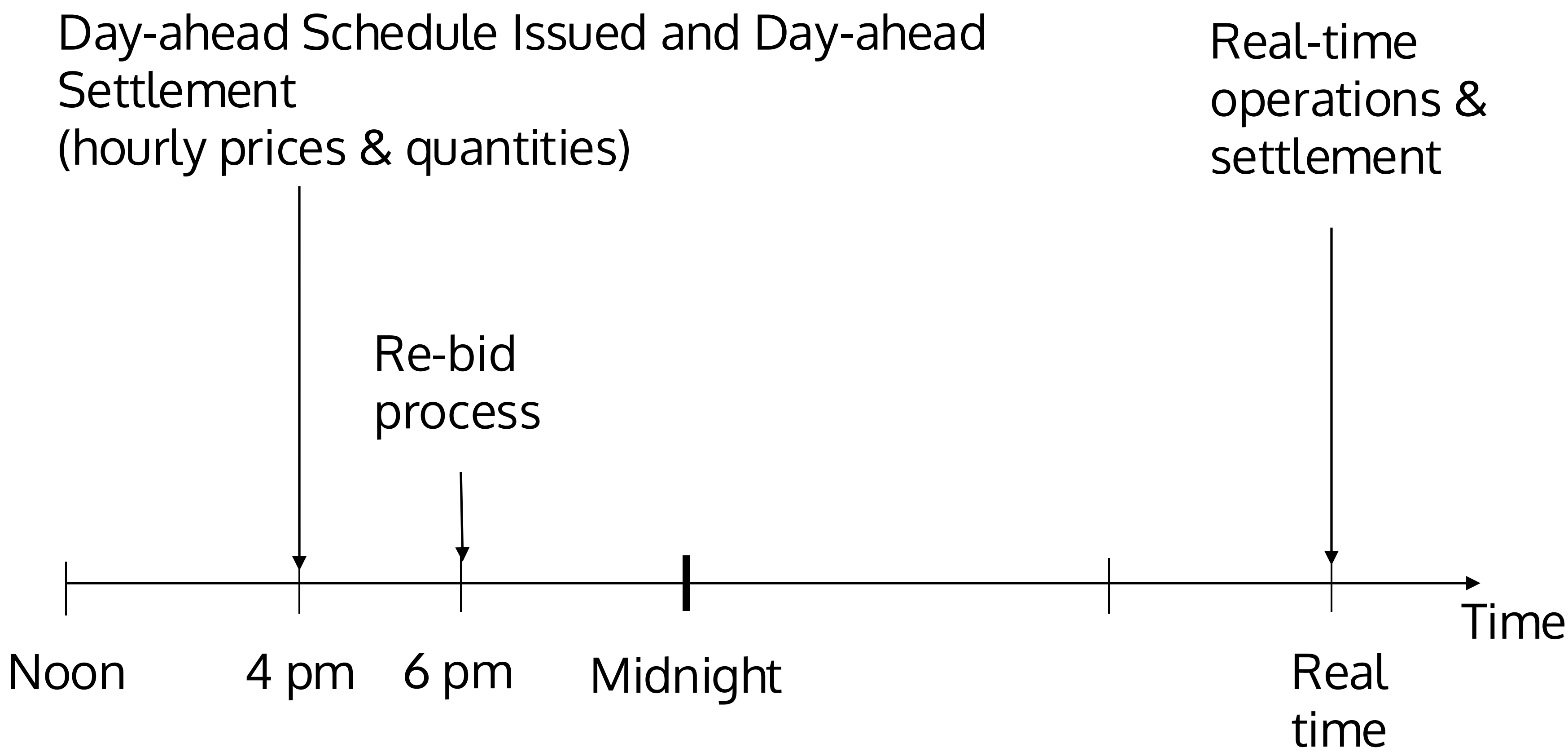
- Account for large majority of volume
- Settlement/scheduling is “virtual,” but is expected to be feasible in real-time (i.e., is “security constrained”)
- Not as subject to price volatility and difficulties in establishing the “marginal” price
- Accounts for start-up and no-load costs, which generation units can bid into the market

Real-time markets

- Based on actual dispatch of system
- Settlement based on deviations from day-ahead settlement
- More volatile than day-ahead markets
- More important in shaping overall pricing (Day-ahead bidding shaped by expectations of real-time price)

=> Economic concept of arbitrage

ISO MULTI-SETTLEMENT TIMELINE



Note: Actual schedule varies significantly across ISOs

DAY-AHEAD AND REAL-TIME MARKETS

Settlement refers to who pays and who gets paid at the close of the market

Day-ahead Settlement = Day-ahead Qty * Day-ahead Price

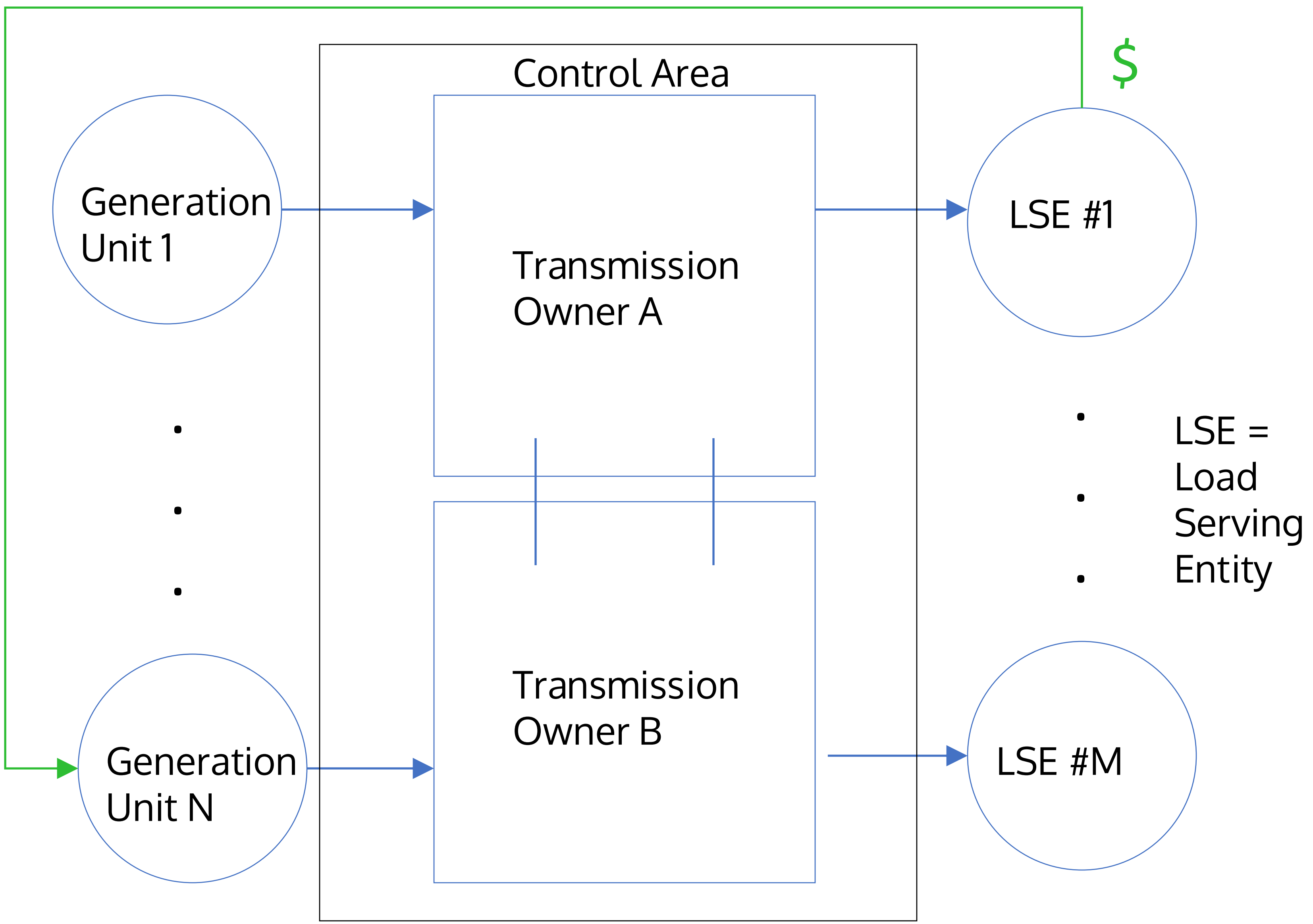
Real-time Settlement = [Real-time Qty - Day-ahead Qty]*Real-time Price

E.g., Generator:

Sells 100MWh day-ahead in Hour 12 but only produces 90 MWh in real-time
Day-ahead price = $40/MWh & Real-time price = $50/MWh
Generator Hour 12 payment =
100 MWh*$40/MWh + [90 MWh – 100 MWh]*$50/MWh = $4,000 - $500 = $3,500

Load is the counterparty to the generator’s day-ahead and real-time position

BILATERAL CONTRACTS



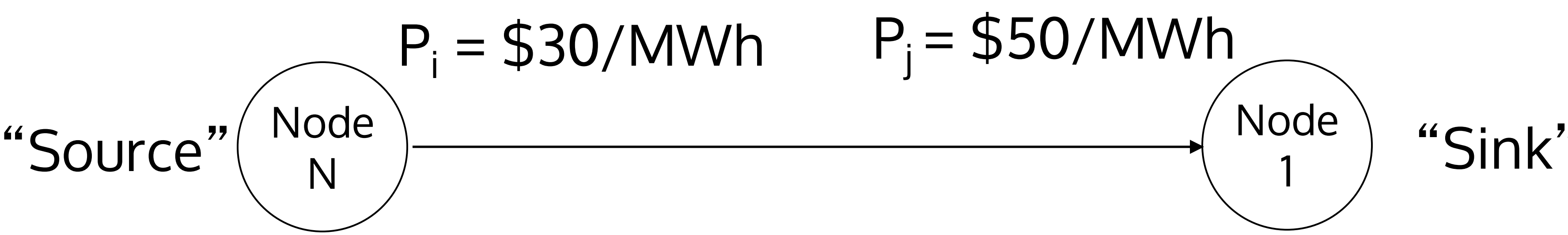
MANAGING LMP RISK

- Transmission Congestion Contracts (TCCs) enable market participants to purchase a hedge against congestion

- Also known as FTRs: Financial Transmission Rights

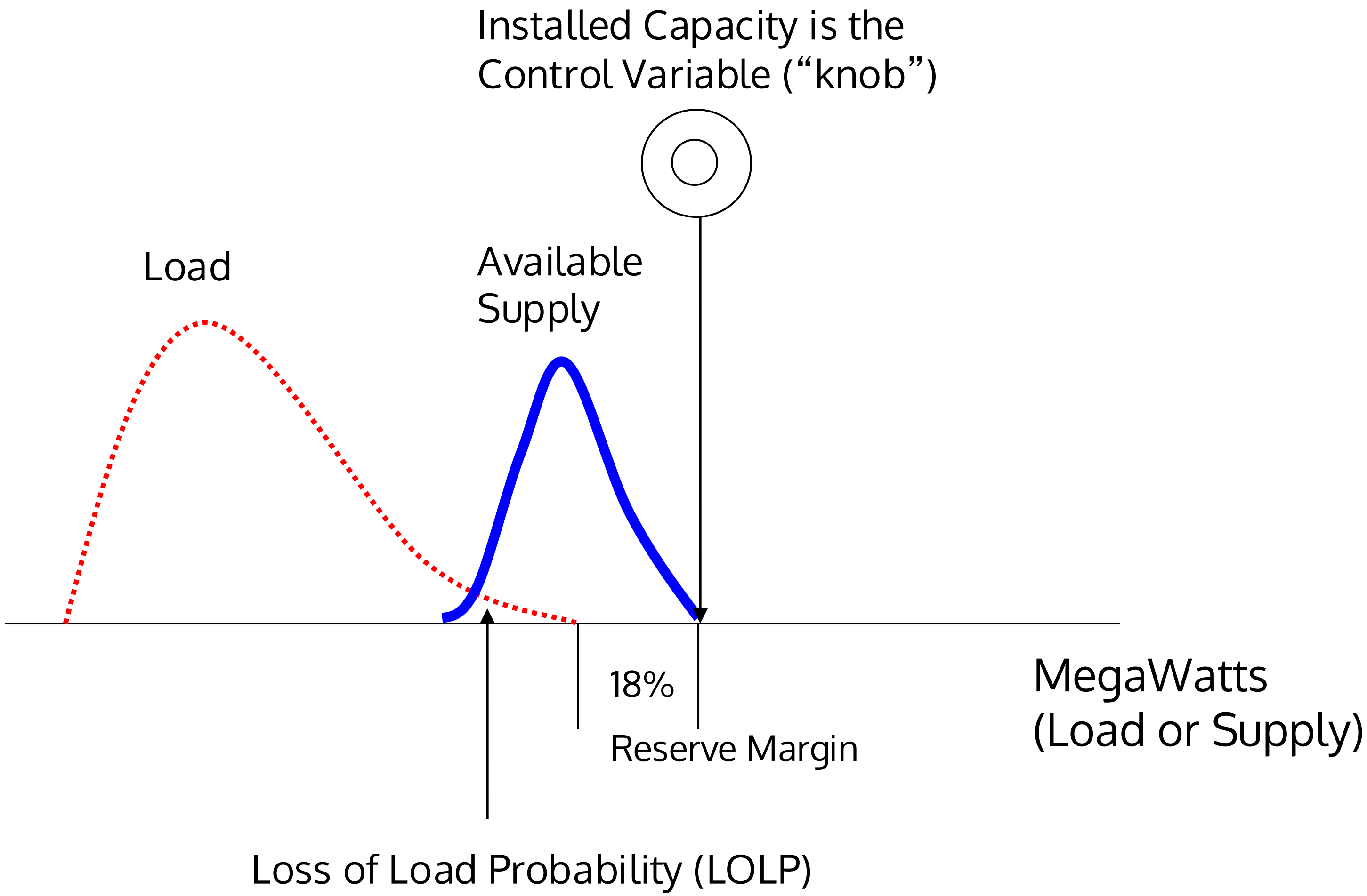
- Owners of TCCs are paid the amount of congestion between the two points of the TCC that they own

- TCCs are directionally dependent



TCC for 1 MW = $50-$30/MWh = $20

CAPACITY MARKETS



CAPACITY MARKETS

- Determine the amount of installed capacity for the region
- Assign a portion to Load Serving Entities (LSEs), usually based on a LSE's % of peak load
- LSE's must procure enough ICAP to satisfy their obligation otherwise pay a deficiency penalty

  LSE's can build or buy ICAP or reduce their peak demand

  LSE's that are short ICAP are required to purchase it from the spot ICAP market

"Competitive Electricity Markets and System Reliability: The Case for New England's Proposed Locational Capacity Market" J. Farr and F. Felder, *The Electricity Journal*, Vol. 18, Number 8, October 2005, pp. 22-33.

"Should Electricity Markets Have A Capacity Requirement: If So, How Should It Be Priced?" A. Jaffe and F. Felder, *The Electricity Journal*, December 1996.

CAPACITY MARKETS

Issues with Capacity Markets:

- Should there only be energy markets (e.g., ERCOT)?
- Should there be a forward capacity market (FCM)?
- If and how should demand response and energy efficiency be compensated?
- How should transmission constraints be handled?
- How should the capacity values of wind, solar, and energy storage be calculated in capacity markets?
- How should capacity markets be modified to account for severe weather?

"Competitive Electricity Markets and System Reliability: The Case for New England's Proposed Locational Capacity Market" J. Farr and F. Felder, *The Electricity Journal*, Vol. 18, Number 8, October 2005, pp. 22-33.

"Should Electricity Markets Have A Capacity Requirement: If So, How Should It Be Priced?" A. Jaffe and F. Felder, *The Electricity Journal*, December 1996.

ANCILLARY SERVICE CHARGES (PJM)

Table 9 Total cost per MWh by category: 2023 and 2024[56 57 58]

Category	2023 $/MWh	2023 ($ Millions)	2023 Percent of Total	2024 $/MWh	2024 ($ Millions)	2024 Percent of Total	Percent Change
Energy	$30.40	$22,956	57.3%	$32.58	$25,549	58.7%	7.2%
Day Ahead Energy	$31.58	$23,847	59.5%	$33.43	$26,215	60.2%	5.8%
Balancing Energy	$0.45	$338	0.8%	$0.57	$444	1.0%	26.6%
ARR Credits	($1.46)	($1,103)	(2.8%)	($1.24)	($971)	(2.2%)	(15.2%)
Self Scheduled FTR Credits	($0.42)	($320)	(0.8%)	($0.53)	($414)	(0.9%)	24.5%
Balancing Congestion	$0.39	$296	0.7%	$0.39	$304	0.7%	(0.9%)
Emergency Energy	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Inadvertent Energy	$0.01	$4	0.0%	$0.01	$9	0.0%	104.8%
Load Response - Energy	$0.01	$6	0.0%	$0.01	$11	0.0%	74.0%
Emergency Load Response	$0.08	$61	0.2%	$0.00	$0	0.0%	(100.0%)
Energy Uplift (Operating Reserves)	$0.21	$156	0.4%	$0.34	$268	0.6%	65.2%
Marginal Loss Surplus Allocation	($0.51)	($385)	(1.0%)	($0.45)	($356)	(0.8%)	(10.9%)
Market to Market Payments	$0.07	$55	0.1%	$0.05	$38	0.1%	(33.3%)
Capacity	$4.63	$3,497	8.7%	$3.65	$2,864	6.6%	(21.1%)
Capacity (Capacity Market and FRR)	$4.53	$3,417	8.5%	$3.56	$2,791	6.4%	(21.3%)
Capacity Part V (RMR)	$0.11	$79	0.2%	$0.08	$65	0.1%	(21.3%)
Load Response - Capacity	$0.00	$0	0.0%	$0.01	$8	0.0%	3,010.6%
Transmission	$16.54	$12,488	31.2%	$17.71	$13,886	31.9%	7.1%
Transmission Service Charges	$14.13	$10,671	26.6%	$15.04	$11,796	27.1%	6.4%
Transmission Enhancement Cost Recovery	$2.32	$1,754	4.4%	$2.57	$2,019	4.6%	10.8%
Transmission Owner (Schedule 1A)	$0.08	$63	0.2%	$0.09	$72	0.2%	10.5%
Transmission Seams Elimination Cost Assignment (SECA)	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Transmission Facility Charges	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Ancillary	$0.89	$670	1.7%	$0.92	$725	1.7%	4.2%
Reactive	$0.52	$389	1.0%	$0.49	$381	0.9%	(5.8%)
Regulation	$0.17	$130	0.3%	$0.23	$183	0.4%	35.7%
Black Start	$0.09	$67	0.2%	$0.09	$74	0.2%	5.7%
Synchronized Reserves	$0.10	$73	0.2%	$0.10	$75	0.2%	(2.1%)
Secondary Reserves	$0.00	$1	0.0%	$0.00	$2	0.0%	76.7%
Non-Synchronized Reserves	$0.01	$9	0.0%	$0.01	$10	0.0%	8.6%
Day Ahead Scheduling Reserve (DASR)	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Administration	$0.62	$465	1.2%	$0.67	$529	1.2%	9.5%
PJM Administrative Fees	$0.57	$428	1.1%	$0.62	$489	1.1%	10.1%
NERC/RFC	$0.04	$31	0.1%	$0.04	$35	0.1%	5.9%
RTO Startup and Expansion	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Other	$0.01	$6	0.0%	$0.01	$5	0.0%	(11.6%)
Total Price	$53.08	$40,076	100.0%	$55.54	$43,554	100.0%	4.6%
Total Day Ahead Load	748,619			775,838			3.6%
Total Balancing Load	(6,433)			(8,345)			29.7%
Total Real Time Load	755,053			784,182			3.9%
Total Cost ($ Billions)	$40.08			$43.55			8.7%

PJM State of the Market, 2024, Table I-9, p. 18, Monitoring Analytics

https://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2024/2024-som-pjm-vol1.pdf

EMISSION PERMIT (ALLOWANCE) MARKETS

- For some emissions, e.g., SO_2 and NO_x, a permit, aka an allowance, is required per unit of emission

  Sulfur dioxide results in acid rain
  Nitrogen oxides leads to health and environmental damages

- These permits can be bought and sold in the market

- The limit on the total number of permits is what limits the amount of emissions

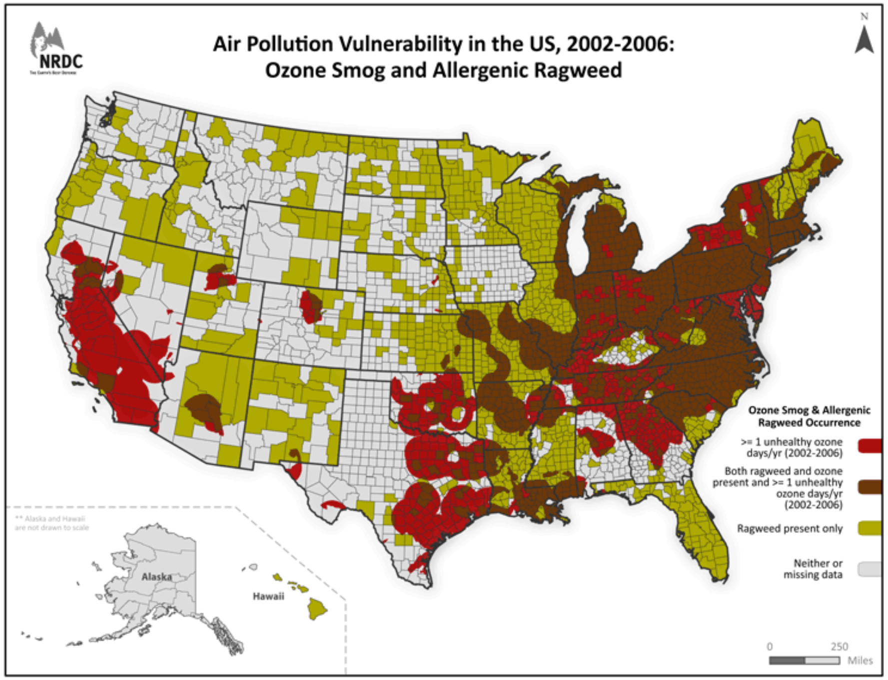
- The cost of a permit is a variable cost adder, which is part of the marginal cost of a generation unit

AIR POLLUTION

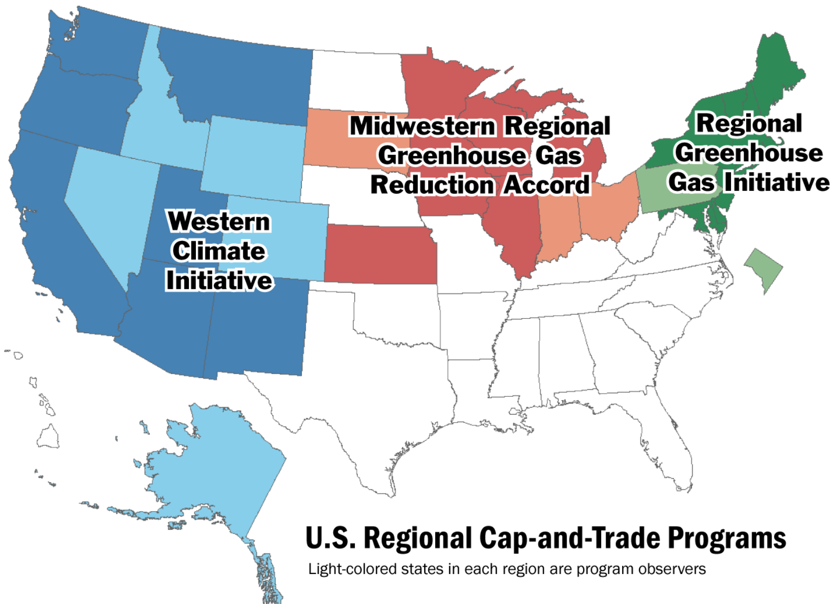
Social Cost of CO_2, 2015-2050 [a] (in 2007 dollars per metric ton CO_2)
Source: Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (May 2013, Revised August 2016)

	Discount Rate and Statistic			
Year	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th percentile)
2015	$11	**$36**	$56	$105
2020	$12	**$42**	$62	$123
2025	$14	**$46**	$68	$138
2030	$16	**$50**	$73	$152
2035	$18	**$55**	$78	$168
2040	$21	**$60**	$84	$183
2045	$23	**$64**	$89	$197
2050	$26	**$69**	$95	$212

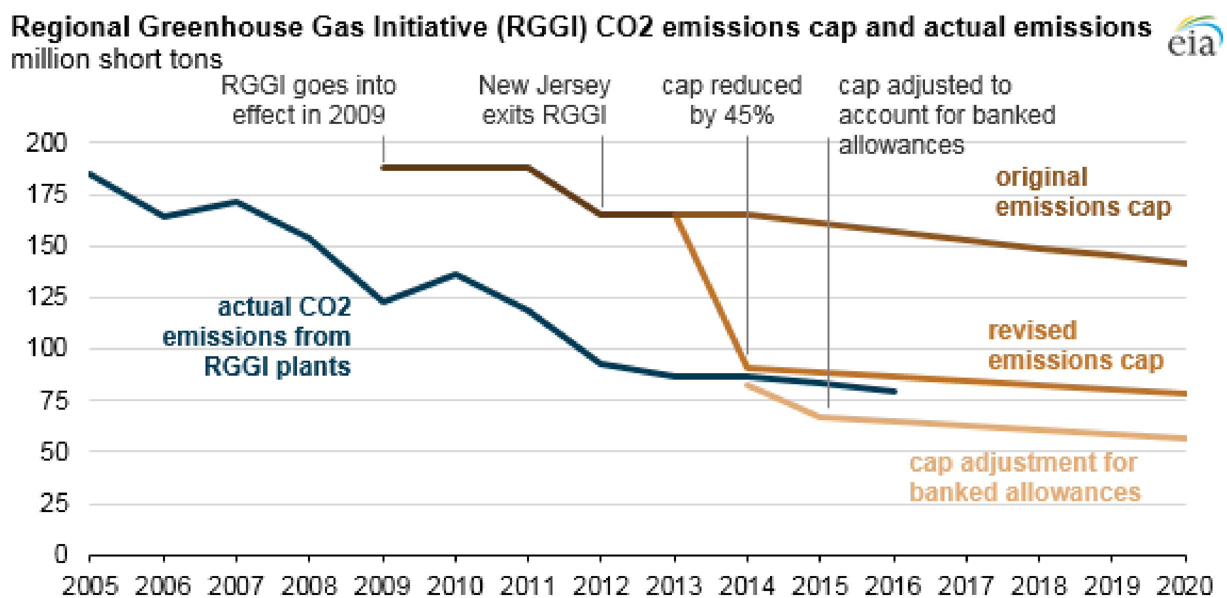
[a] The SC-CO_2 values are dollar-year and emissions-year specific.



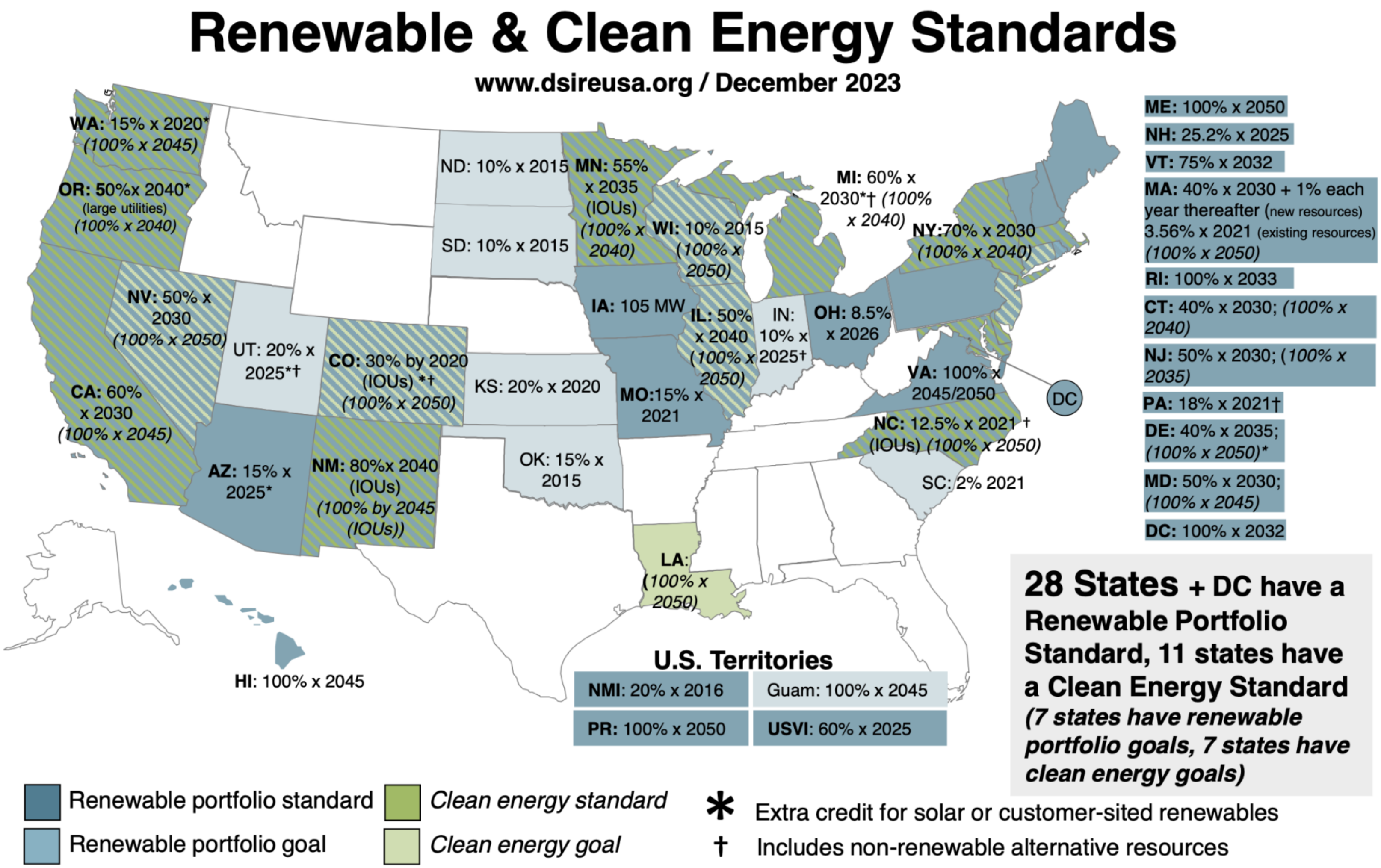
GREEN HOUSE GAS MARKETS



IL and NY have implemented Zero Emission Credit (ZECs) programs to prevent the retirement of nuclear units

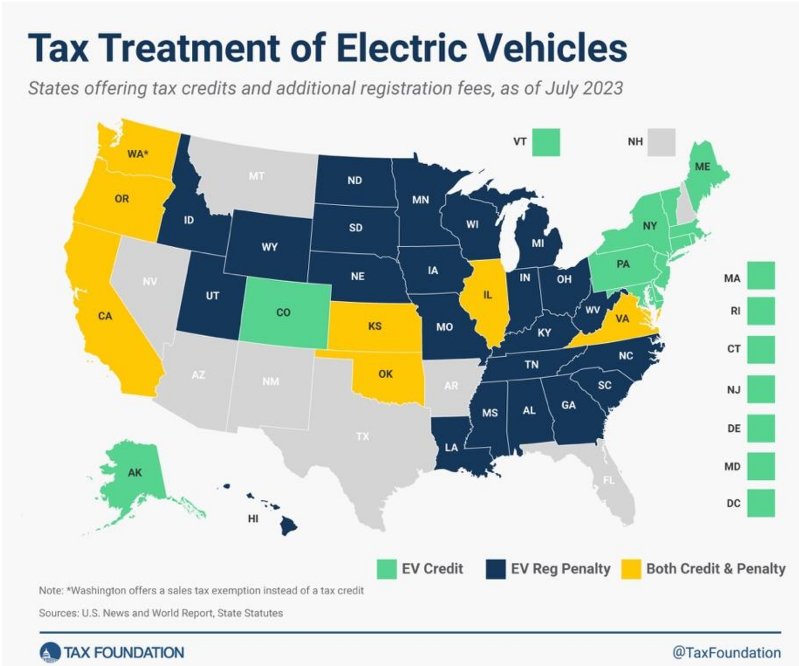


RENEWABLE MARKETS



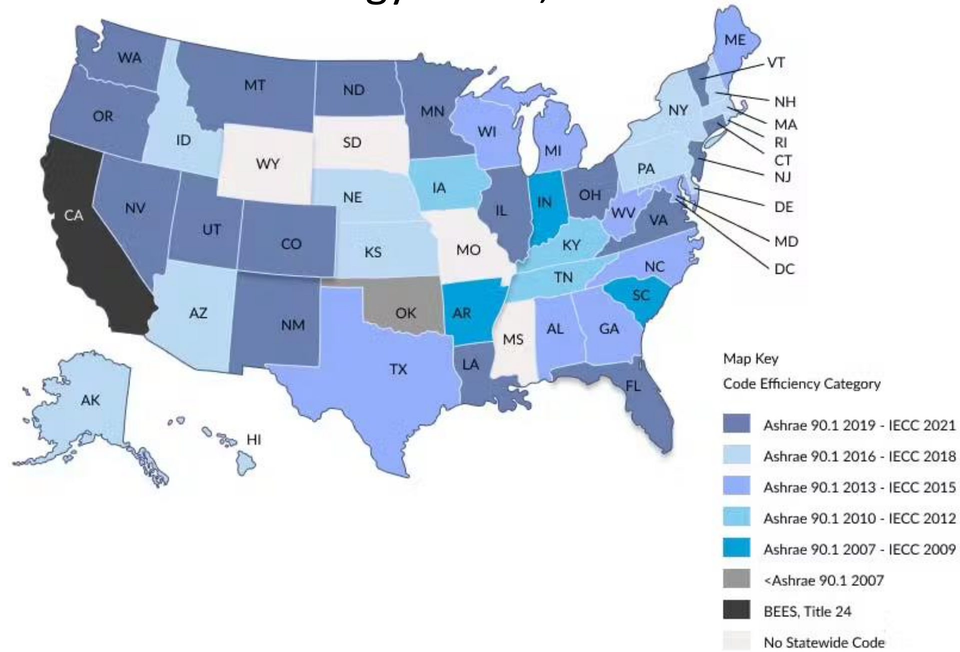
https://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2023/12/RPS-CES-Dec2023-1.pdf

STATE POLICIES



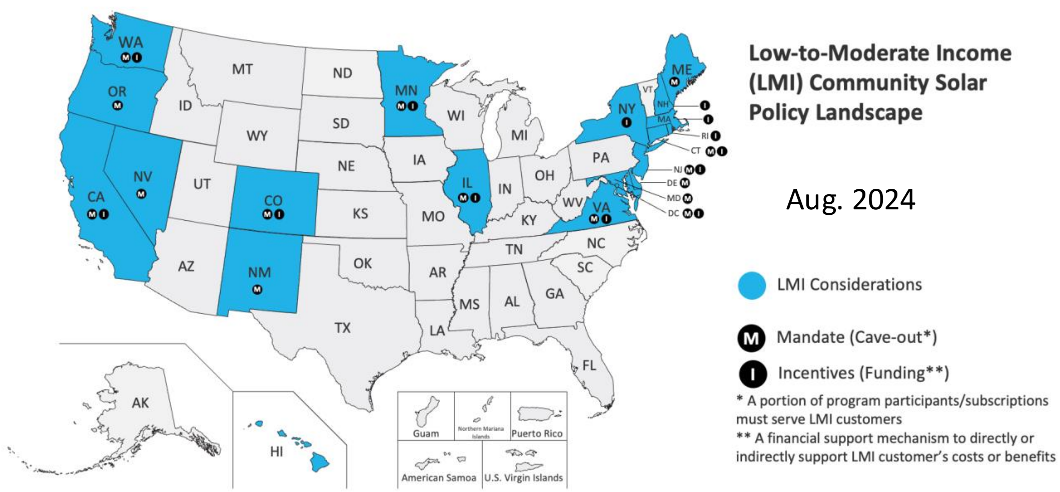
https://taxfoundation.org/data/all/state/electric-vehicles-ev-taxes-state/

State Energy Codes, 2024



https://cove.inc/blog/energy-us-energy-codes-adopted-2023

States have major impacts on electricity supply and demand



https://www.energy.gov/communitysolar/community-solar-market-trends

CAP [FLOOR] & TRADE

- ICAP aka UCAP: FLOOR & TRADE
  UCAP is unforced capacity, i.e., a unit's availability times its capacity
    e.g., A 100 MW unit with 90% availability can sell 90 MW of UCAP

- PJM's capacity market is called the Reliability Pricing Model (RPM)

- New England's capacity market is a forward capacity market (FCM)

- Renewable Portfolio Standard: FLOOR & TRADE

- Emission Allowance Markets: CAP & TRADE

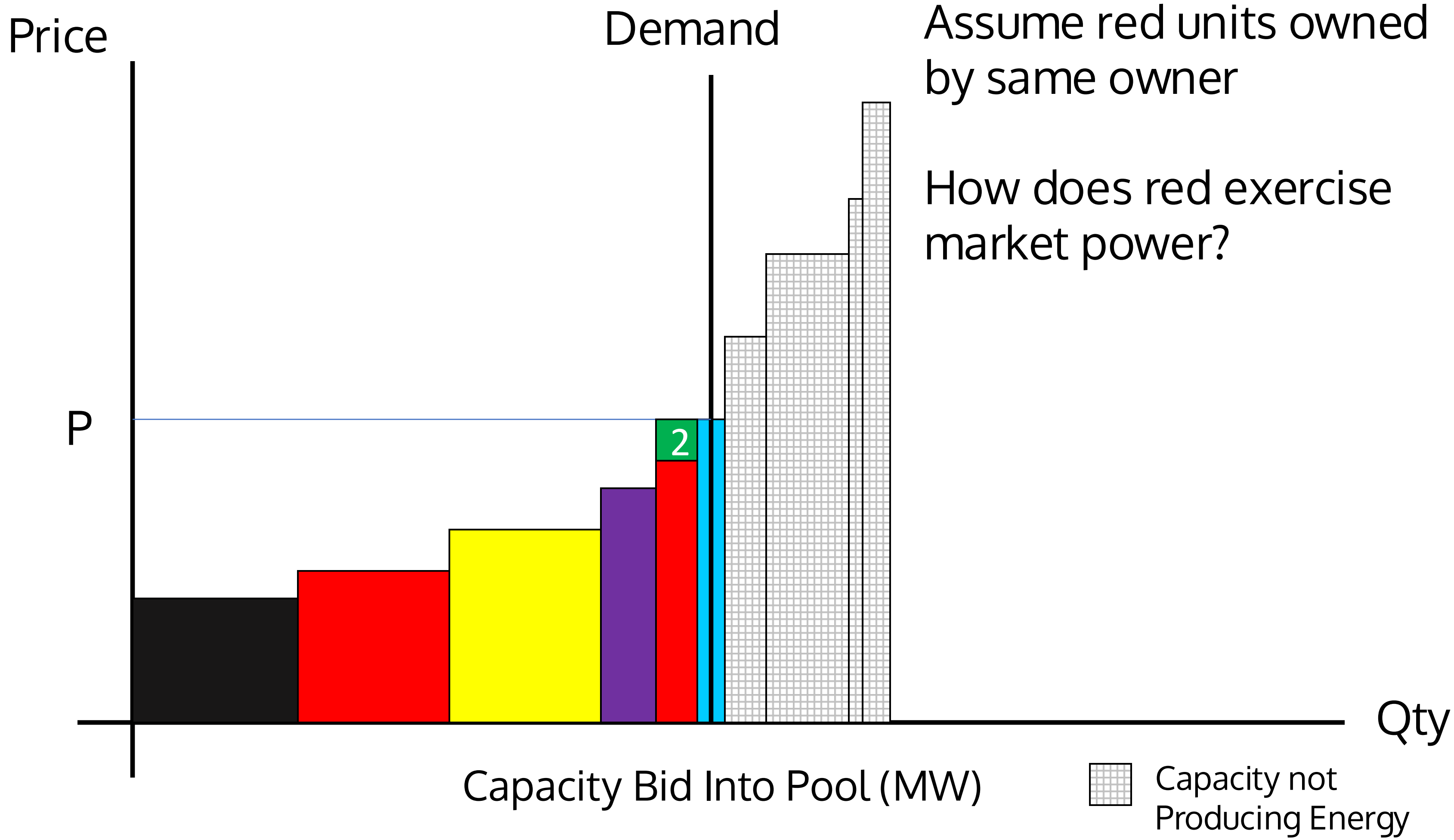
- These markets for capacity, renewable energy credits and emission permits interact with energy markets

- In addition, production tax credits (PTC) affect marginal costs, which therefore affect energy markets

SUMMARY OF MARKET DESIGN CHOICES

Design Element	Comment
Multi-settlement	Needed to align incentives between unit commitment and dispatch
Congestion Pricing (i.e. LMPs)	Needed to reflect transmission constraints
Ancillary Services Markets	At a minimum need opportunity cost pricing
Capacity Markets	Depends on willingness to tolerate extremely high prices and amount of price-responsive demand
Transmission	Avoid having transmission policies undercut wholesale electricity markets
Wholesale Demand Response	A must if there is no retail price responsive demand
Retail Demand Response	Need political will and should consider advanced metering infrastructure (AMI)

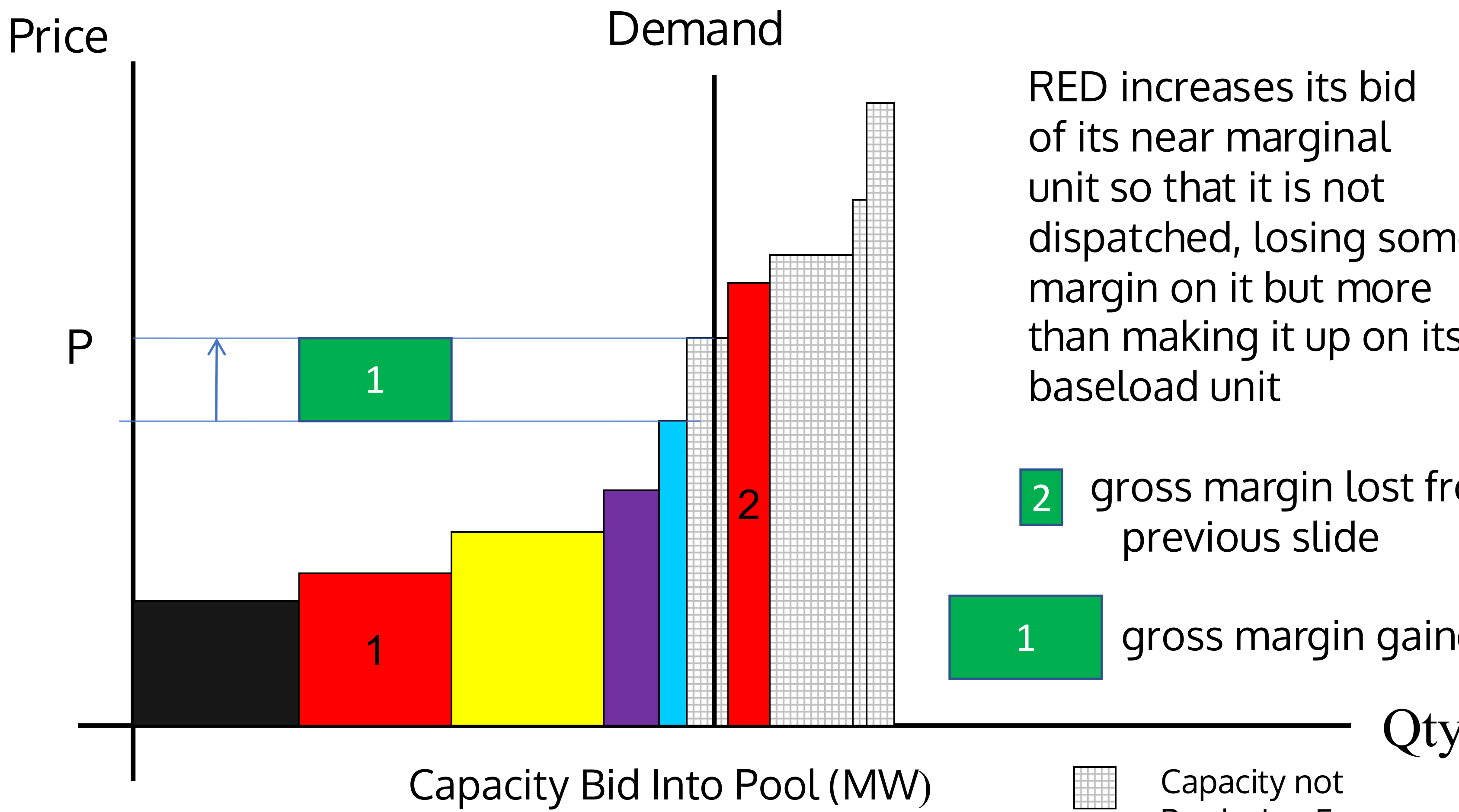
MARKET POWER EXAMPLE



Assume red units owned by same owner

How does red exercise market power?

MARKET POWER EXAMPLE



RED increases its bid of its near marginal unit so that it is not dispatched, losing some margin on it but more than making it up on its baseload unit

2 gross margin lost from previous slide

1 gross margin gained

Capacity not Producing Energy

MARKET POWER ANALYSIS

Herfindahl Index (HHI)

HHI = sum of the squares of firms' market share

$0 \leq HHI \leq 10{,}000$

e.g., A = 10%, B = 30%, C = 40%, D = 20% =>

HHI = 100 + 900 + 1600 + 400 = 3,000

Lerner Index (L) = (P - MC)/P, relative price mark up

L = HHI/(elasticity of demand)

Demand price elasticity = (% change in Q)/(% change in P)

e.g., if a 1 % increase in price results in a 2 % decrease in demand, then the demand price elasticity is -2

Structural approach

Market share and HHI

Size of the market depends on the amount of congestion, which depends on:

- Transmission system
- Available generation
- Reliability rules

"All generators have market power when demand exceed supply"

MARKET MONITORING

- Estimate generators marginal costs
- Consider establishing a pseudo market participant that attempts to game the system
- Need to monitor the exercise of market power/gaming across markets, e.g., intentionally losing money in one market (FTR) to make even more in another (day-ahead market)
- Credit compliance may be susceptible to gaming and should be part of market monitoring
- Should market monitoring include ISO governance?

MARKET POWER SOLUTIONS

- Structural – restrict actual ownership of assets
  - Prevent mergers
  - Divestiture
  - Increasing the amount of price-responsive load

- Behavioral – restrict the behavior of owners of assets
  - Not granting market-based rates
  - Bidding restrictions
    - Types of limits:
      - Hard limits – e.g., bid cap of $1,000/MWh
      - Soft limits – e.g., restrict a generation unit to bid in high-demand hours what it bid in low-demand hours
    - Determining bidding restrictions
      - Index, e.g., to fuel prices
      - Historical bids
      - Market conditions, e.g., congestion

SUMMARY

- LMPs are calculated using complex algorithms
- These calculations are complicated and depend on transmission congestion (i.e., when transmission constraints are binding)
- Multi-part bidding is used to accommodate startup and running costs as well as the changing efficiency of generation units over their operating range
- There is a paucity of demand response
- U.S. RTO/ISO markets have uniform clearing prices that vary by time and location
- Distinguishing between the exercise of market power and scarcity is difficult

KNOWLEDGE SELF-CHECK

1. If there were not transmission constraints, what would set wholesale energy prices?
2. What is the implication of having steep demand and supply curves in wholesale electricity markets?
3. What is the difference between retail electricity markets and wholesale electricity markets?
4. How does transmission congestion affect wholesale energy prices?
5. What is meant by a uniform or single-price auction?
6. How do day-ahead and real-time energy markets work together to improve reliability and reduce market power?
7. How are bilateral contracts executed within an RTO/ISO?
8. What is the basis for capacity markets?
9. How much revenue do ancillary service markets generate?
10. How do generators exercise market power?

TERMINOLOGY AND ABBREVIATIONS CHECK

Consumer surplus

Producer surplus

TCCs, FTRs, FCRs

LMPs

Offers

Bids

Uniform auction

Multi-settlement

SCUC (security constrained unit commitment, reliability unit commitment (RUC)

SCD (security constrained constrained dispatch)

DR

GHGs

HHI

Lerner Index

Session 4:
Political, Regulatory and Business Context

OVERVIEW OF ECONOMIC REGULATION

Topics

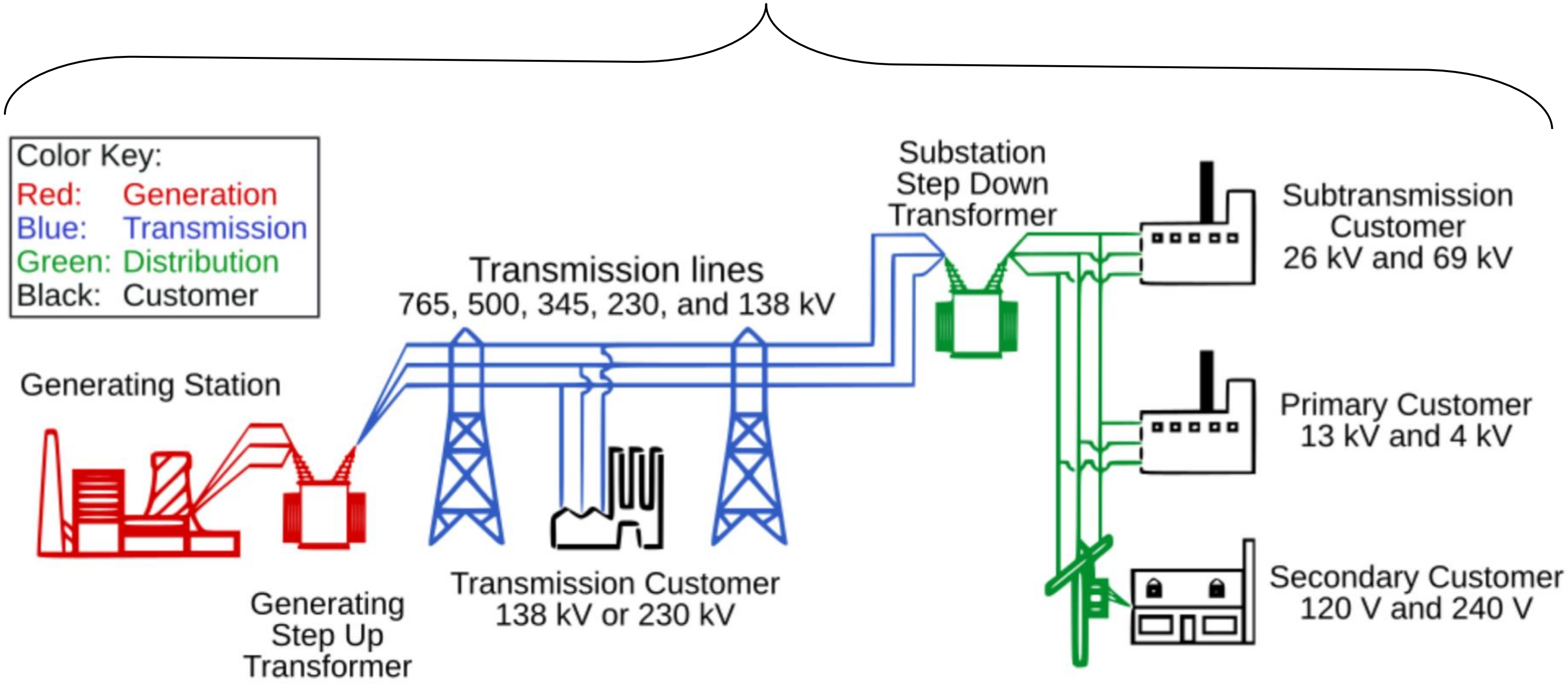
- Historical cost-of-service model
- Role of economies of scale (bigger is better)
- Motivation and history of the development of US electricity markets
- Qualifying Facilities (QFs), Independent Power Producers, and Non-utility generators
- RTO/ISO Governance
- Transmission polices
- Outstanding issues

Key Questions

- What role has economies of scale played in the structure of the electric power industry?
- What portions of the industry remain economically regulated and why?
- What is ISO governance?
- What are the roles of the federal and state governments in the power sector?
- Why is transmission planning necessary and what are the major issues?

FORMER REGULATORY STRUCTURE

Investor-Owned Utilities (IOUs)- Integrated



<u>Cost-of-Service (COS) regulation</u> - IOUs are paid their total costs (capital & operating costs) plus a reasonable return on investment for prudently incurred investments

UTILITY RATEMAKING

Utilities have the opportunity to earn fair rate of return & recover costs (operating costs + capital investments) that are prudently incurred or used and useful

Rate Case (Quasi judicial process)

- Uniform system of accounts
- Cost of service & annual Revenue Requirement (RR)
- Test year (historic or future)
- Cost causation and allocation among rate classes
- Rate design

UTILITY RATEMAKING

Attenuate Issues:

- Multi-utility
- Construction Work in Progress (CWIP)
- Allowance for Funds Used During Construction (AFUDC)
- Weather normalization
- Fuel clause
- Regulatory lag
- Rate shock
- Cross subsidies among rate classes
- Low income policies
- Environmental policies

UTILITY RATEMAKING

Revenue Requirements = Expenses + Rate of Return*Ratebase

Expenses

- Operating expenses
- Depreciation
- Interest on debt
- Franchise fee
- Income taxes (state and federal)
- extraordinary expenses

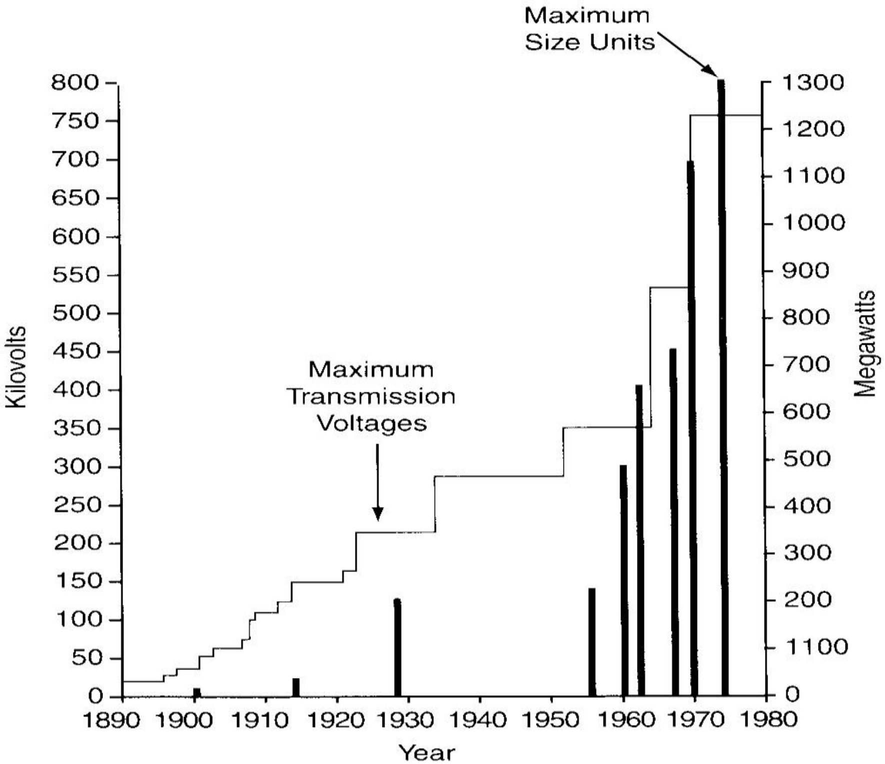
Rate of Return

- Weighted cost of capital (mixture of debt and equity)

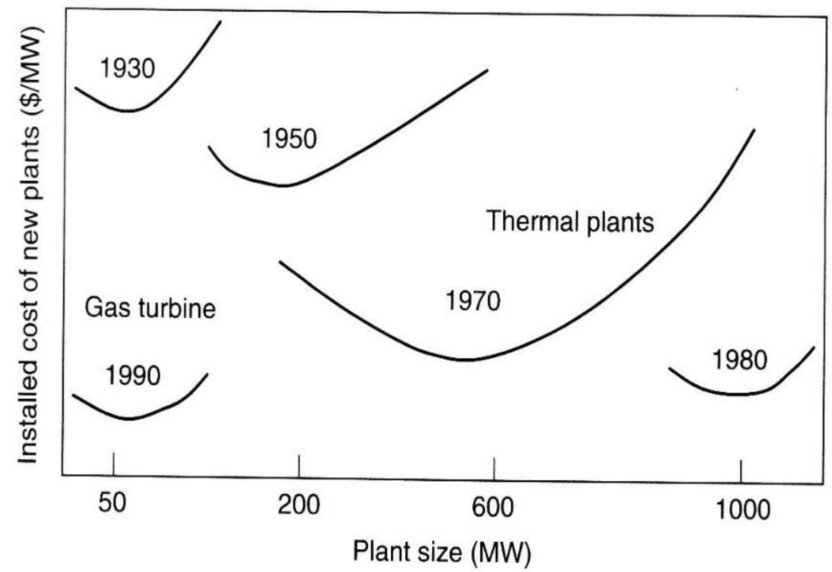
Ratebase

- Original-accumulated depreciation
- Replacement
- Fair market value

ECONOMIES OF SCALE

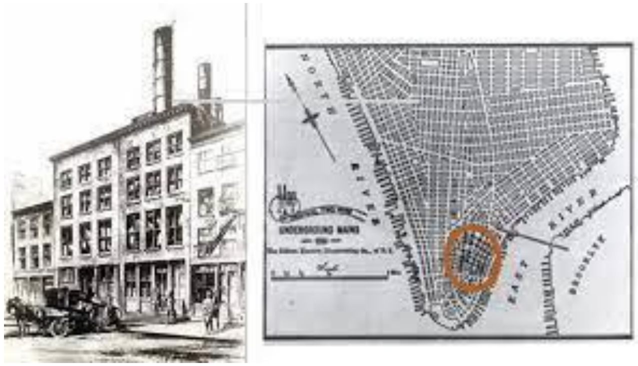


Source: J. Casazza and F. Delea, Understanding Electric Power Systems: An Overview of the Technology and the Marketplace, IEEE Press, 2003 p. 4.

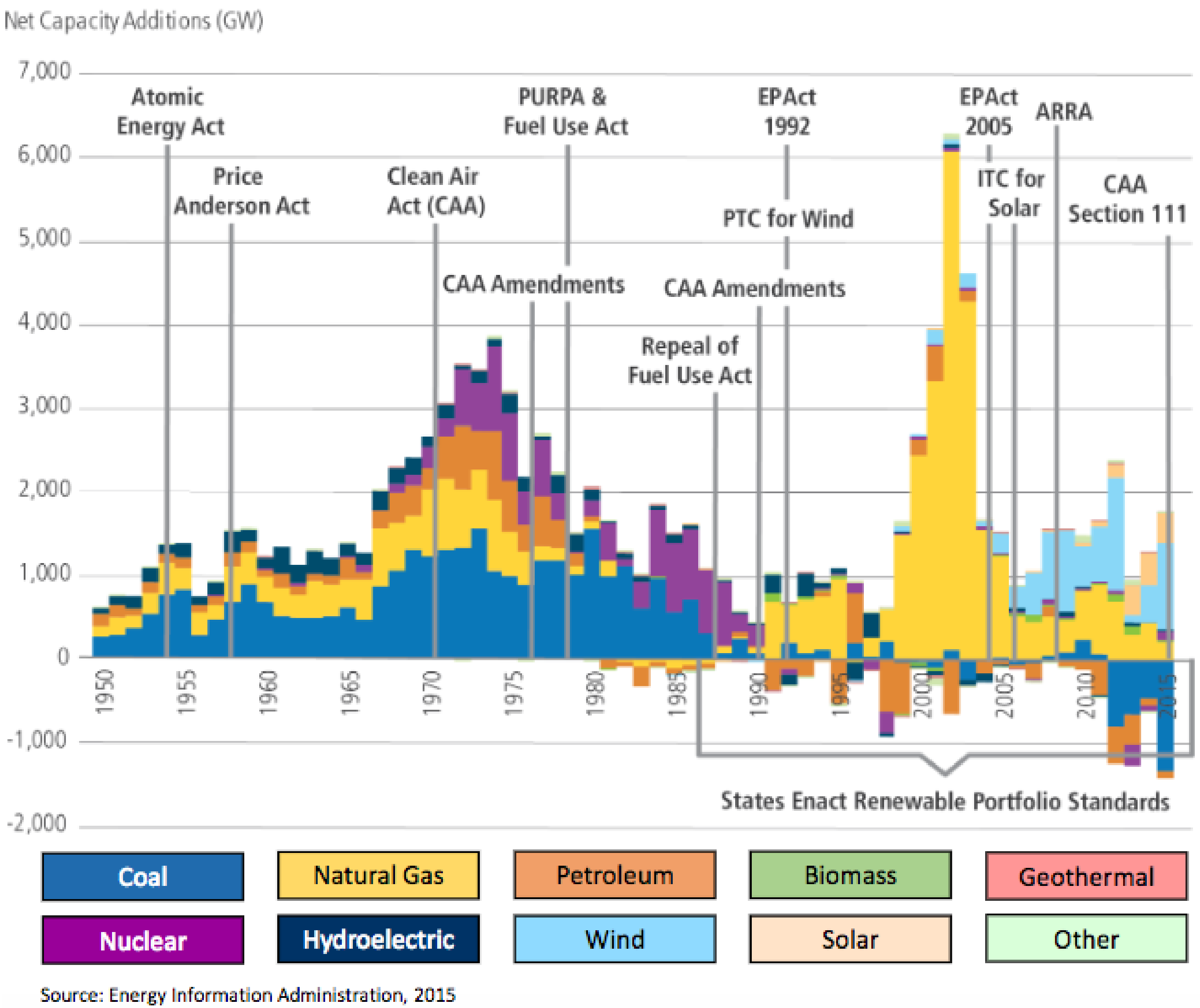


Source: C. Bayliss, "Less is More: Why Gas Turbines Will Transform Electric Utilities," *Public Utilities Fortnightly*, Dec. 1, 1994, pp. 21-25.

Historical Note: First workable electric system built by Edison at Pearl Street Station, Financial District, NYC

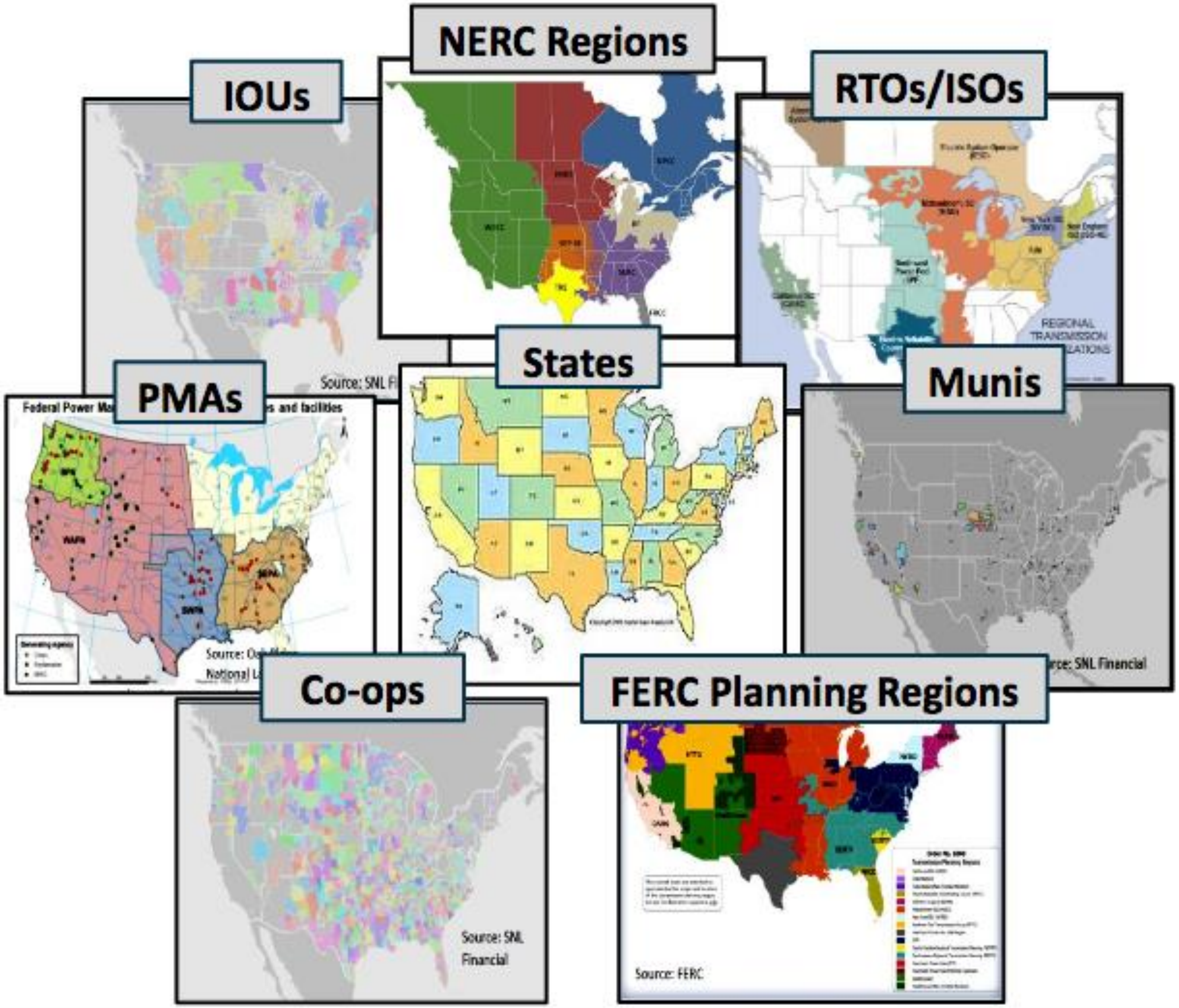


FEDERAL ELECTRICITY POLICY



Also the US Inflation Reduction Act (2022) and the US Infrastructure Investment and Jobs Act (2021).

ELECTRIC POWER SECTOR GOVERNANCE



HISTORY OF US ELECTRICITY MARKETS

In the 1970s, various other U.S. industries were deregulated with apparent success such as trucking, airlines, banking, finance, and oil

One of these was the natural gas industry in which the commodity portion deregulated whereas interstate transportation continued to be regulated at cost-base rates

Transportation and the commodity were unbundled and transportation is regulated because it is a natural monopoly

HISTORY OF US ELECTRICITY MARKETS con't

In the 1980s, the electric utility industry had huge costs and over capacity

The development of Combined Cycle (CC) generation reversed the economies of scale trend, enabling multiple units to replace much larger generation units

$\Rightarrow$ Restructure (unbundle) the electric power industry

Wholesale unbundling
Retail unbundling

US REGULATORY STRUCTURE

Federal Level

- The Federal Energy Regulatory Commission (FERC) regulates, among other industries, the wholesale production and transmission of electric power

- Federal government regulates interstate power sales and services, mergers, and corporate structure

State Level

- Public Service Commissions (PSC) and Department of Public Utilities (DPU) regulate distribution assets and retail service

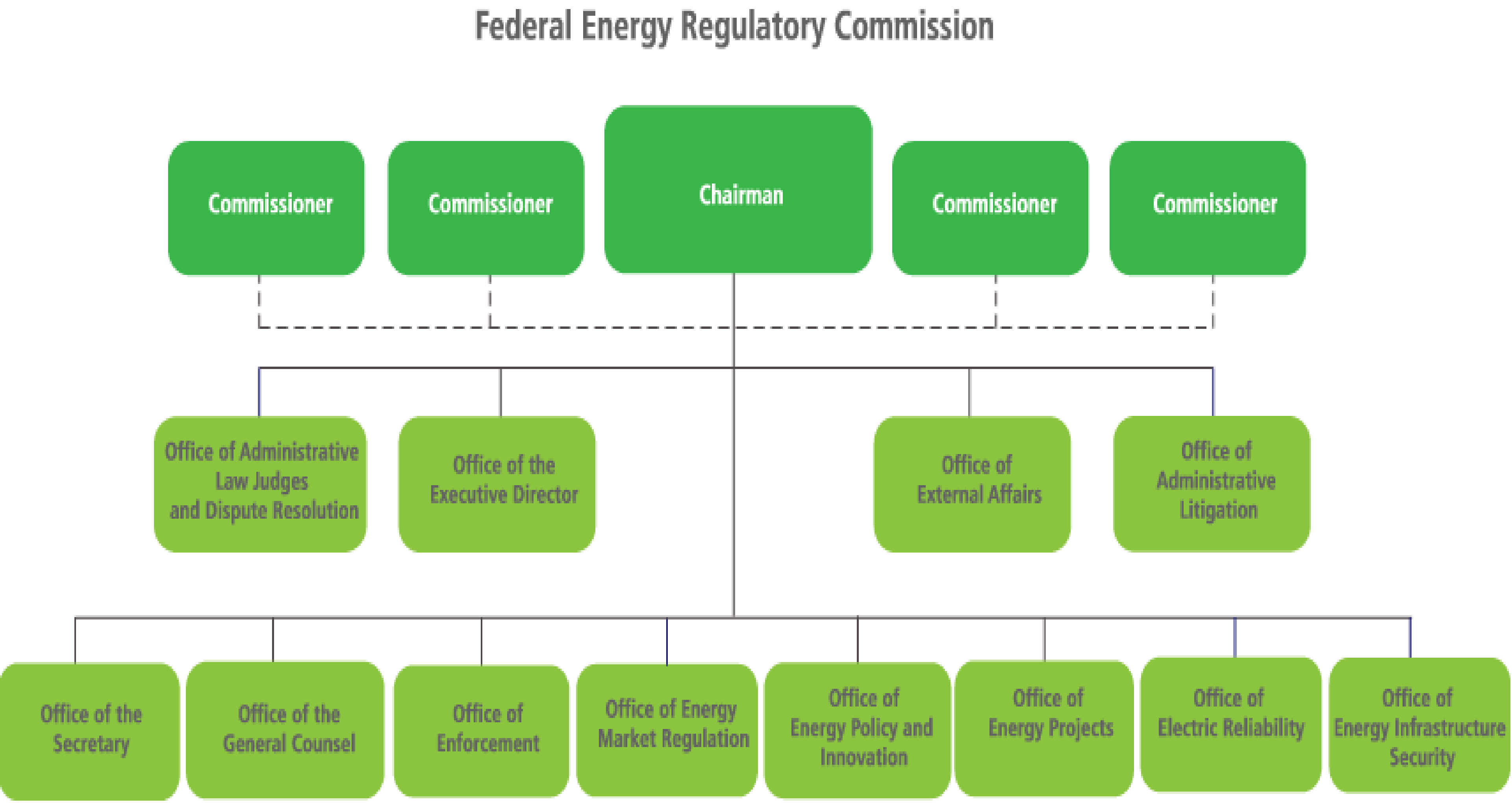
- Utilities are granted an exclusive franchise and an obligation to serve

- State governments regulate retail electricity service, mergers, facility planning and siting

- Regulation at the state level started in 1907 in New York and Wisconsin

- 2/3 of the states regulated the industry by 1920

FEDERAL ENERGY REGULATORY COMMISSION (FERC)



US LEGAL FRAMEWORK

1935 Federal Power Act
- Gave the Federal Power Commission, now the FERC, regulatory authority over terms, conditions, and rates of interstate and wholesale transactions and transmission
- Electricity rates must be “reasonable, non-discriminatory, and just to the consumer”

1978 PURPA: Public Utility Regulatory Policy Act
- Qualifying Facilities (QFs) established, utilities compelled to purchase QF energy from qualified non-utility generators

1992 Energy Policy Act (EPAct)
- Exempt Wholesale Generators (EWGs) established and nondiscriminatory transmission access required

1995 Mega-NOPR (Notice of Proposed Rulemaking)
- FERC’s initial proposal for uniform open access transmission rules and stranded cost recovery

1996 FERC Orders 888/889
- Require utilities to file and use open access transmission tariffs, permits wholesale stranded cost recovery, creates Open Access Same-time Information System (OASIS)

RTO Order (Order 2000)
- FERC orders the formation of Regional Transmission Organizations

US LEGAL FRAMEWORK (con't)

2002 Standard Market Design (SMD) NOPR
FERC has laid this NOPR to rest

Energy Policy Act of 2005 makes reliability rules mandatory

Energy Independence and Security Act of 2007

Order 890, Feb. 2007: Strengthen the OATT and improve transmission planning and transparency

Order 719, Oct. 2008: Improved operations of organized (aka ISO) wholesale electricity markets

Order 745, March 15, 2011: DR in organized markets must get paid LMPs

Order 1000, July 21, 2011: Transmission Planning and Cost Allocation

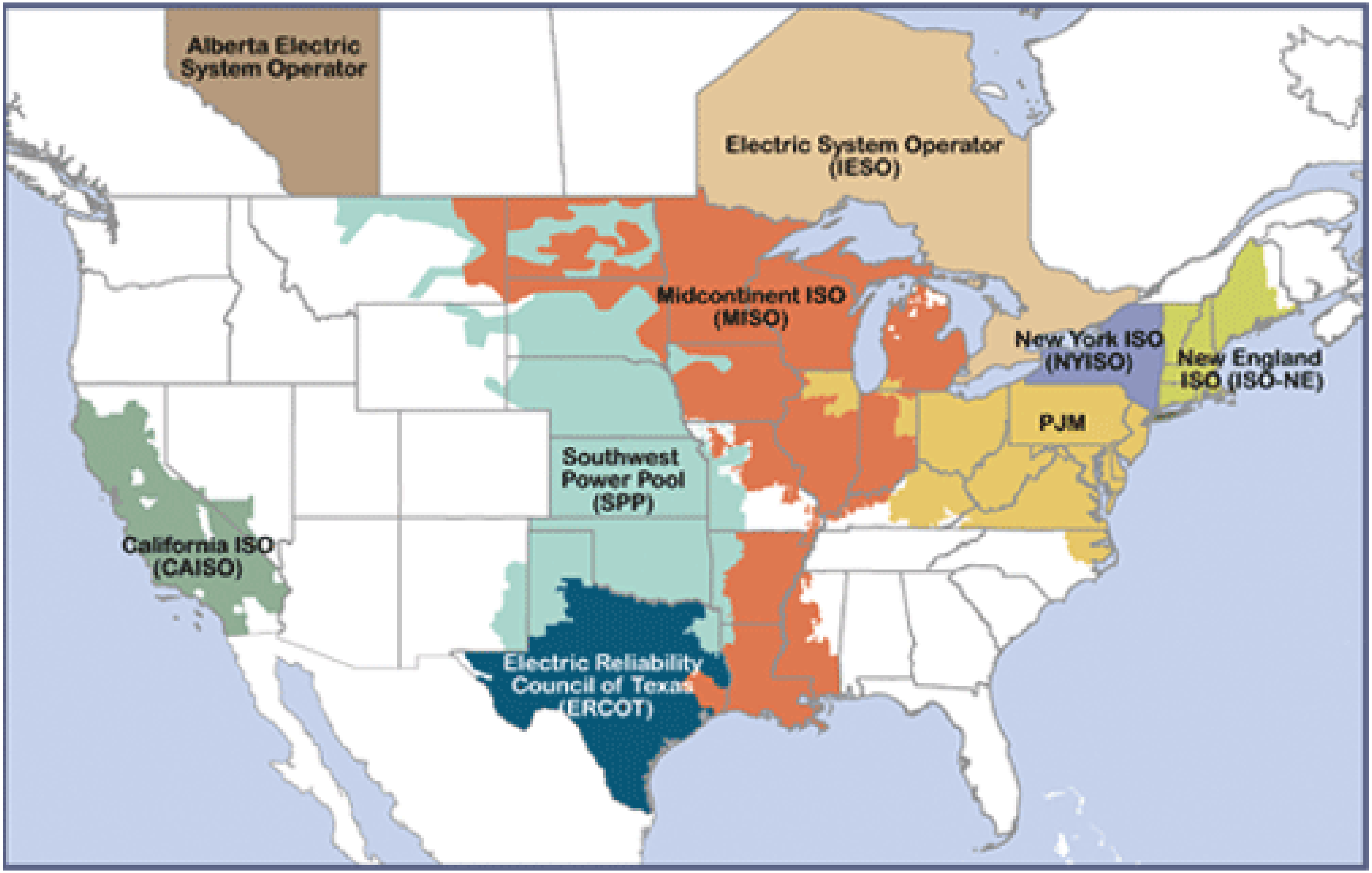
Dept. of Energy has requested that the FERC impose rules on RTOs/ISOs to address the reliability and resiliency issues due to the retirements of baseload units (Oct. 2017)

RECENT FERC ELECTRICITY ORDERS

Order No.	Date	Title
Order 1977-A	October 17, 2024	Applications for Permits to Site Interstate Electric Transmission Facilities Rehearing | Item E-1 | News Release
Order No. 1920	May 14, 2024	Electric Regional Transmission Planning and Cost Allocation | Item E-1 | Presentation | Fact Sheet | Chairman Phillips' Statement Concerning Order No. 1920
Order No. 1977	May 14, 2024	Backstop Transmission Siting Procedures News Release | Presentation
Order No. 2023	July 27, 2023	Improvements to Generator Interconnection Procedures and Agreements | News Release | Fact Sheet | Presentation
RM22-14-000	June 16, 2022	Improvements to Generator Interconnection Procedures and Agreements | News Release | Presentation
RM22-10-000	June 16, 2022	Transmission System Planning Performance Requirements for Extreme Weather | News Release | Presentation
RM22-16-000 AD21-13-000	June 16, 2022	One-Time Informational Reports on Extreme Weather Vulnerability Assessments | News Release | Presentation
RM21-17-000	April 21, 2022	Building for the Future Through Electric Regional Transmission Planning and Cost Allocation and Generator Interconnection
Order No. 2222 (RM18-9-00)	September 17, 2020	Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators (Final Rule)

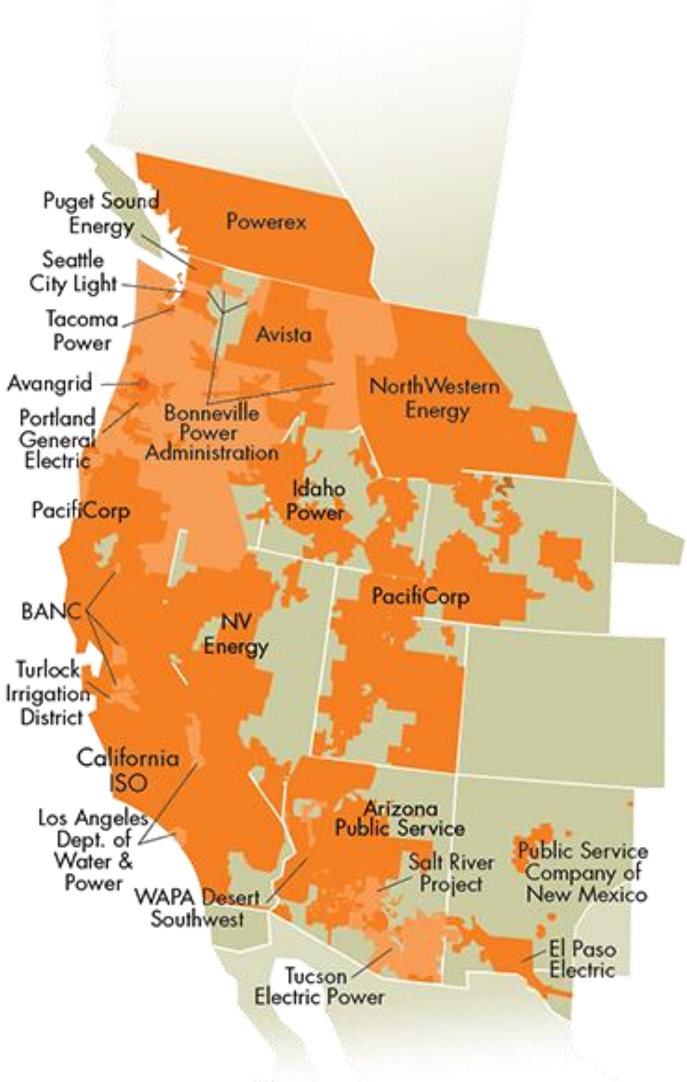
https://www.ferc.gov/major-orders-regulations

RTO/ISO MAP

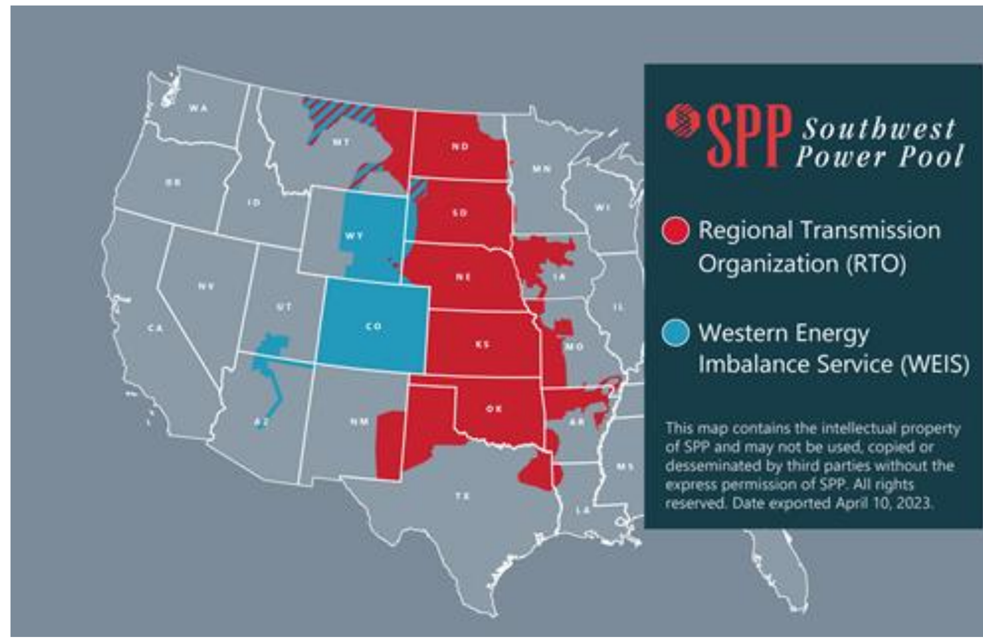


In the Northeast, RTOs/ISOs were formed from pre-existing “tight” power pools

WESTERN MARKETS

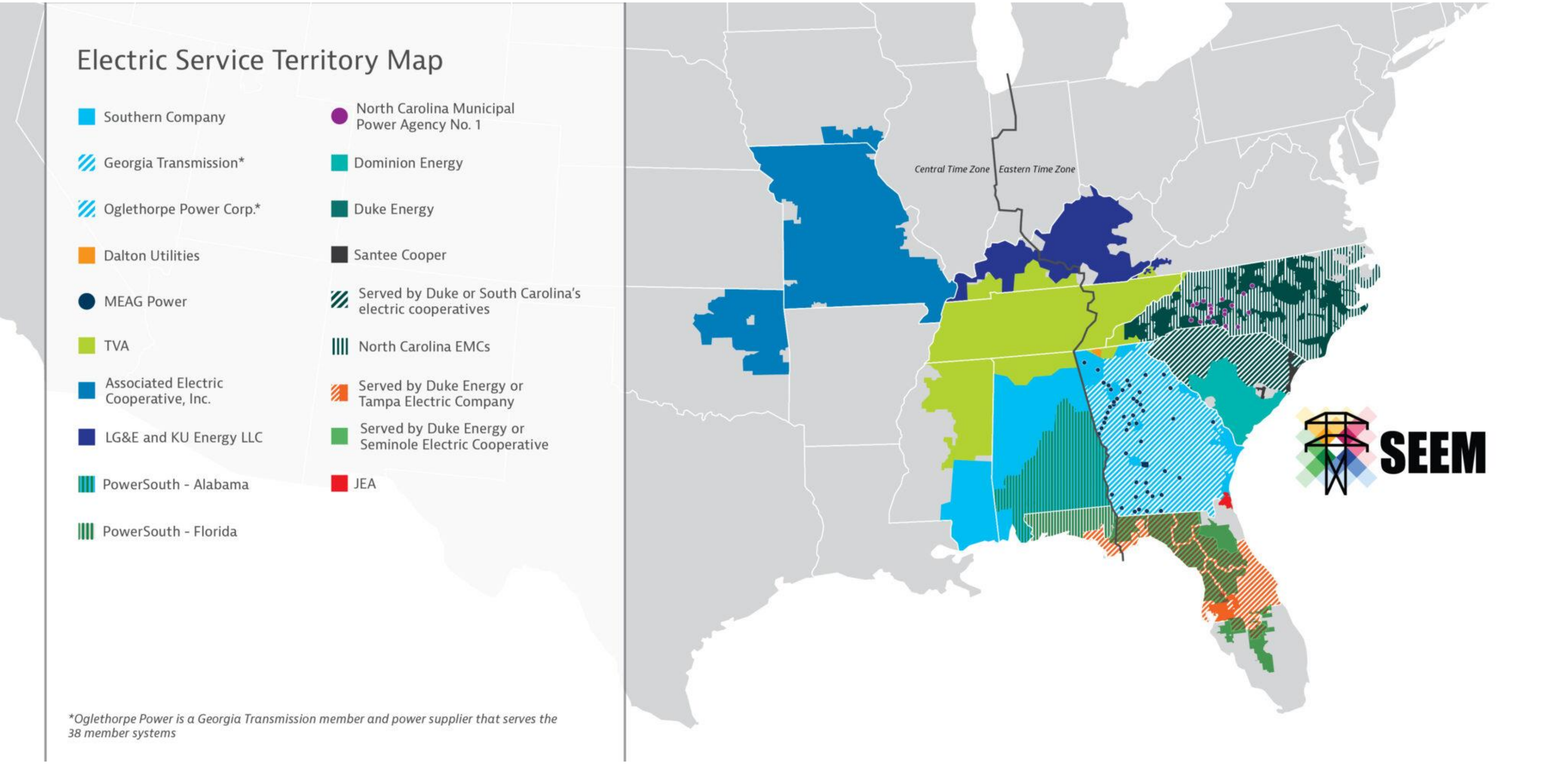


https://www.westerneim.com/Pages/About/default.aspx



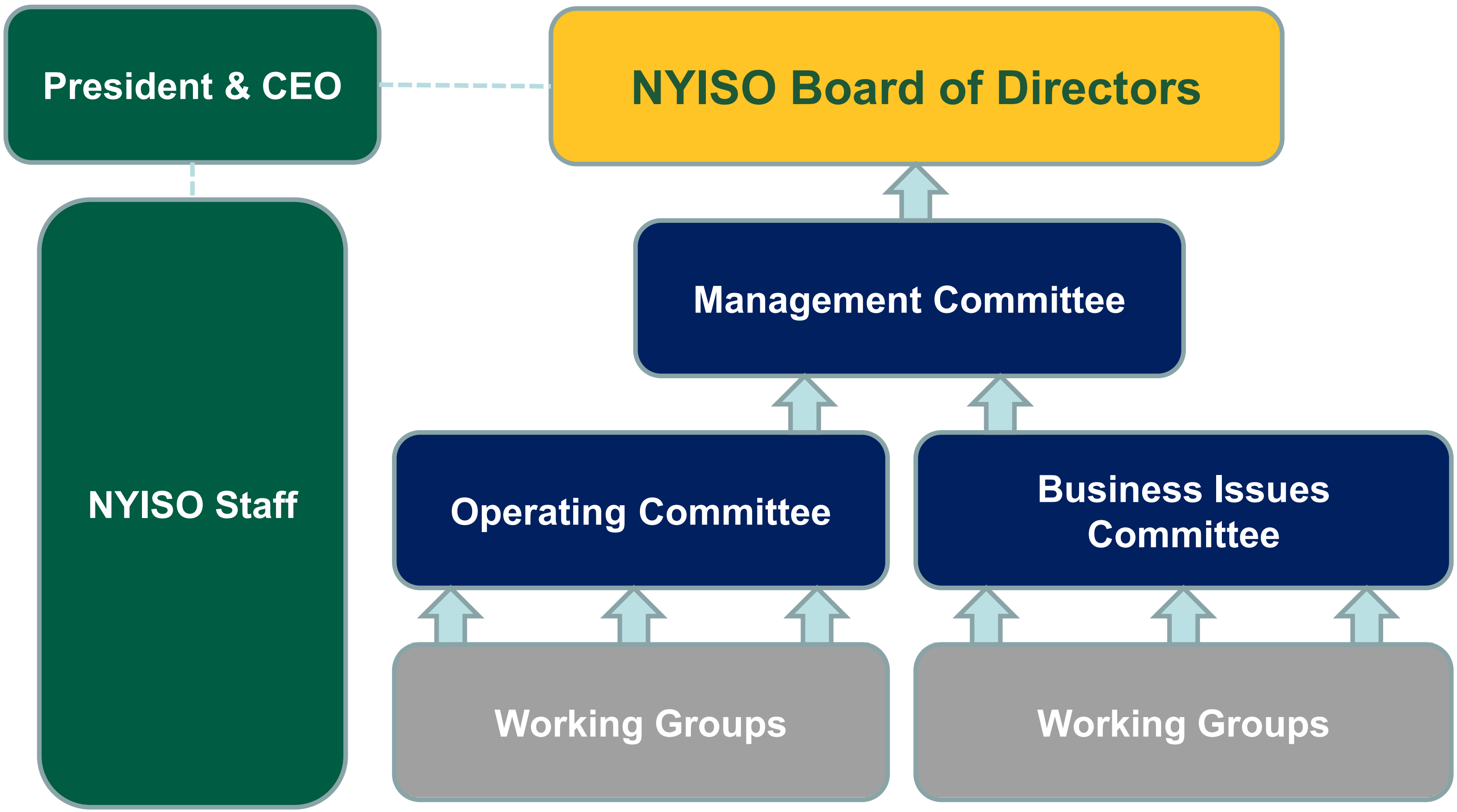
https://spp.org/western-services/weis/

U.S. SOUTHERN ELECTRICITY MARKETS

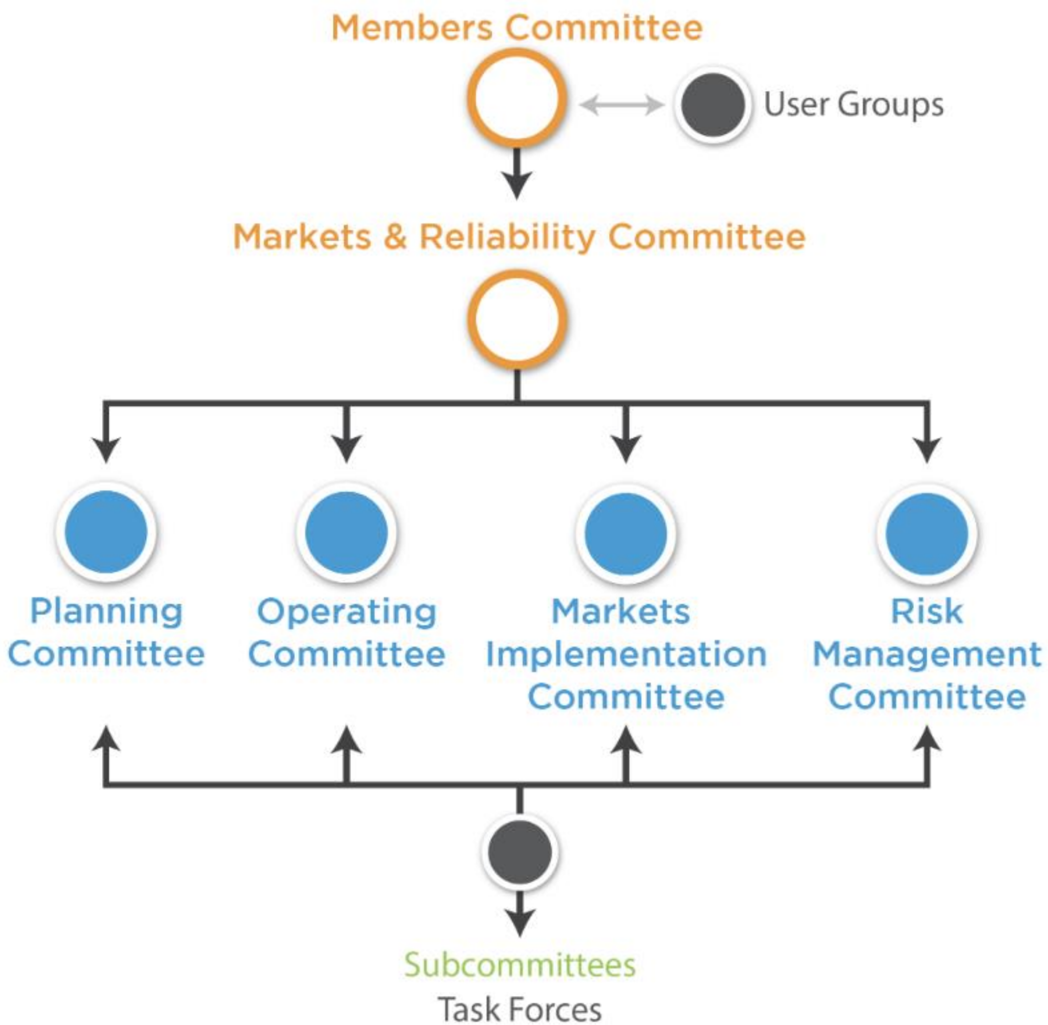


https://southeastenergymarket.com

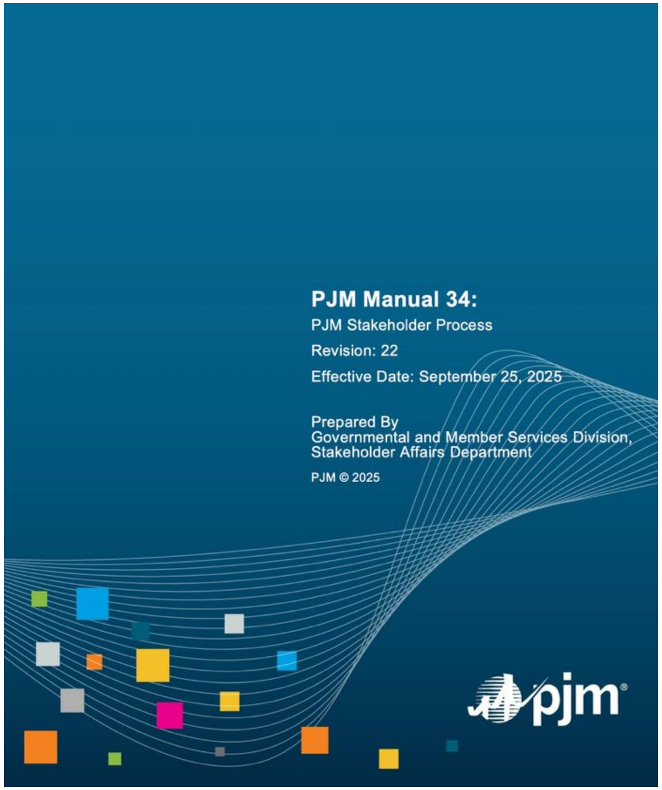
NYISO GOVERNANCE



PJM GOVERNANCE



https://www.pjm.com/committees-and-groups/committees



https://www.pjm.com/-/media/DotCom/documents/manuals/m34.pdf

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TRANSMISSION

Economic Characteristics of Transmission

- Large, lumpy (i.e., large economies of scale), sunk investments
- Difficult to define property rights
- Issues of free-ridership due to positive externalities
- Cannot separate generation from transmission; that is what LMPs are all about
- Transmission is both a complement and a competitor to generation and load resources
  - Complements are products that tend to be used together, e.g., cameras and film
- Generation and load management are procured competitively but transmission, for the most part, is procured via regulation

TRANSMISSION

Key Policy Questions:

- How to connect markets with transmission expansion policies?
- When should regulators intervene in the market to provide additional transmission resources?
  - Economic upgrades
  - Reliability upgrades
- Who should pay for such upgrades?
- Should other types of resources be procured to meet “transmission needs”?
- How to accelerate the interconnection process for new generation units?
- How to plan transmission in the context of a rapid energy transition?

FERC TRANSMISSION POLICY, ORDER 1000

- Public utility transmission providers must participate in a regional transmission planning process that satisfies Order 890 principles
- Cost allocation must satisfy six cost allocation principles:
    - Costs allocated roughly commensurate with benefits
    - No involuntary allocation of costs to non-beneficiaries
    - If a benefit to cost ratio threshold is used, cannot be too high
    - Costs can only be allocated solely within the transmission planning region unless those outside it voluntarily assume costs
    - Transparent method required to determine benefits and to identify beneficiaries
    - Different cost allocation methods are permitted for different facilities
- Federal rights of first refusal must be removed
- Consideration of transmission needs driven by public policy
- New FERC Transmission Related NOPR/Orders:
    - Building for the Future Through Electric Regional Transmission Planning and Cost Allocation and Generator Interconnection, Docket No. RM21-17-000
    - Order 2023: Generation Interconnection Order

DATA CENTERS

DATA CENTERS

DATA CENTERS

DATA CENTERS

1. A data center is a physical facility that houses computer hardware and equipment to store, process, and distribute data
2. Also referred to as “large loads” and “hyperscalers”
3. Computer servers
4. Data storage
5. Software applications
6. Network equipment
7. Power infrastructure: UPS and backup generators
8. Types of data centers
   - Colocation data centers
   - Enterprise data centers
9. Edge computing – conduct computing close to the data source and not at a centralized data center

DATA CENTERS

1. Data center investors: growth capital, buyout, real estate, infrastructure investors

2. Data center investments typically have steady, utility-like cash flows and risk-adjusted yields

3. Typically owned by cloud vendors, banks, or telcos

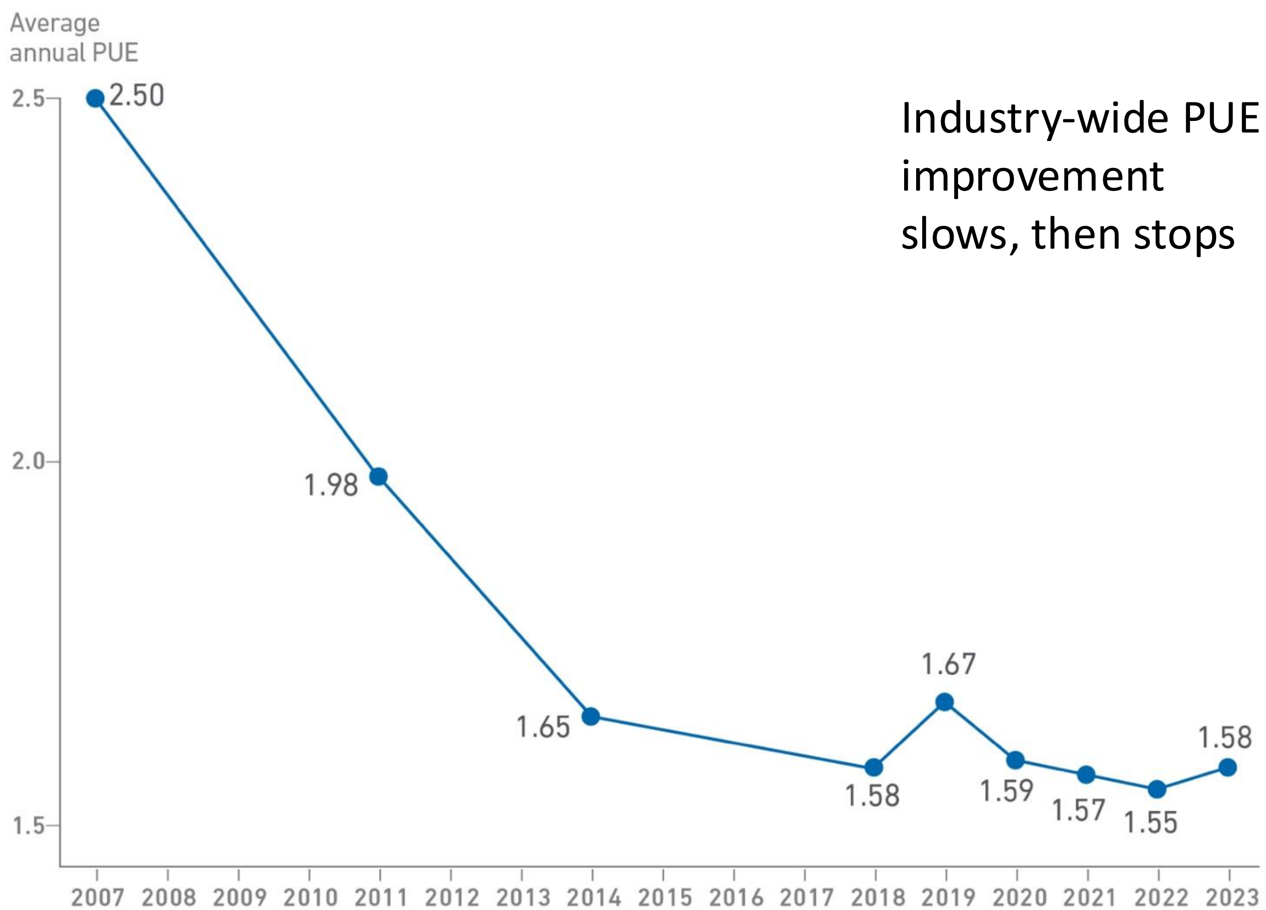
4. Co-location companies lease out the space and typically provide network capacity and power and cooling equipment, and their tenants bring their own IT equipment

5. U.S. accounts for 40% of the global data center market

https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/investing-in-the-rising-data-center-economy

DATA CENTER LOAD

Power usage effectiveness (PUE) – amount of power the computing equipment in a data center uses relative to its total energy consumption



Industry-wide PUE improvement slows, then stops

https://journal.uptimeinstitute.com/global-pues-are-they-going-anywhere/

DATA CENTER INVESTMENTS

1. MPE – mechanical, electrical, and plumbing

2. IaaS: Infrastructure as a Service

3. 24/7 PPAs – power purchase agreements that match each hour of electricity consumption with a combination of carbon-free supplies and stored renewable energy

4. Data centers backup power – presently diesel generators

5. Data centers and real estate

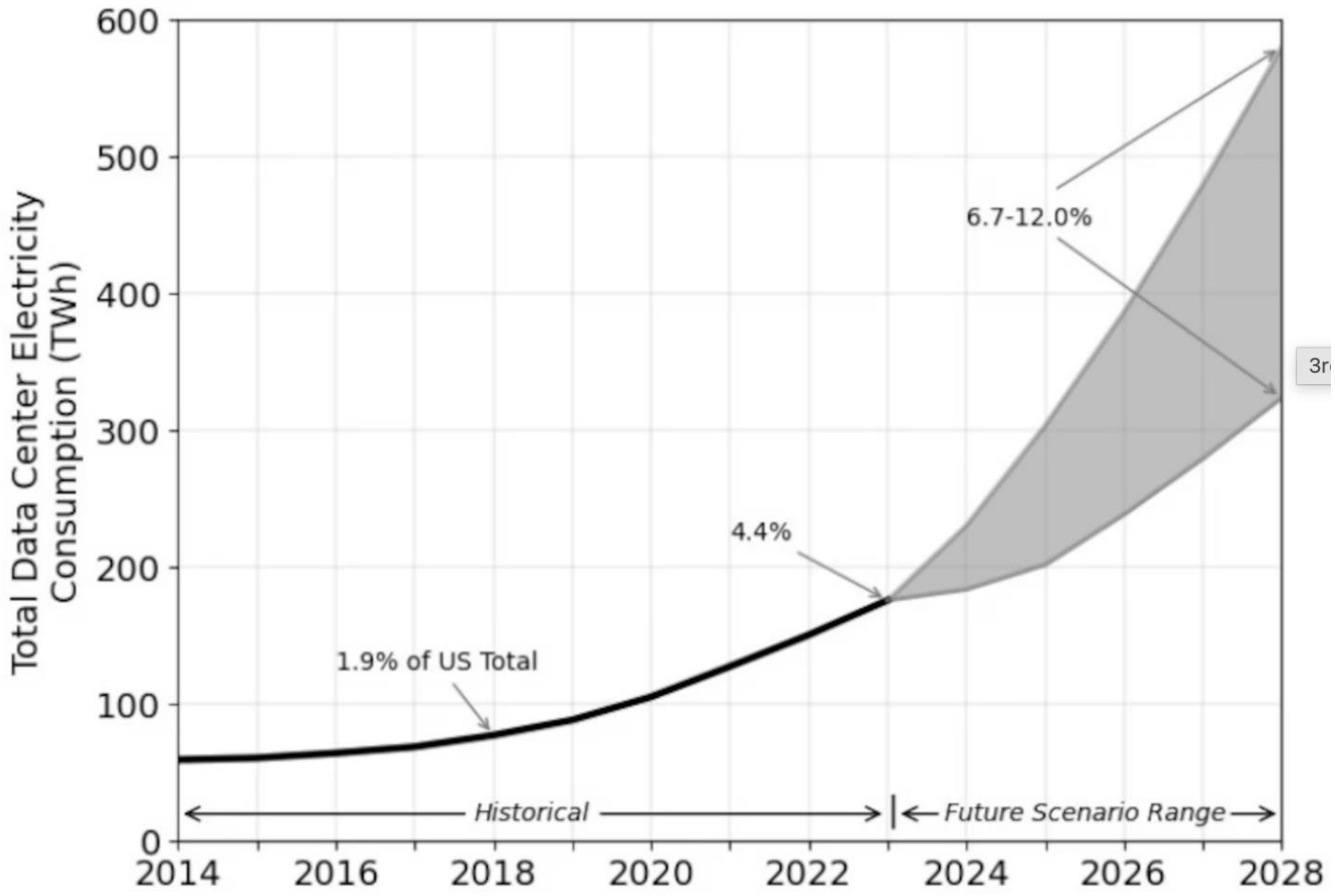
   - Near fiber optic system
   - Land cost
   - Smaller, more decentralized data centers

https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/investing-in-the-rising-data-center-economy

DATA CENTERS PROJECTED GROWTH

The U.S. power market is facing "a moment of peak uncertainty," Rebecca Carroll, Senior Director of Market Analytics at energy advisors Trio, said.

CHART: Forecast US data center electricity demand



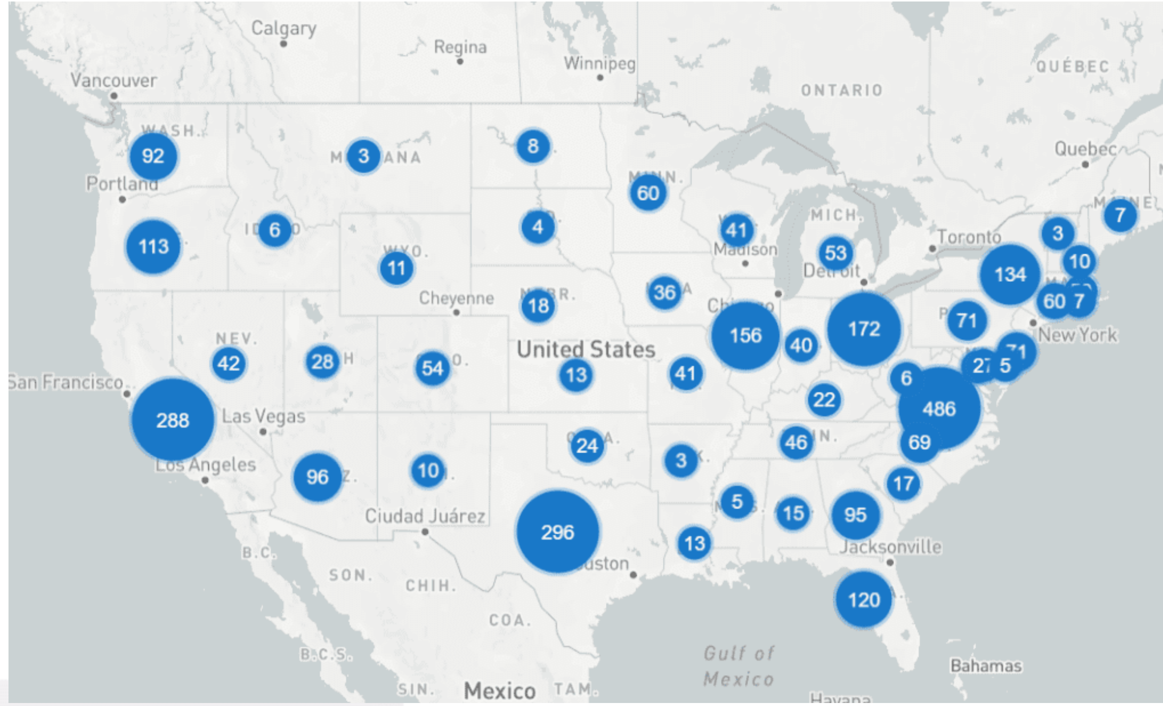
Source: Berkeley Lab's 2024 United States Data Center Energy Usage Report, December 2024. Purchase Licensing Rights

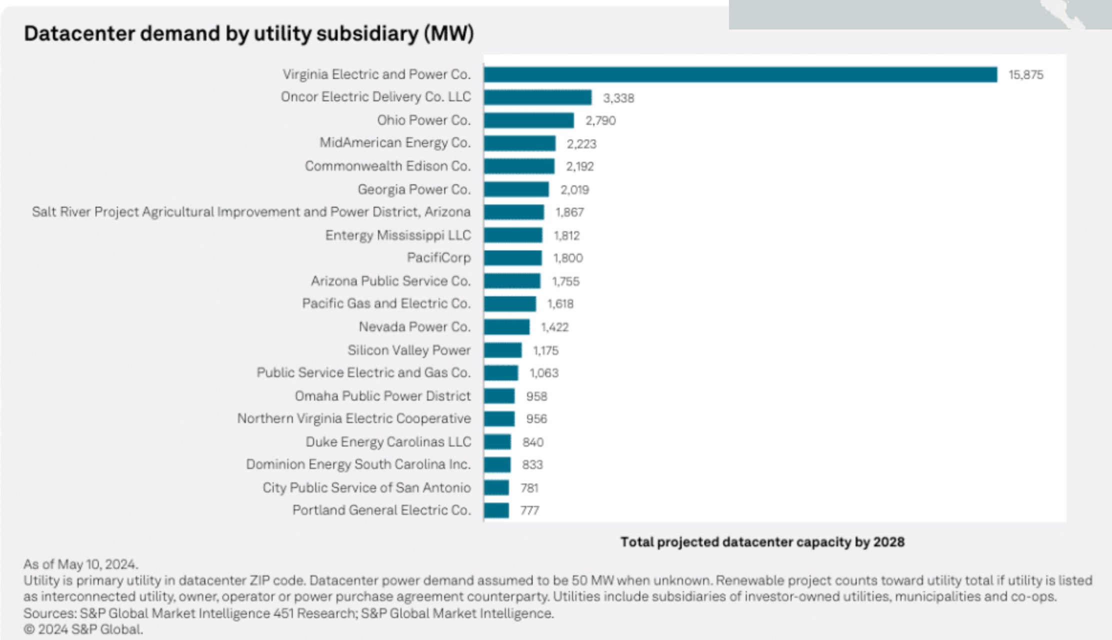
https://www.reuters.com/business/energy/dash-data-centers-creates-revenue-risks-power-developers-2025-07-01/

US FIBER OPTICS MAP

https://www.landgate.com/news/unlocking-the-potential-of-data-centers-and-fiber-optics

DATA CENTERS

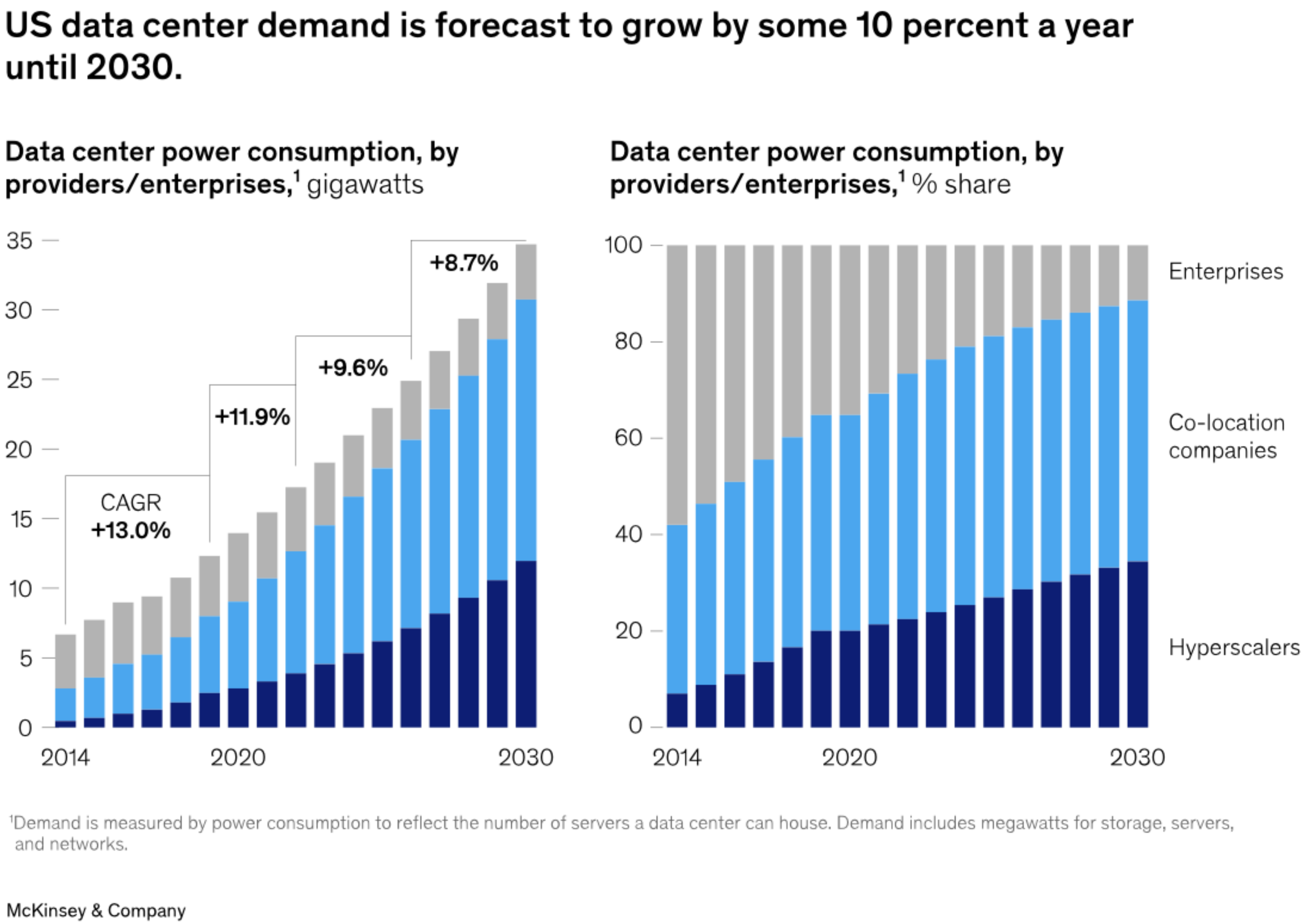




https://www.power-eng.com/news/data-centers-are-flocking-to-ohio-here-comes-the-transmission-to-support-them/

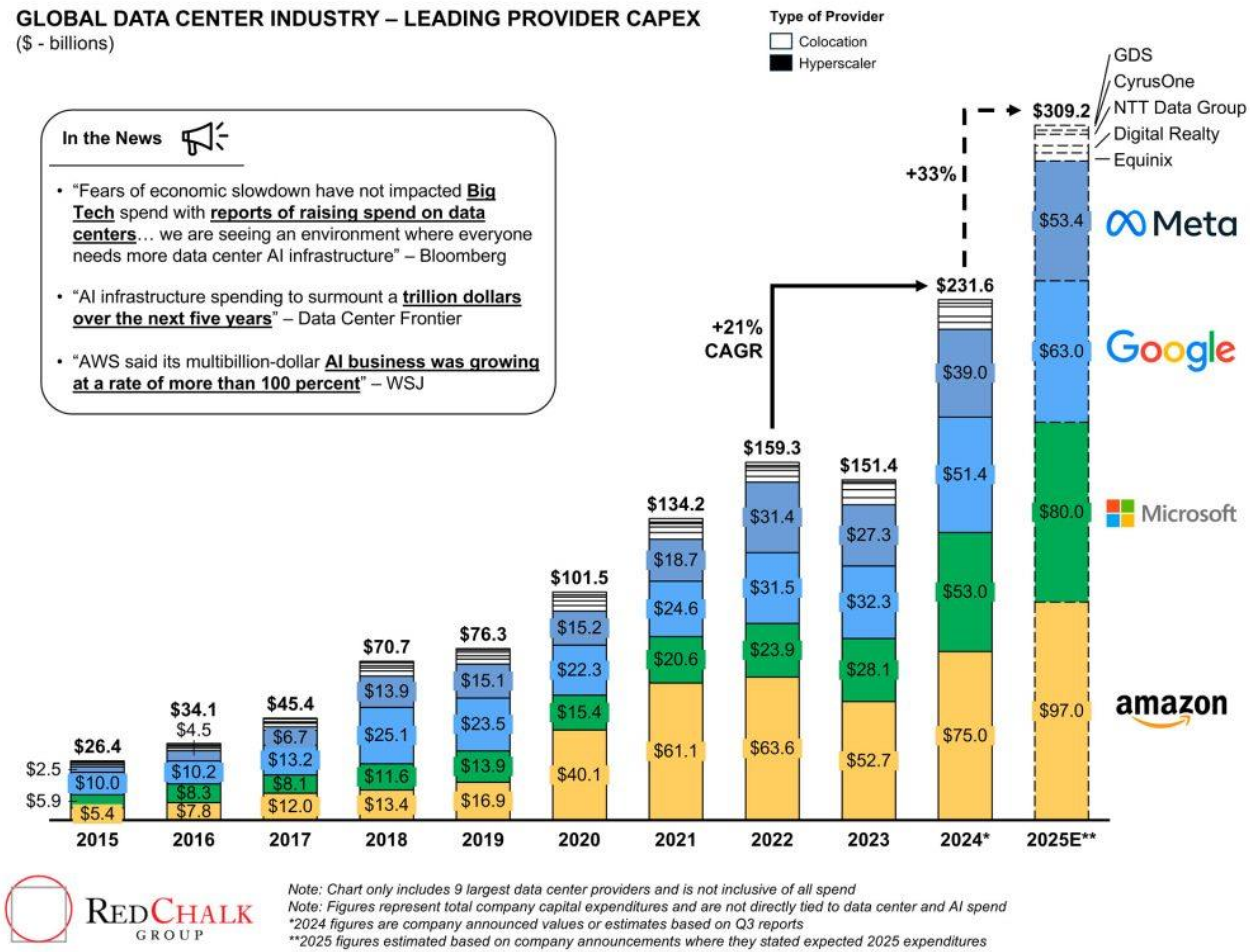
https://carboncredits.com/who-leads-the-data-center-surge-in-the-us-sp-global-report-power-demand/

DATA CENTERS



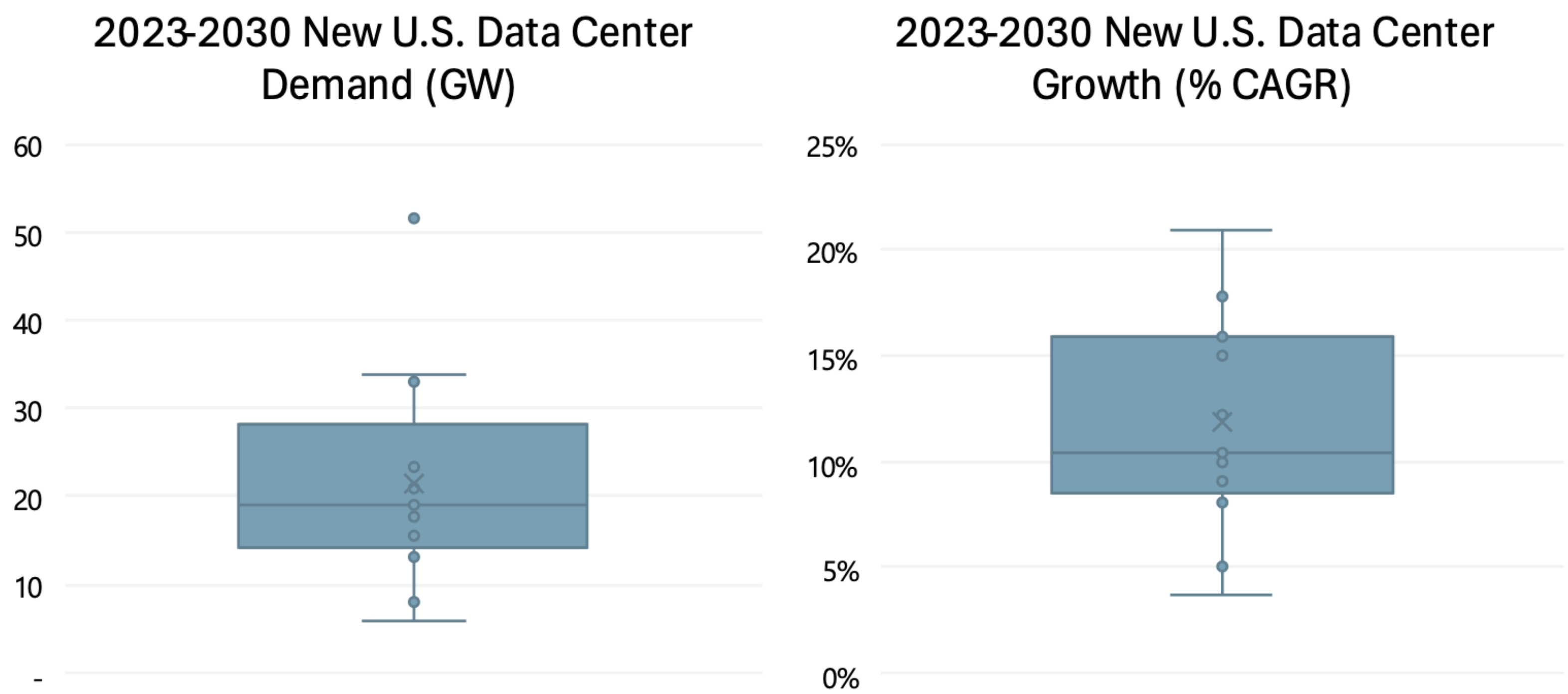
https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/investing-in-the-rising-data-center-economy

DATA CENTERS



https://www.redchalk.com/the-new-gold-rush-the-data-center-investment-boom/

DATA CENTERS

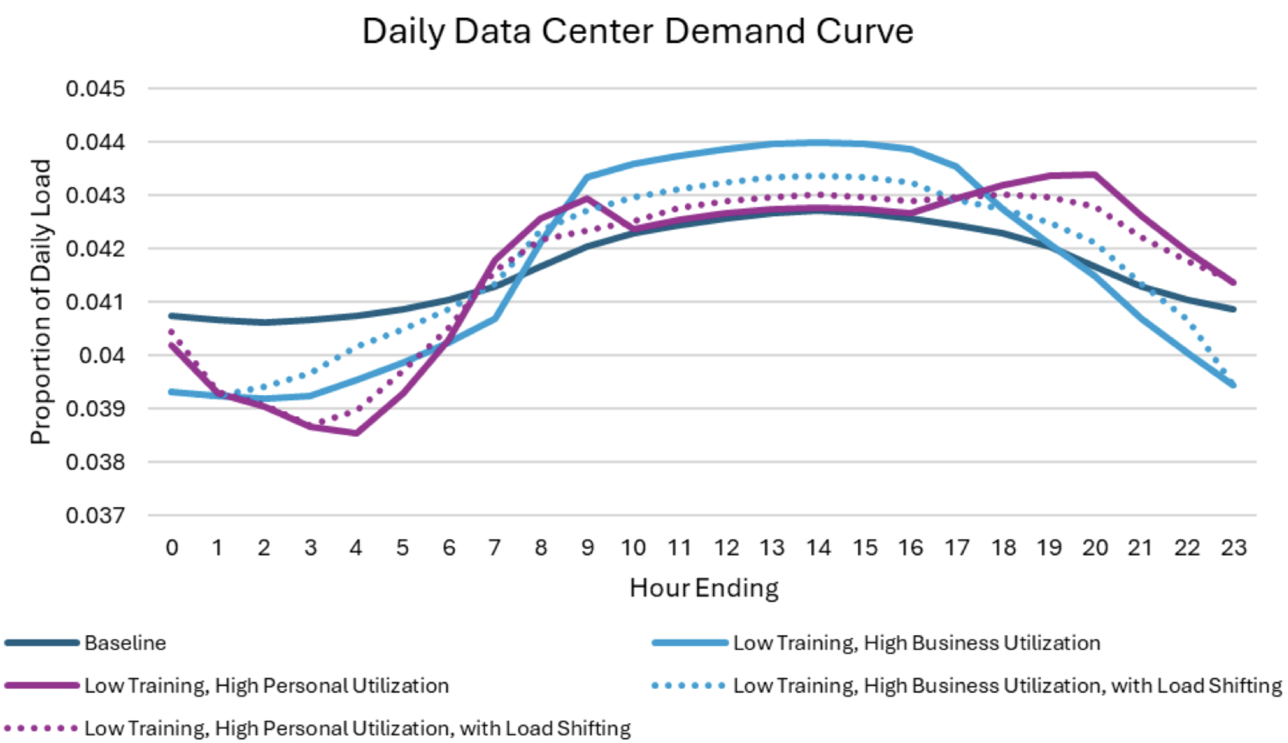


Projections from JLL, McKinsey, EPRI, IEA, BCG, Mordor and Goldman Sachs (total n = 13). E3 estimates data center capacity from energy estimates using an assumed 86% data center load factor and, as needed, linearly extrapolates projections to estimate changes from 2023 to 2030. BCG's "US Data Center Power Outlook" report issued in July 2024 provides its more updated view, projecting new data center demand growth ranging from 60 to 90 GW in 2023-2030.

https://www.ethree.com/wp-content/uploads/2024/07/E3-White-Paper-2024-Load-Growth-Is-Here-to-Stay-but-Are-Data-Centers-2.pdf

DATA CENTERS HOURLY LOAD PROFILES

Figure 5: Projected AI Daily Load Curve Under Various Usage Scenarios

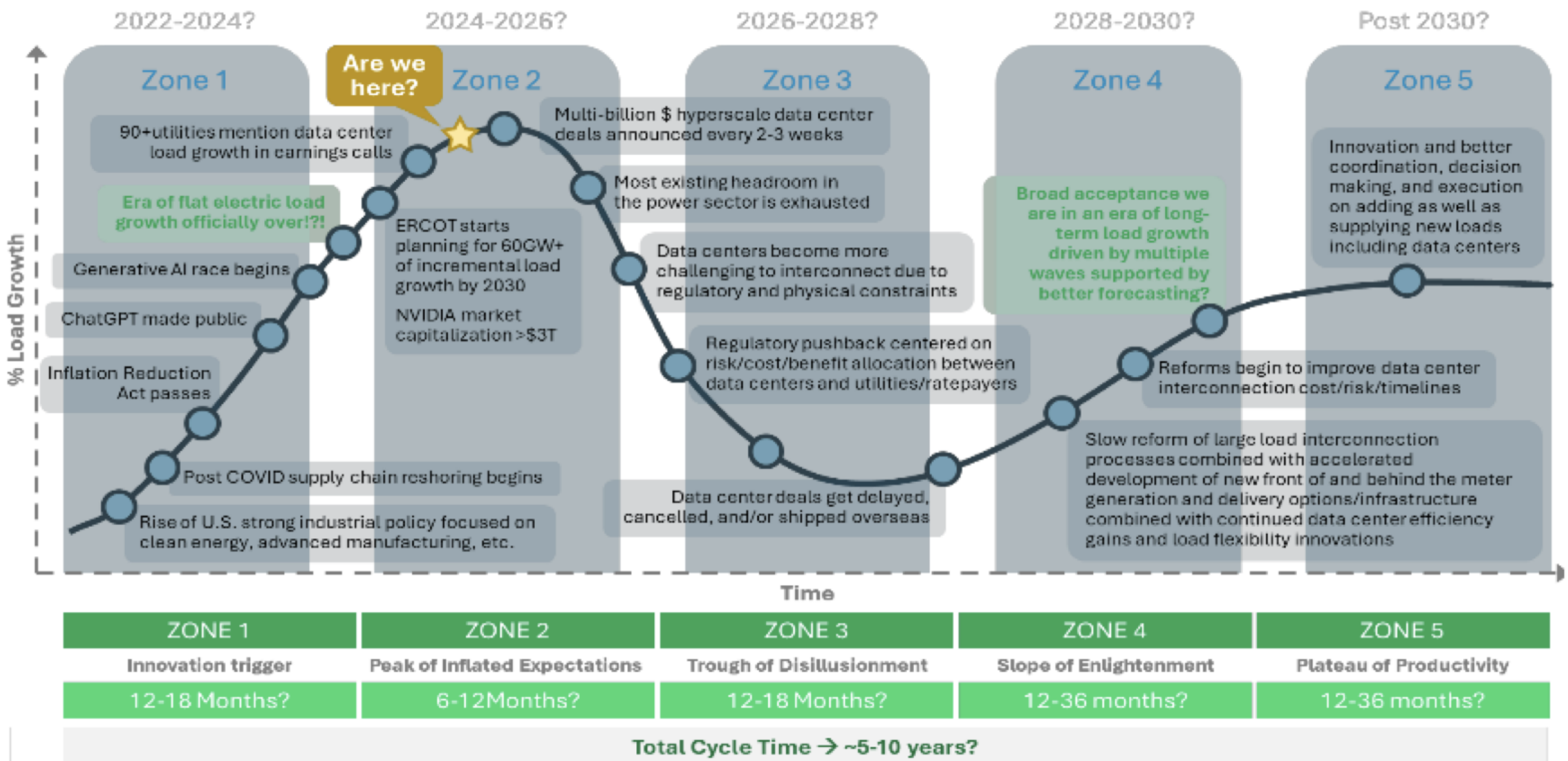


However, if usage overtakes training as the dominant load source, then the daily peak would be more dependent on usage time and type. If AI is primarily a business tool, then peak demand may mostly coincide with business hours. If AI is mostly a personal tool, then twin morning and evening peaks may be more likely, resembling today's residential load shapes. Figure 5 illustrates these possible load shapes. There may be additional possible load shapes that reflect having more flexibility around AI computing, such as batching AI queries and running them flexibly during the day, moving other computing loads optimized around variables such as clean energy availability, and utilizing on-site behind-the-meter generation. Similar to the overall load growth trajectories to 2040, there is substantial uncertainty around future load shape, but it is unlikely to be truly flat, which has significant ramifications for grid planners and system operators on how to serve this demand.

https://www.ethree.com/wp-content/uploads/2024/07/E3-White-Paper-2024-Load-Growth-Is-Here-to-Stay-but-Are-Data-Centers-2.pdf

DATA CENTERS HYPE CYCLE?

Figure ES-3: Are we in a Power Sector Data Center Hype Cycle? Illustrative Visualization based on Gartner Hype Cycle[2]



https://www.ethree.com/wp-content/uploads/2024/07/E3-White-Paper-2024-Load-Growth-Is-Here-to-Stay-but-Are-Data-Centers-2.pdf

Figure 1. Selected Financial Bubbles Throughout History

Bubble	Asset class	Approx. # days to peak	Approx. # days decline	Total length of bubble (yrs)	Max. multiple of starting price	% decline from peak
Dutch tulips: *1634-1639*	Commodities	148	164	1	39.9x	-93%
Mississippi Company: *1718-1720*	Equities	520	322	2	36.9x	-64%
South Sea Company: 1719-1720	Equities	324	150	1	8.4x	-81%
DJIA: *1921-1932*	Equities	2,987	1,031	11	5.6x	-89%
US rail stocks: *1923-1932*	Equities	2,162	1,033	9	2.4x	-92%
Gold: *1977-1982*	Commodities	766	632	4	6.3x	-60%
Oil: *1973-1986*	Commodities	1,005	1,612	7	2.8x	-73%
Nikkei: *1982-1992*	Equities	2,919	914	11	5.1x	-59%
Japan RE: *1982-1992*	Real Estate	2,894	940	11	6.5x	-74%
Polish equities: *1992-1995*	Equities	616	388	3	28.7x	-70%
DM Tech: *1995-2002*	Equities	1,365	721	6	7.9x	-78%
US RE: *2000-2009*	Real Estate	2,595	783	9	2.9x	-73%
Saudi equities: *2003-2007*	Equities	1,514	342	5	8.5x	-66%
US Financials: *2002-2009*	Equities	1,604	738	6	1.9x	-78%
Gold: *2002-2015*	Commodities	3,534	1,578	14	6.8x	-44%
Japan RE: *2003-2009*	Real Estate	1,425	767	6	5.9x	-76%
Copper: *2004-2008*	Commodities	1,151	127	4	4.1x	-66%
Uranium: *2005-2010*	Commodities	911	1,005	5	6.6x	-70%
Oil: *2006-2008*	Commodities	660	128	2	2.5x	-69%
China A shares: *2005-2008*	Equities	685	381	3	6.7x	-71%
Bitcoin: *2014 - present*	FX	512	21	1	43.2x	-44%
AVERAGE	**N/A**	**1,443**	**656**	**6**	**11.4x**	**-71%**

Source: Bloomberg, Federal Reserve Bank of St Louis, Yale School of Management – International Centre for Finance; as of 24 January 2018. Tulipmania data collated from primary sources collated by A Maurits van der Veen in the The Dutch Tulip Mania: The Social Foundations of a Financial Bubble. This dataset is sporadic and inconsistent – we have taken a 20 year price moving average in order to smooth the data, and focussed only on the period at the centre of the bubble, due to data availability and quality. The periods selected are exceptional and the results do not reflect typical performance. The start and end dates of such events are subjective and different sources may suggest different date ranges, leading to different performance figures.

https://www.man.com/insights/a-brief-history-of-bubbles

NUCLEAR POWER

In 2024, U.S. utilities operated 94 nuclear reactors with a total net generating capacity of nearly 97 gigawatts, the largest commercial nuclear power generation fleet in the world.

The next three countries with the largest programs:

•France: 57 units, 63.0 GW

•China: 57 units, 55.3 GW

•Russia: 36 units, 28.6 GW

America's nuclear reactor fleet consists of 54 power plants, each of which has one to four operating units. Plant Vogtle in Georgia is the largest nuclear power plant with four reactors and a total generating capacity of around 4.5 GW. The R.E. Ginna plant in New York is the smallest nuclear power plant with its one 0.6-GW reactor.

Twelve U.S. nuclear power reactors have permanently closed since 2013. However, plant operators have maintained consistently high annual capacity factors, which measure how much time units are operating. U.S. nuclear capacity factors have increased in part because of shorter refueling and maintenance outages and improved operational experience.

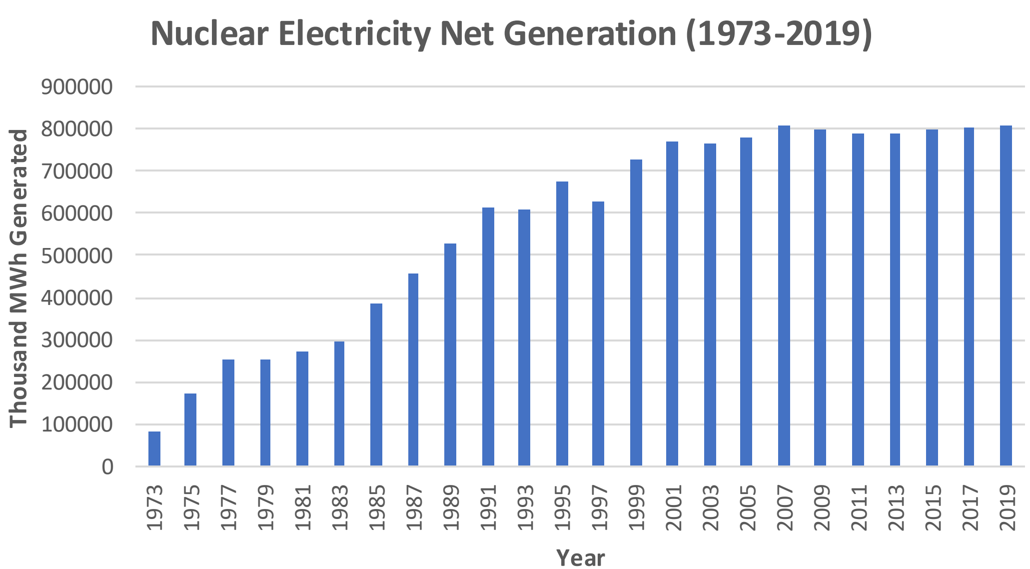
NUCLEAR GENERATION

Corporate Strategy:

- Production of electricity using nuclear power plants

Business Strategy:

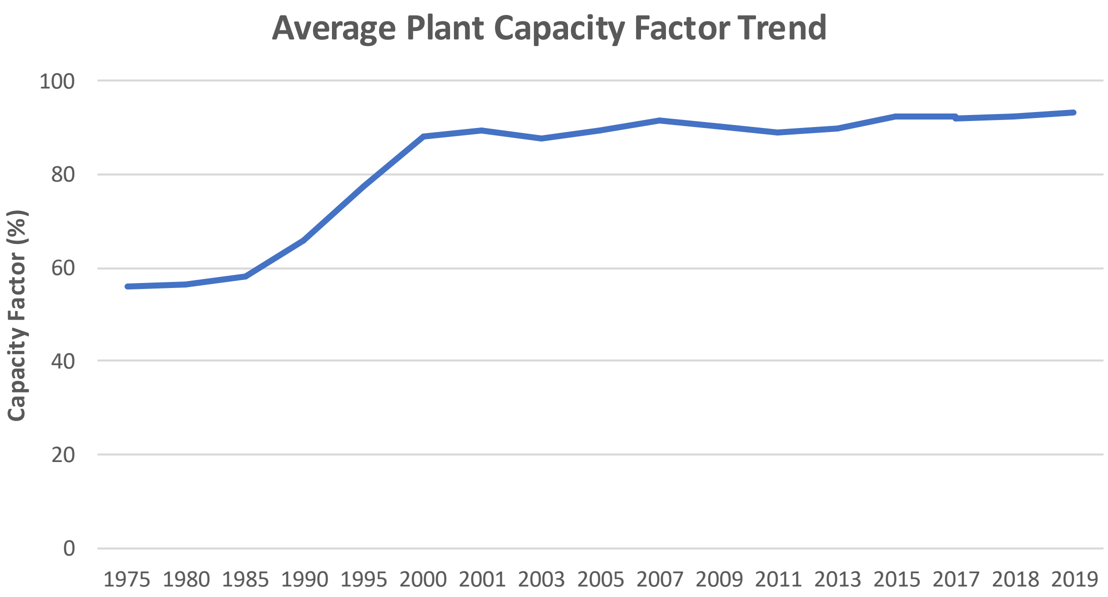
- Mark capital down to market
- Economies of scale
- Improved utilization (2007 capacity factor: 91.8%)
- Low production costs (2007: 1.68 cents/kWh)
- Increase capacity through uprates
- Roughly 5,200MW of uprates have occurred since 1977 and another 2,900MW have been proposed



Source: EIA- *May 2020 Monthly Energy Review*

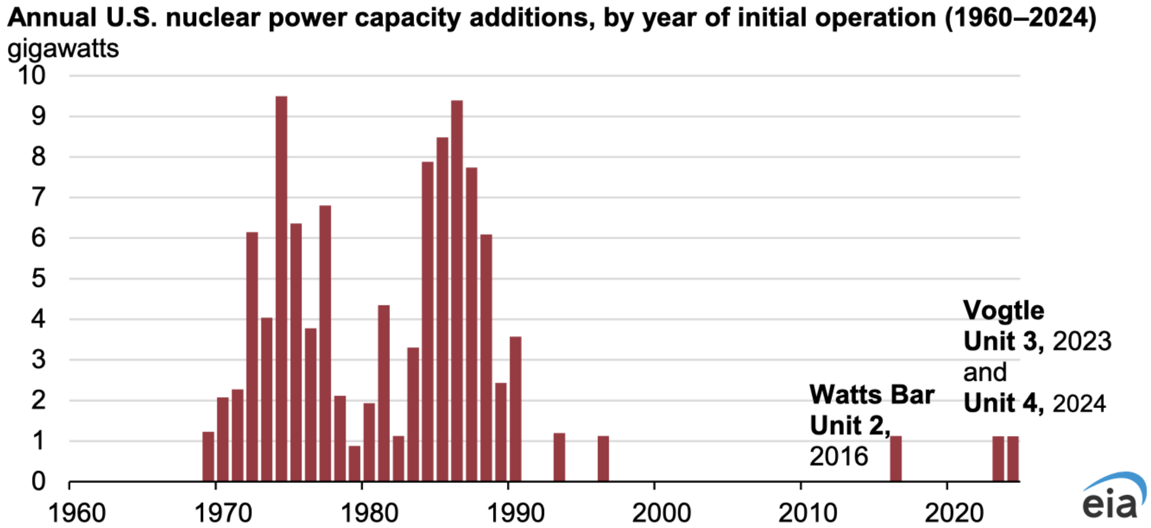
NUCLEAR GENERATION

- Life extension (license extension of 20 years) to amortize capital
- Large, existing utilities that already own and operate nuclear power plants
- The Energy Policy Act (EPA) of 2005 provides incentives for the construction of new nuclear power plants
- State incentives (ZECs: Zero Emission Credits)



Source: EIA- *May 2020 Monthly Energy Review*

NUCLEAR GENERATION



https://www.eia.gov/todayinenergy/detail.php?id=61963, May 1, 2024

Data source: U.S. Energy Information Administration, *Annual Electric Generator Report*

United States Government, Brookfield and Cameco Announce Transformational Partnership to Deliver Long-term Value Using Westinghouse Nuclear Reactor Technology

OCT 28, 2025

At least $80 billion to construct new Westinghouse nuclear power reactors

Partnership will accelerate nuclear power and artificial intelligence deployment in America

https://bam.brookfield.com/press-releases/united-states-government-brookfield-and-cameco-announce-transformational-partnership

NON-NUCLEAR GENERATION

Corporate Strategy:

- Production of electricity

Business Strategy

- Large market share (i.e., market power)
- Develop new projects at existing and/or new sites
- Load pocket
- To diversify or not to diversify: geography, fuel, baseload/intermediate/peaking
- Power marketing and trading
- Operational excellence
- Preparing for U.S. Environmental Protection Agency (EPA) regulations

LARGEST US RENEWABLE DEVELOPERS, MW

Rank	Companies	Installed Renewable Capacity	Established in	Headquarters
1	NextEra Energy	38000 MW	1925	Juno Beach, Florida
2	Constellation Energy	32400 MW	1816	Baltimore, Maryland
3	Invenergy	13800 MW	2001	Chicago, Illinois
4	Cypress Creek Renewables	12000 MW	2014	Durham, North Carolina
5	Duke Energy	11900 MW	1904	Charlotte, North Carolina
6	Recurrent Energy	11000 MW	2011	Austin, Texas
7	Clearway Energy	9000 MW	2018	San Francisco, California
8	Brookfield Renewable US	8922 MW (US capacity)	2011	New York City
9	Vistra Energy Corp.	7800 MW	2016	Irving, Texas
10	Arevon Energy	4500 MW	2017	Scottsdale, Arizona

https://www.blackridgeresearch.com/blog/latest-list-top-biggest-largest-renewable-energy-companies-in-the-us-united-states/

LARGEST US RENEWABLES BY MARKET CAP, 2024

Company	**Market Capitalization ($ Billions)**
NextEra Energy	$145
GE Vernova	$115
First Solar	$20
Nextracker	$6.3
Bloom Energy	$5.9
Clearway Energy	$5.1
Brookfield Renewable US	$4.6
Ormat Technologies	$4
Sunrun	$2.1
Fluence Energy	$1.3

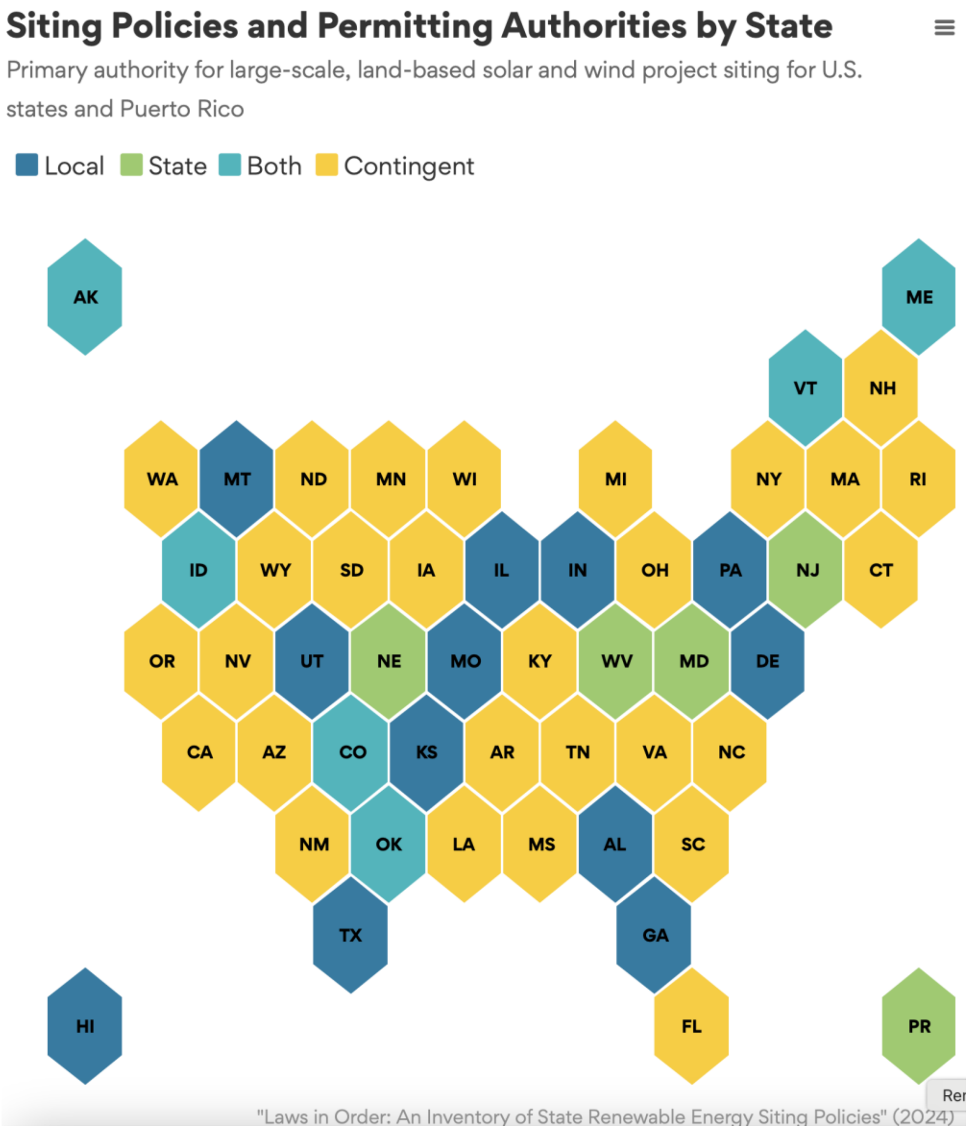
https://www.maximaconsulting.com/newsroom/top-renewable-energy-companies-in-the-usa-by-market-cap-in-2024

RENEWABLE DEVELOPER CORE FUNCTIONS

- Site evaluation and selection
- Land acquisition and permitting
- Project feasibility analysis
- Investor engagement
- Community outreach and engagement
- Technology selection and optimization
- Supply chain management
- Grid integration and interconnection
- Marketing and branding
- Public advocacy

RENEWABLE SITE EVALUATION & SELECTION

- Community priorities
- Job creation
- Permitting requirements
- Tax revenues
- Environmental impacts
- Resource and transmission availability
- Project economics: land and labor costs
- Traffic and noise



https://www.energy.gov/eere/siting-large-scale-renewable-energy-projects

OUTSTANDING WHOLESALE MARKET ISSUES

- Investment in a partially regulated and market-based system
  - Clean energy resources whose out-of-market revenue streams are increasing
  - Building large amounts of transmission

- Increasing the amounts of renewables

- Accounting for severe weather

- Addressing seams issues between electricity markets such as inefficient intertie transactions

- Development of offshore wind and their related transmission investments

OVERVIEW OF RISK MANAGEMENT AND STRATEGY

Topics

- Forecasting
- Risk management
- Business strategies

Key Questions

- What are the different types of forecasting techniques?
- Why is risk management so important in electric power systems?
- What is meant by the statement that natural gas is typically the marginal fuel for electricity production?
- What are the different strategies pursued in each portion of the electric power supply chain?
- How does cost-of-service regulation result in rates?

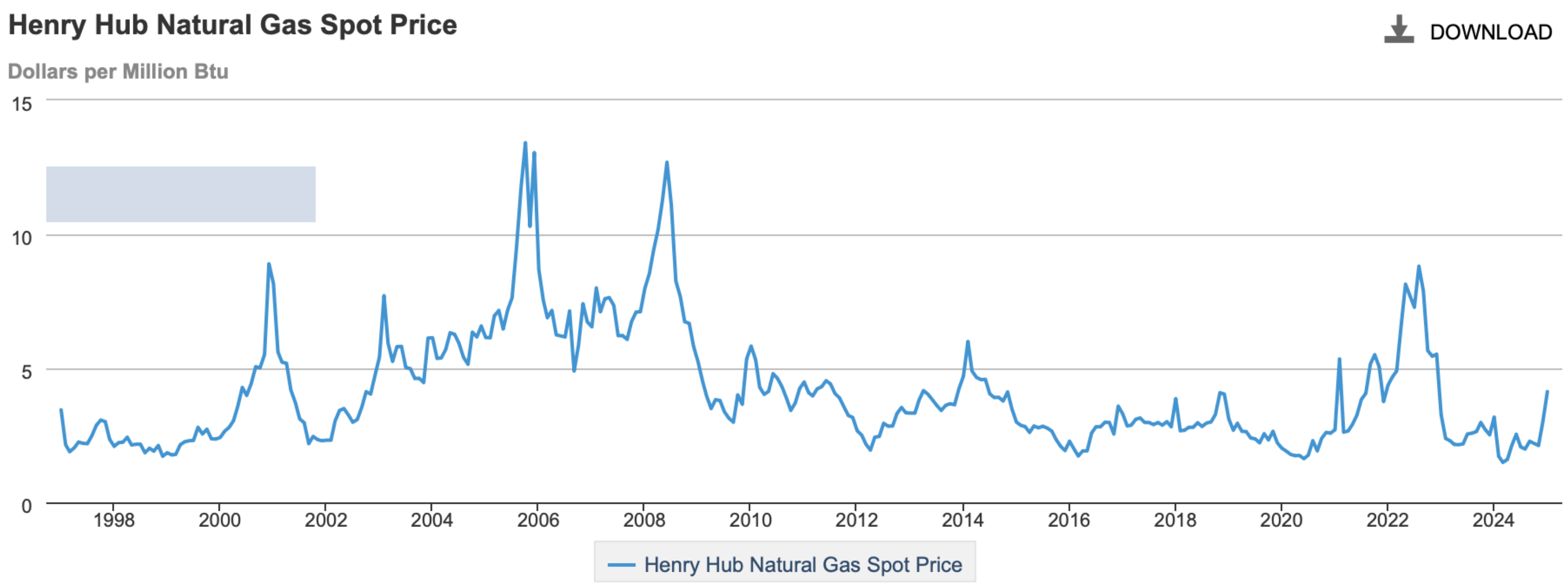
IMPORTANCE OF RISK MANAGEMENT

Electricity Prices are the most volatile energy prices

- Volatility is the percentage change in prices over a specified time period

Causes of electricity price volatility:

- Volatility of input fuels, e.g., natural gas (frequently the marginal fuel)
- Large random fluctuations in demand
  - Short-term: weather
  - Long-term: economic growth
- Storage is extremely expensive and limited
- Random outages of generation and transmission facilities
- Congestion
- Small amounts of price-responsive load



https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm

PURPOSE OF FORECASTING

- Forecast future prices (create a forward curve), e.g., what is the price of electricity in 30 years when current PPA's end?

- Forecast ranges of future prices

- Two types of forecasting:

  Technical - assumes that pricing patterns in the past will repeat themselves leveraging off the daily, weekly and seasonal patterns associated with electricity demand

  Fundamentals - using fundamental market relationships to estimate future prices and used, for example, by ISOs in their day-ahead markets

- "The forecast is always wrong." Fred Schweppe

Modeling Prices in Competitive Electricity Markets, ed. Derek W. Bunn, Wiley 2004.

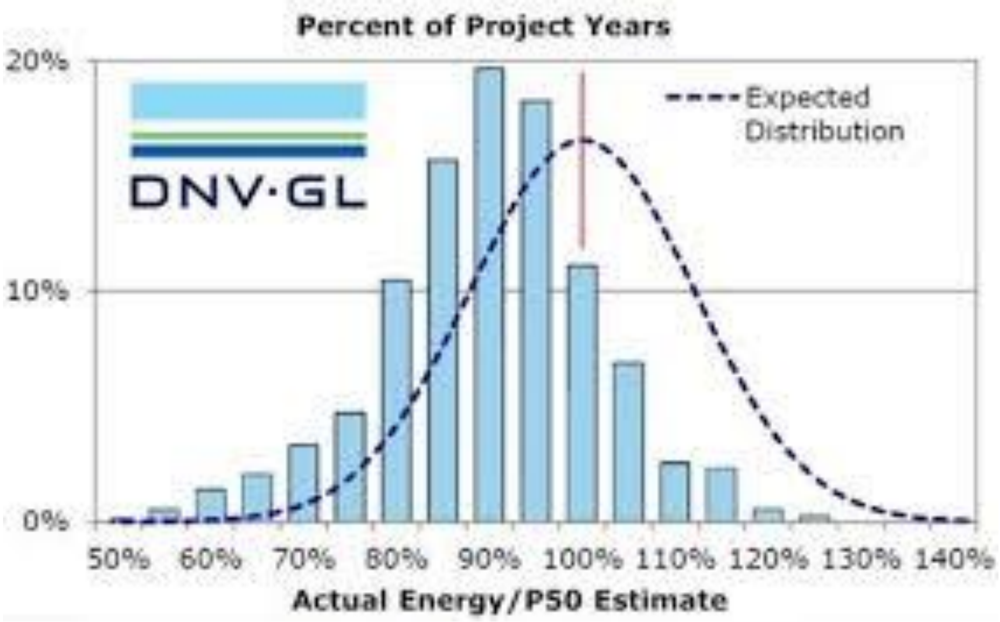
"Accounting for Extreme Values in GARCH Forecasts of Day-Ahead Electricity Prices", H. Guirguis and F. Felder, *KIEE International Transactions on Power Engineering*, Vol. 5-A, No. 3, September 2005, pp. 300-302.

"Further Advances in Forecasting Day-Ahead Electricity Prices Using Time Series Models", H. Guirguis and F. Felder, *KIEE International Transactions on Power Engineering*, Vol. 4-A, No. 3, September 2004, pp. 159-166.

FORECASTING AND PROBABILITIES

- P90 means that there is a 90% chance the energy production or energy demand will be equal to or exceed the projected P90 value over the system's lifetime based on an average annual power generation or demand.

- For example, a P90 value of 10 MWh would mean that the energy system would have to generate 10 MWh 90% or more of the time.



FUNDAMENTAL FORECASTING

- At its core, this type of forecasting assesses future supply and demand conditions and from that assessment forecasts future electricity prices based on the intersection of supply and demand

- Can range from simple to extremely complex modeling

- Determine the sophistication of supply-demand analysis (a tradeoff of time/money and accuracy)

- Determining where supply and demand intersect

  Relative changes from history

  Dispatch, unit commitment and capacity expansion models

    - Generation constraints
    - Generation outages
    - Transmission constraints
    - Transmission outages
    - Load forecasts

COMPARISON OF FORECASTING APPROACHES

Technical

- Relatively inexpensive
- Require historical data
- May require advance mathematical models that are difficult for non-experts to understand
- Do not provide intuition or predictions when structural changes occur

Fundamental

- Provide intuition
- Can be used when structural changes occur in the market
- Can be expensive and data intensive
- Assume perfectly competitive conditions for large-scale and detailed models

Typically, firms pursue both approaches, tailored to the problem at hand

RISK MANAGEMENT INSTRUMENTS

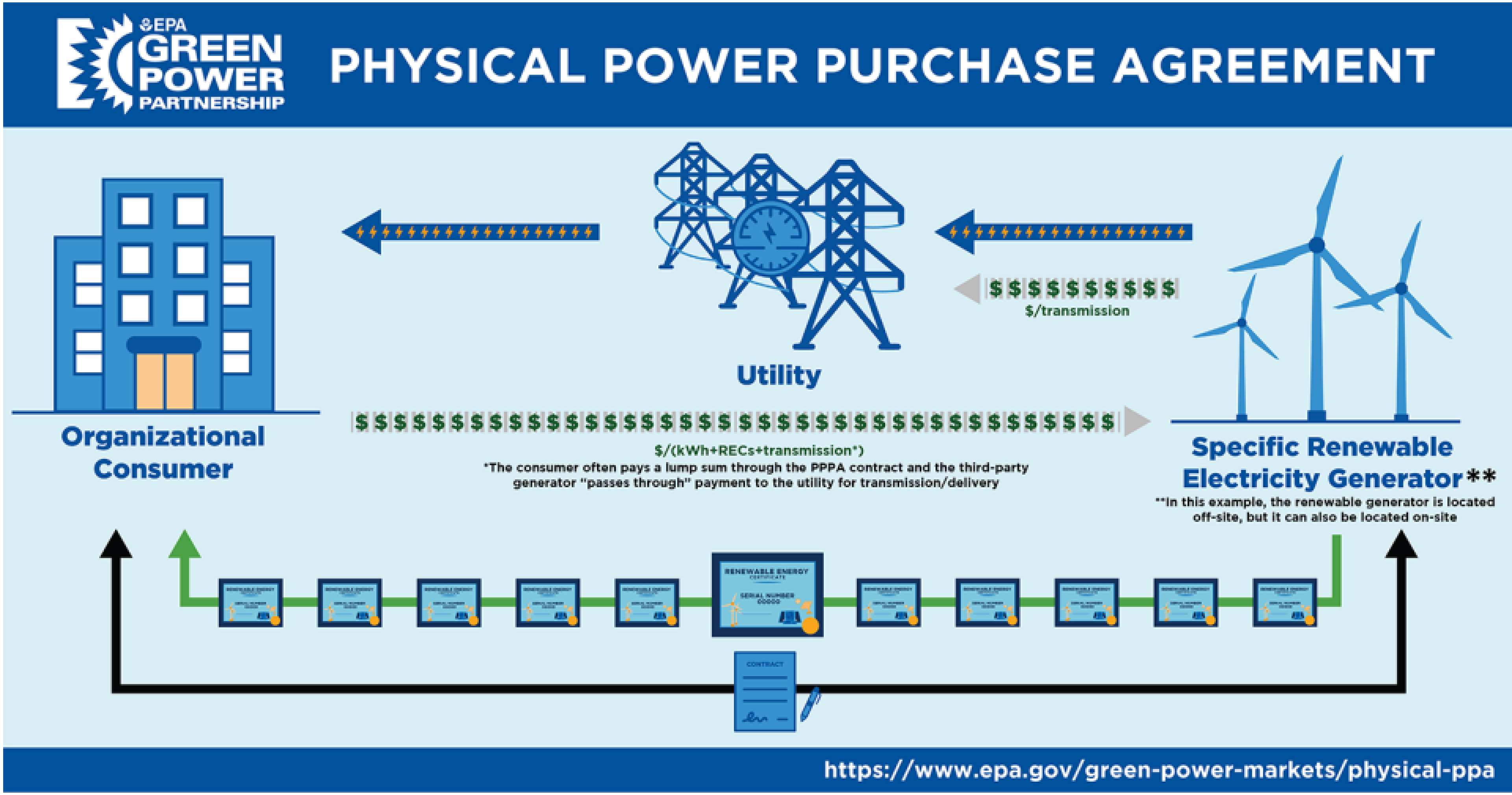
- Futures contracts: a standardized contract with specific terms and conditions that is bought and sold on an organized exchange; the exchange assumes the credit risk of non-performance by either party
- Bilateral (forward) contract, e.g., power purchase agreements
- Options, swaps and other types of derivatives
- Physical assets
  Remember, a new physical asset changes the underlying market whereas a financial instrument does not
- Can hedge price or some factor that affects price, e.g., weather (e.g., degree day), generation unit performance, fuel price, price differences (e.g., spark spread)….

POWER PURCHASE AGREEMENTS (PPAs)

- PPA is a contract for the purchase of power from a specific power plant
- If the generator is renewable, the PPA includes the purchase of the associated renewable energy credits (RECs)
- Typically, 10-30-year agreements that define all the commercial terms for the sale of electricity including start of commercial operation, delivery schedule, penalties, payment terms, and termination
- PPA seller agrees to build, maintain, and operate the power plant
- Price is set over the term of the PPA but may include a price escalator
- At the end of the PPA, a new agreement may be sign or the plant sold to the PPA buyer
- Financial PPAs, aka's "virtual" or "synthetic" PPAs, are a hedge that offers buyers cost predictability

https://www.epa.gov/green-power-markets/physical-ppa

POWER PURCHASE AGREEMENTS (PPAs)

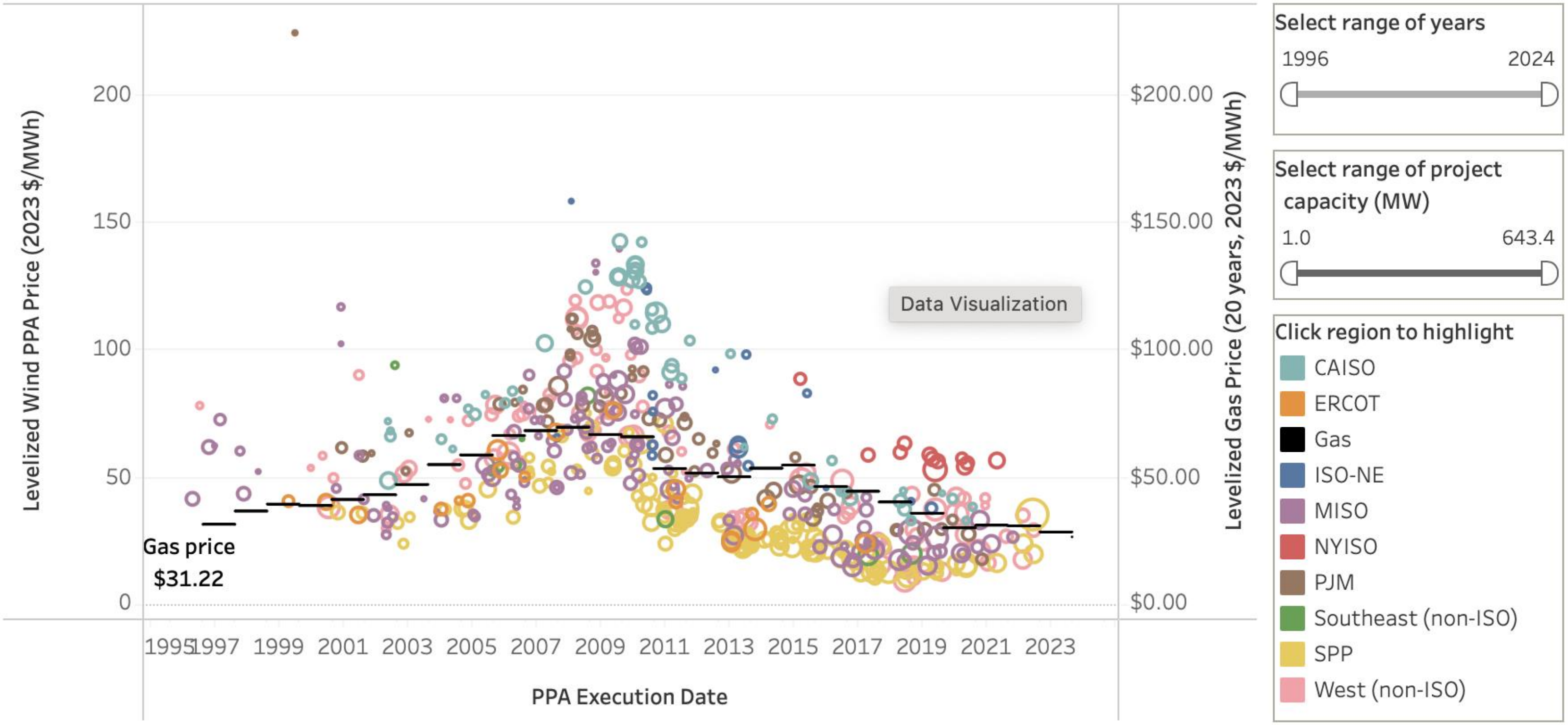


https://www.epa.gov/green-power-markets/physical-ppa

Wind Power Purchase Agreement (PPA) Prices

Land-Based Wind Market Report: 2024 (WindReport.lbl.gov)

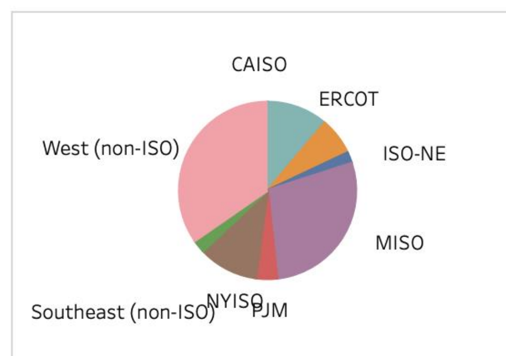
BERKELEY LAB



- Click on the region in the legend or pie chart to show projects by region.
- Use sliders to filter by project capacity (MW) and contract date.
- Circle size indicates project size (MW).
- PPA prices include the effect of any state and federal incentives, including the federal Production Tax Credit

Share of MW by region

Click region to see projects only from that region.
Click again to reset.



For more information on US wind energy from Berkeley Lab see the *Land Based Wind Market Report: 2024* at windreport.lbl.gov

ADDITIONAL RISK MANAGEMENT INSTRUMENTS

- Block energy
  Peak and off-peak blocks of energy at fixed prices and quantities used to inexpensively manage load variations
- Hourly shaped energy
  Purchase the energy based upon a forecasted load shape
- Spreads: Basis (location), Cross commodity, Cross time (calendar spreads)
- Options (following slides)
- Swaps/Contract for Differences (e.g., LMP for fixed payment)
- Tolling arrangements
  Similar to leasing a generating facility: one party pays the power plant owner a fixed fee for the right to dispatch the facility over a predetermined period

DERIVATIVES AND OPTIONS

- A Derivative is any financial instrument whose value derives from something else

- Companies use derivatives in the following ways (in order of frequency):

  Risk management/hedging
  Do not use
  Obtain financing
  Investment/trading

- Option: The right to buy (call)/sell (put) a commodity at (European)/before (American) a predetermined time (expiration date) at a specified (strike) price

  Options are a type of derivative

DERIVATIVES AND OPTIONS EXAMPLE

e.g., Call option to buy 50 MWh of electricity tomorrow at 12 noon at $100/MWh

Buyer pays the seller an agreed to price

If the electricity price tomorrow at noon is greater than $100/MWh the buyer of the option exercises the option at the strike price of $100/MWh

Otherwise, the option expires without being exercised

Factors that Determine the Value of a Call Option:

- Price volatility of the commodity
- Expiration date of the option
- Strike price
- Risk free interest rate

OTHER RISK RELATED DEFINITIONS

- Basis risk - is the risk that the value of a futures contract does not move in line with that of the underlying exposure

  e.g., locational basis risk

- Liquidity - the ability to get out of a position quickly without driving the price down if selling or up if buying

- VAR - is a statistically defined metric. It uses forecasting and simulation techniques to estimate the risk of a "worst possible scenario" over a single day. It calculates, as a single point in time, the maximum change in total portfolio value assuming the best and worst reasonably predictable market movements in the course of a single day at a 95% confidence interval

  Definitions and policies vary among companies

OTHER RISK RELATED DEFINITIONS

- Mark-to-market: An entity's risk exposure and therefore the amount of credit it has available is adjusted as the value of its position changes, usually daily
- Netting: A single payment/receipt occurs covering all transactions within a given time period
- ISOs have credit policies, and its members are liable for the default of other members

HEDGING ADVICE

- A hedging strategy can vary from a long-term fixed-rate contract to a fully staffed trading desk
- Electricity derivatives are less liquid than other energy derivatives
- Insurance is an option to consider
- Credit issues are part and parcel of any hedging strategy
- Crash test your hedging strategy

IF YOU DO NOT UNDERSTAND THE HEDGING INSTRUMENT, DO NOT USE IT

GENERATION STRATEGY

- Two fundamental strategic questions for the electric power industry:

  Corporate: Which part of the supply chain to compete in?

  Business: How to compete within that part of the supply chain?

- Many of the strategies that are discussed are not mutually exclusive

- A particular company's failure could be due to picking the wrong strategy, executing the correct strategy poorly, or bad luck

GENERATION STRATEGY

- Nuclear acquisitions, improved performance and construction
- Large market share through acquisitions, project development or both
- Location in load pockets (i.e., transmission constrained areas)
- Independent power producer (IPPs) vs. utility owned generation
- Multiple types of generation (fuel and type) vs. single type of generation
- Role of trading in generation strategy

TRANSMISSION

Regulated (cost-of-service) transmission owner

- Provide regulated transmission services with existing and new assets
- Achieve economies of scale via mergers
- May pursue performance or incentive-based rates to increase profitability
- Sole provider of regulated, backstopped transmission expansion services
- May or may not also be affiliated with generation and distribution companies

Merchant transmission provider

- Corporate Strategy: develop market-based projects in response to market conditions or regulatory needs for more transmission
- Business Strategy: build modular Direct Current (DC) facilities
  - Small footprint
  - Scalable
  - Small economies of scale

TRADING

- Traders buy stuff they have no intention of consuming or sell stuff they have no intention of producing (Note: Marketing is selling stuff you have)
  - Short selling – sell first and buy back later
- Supply liquidity to the market
  - Liquidity – ability to transact large volumes without incurring significant price movements, e.g., For buyers of large amounts of energy, a trader can arrange a transaction with minimal price increase
- Provide risk management services
- Trading Business Strategies
  - Trading without physical assets
  - National trader with assets
  - Regional trader affiliated with an Investor Owned Utility (IOU)
  - Retail middleman

See Frank A. Wolak, *Arbitrage, Risk Management, and Market Manipulation: What Do Energy Traders Do and When is it Illegal*, Stanford Univ.

RETAILERS

- Corporate Strategy: buy wholesale and sell to retail customers in states/regions that have retail access or retail competition

- Business Strategy
  - Can combine with other energy products such as natural gas
  - Use brand name developed in providing other energy services

- Some Key issues
  - Matching wholesale market position to retail market position
  - Marketing a product that up until now was never marketed

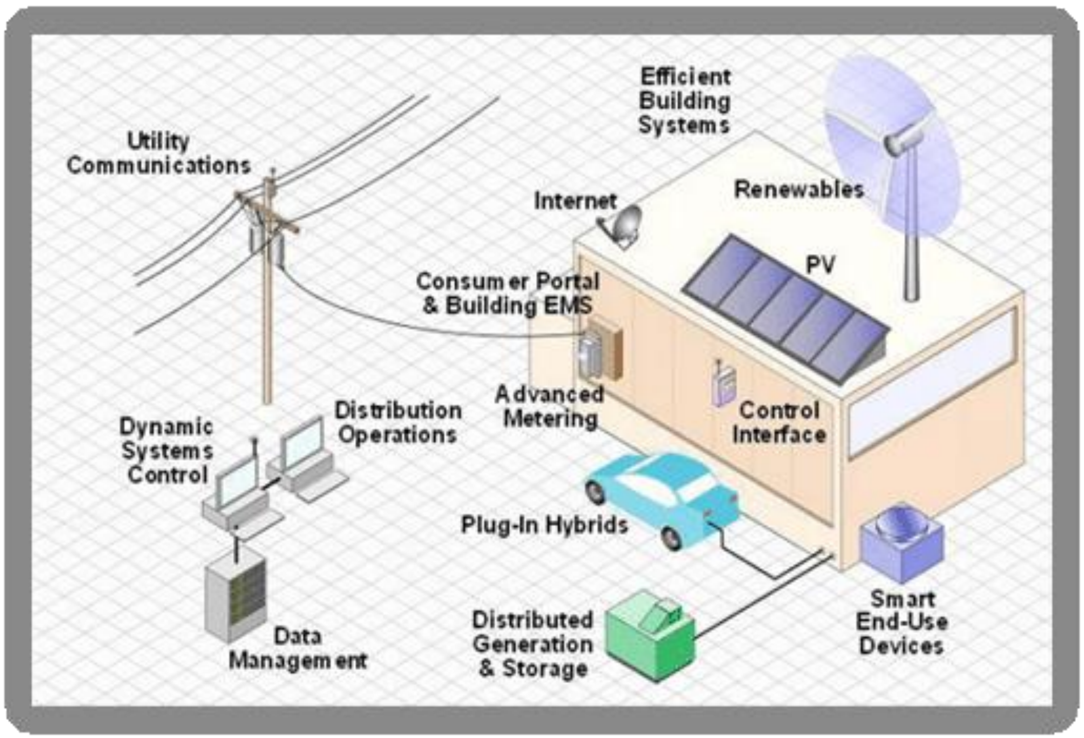
- Typical pricing offerings (See Mirant's offerings in Texas)
  - Fixed prices
  - Flexibility plans with no long-term contract
  - Green plans
  - Package plans with online services

- Margins are very thin

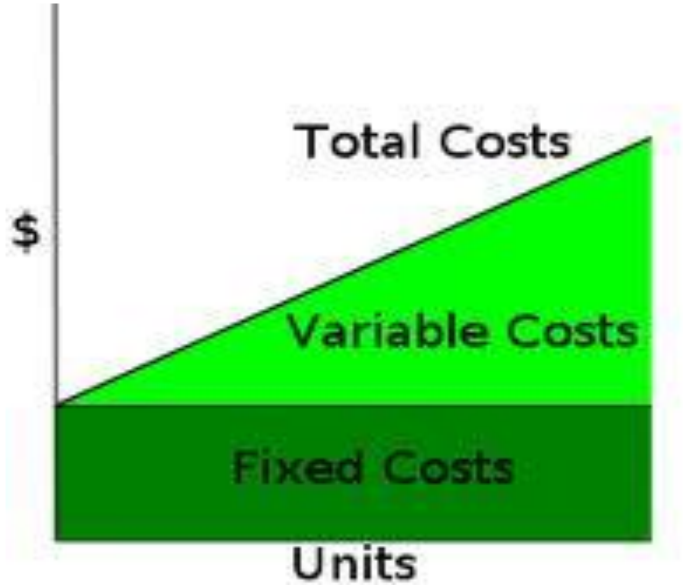
- Also referred to as Third Party Providers, Energy Service Companies (ESCo's), and Retail Aggregators

UTILITIES

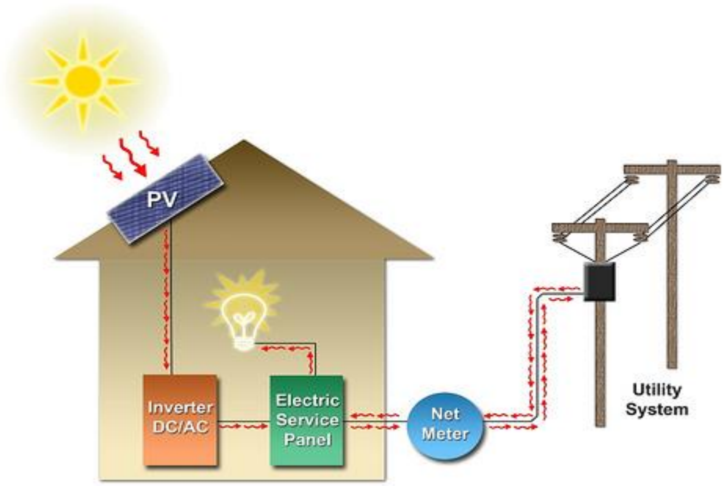
- Public power and IOUs are alive and well
- Despite the radical changes in the industry, many of these types of organizations have not had to fundamentally change their business models
- Smart grid investment

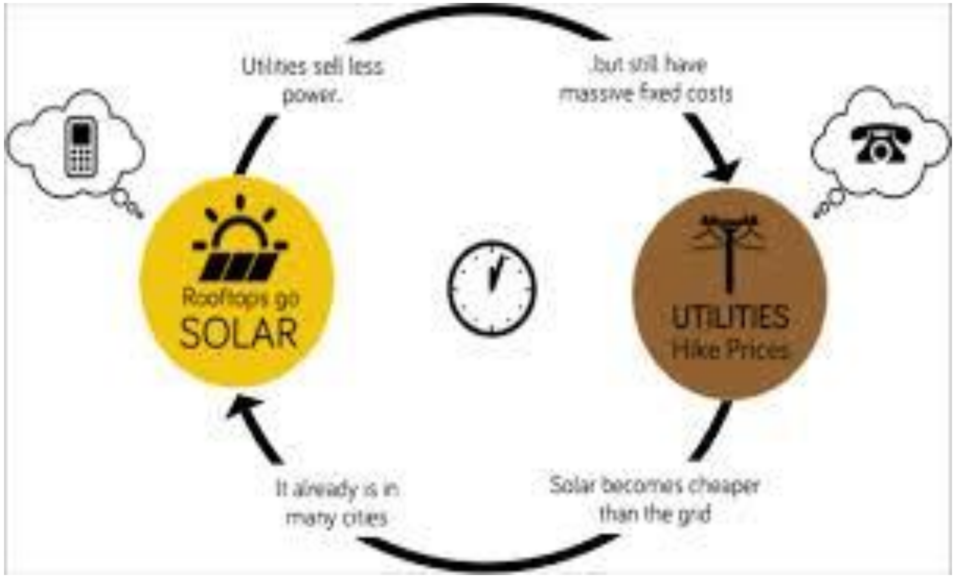


NET METERING & DEATH SPIRAL

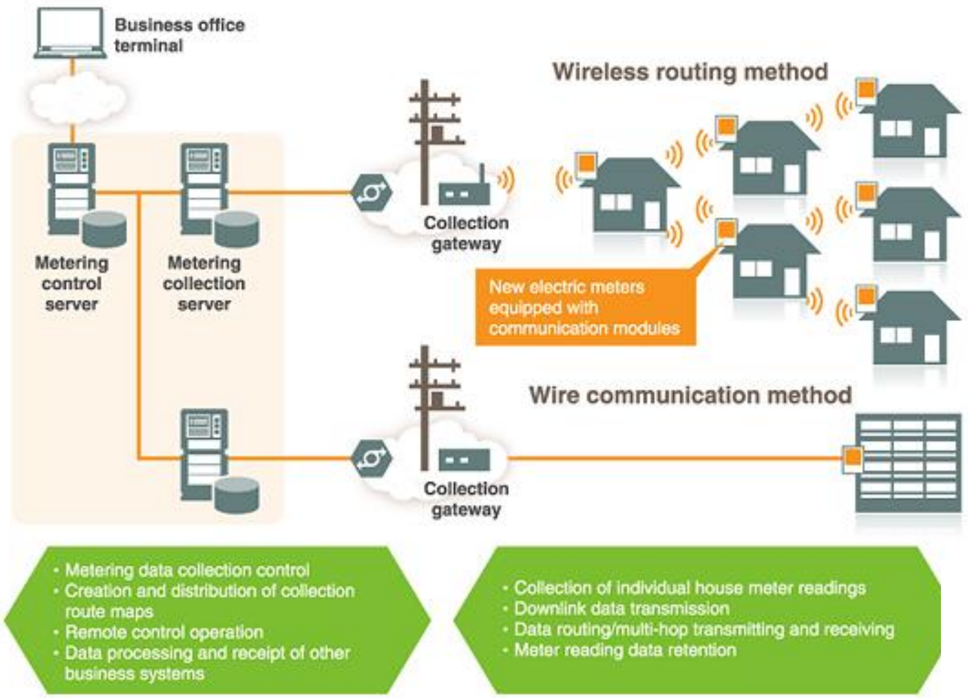


Rate = (Total Cost)/Quantity
= Average Cost





SMART GRID DISTRIBUTION SYSTEM



KNOWLEDGE SELF-CHECK

1. What is meant by out-of-market revenues and why is this important for generators?
2. What is economies of scale and what is its role in the development of electricity markets?
3. Describe the current U.S. federal and state regulatory and market structure.
4. How are RTOs/ISOs governed?
5. What are the current transmission challenges in the context of the energy transition?
6. What are different methods of forecasting electricity prices?
7. What are some ways to manage electricity price risk of generation assets?
8. What is the difference between marketing and trading?
9. What are the major challenges existing utilities are facing?
10. What is cost-service-ratemaking?

TERMINOLOGY AND ABBREVIATIONS CHECK

Revenue requirement

WACC

Ratebase

Economies of scale

FPA

NOPR

OATT

Order 888

Derivatives

Options

Net metering

COURSE WRAP UP

The industry and society still have not answered three key questions:

- What technological strategy should the industry pursue?
- How should the industry be structured between markets and economic regulation?
- What is the purpose of the electric power industry?

Please contact me at any time if you have questions, comments or want more information

THE END IS HERE

MORE INFORMATION

Key Legal References and Documents

Key FERC documents regarding electricity markets are available at http://www.ferc.gov/docs-filing/docs-filing.asp

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Steven Stoft, Power System Economics: Designing Markets for Electricity

Video of power plant tripping offline, https://www.youtube.com/watch?v=bdBB4byrZ6U

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Potomac Economics, ERCO, MISO, ISO-NE, NYISO, RGGI
Market Monitor, CAISO
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Conspiracy of Fools: A True Story, Kurt Eichenwald, 2005, Broadway Books (about Enron)

Electric Universe: The Shocking True Story of Electricity, David Bodanis, 2005, Crown Publishers

Electricity Restructuring in the United States: Markets and Policy from the 1978 Energy Act to the Present, Steve Isser, 2015, Cambridge University Press

Market Power and Market Manipulation in Energy Markets: From the California Crisis to the Present, Gary Taylor, Shaun Ledgerwood, Romkaew Broehm, and Peter Fox-Penner, 2015, Public Utilities Reports

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https://www.ethree.com/wp-content/uploads/2024/07/E3-White-Paper-2024-Load-Growth-Is-Here-to-Stay-but-Are-Data-Centers-2.pdf