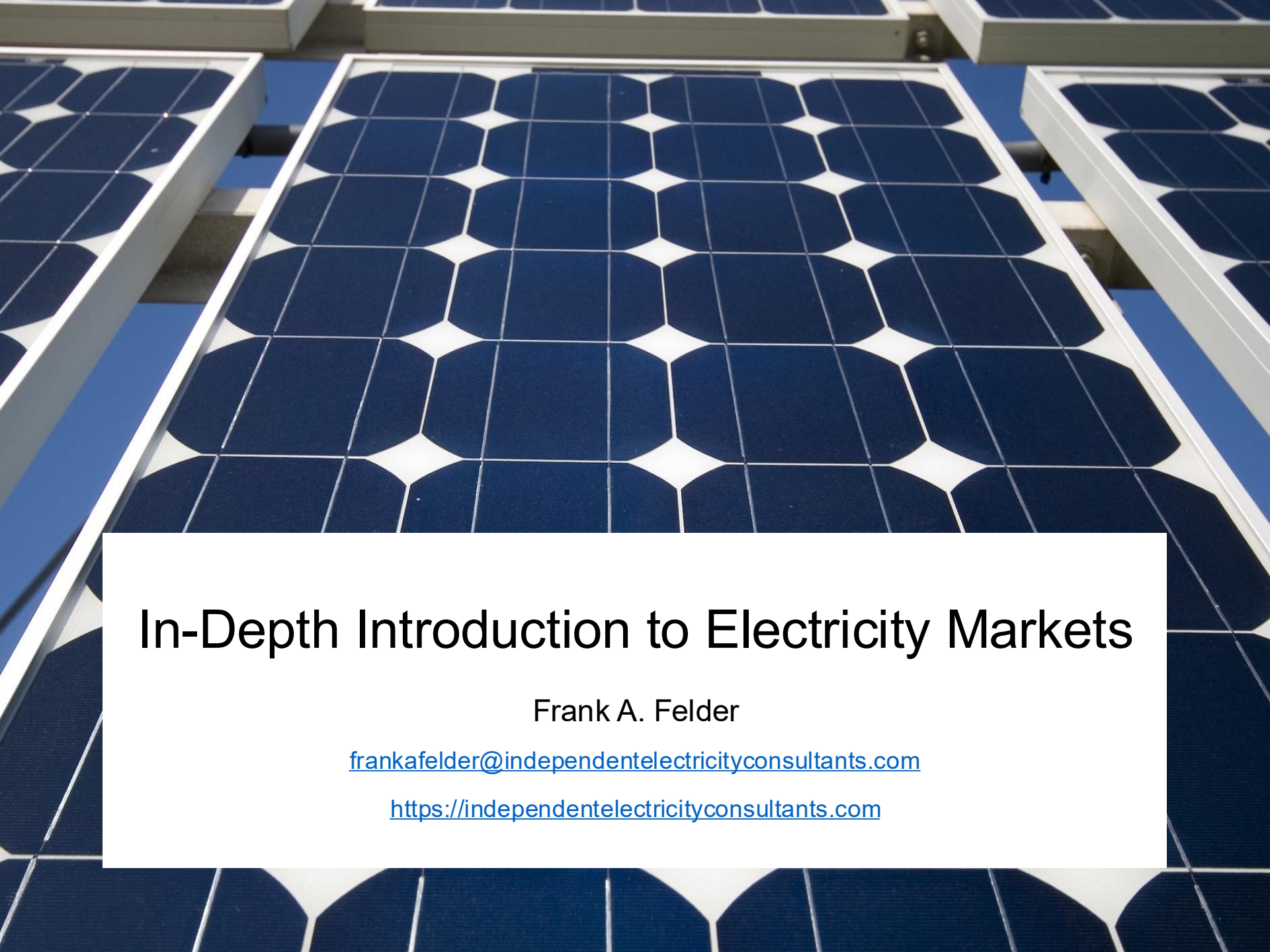


In-Depth Introduction to Electricity Markets

Frank A. Felder

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https://independentelectricityconsultants.com

November 2026 TRAINING – ALL VIRTUAL

- Nov. 10: What the Heck is Going on in PJM, 3-4 pm

- Nov. 11: Introduction to the Electricity Sector, 9:30-12:30
- Nov. 12: Power System Fundamentals, 9:30-12:30
- Nov. 18: Electricity Markets, 9:30-12:30
- Nov. 19: Political, Regulatory and Business Context, 9:30-12:30

- Nov. 19: U.S. Data Centers Politics, Policies, & Protests, 3:00-4:00
- Dec. 8: Developments in Energy Storage in U.S. Electricity Markets, 3:00-4:00

CONTACT ME anytime:
frankafelder@independentelectricityconsultants.com

2026 Training slides available at
https://www.independentelectricityconsultants.com/training-presentations

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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

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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

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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
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ADDITIONAL SESSION

Thursday, Nov. 19, 3-4 pm: U.S. Data Centers Politics, Policies, and Protests

Update on the politics, policies and protests revolving around data centers in the U.S. with a focus on the implications for electricity markets and generation development

40 minutes of presentation and 20 minutes of Q&A/discussion

CONTACT ME! in person and/or via email:

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Session 1
Introduction to the Electricity Sector

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IN THE NEWS

• LIVE Nov. 3 at 12:45pm ET

Data Centers, Electricity Prices on the Ballot, Too

By WSJ Staff



The Nscale data-center project in Barstow, Texas. ELI HARTMAN/BLOOMBERG NEWS

DIVE BRIEF

Retail electric rate increases outpace inflation with prices set to rise higher

Regulators approved 64% of the dollar value of revenue increase requests over the past five years, a Lawrence Berkeley National Lab report says.

Published July 16, 2026

By Brian Martucci

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https://www.utilitydive.com/news/retail-electric-rate-increases-outpace-inflation-with-prices-set-to-rise-hi/825391/

Big, noisy and coming to a town near you - why the data centre backlash is growing

25 October 2026

Share Save Add as preferred on Google

Daniel Thomas and **the Visual Journalism Team**

https://www.bbc.com/news/articles/cq2e9we7w2ejo

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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

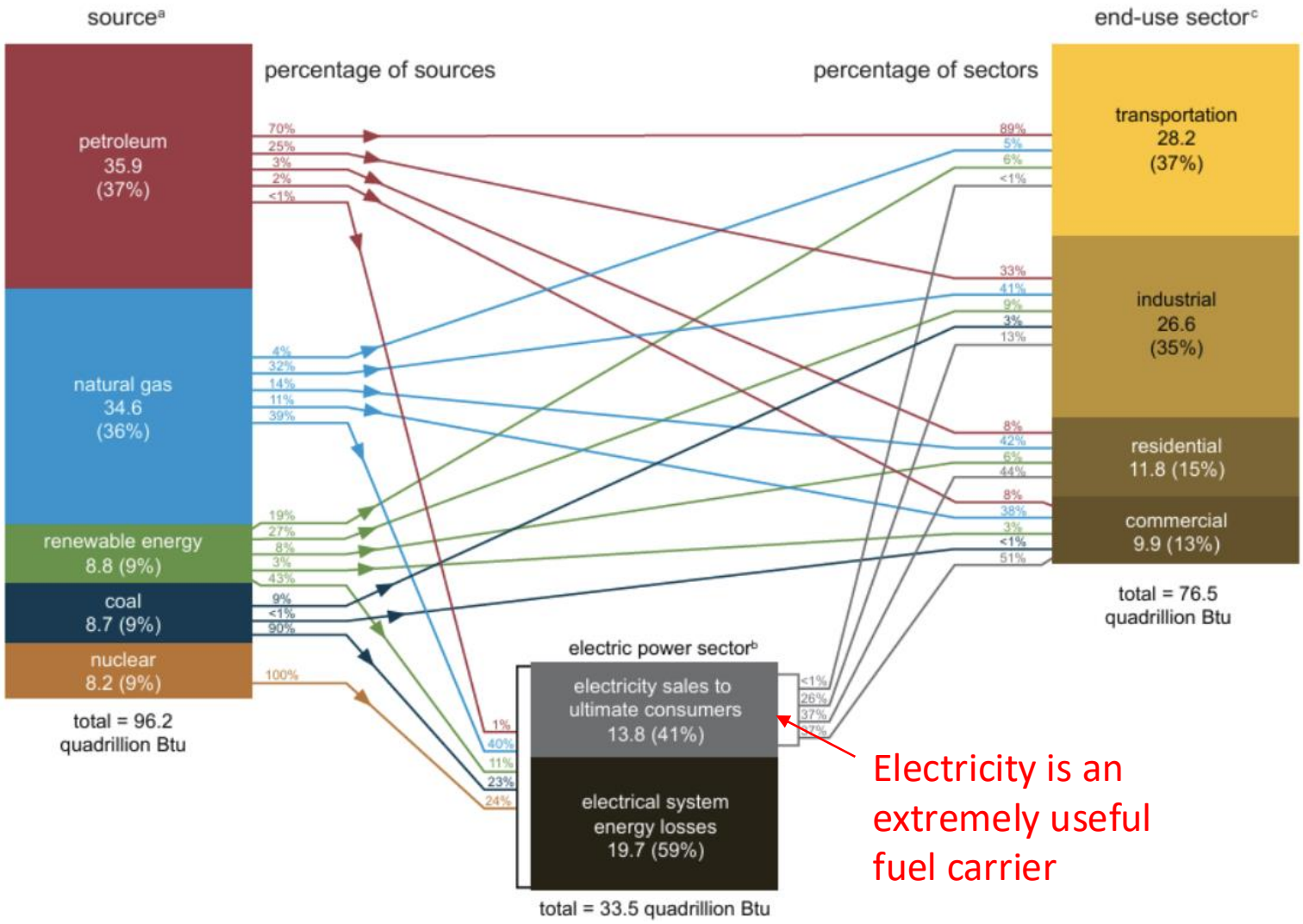
*Many slides include references and the final slides list additional ones

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U.S. energy consumption by source and sector, 2025

quadrillion British thermal units (Btu)



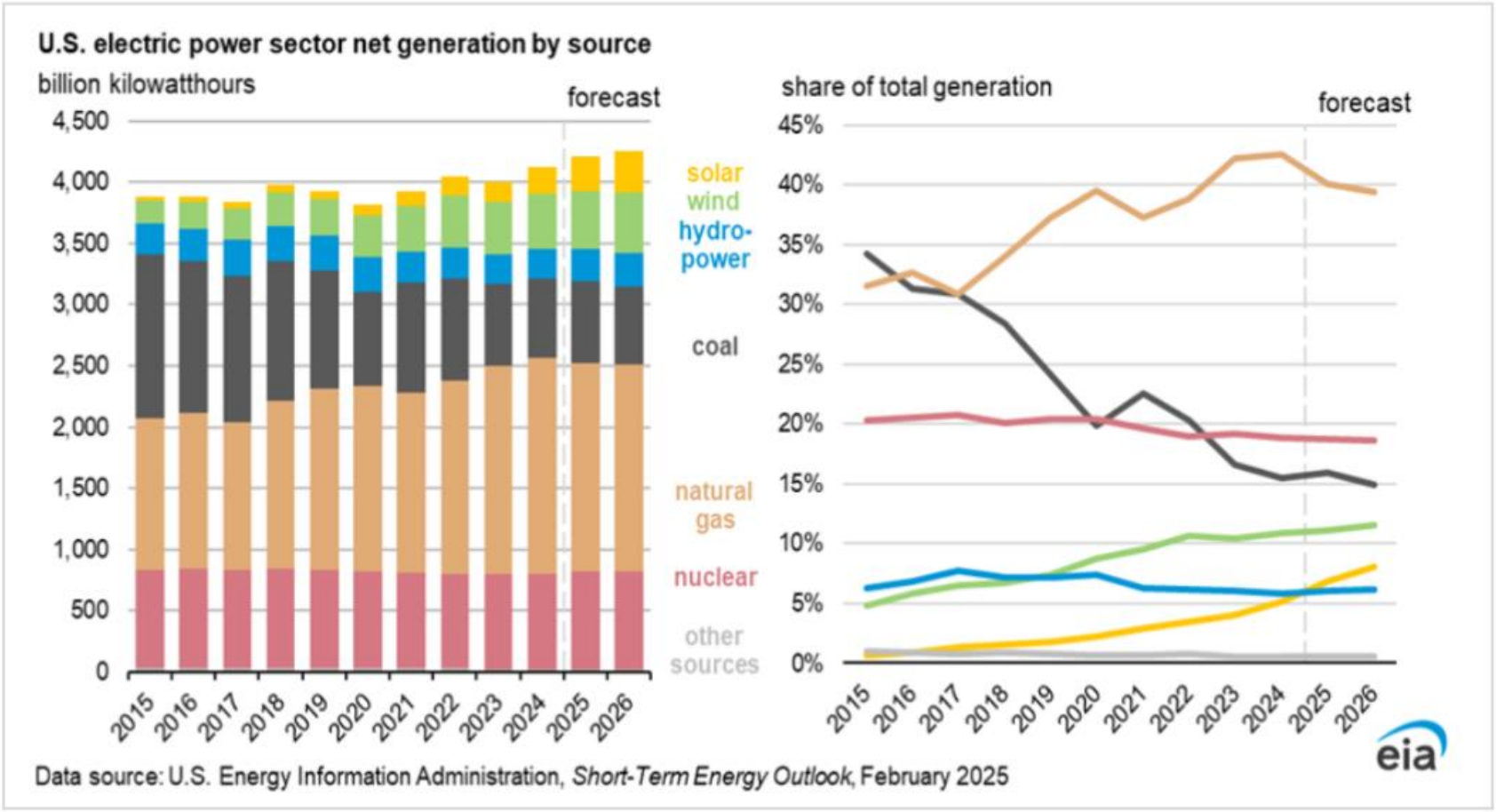
Electricity is an extremely useful fuel carrier

https://www.eia.gov/energyexplained/us-energy-facts/

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US ELECTRICITY GENERATION BY FUEL SOURCE



Natural gas is displacing coal

Wind & solar PV are increasing substantially

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

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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/

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SUPPLY CHAIN

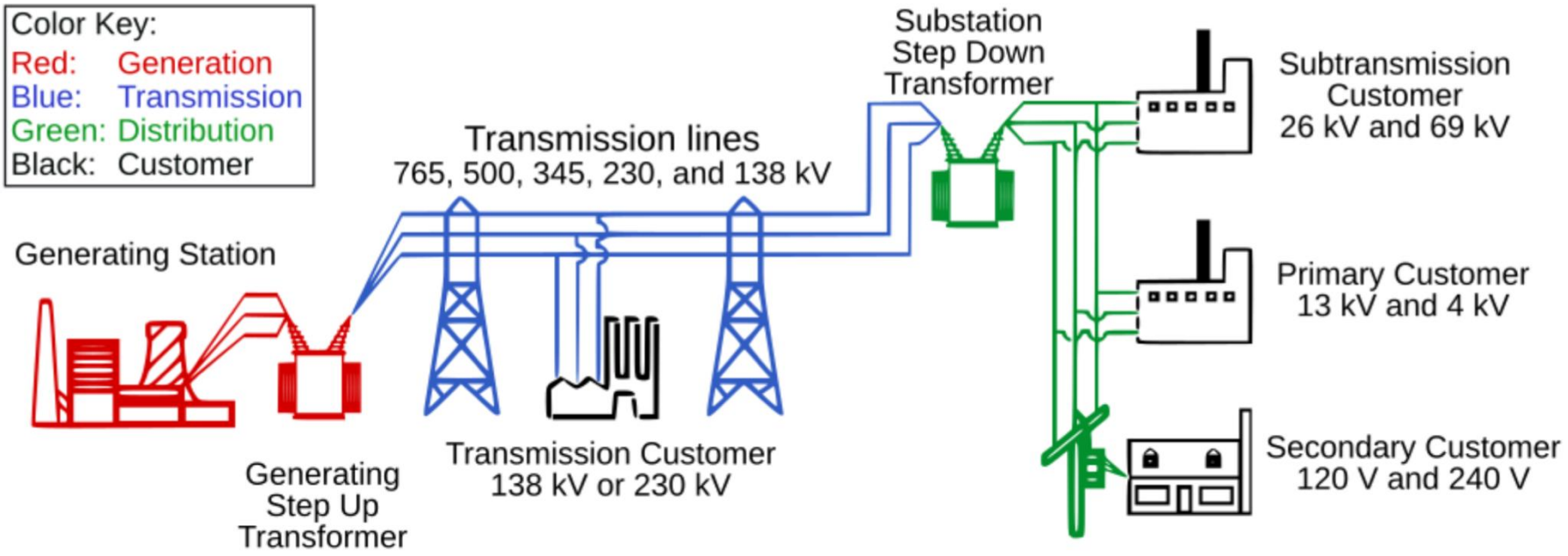


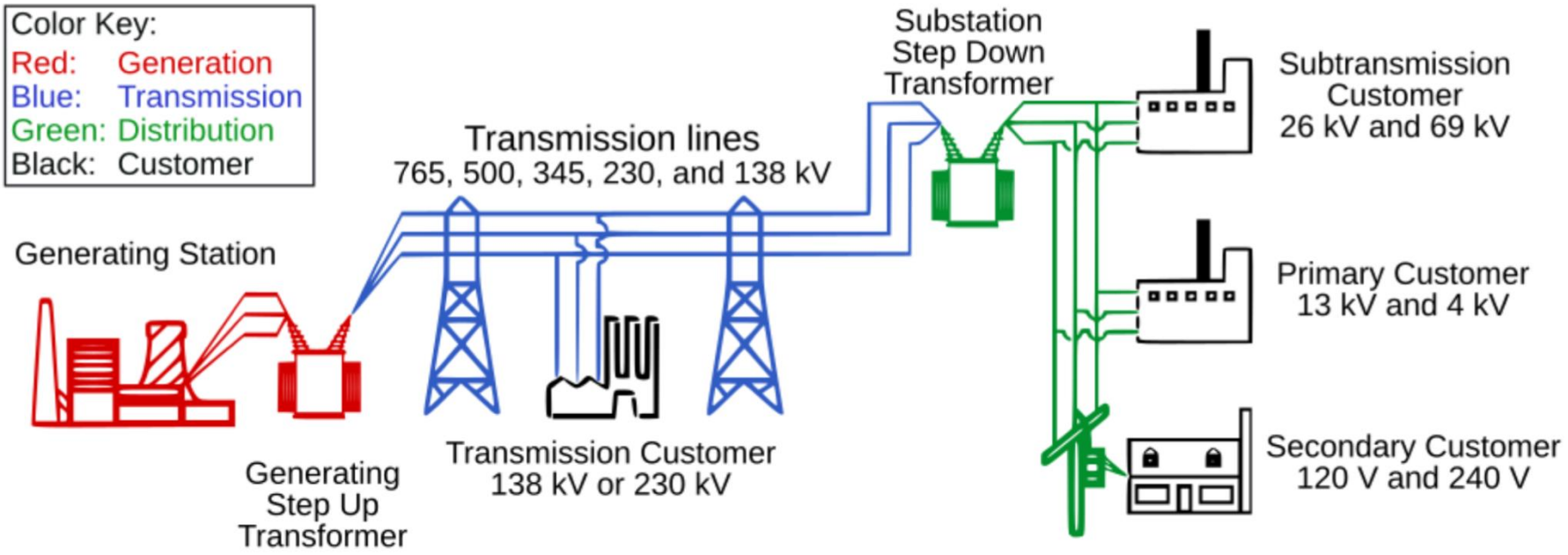
Figure from the U.S.-Canadian Power System Outage Task Force final report on the 2003 Blackout, p. 5.

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

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REGULATORY AND MARKET STRUCTURE



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

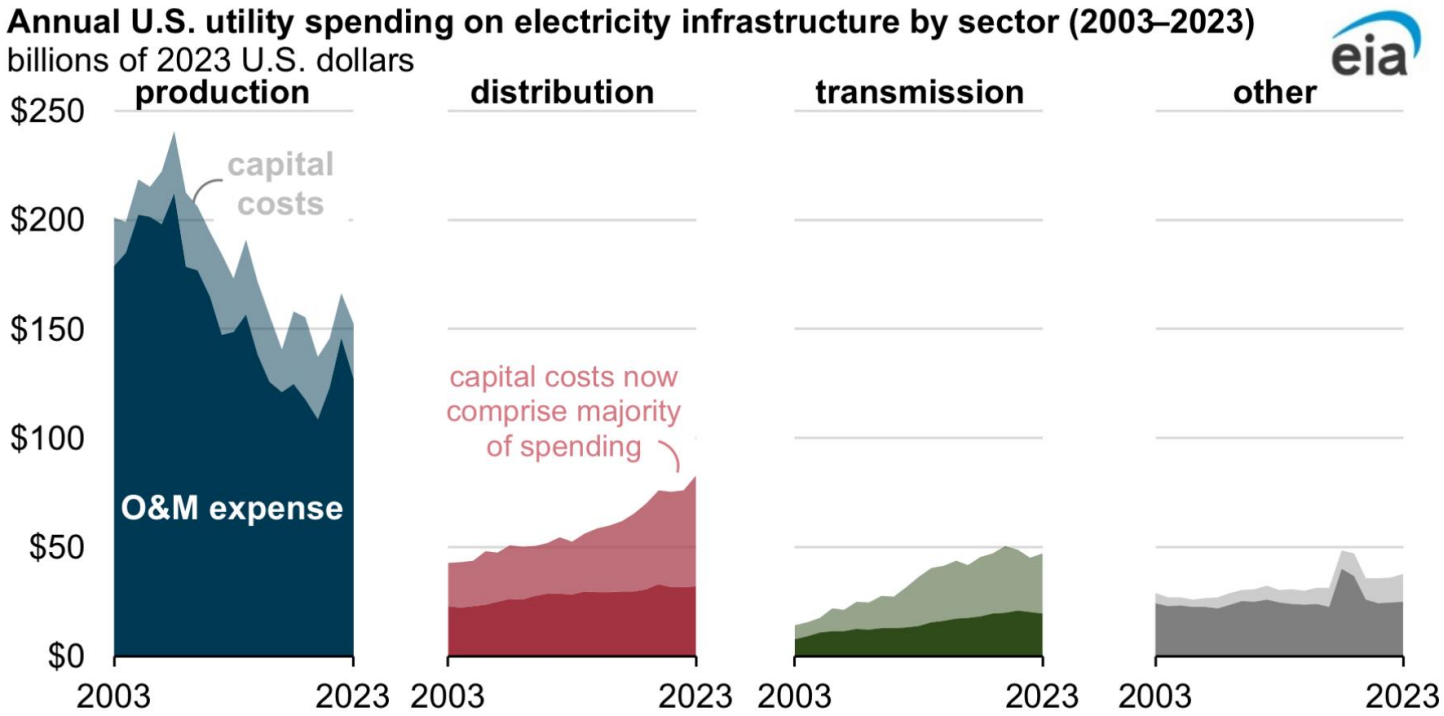
- **Generation – either market based or economically regulated (e.g., cost of service)**
- **Transmission – economically regulated**
- **Distribution – economically regulated**
- **Load – either market based (if there is a wholesale market) or economically regulated)**

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

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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.

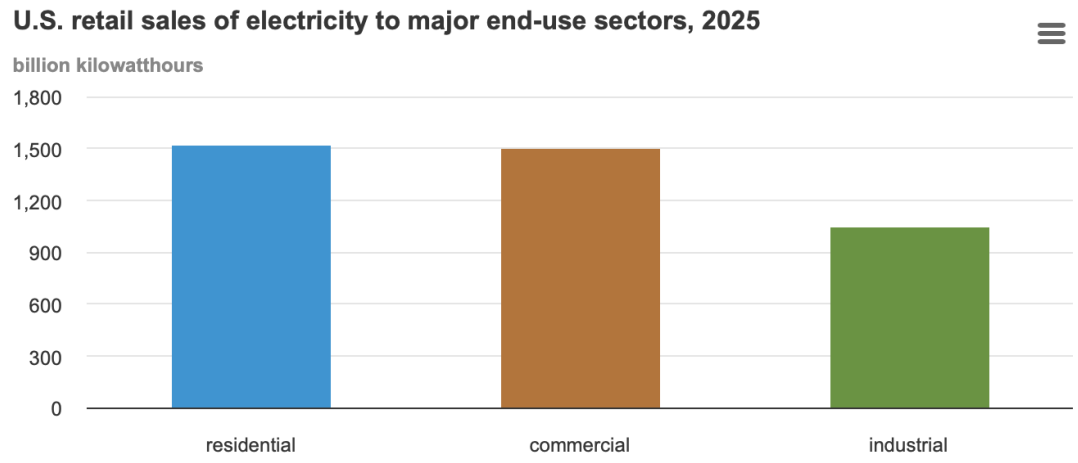
Published July 23, 2025

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

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U.S. ELECTRICITY SALES BY CUSTOMER CLASS

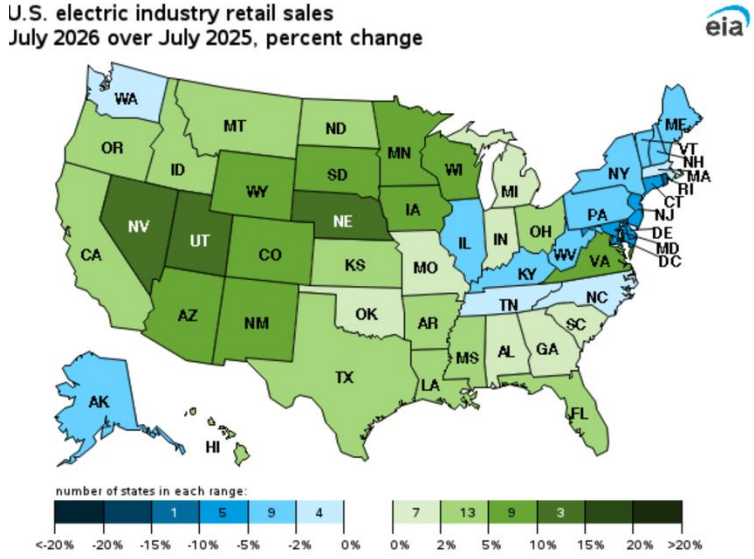


https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

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.



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

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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



Note: diagram not drawn to scale

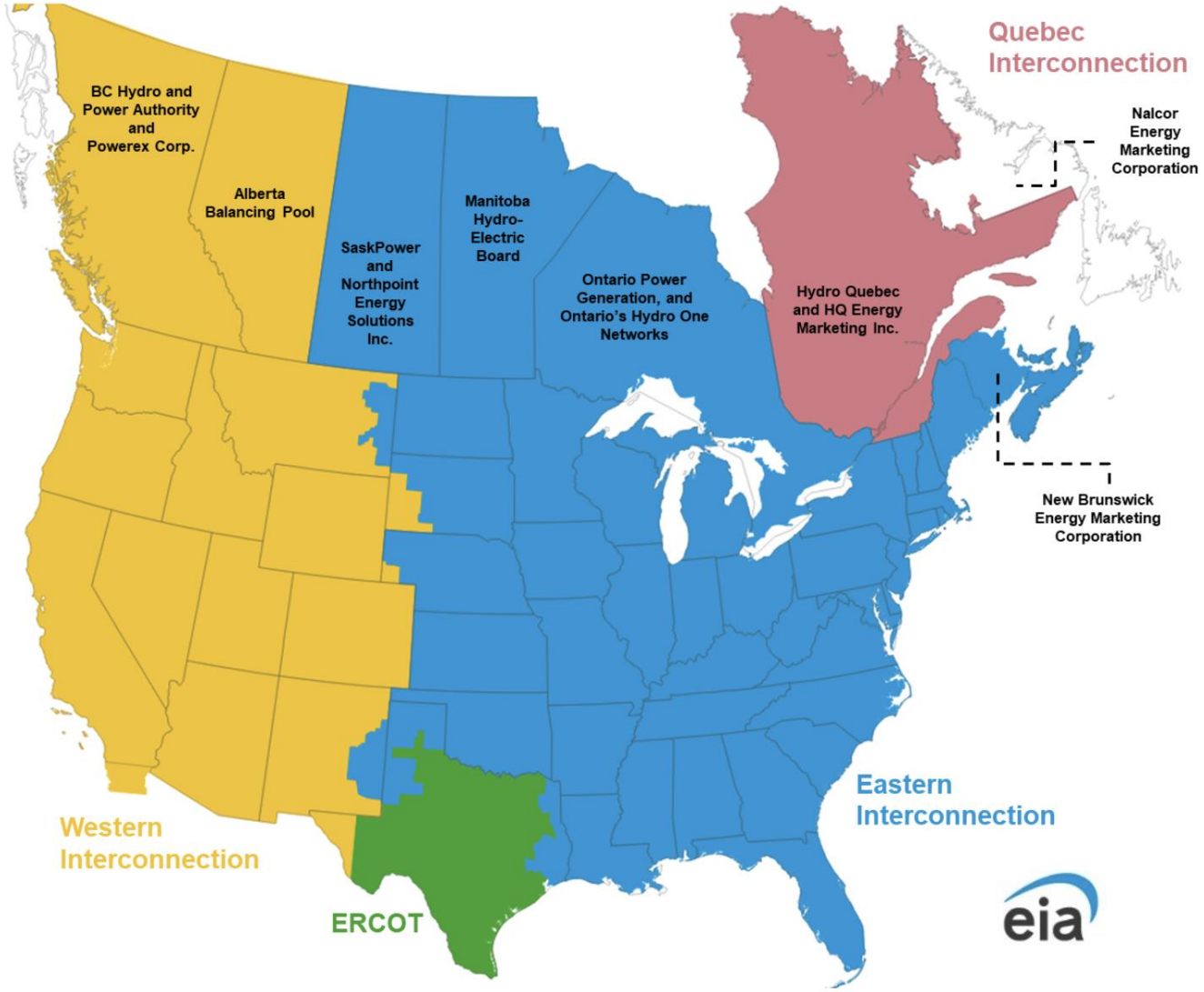
Electricity time scale covers fractions of a second to decades

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

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

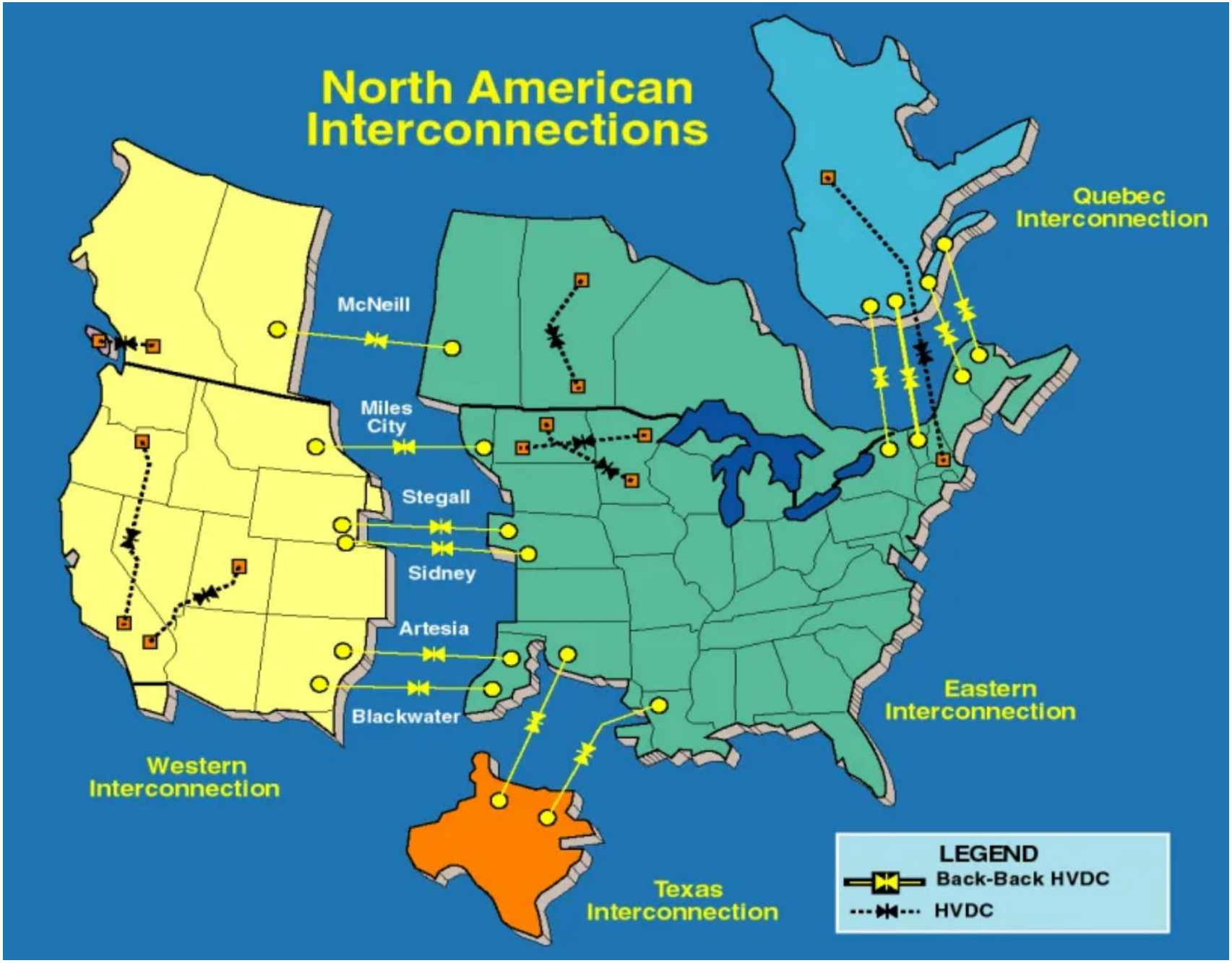


Data source: The North American Electric Reliability Corporation and Canadian Energy Regulator
Note: ERCOT=Electric Reliability Council of Texas

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

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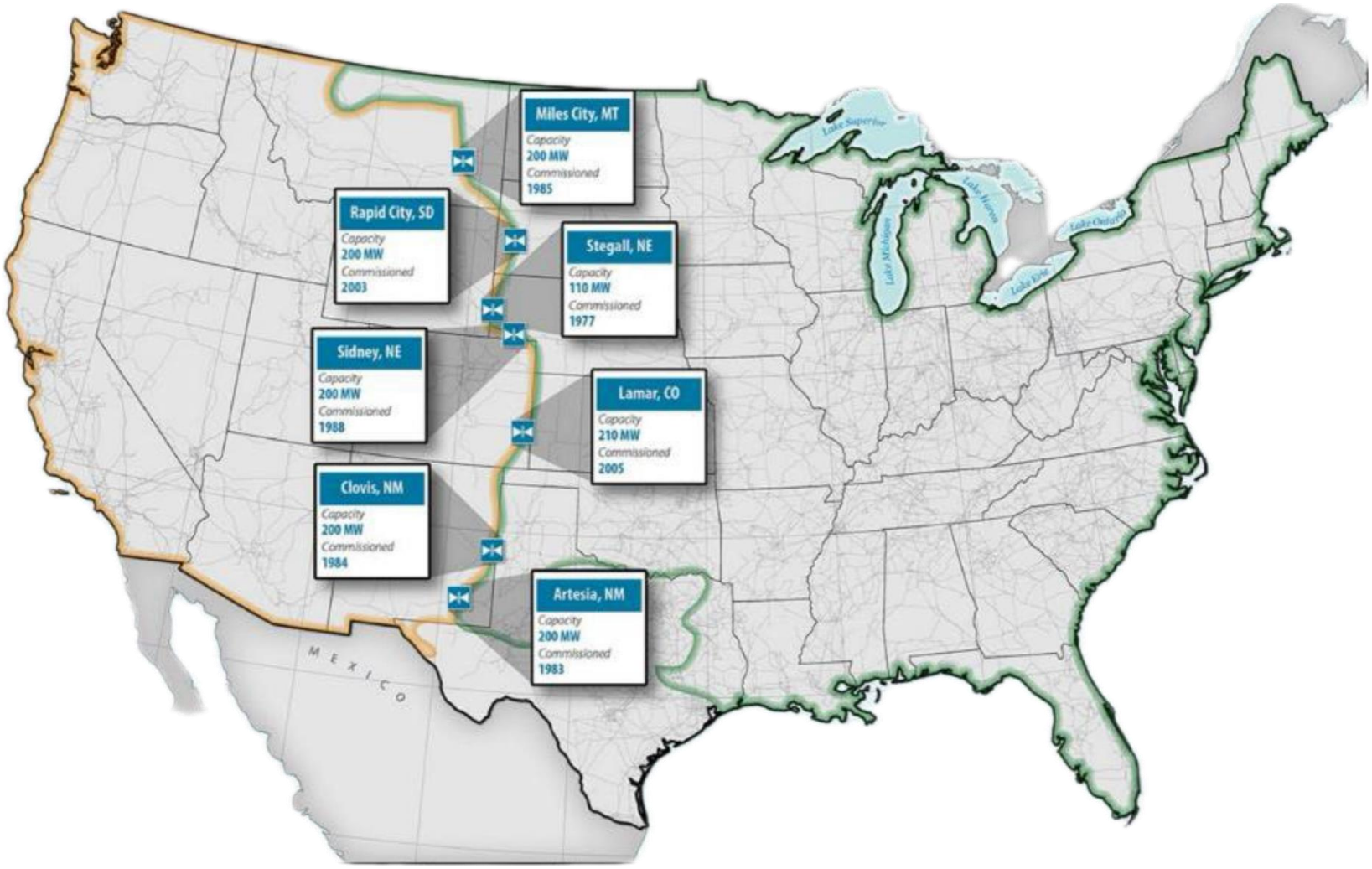
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https://jasondoering.substack.com/p/the-grids-org-chart

May not include all interconnections

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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

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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

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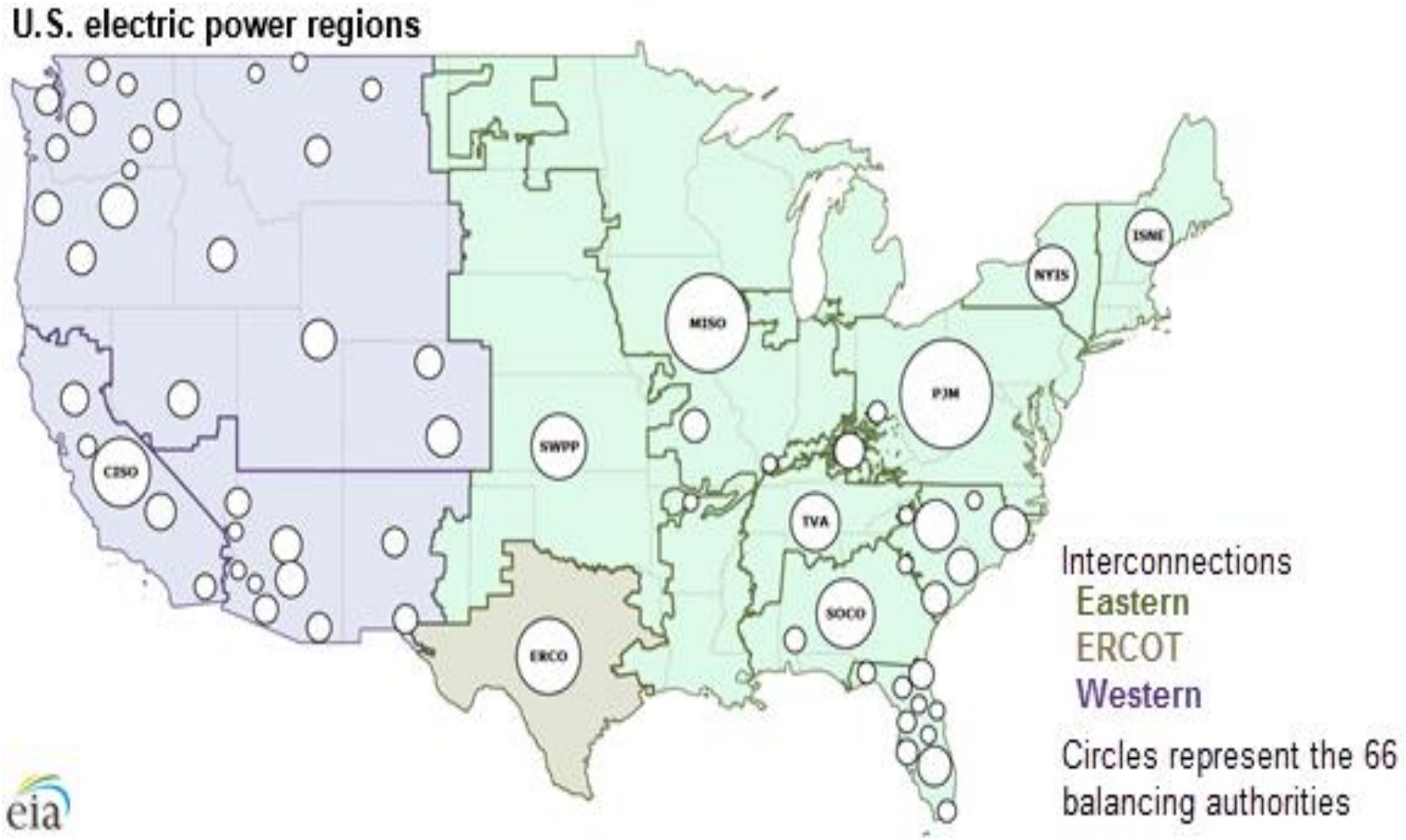
NERC RELIABILITY COORDINATORS



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

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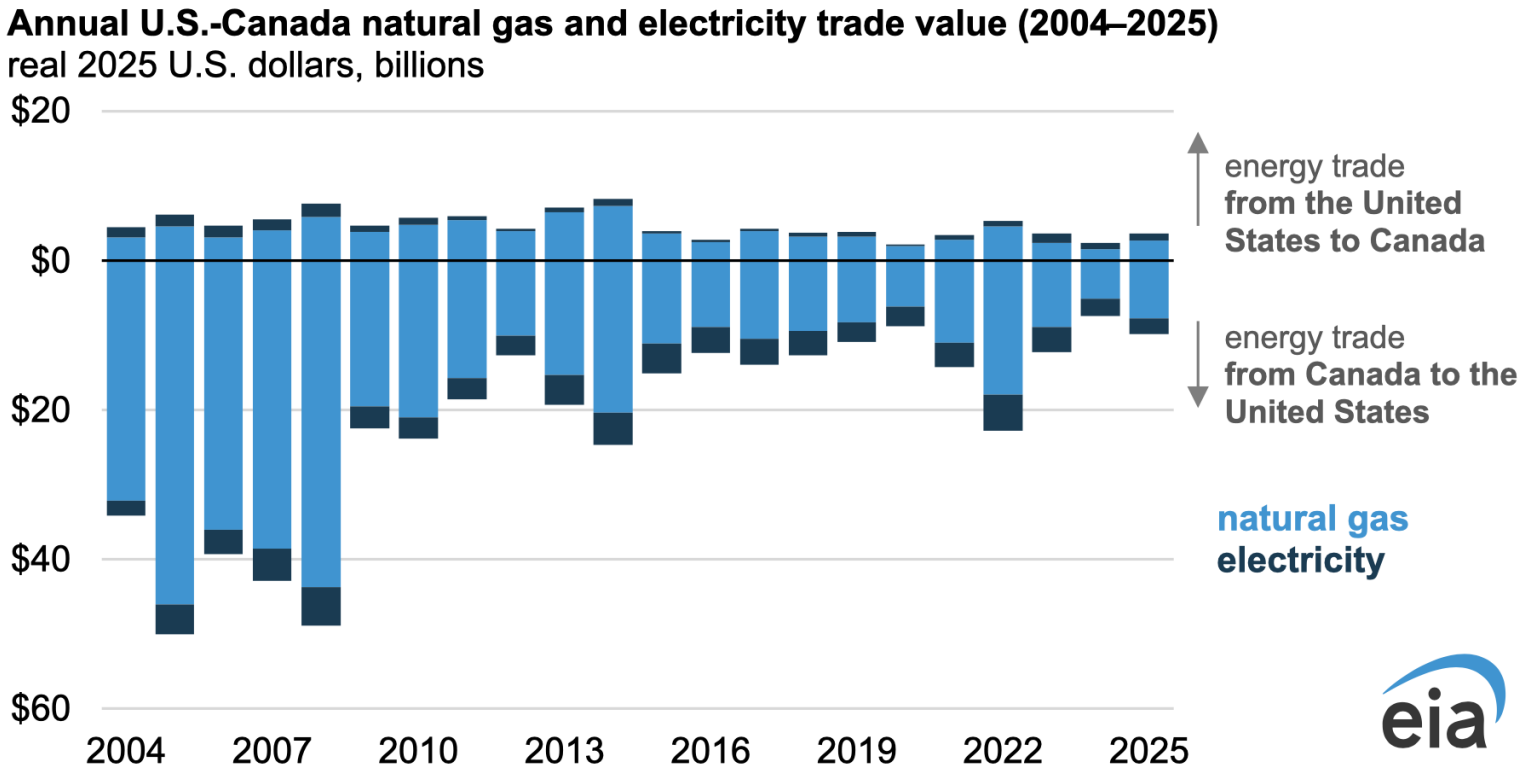
CONTROL AREAS/BALANCING AUTHORITIES



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

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Data source: Standard International Trade Classification data, U.S. Census Bureau
Note: Prices are adjusted for inflation.

The value of electricity trade between the U.S. and Canada totaled $3.2 billion in 2025, 67% of which was electricity imported from Canada to the U.S.

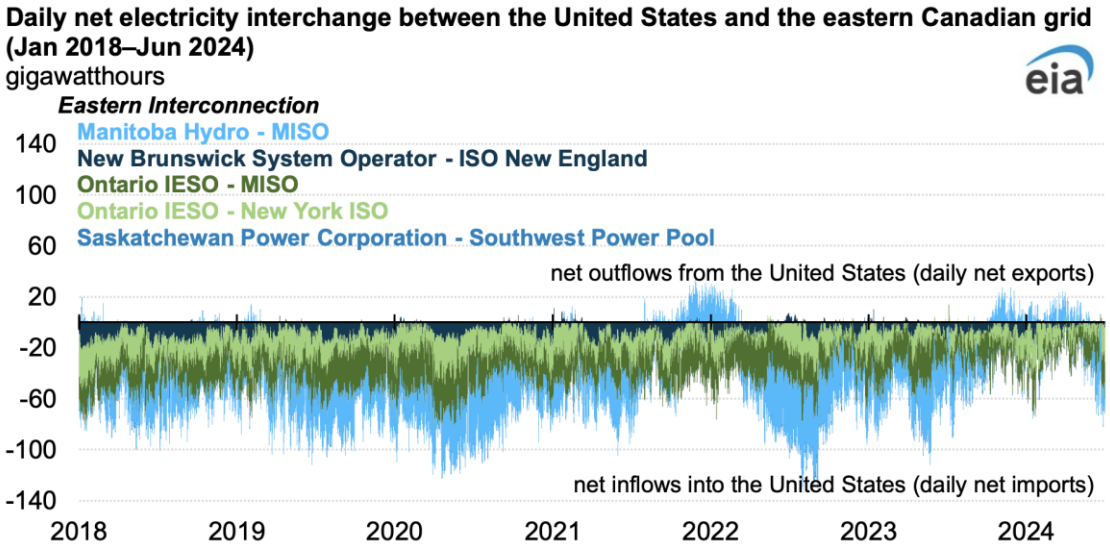
New transmission lines, New England Clean Energy Connect & Champlain Hudson Power Express, which began operations in 2026 has the potential to increase US electricity imports from Canada going forward

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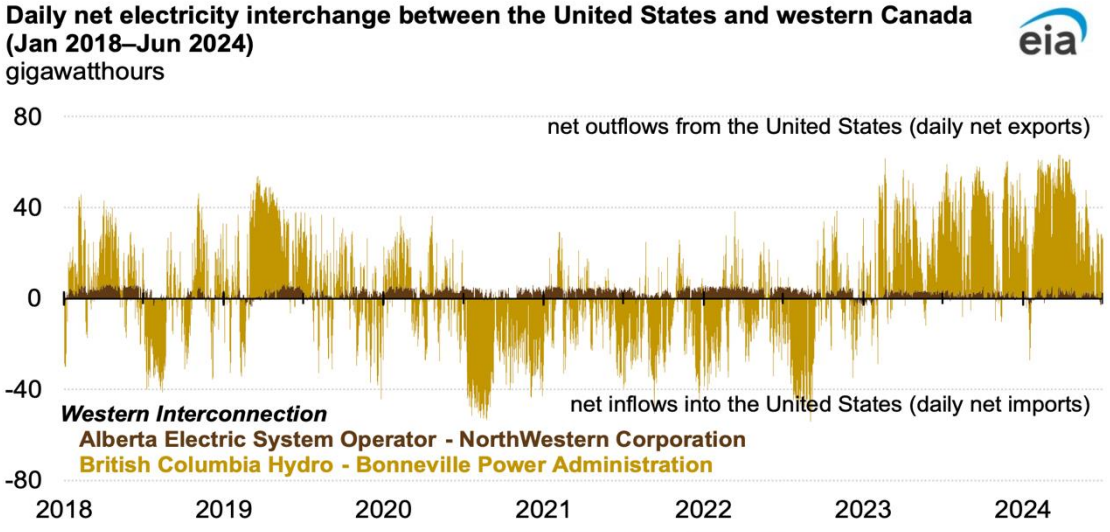
https://www.eia.gov/todayinenergy/detail.php?id=67924

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Daily exchanges are highly variable



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.



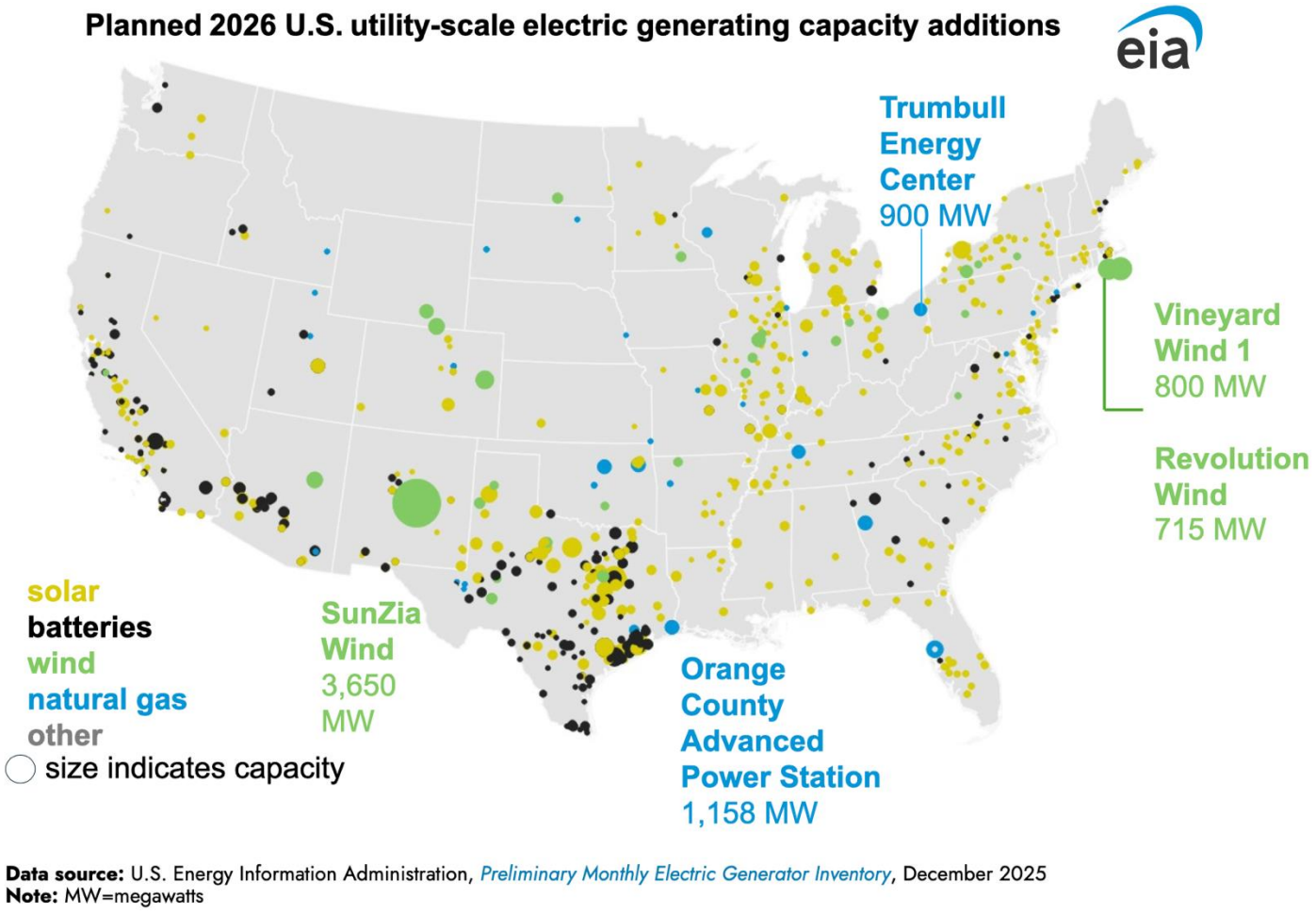
Data source: U.S. Energy Information Administration, Form EIA-930, *Daily Balancing Authority Operations Report*
Note: The net values represent the interchange from a U.S. balancing authority to a Canadian balancing authority. Values are reported by U.S. balancing authorities. Negative interchange values 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.

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LOCATION OF EMERGING GENERATION RESOURCES IN THE U.S.

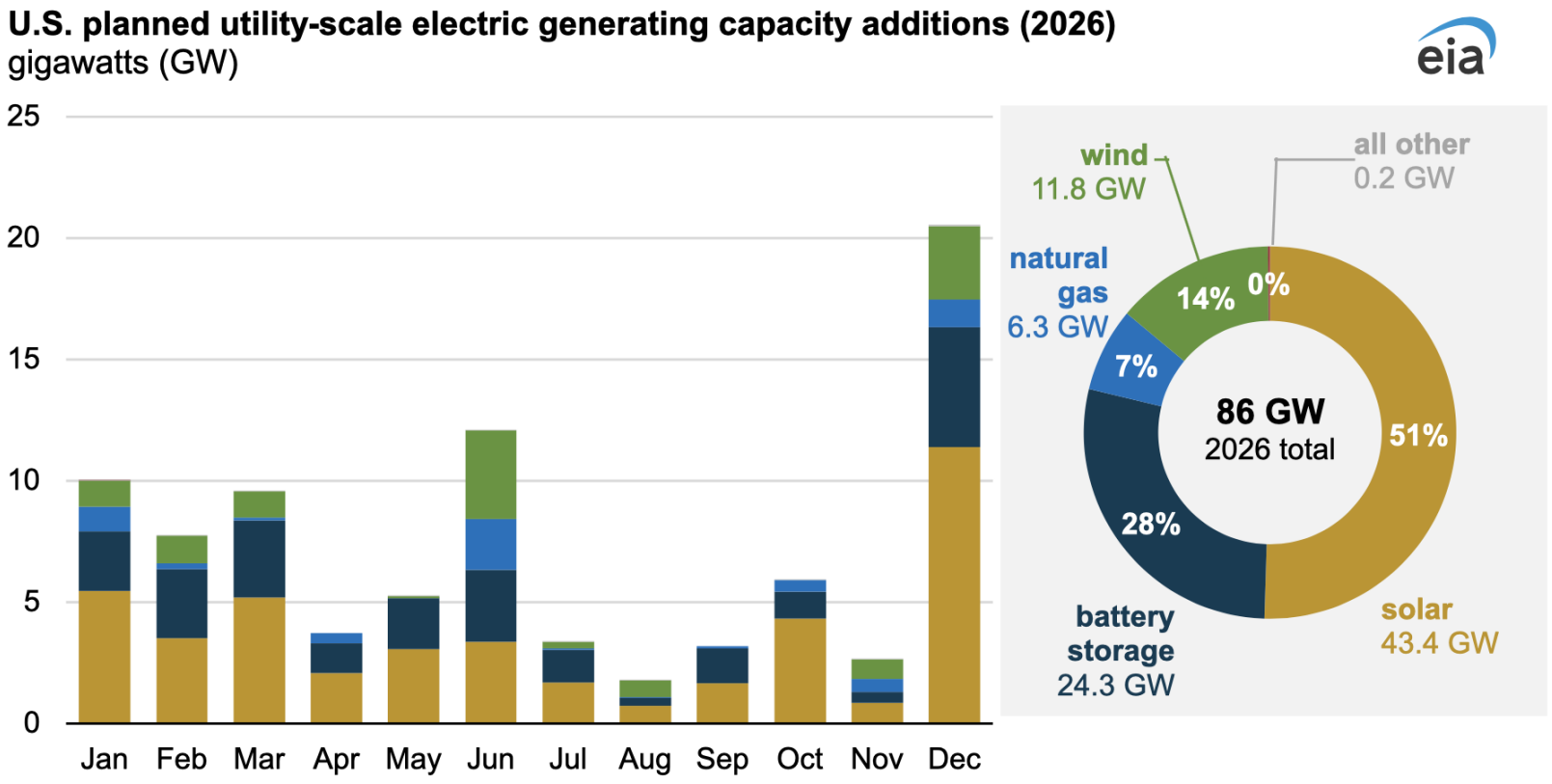


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New U.S. electric generating capacity expected to reach a record high in 2026

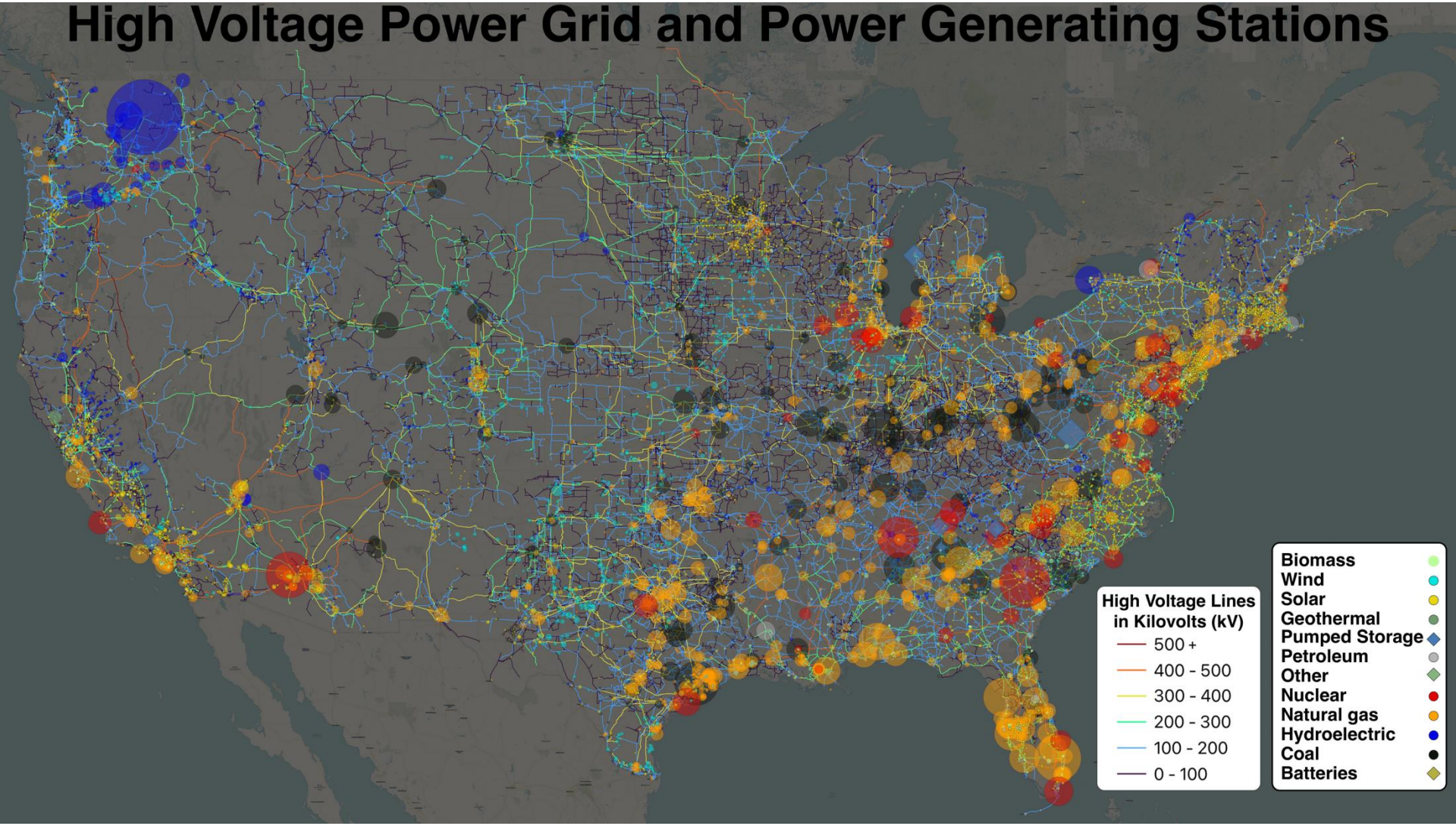


Data source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory*, December 2025

https://www.eia.gov/todayinenergy/detail.php?id=67205

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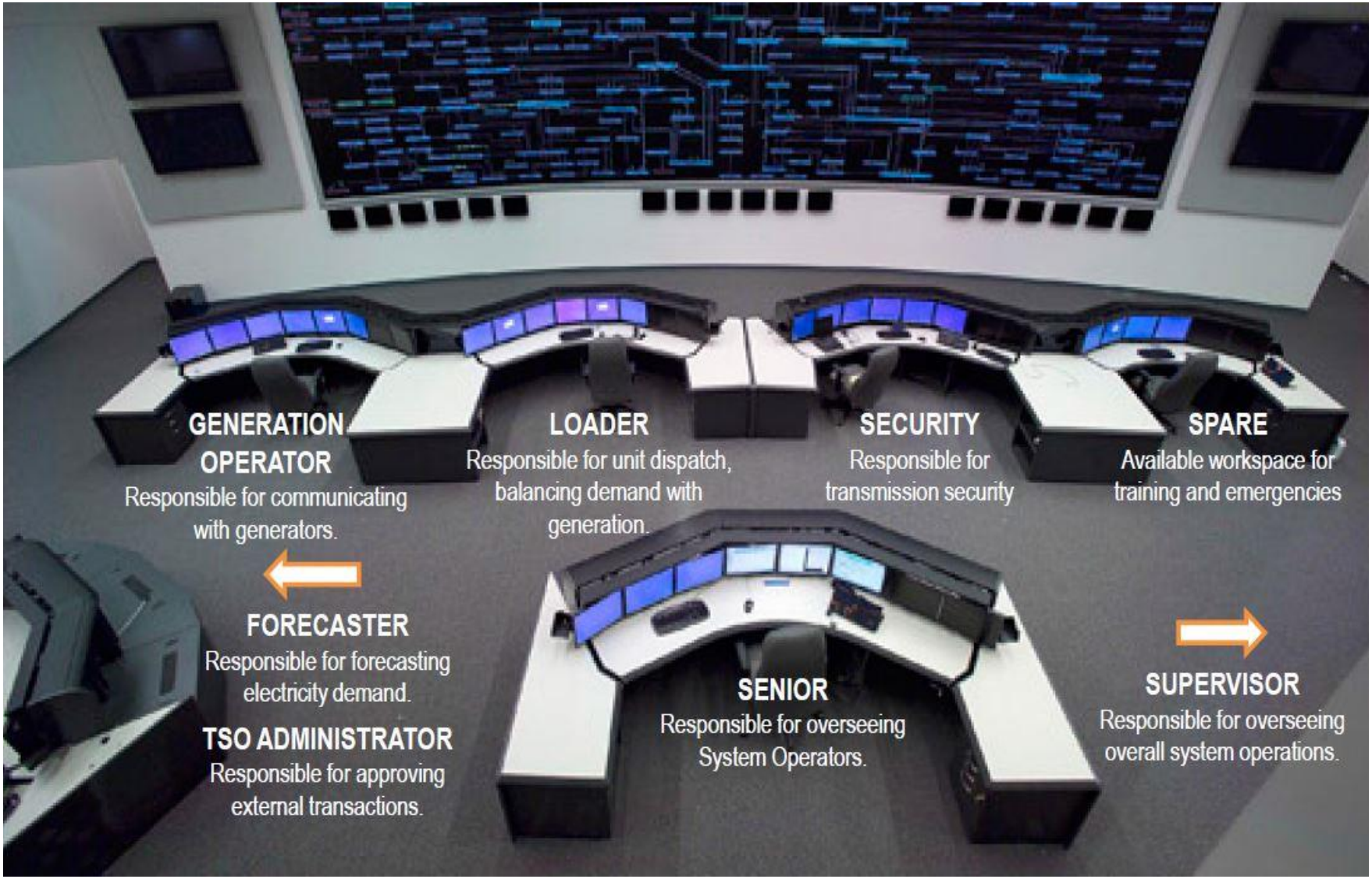


https://commons.wikimedia.org/wiki/File:High_voltage_power_grid_of_the_United_States.webp#/media/File:Electrical_grid_and_power_plants.webp

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CONTROL ROOM



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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.)

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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:

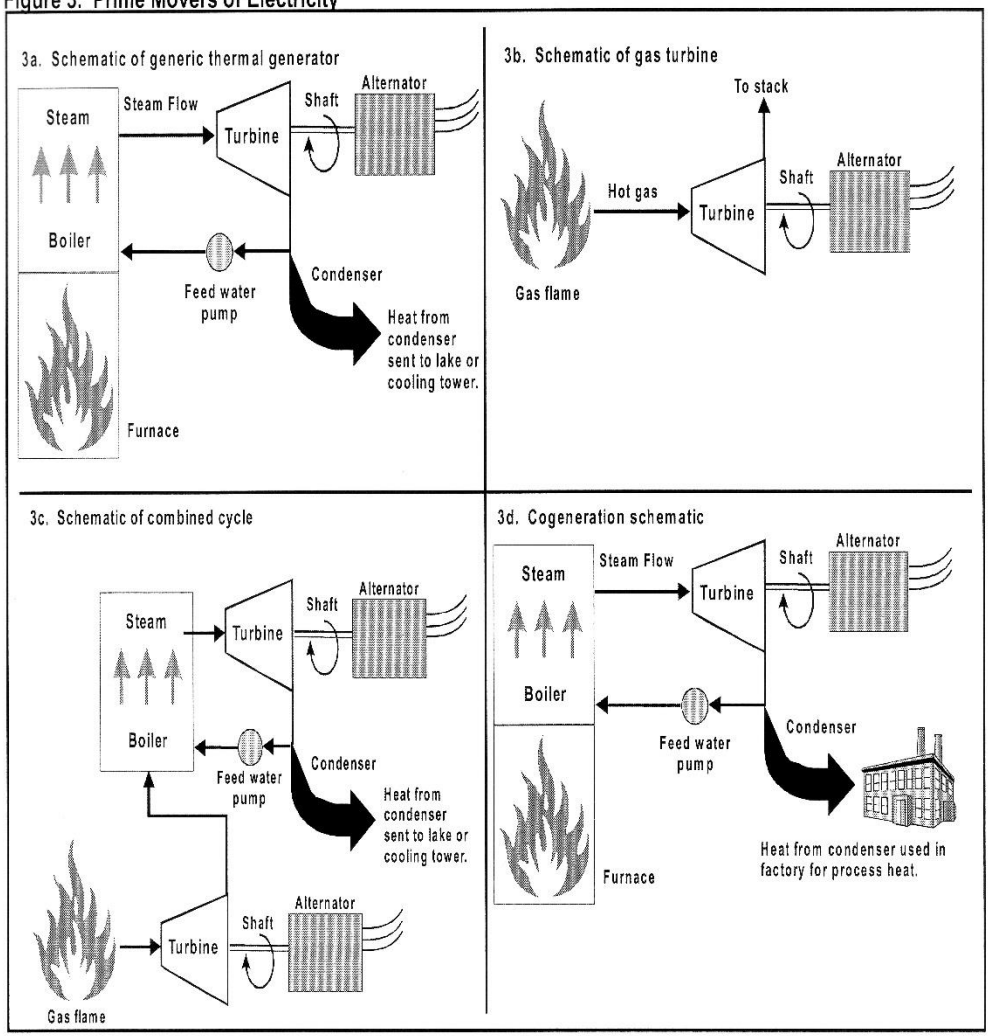
Heat Rate (Btu/kWh) * (Fuel + Environmental Cost ($/Btu)) = Cost ($/kWh)

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GENERATION

Figure 3. Prime Movers of Electricity



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

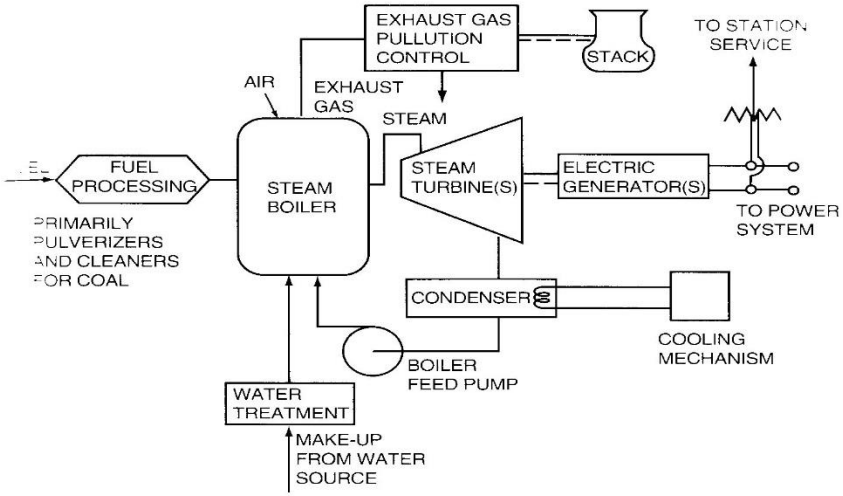
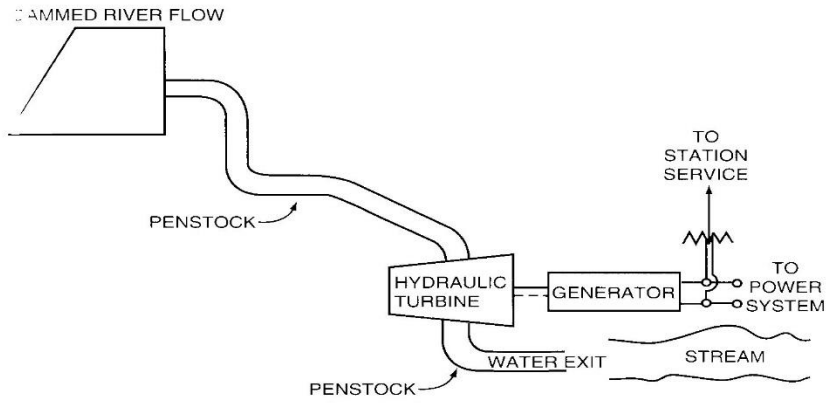


Figure 5.2. Schematic of conventional fossil steam power plant.



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

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COMBINED CYCLE GENERATION

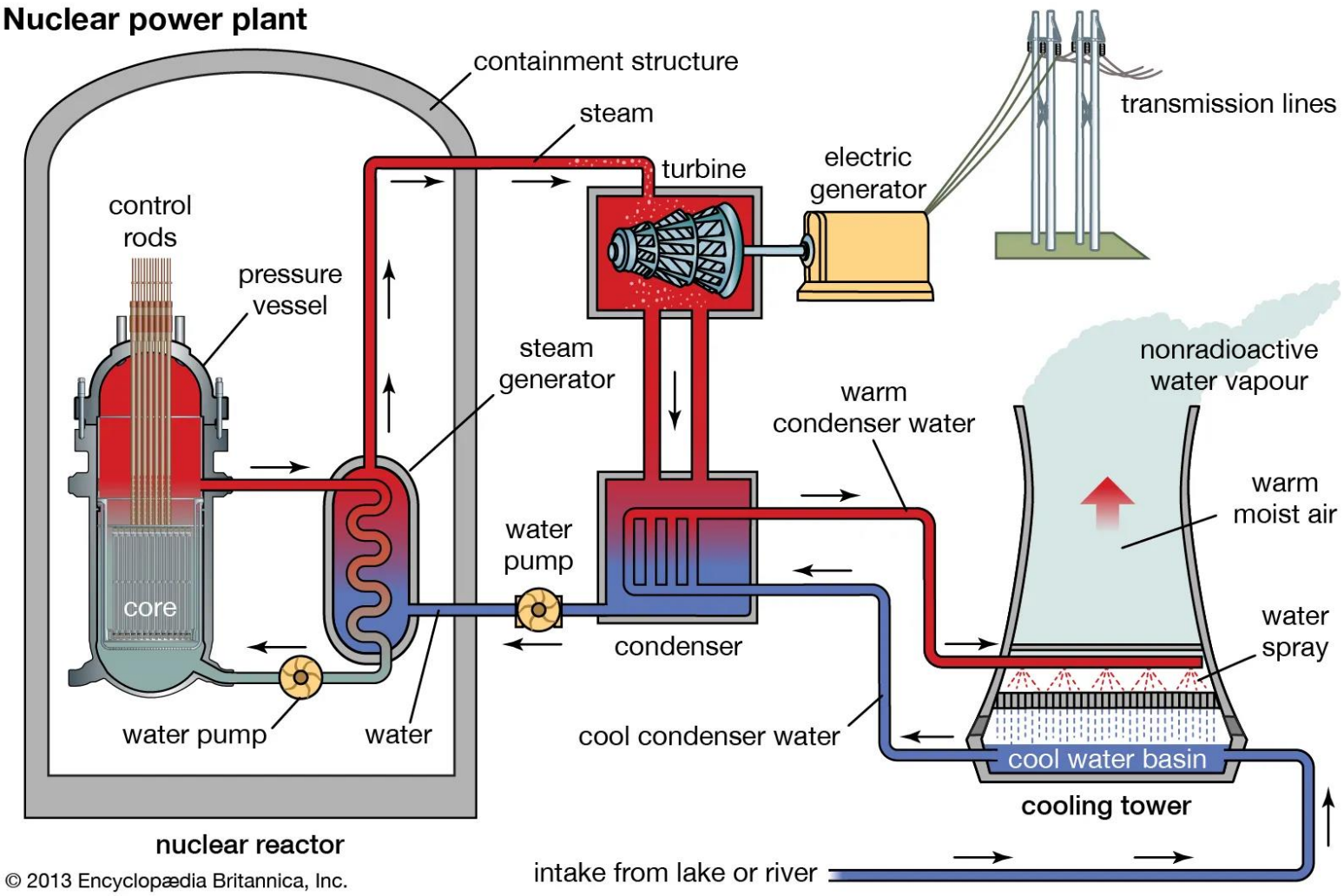


https://www.youtube.com/watch?v=qG7SlVfAuPA

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NUCLEAR POWER – LARGE SCALE

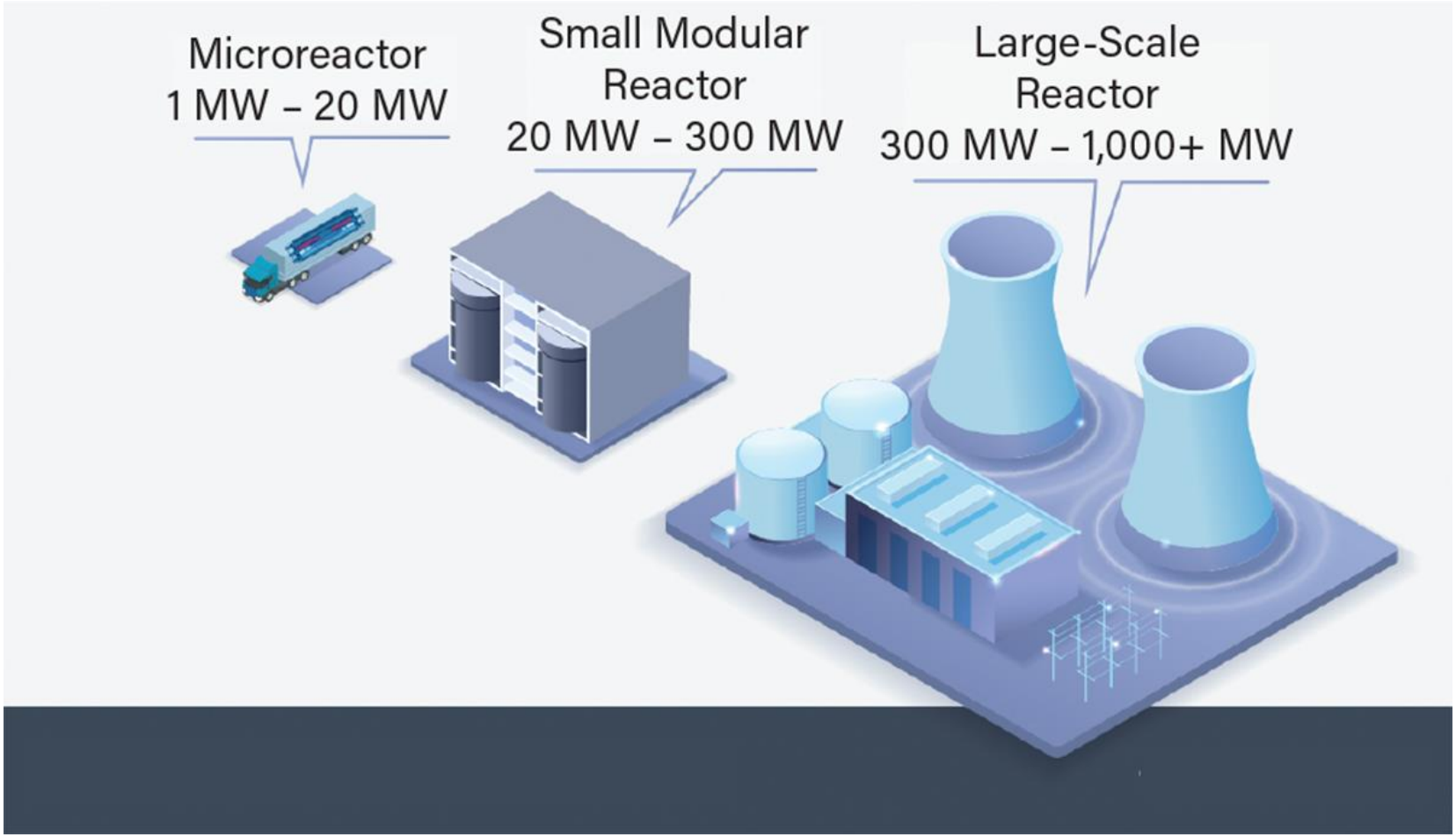


https://www.britannica.com/technology/nuclear-power

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NUCLEAR POWER – SMALL MODULAR REACTORS (SMRS) & MICROREACTORS

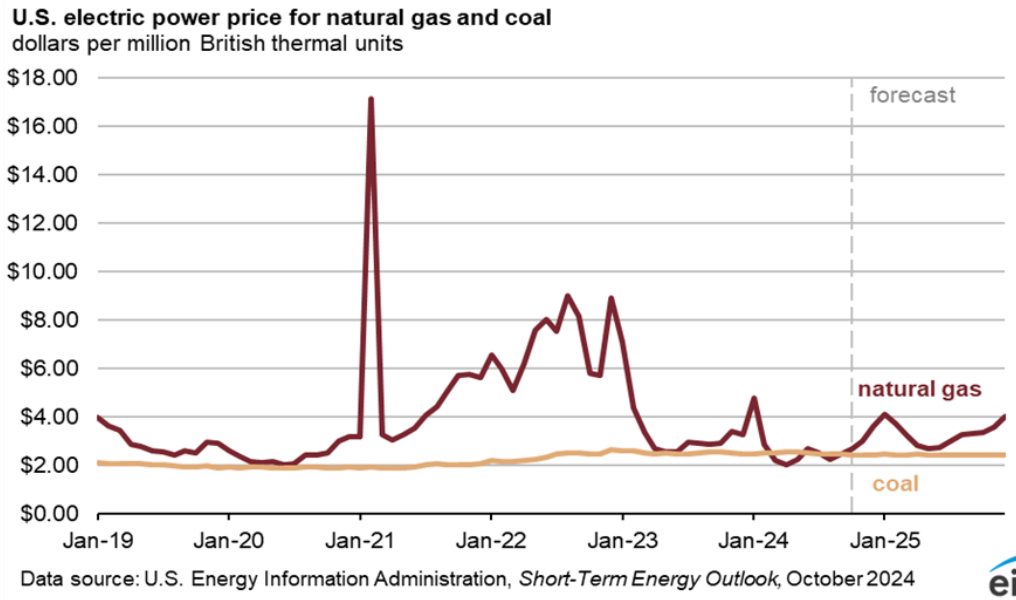


https://www.aiche.org/resources/publications/cep/2022/april/advances-very-small-modular-nuclear-reactors

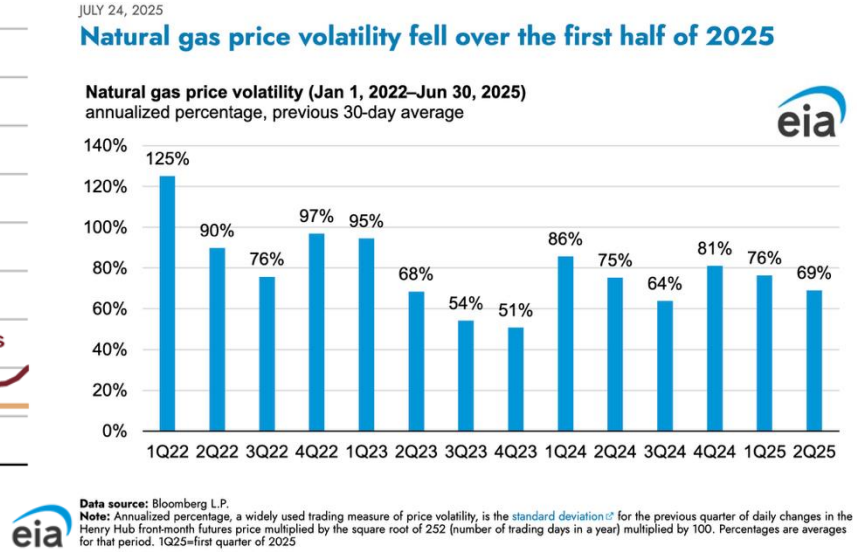
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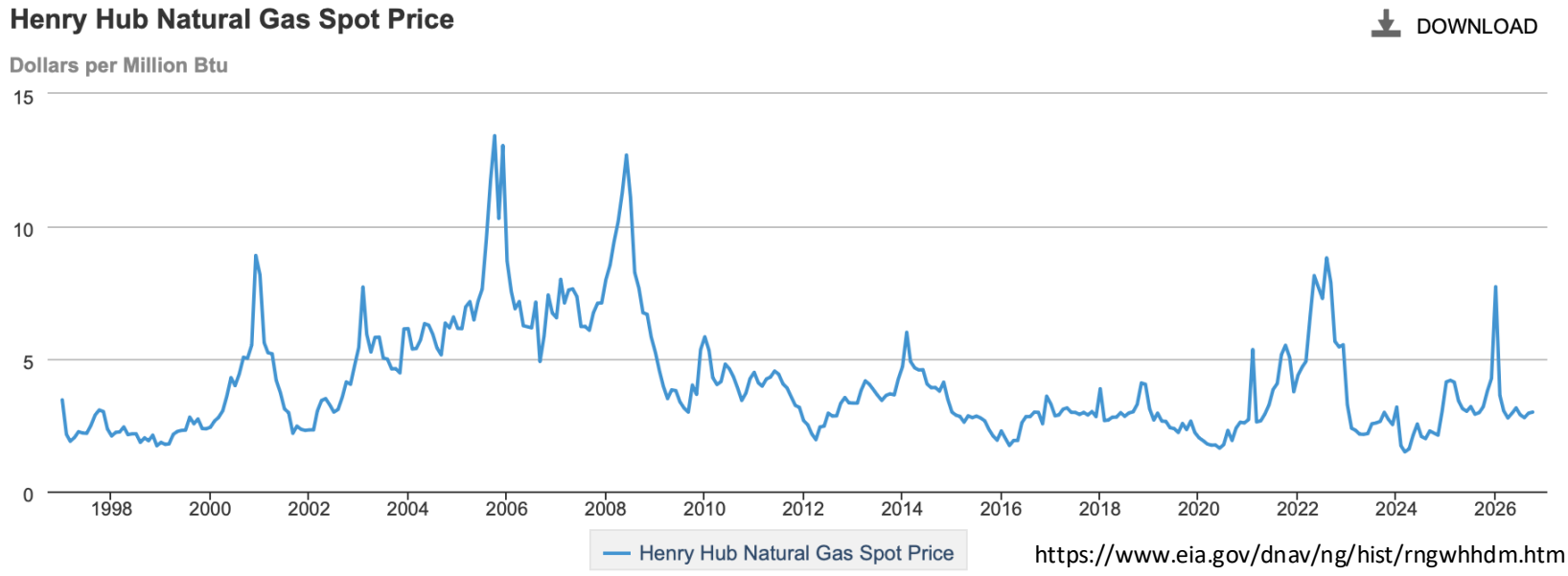
US COAL AND NATURAL GAS PRICES



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



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



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

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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

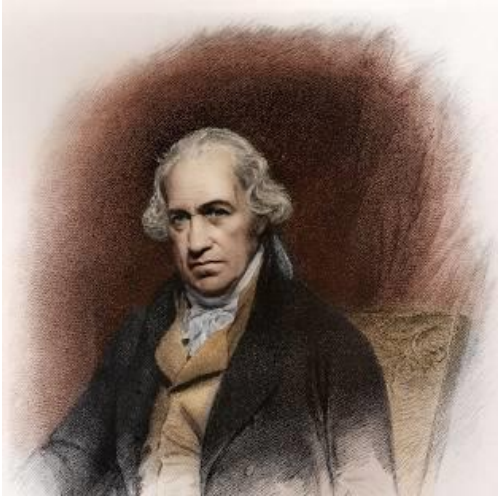
  1,000 kWh = 1 MWh 1,000 kW = 1 MW
  1,000 MWh = 1 GWh 1,000 MW = 1 GW

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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

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CAPACITY FACTORS OF US ELECTRICITY SOURCES

Yearly Capacity Factors

	Geothermal		Hydroelectric		Nuclear		Other Biomass		Other Fossil Gas		Solar				Wind		Wood	
Year/Month											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	Time Adjusted Capacity (MW)	Capacity Factor
Annual Data																		
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%	8,979.8	58.3%
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%	8,807.5	60.2%
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%	8,760.2	60.6%
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%	8,485.0	59.0%
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%	8,327.2	57.8%
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%	7,959.0	59.9%
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%	7,817.6	57.9%
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%	7,830.2	53.5%
2024	2,690.2	64.6%	79,883.9	34.6%	98,022.9	90.8%	4,054.5	59.5%	1,685.1	49.0%	102,319.5	23.2%	1,392.0	25.0%	149,299.0	34.3%	7,476.0	55.8%
2025	2,695.5	65.9%	79,890.5	35.3%	98,436.4	91.0%	3,989.2	59.0%	1,656.7	52.2%	133,940.2	24.4%	1,392.0	23.6%	154,574.1	34.2%	7,331.2	56.8%

2026 Monthly Capacity Factors

Year 2026																		
January	2,700.9	69.9%	79,942.9	46.9%	98,437.9	100.0%	3,967.5	56.6%	1,615.1	53.6%	149,992.2	15.7%	1,392.0	7.6%	159,111.4	37.5%	7,202.9	61.0%
February	2,692.9	69.3%	79,949.4	41.8%	98,440.9	94.3%	3,949.7	57.5%	1,776.1	56.3%	153,607.2	20.3%	1,392.0	12.8%	159,516.2	37.0%	7,202.2	60.7%
March	2,692.9	66.1%	79,947.0	45.3%	98,423.9	84.8%	3,957.2	56.3%	1,776.1	58.2%	153,967.9	24.7%	1,392.0	21.6%	158,617.9	44.1%	7,179.2	55.7%
April	2,692.9	62.7%	79,971.6	39.1%	98,423.9	81.0%	3,959.4	54.2%	1,776.1	67.1%	155,799.2	26.3%	1,392.0	26.4%	158,800.6	42.3%	7,172.6	48.7%
May	2,683.9	63.6%	79,973.6	38.2%	98,423.9	88.8%	3,960.2	55.9%	1,772.3	47.2%	158,951.5	29.4%	1,392.0	34.6%	160,831.5	33.6%	7,135.3	55.9%
June	2,683.9	65.4%	79,969.8	41.2%	98,423.3	97.1%	3,962.2	59.9%	1,772.3	39.9%	160,833.3	31.9%	1,392.0	36.8%	164,810.4	35.0%	7,099.2	57.6%
July	2,683.9	64.7%	80,046.3	34.0%	98,423.3	97.2%	3,959.2	58.6%	1,772.3	48.5%	163,444.7	32.4%	1,392.0	30.6%	165,461.3	26.0%	7,099.2	60.1%

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

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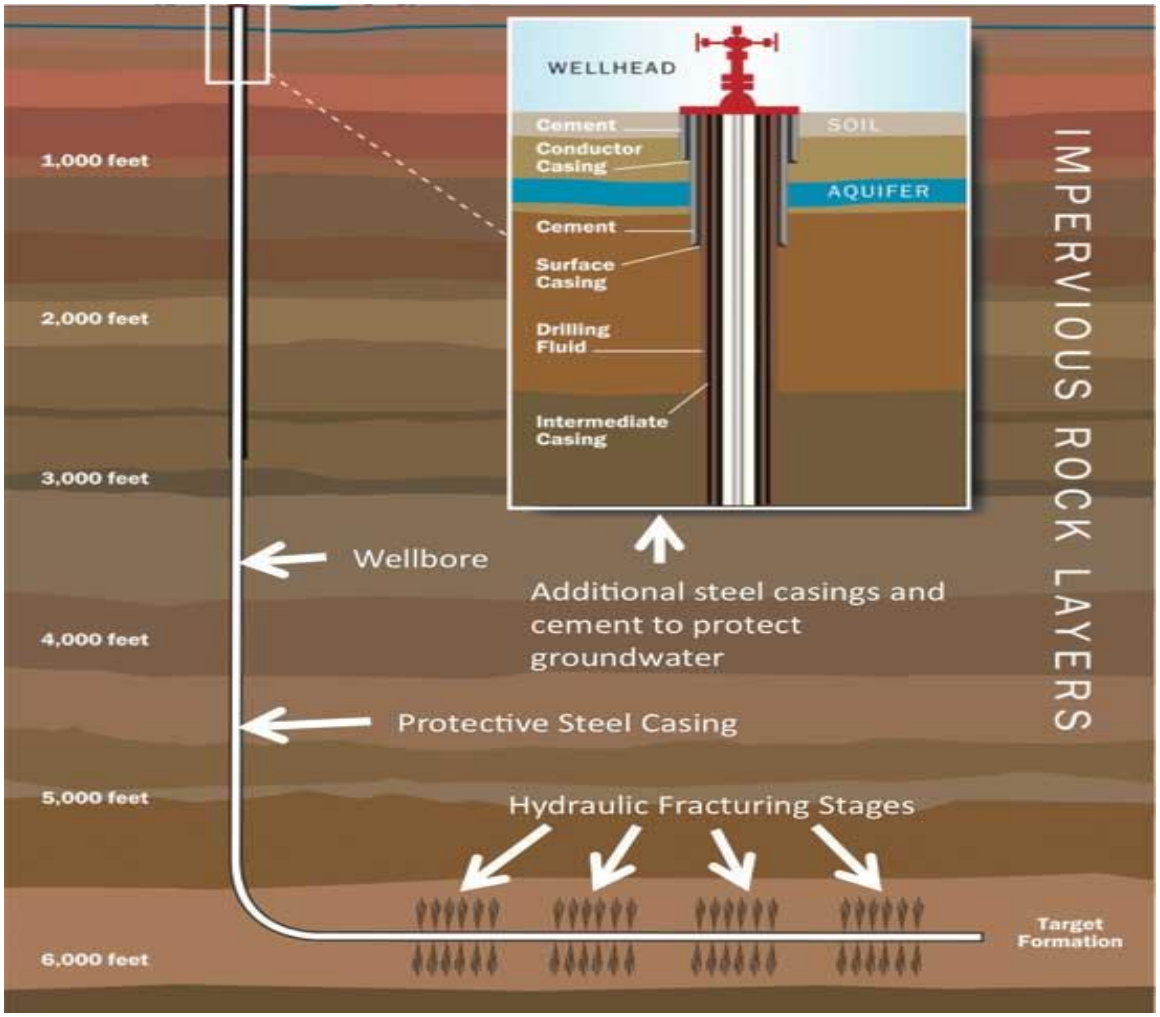
NORTH AMERICAN NATURAL GAS RESOURCES



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SHALE NATURAL GAS & FRACKING



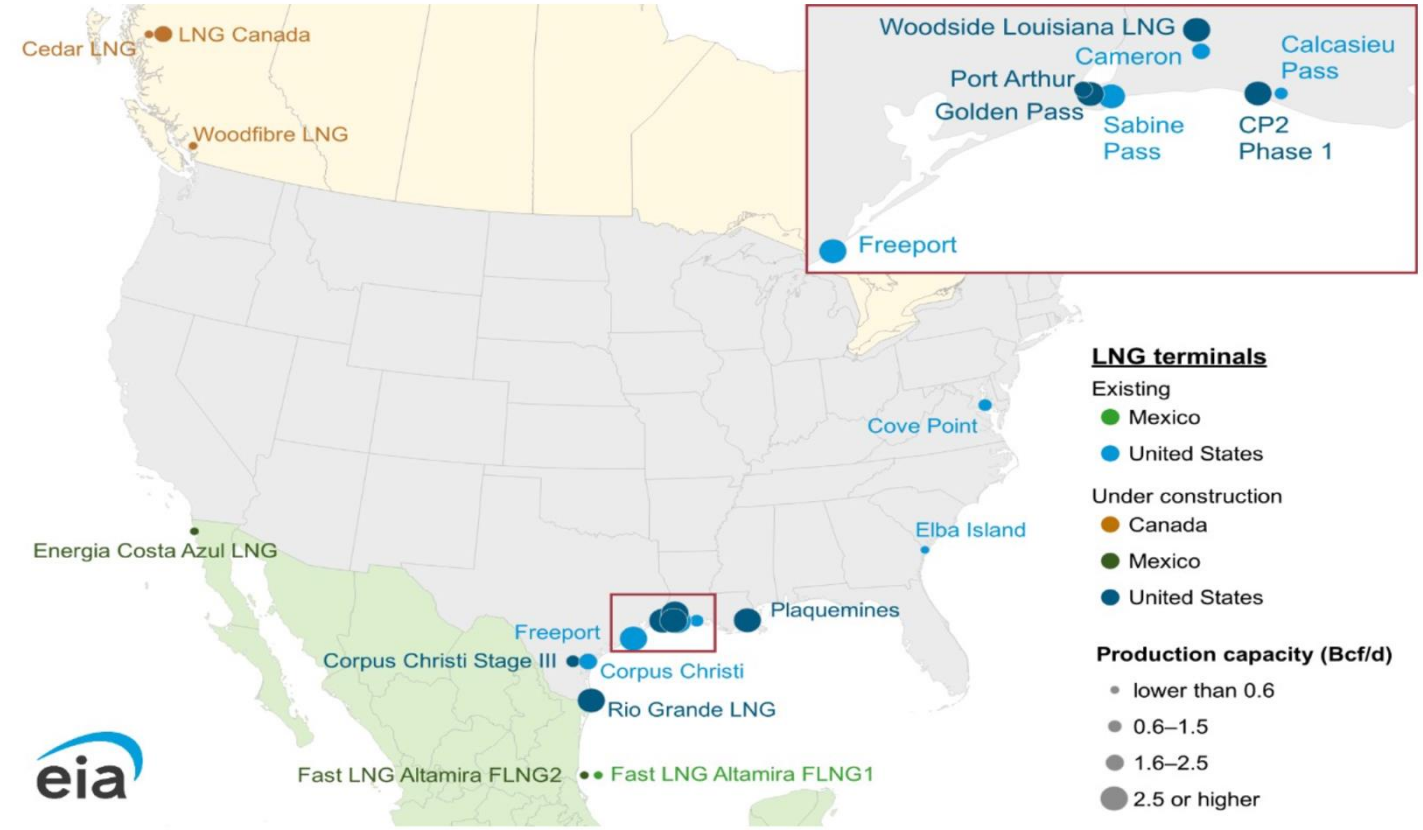
Fracking is a method of extracting oil and natural gas from rock formations

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U.S Liquefied Natural Gas (LNG) Terminals

North America liquefied natural gas export facilities, existing and under construction (2016–2029)



Data source: U.S. Energy Information Administration, *Liquefaction Capacity File*, and trade press
Note: Bcf/d=billion cubic feet per day; LNG=liquefied natural gas; FLNG=floating liquefied natural gas

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.eia.gov/todayinenergy/detail.php?id=66384

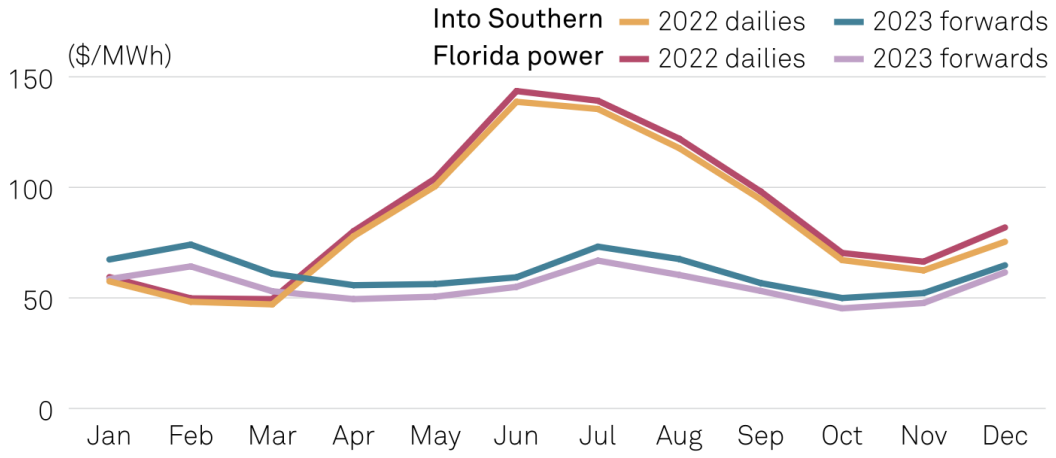
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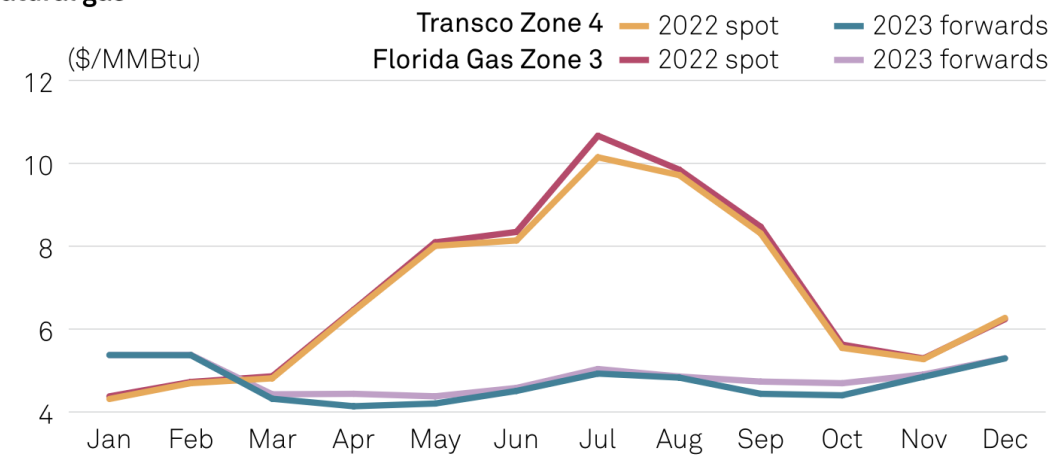
Electricity & Natural Gas Prices are Highly Positively Correlated

Southeastern power and gas 2023 forwards, 2022 daily indexes

Power



Natural gas



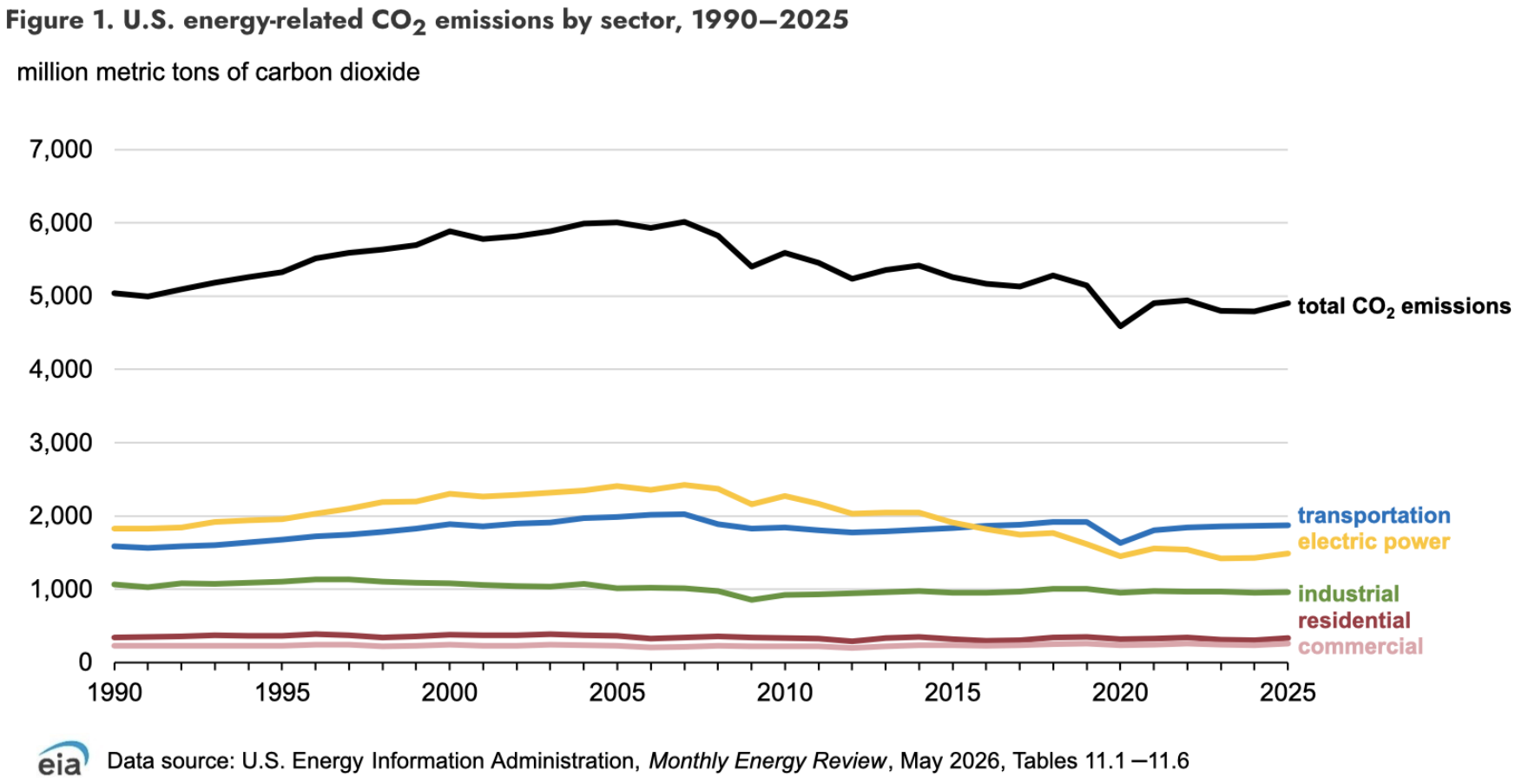
Notes: All power day-ahead indexes and forwards are on-peak. Day-ahead indexes are for delivery through Dec. 29. Forwards as of Dec. 28, 2022.
Source: S&P Global Commodity Insights

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

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U.S Energy-Related Carbon Dioxide (CO_2) Emissions

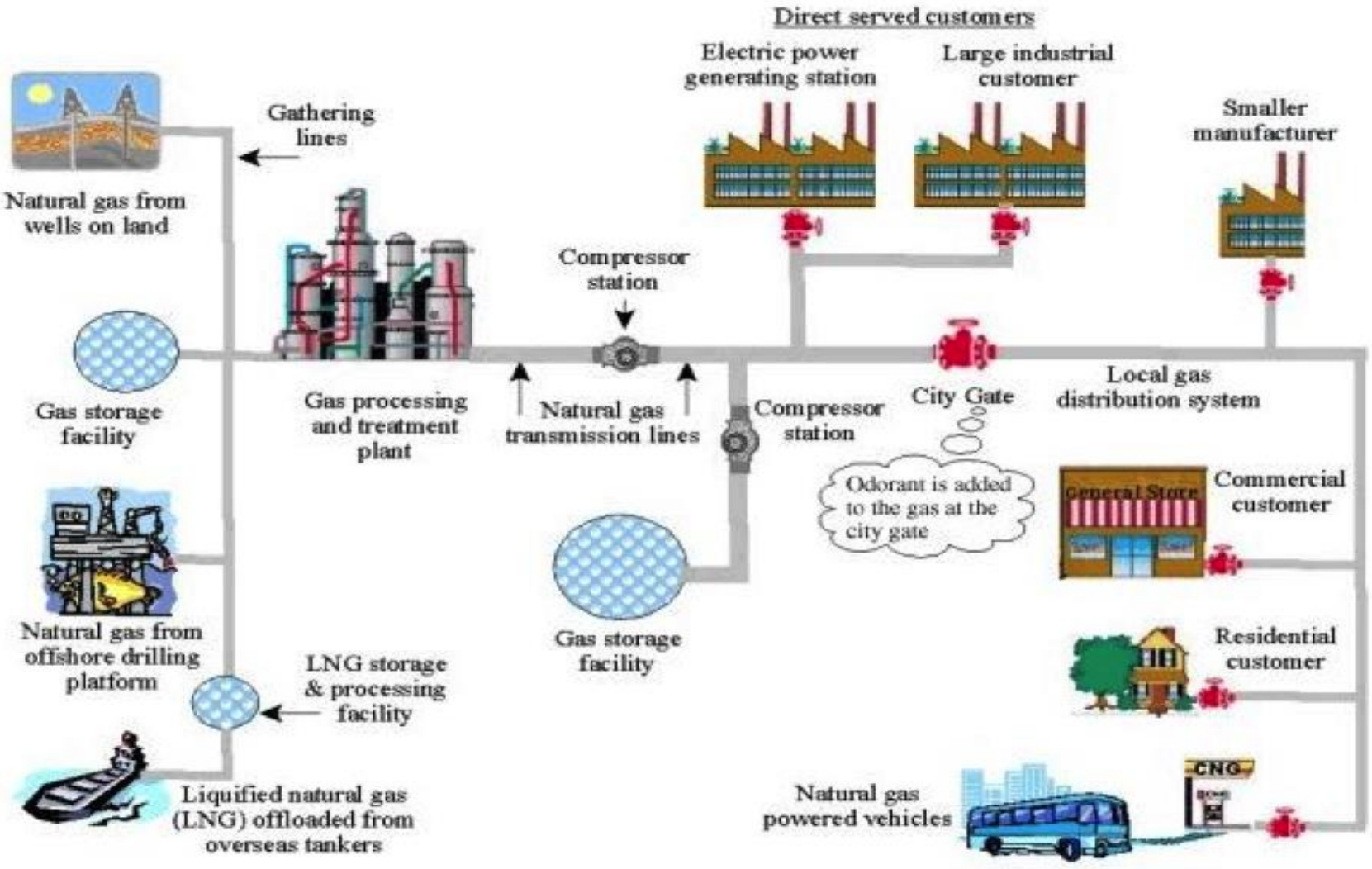


https://www.eia.gov/environment/emissions/carbon/

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GAS-ELECTRICITY INTERDEPENDENCE

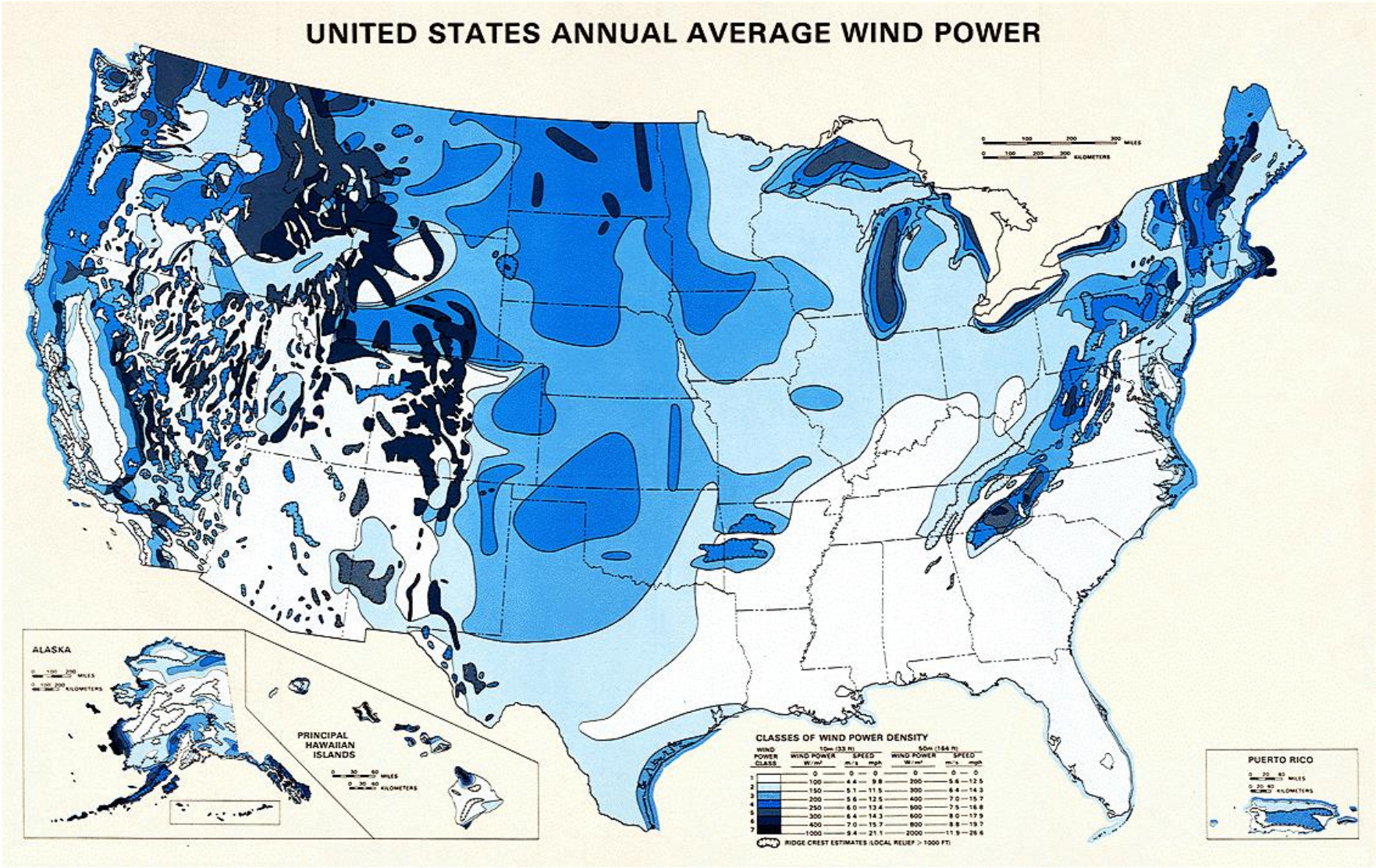


Natural gas disruption or extreme cold weather can severely impact electricity reliability and prices

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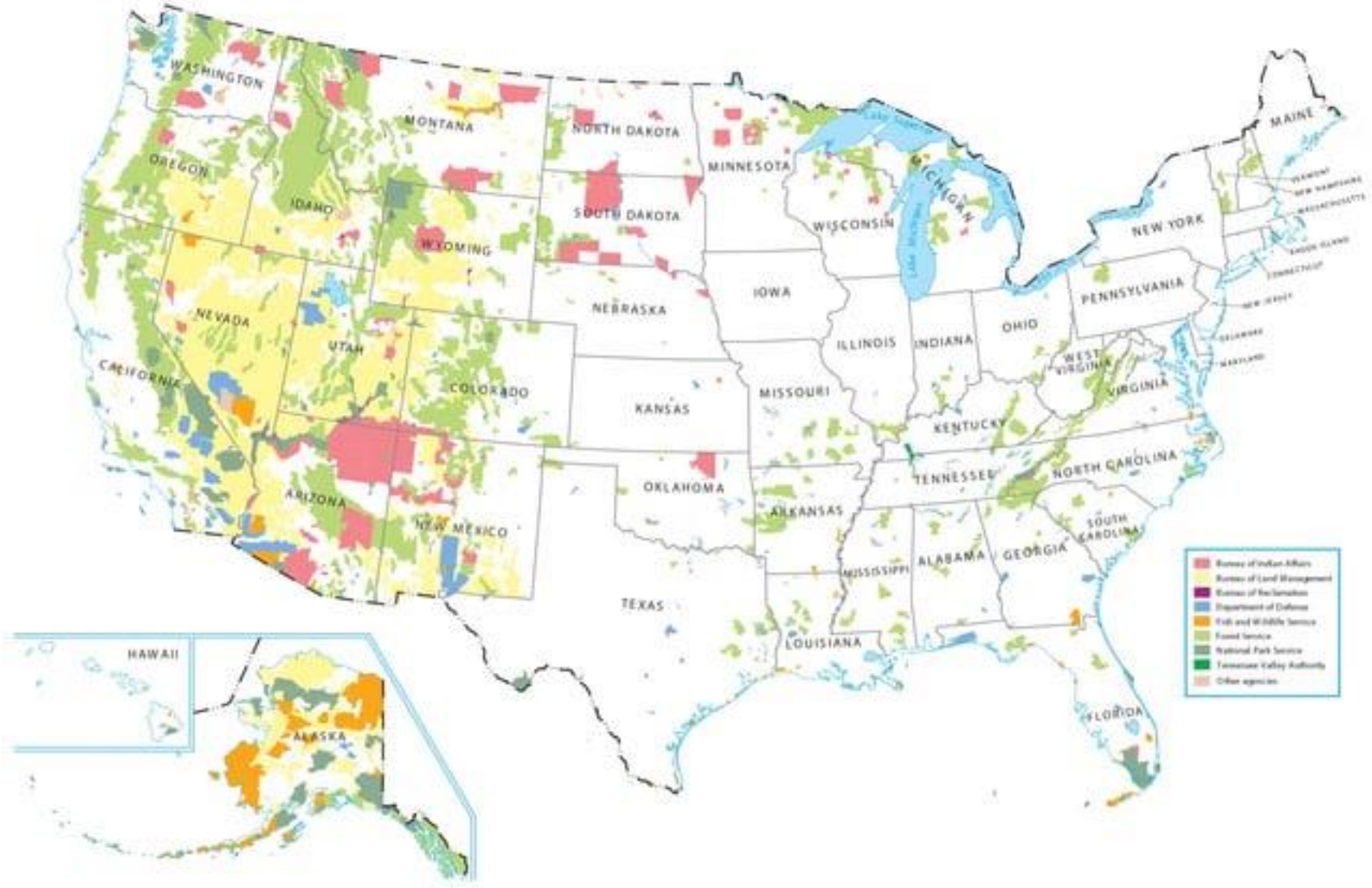
US WIND RESOURCES



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U.S. FEDERAL LANDS

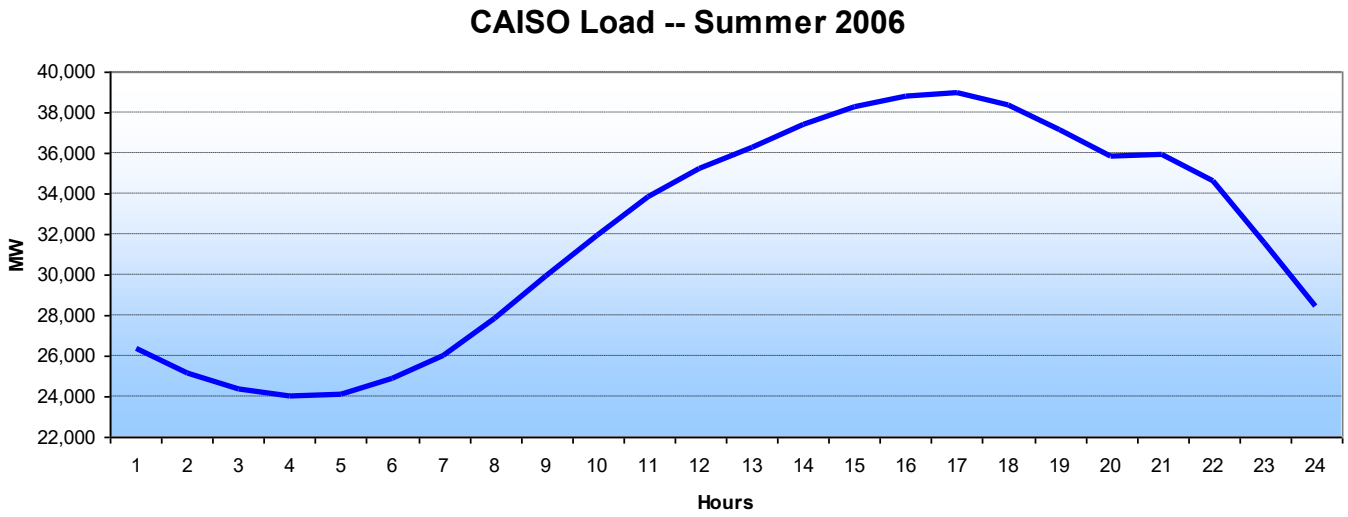


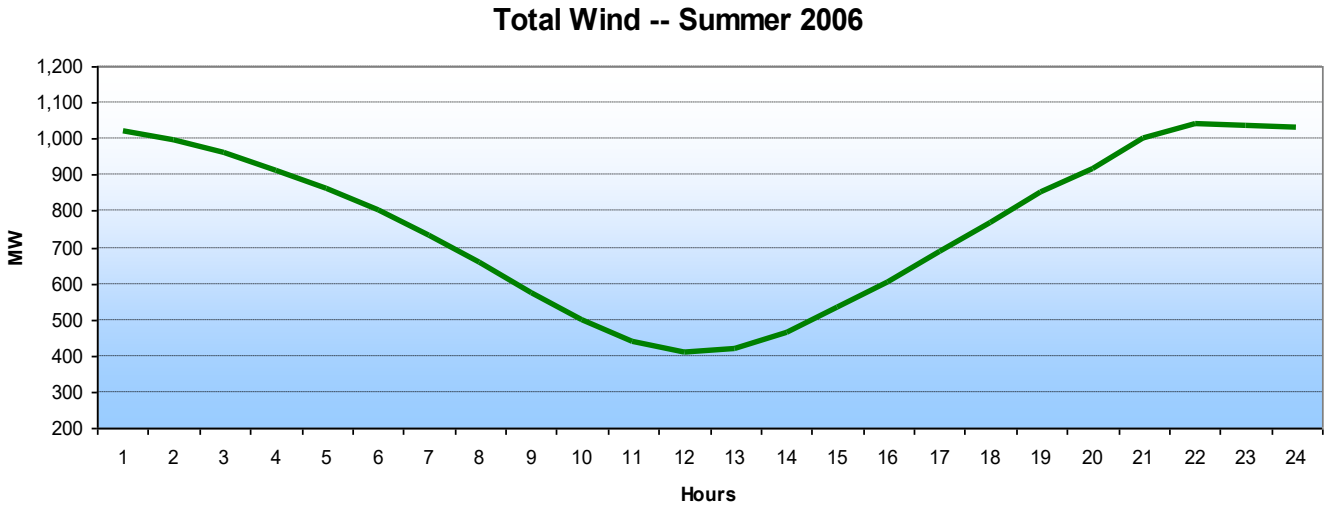
https://www.reddit.com/r/neoliberal/comments/151o35d/what_should_the_united_states_government_do_with/?rdt=33357

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WIND AVAILABILITY



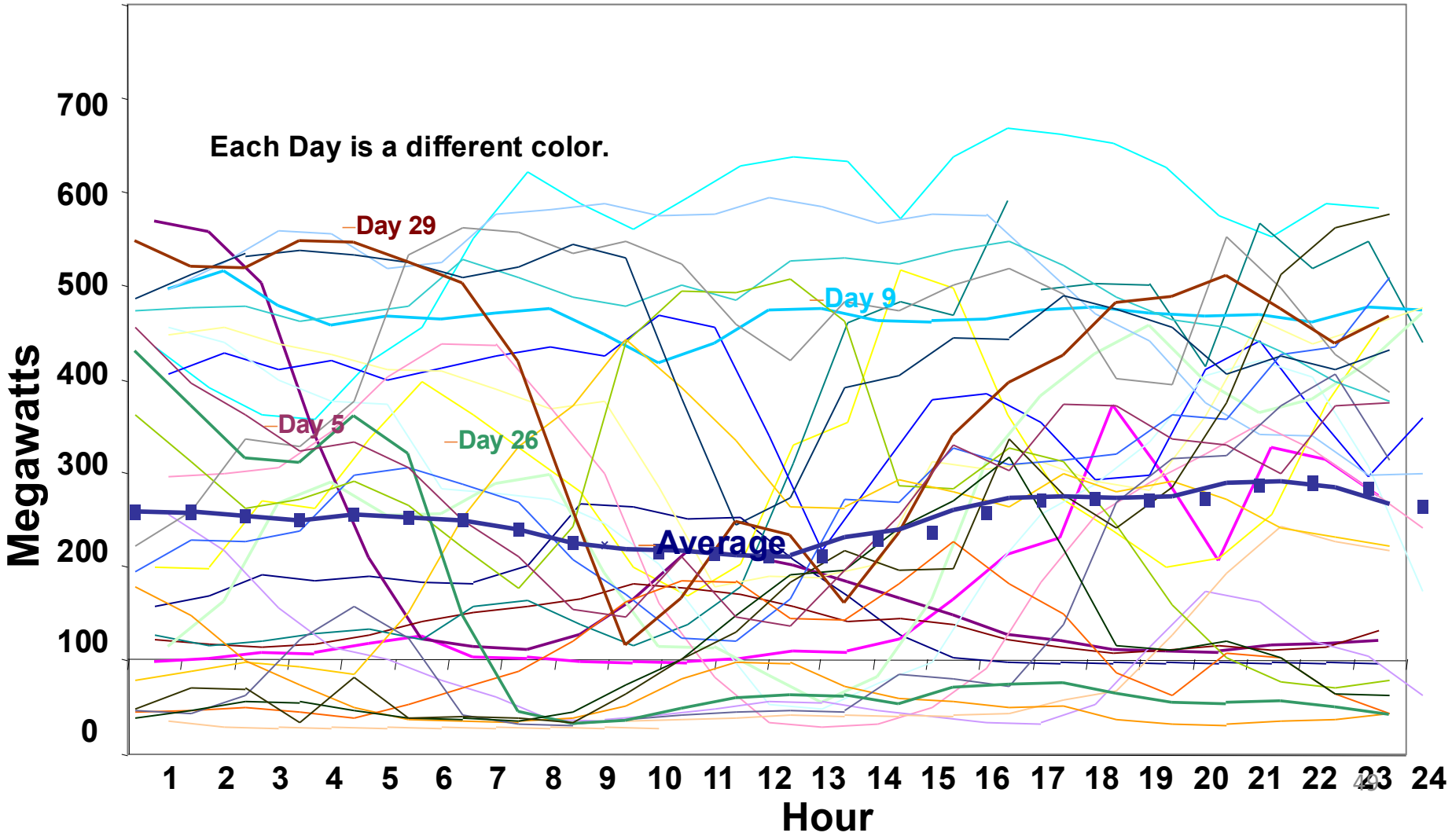


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WIND VARIABILITY

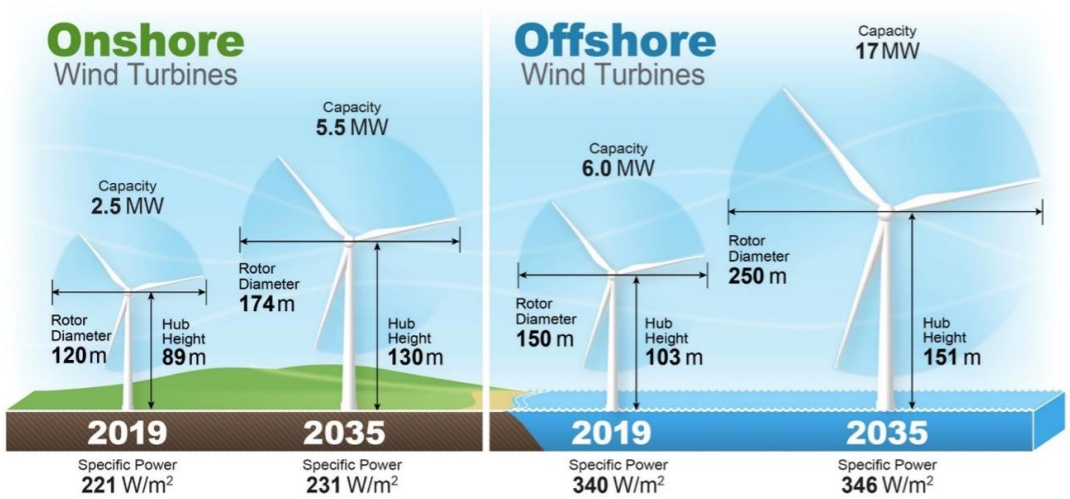
The average for April 2005 is smooth, but the day-to-day variability is great, showing the importance of improved forecasting tools and telemetry to the operating floor.

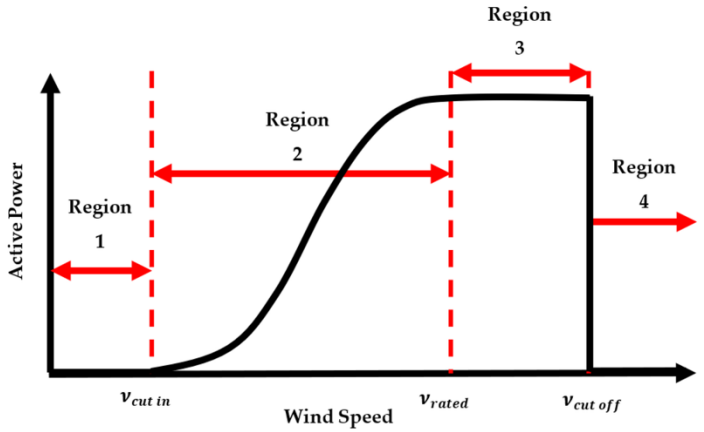


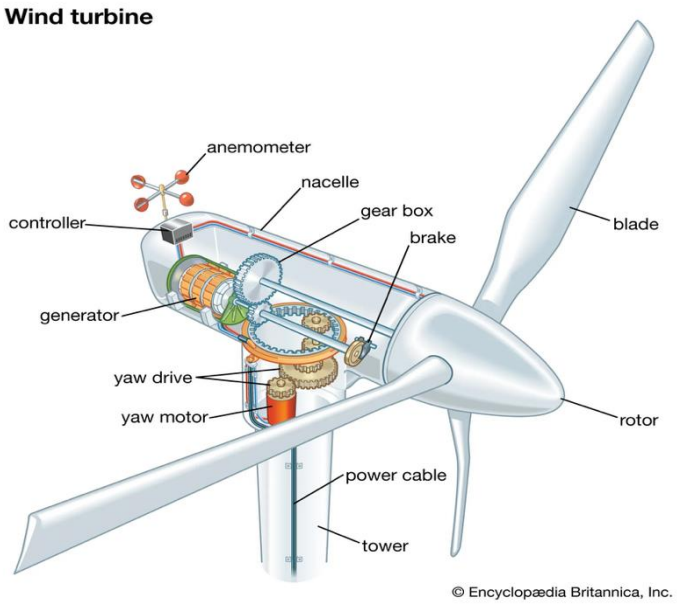
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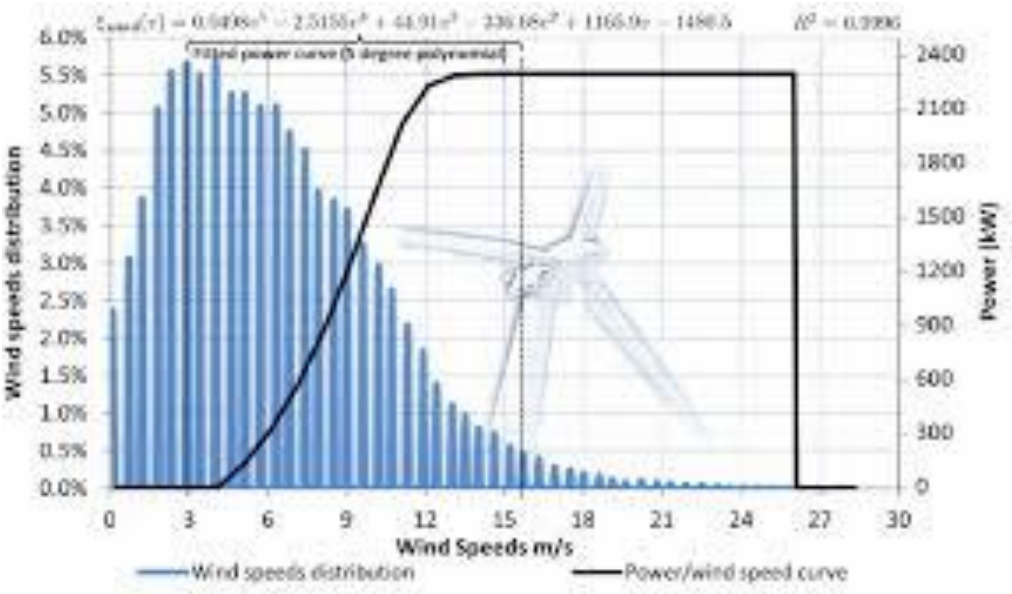
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WIND TURBINES





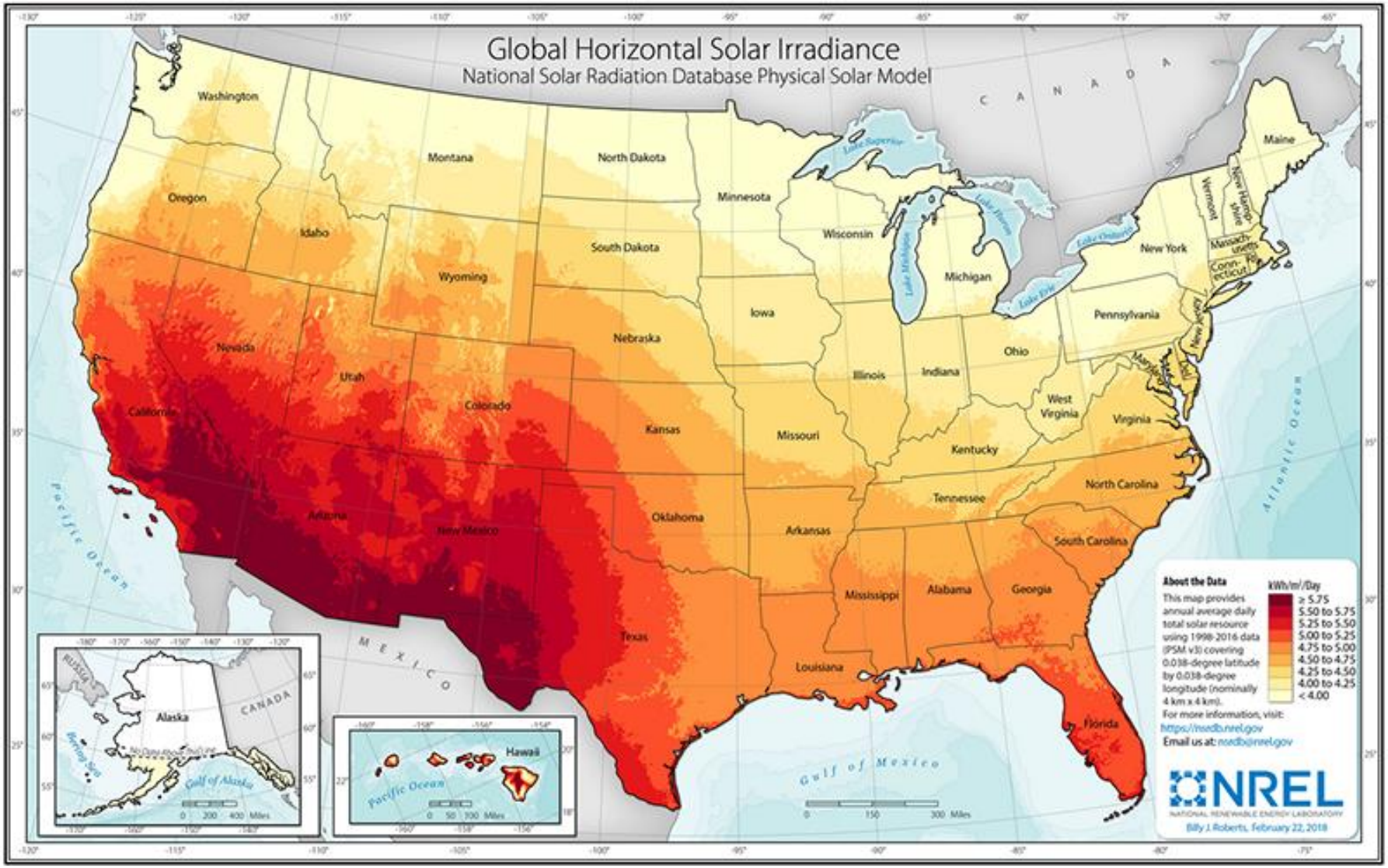




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U.S. SOLAR AVAILABILITY

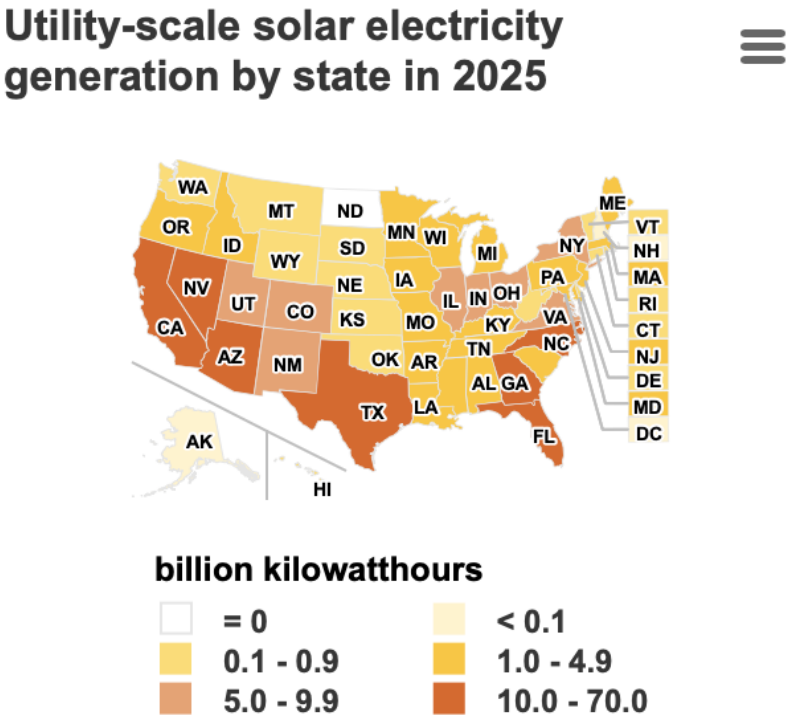


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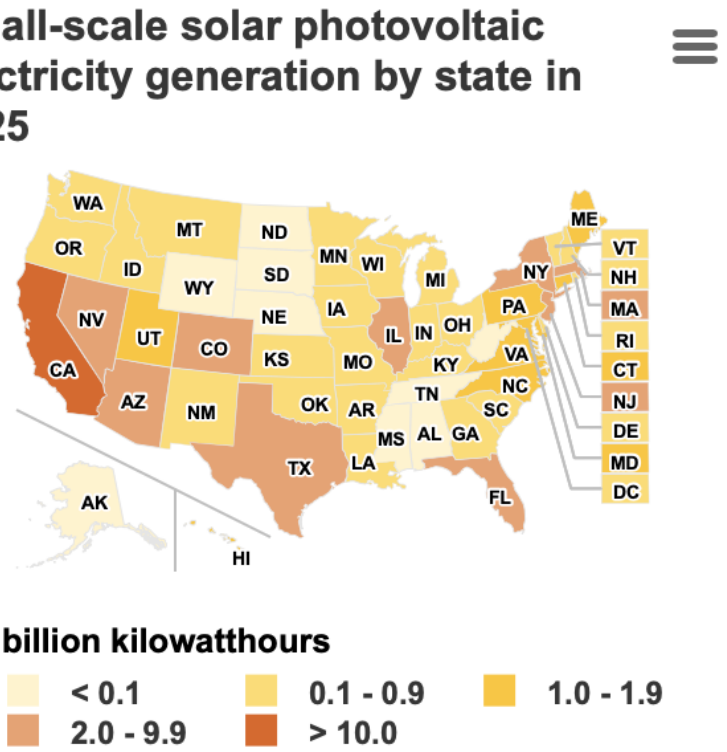
https://www.eia.gov/energyexplained/solar/where-solar-is-found.php

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SOLAR GENERATION BY STATE



Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2026, preliminary data
Note: Includes solar photovoltaic and solar thermal-electric power plants with at least 1 megawatt of alternating current electricity generation capacity.



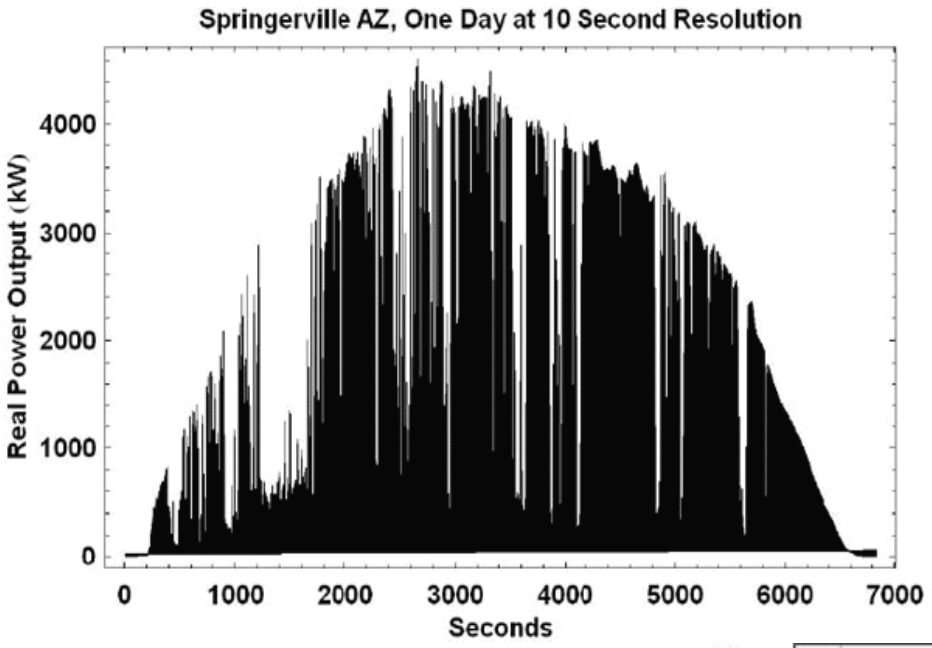
Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2026, preliminary data
Note: Small-scale plants have less than 1 megawatt of alternating current electricity generation capacity.

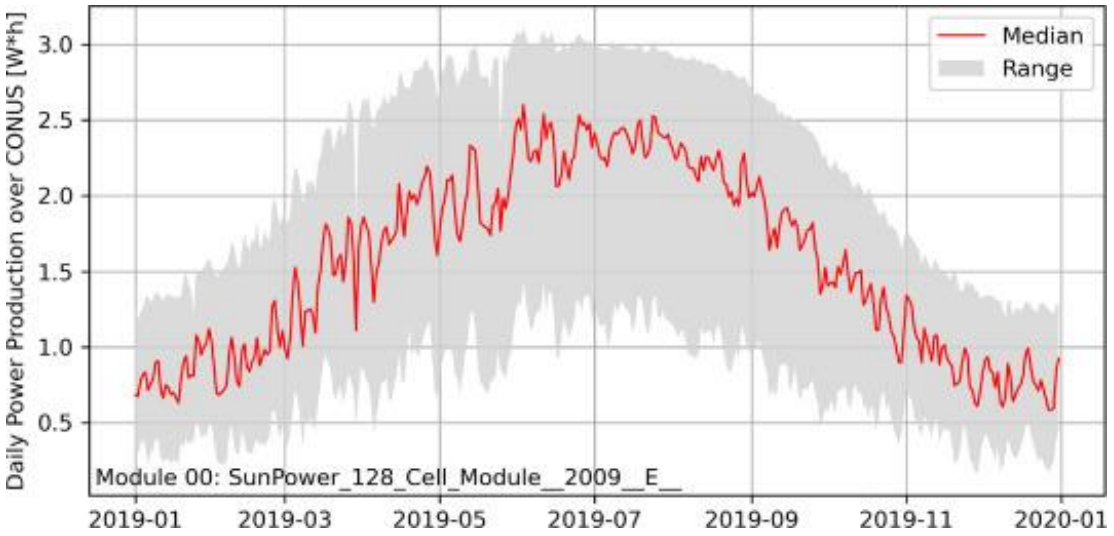
https://www.eia.gov/energyexplained/solar/where-solar-is-found.php

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SOLAR VARIABILITY

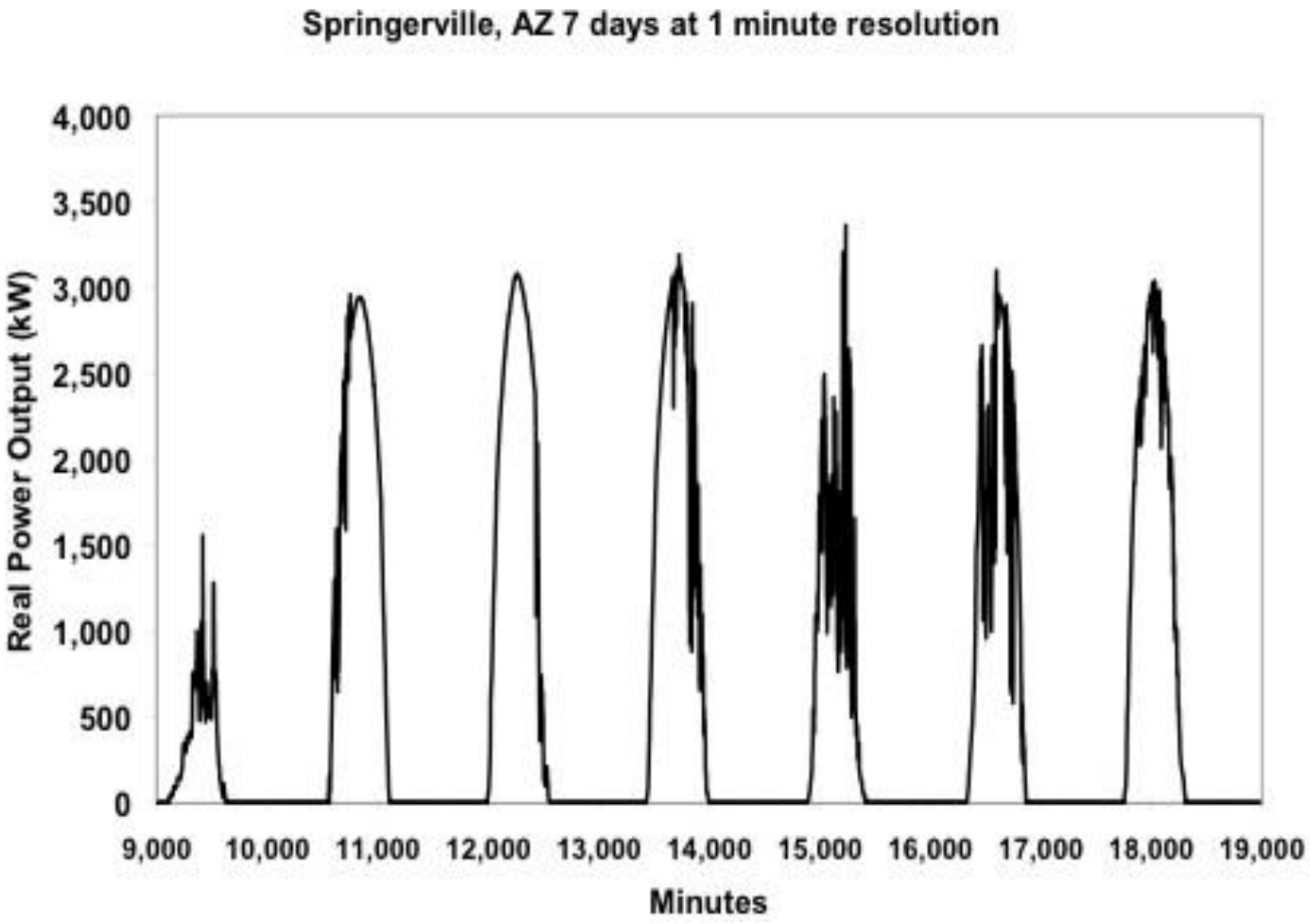




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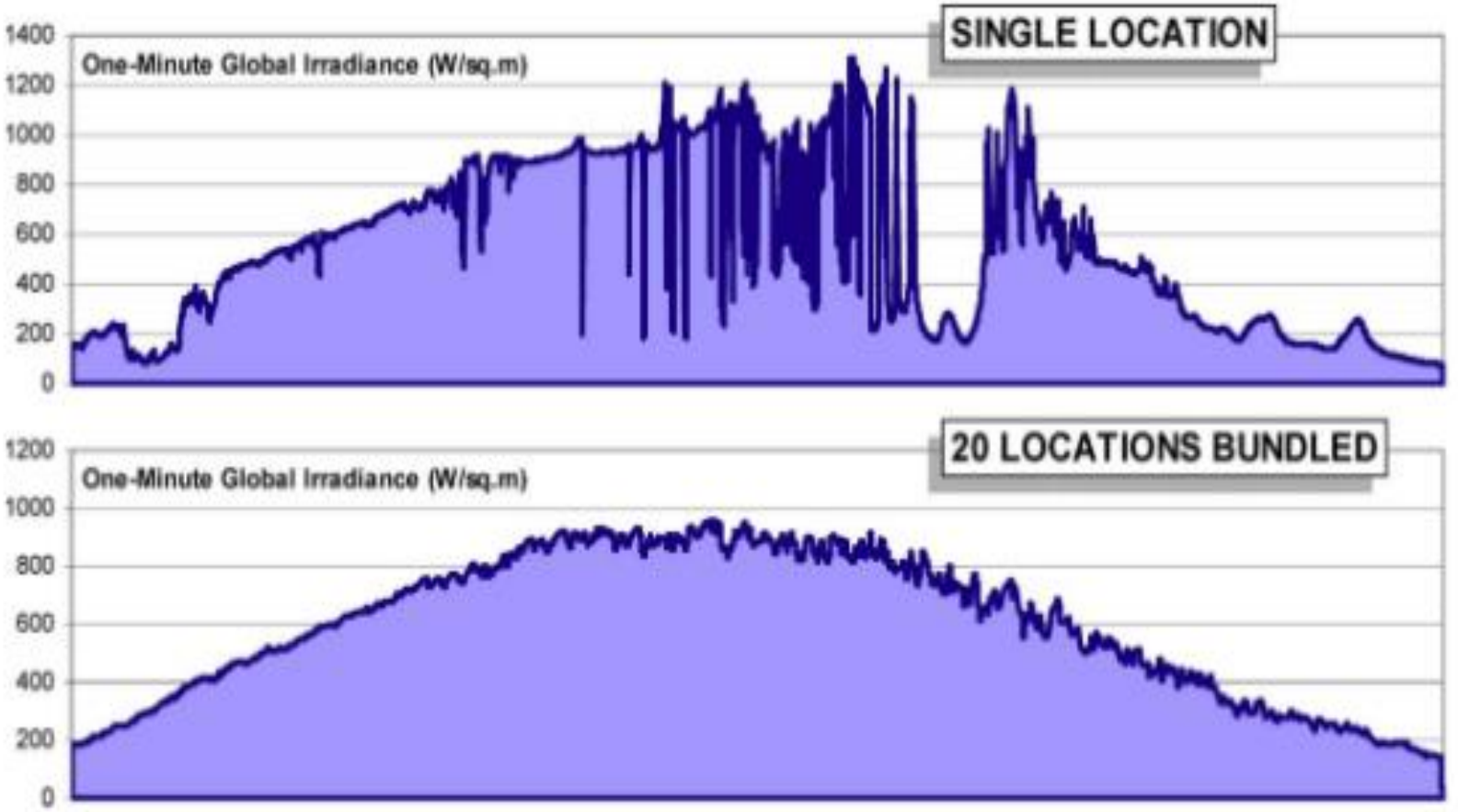
SOLAR VARIABILITY



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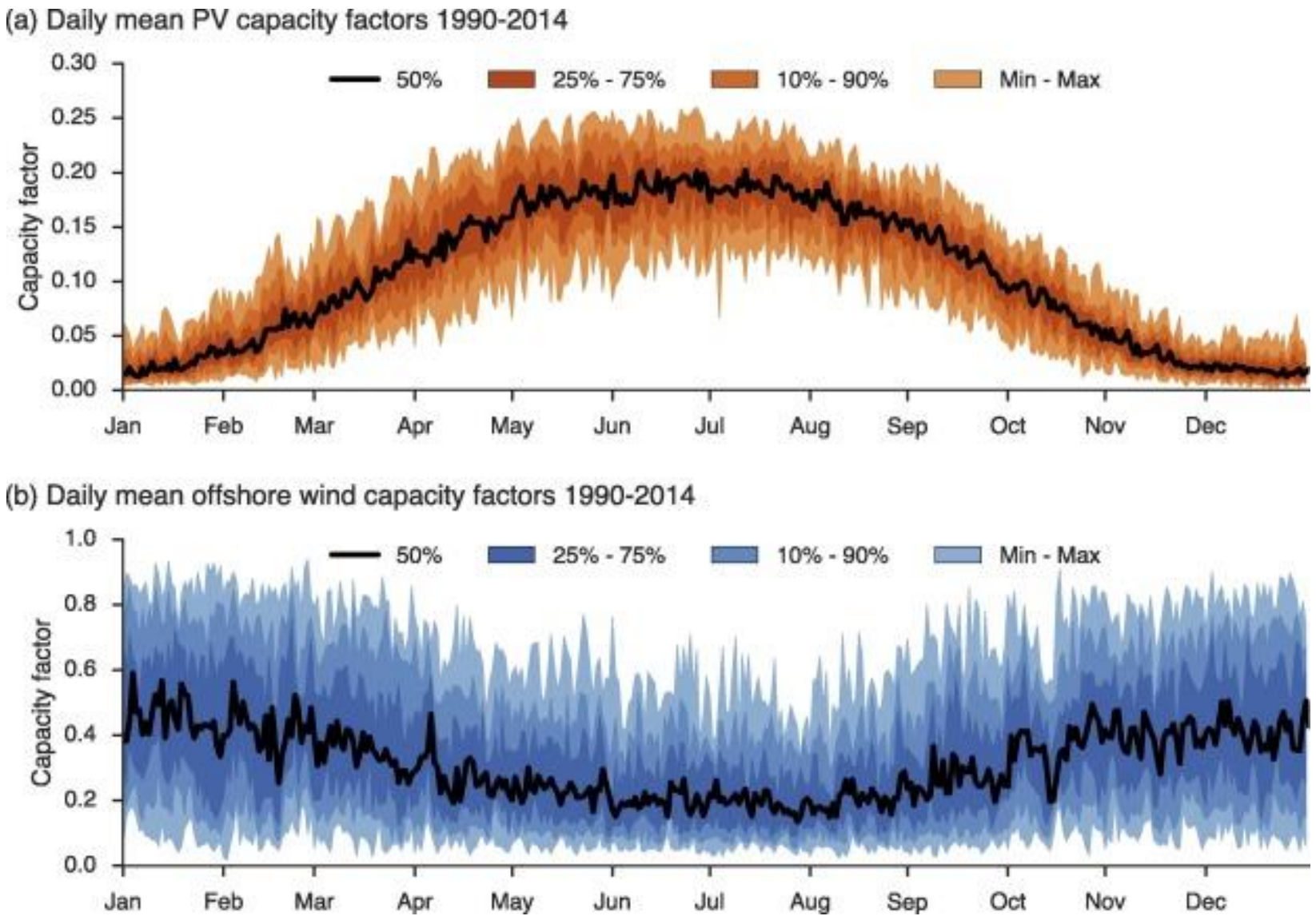
SOLAR VARIABILITY



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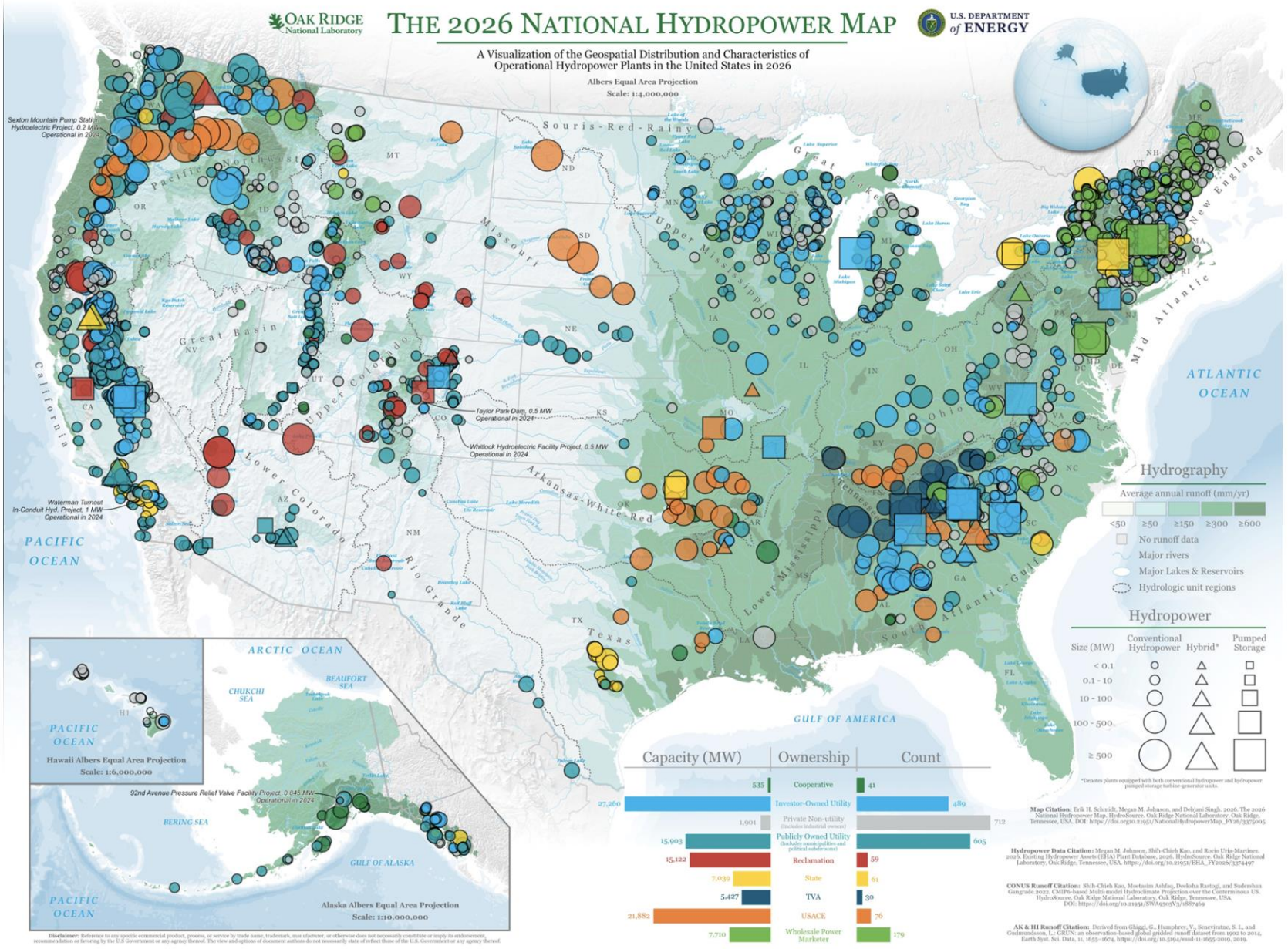
WIND & SOLAR CORRELATION



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

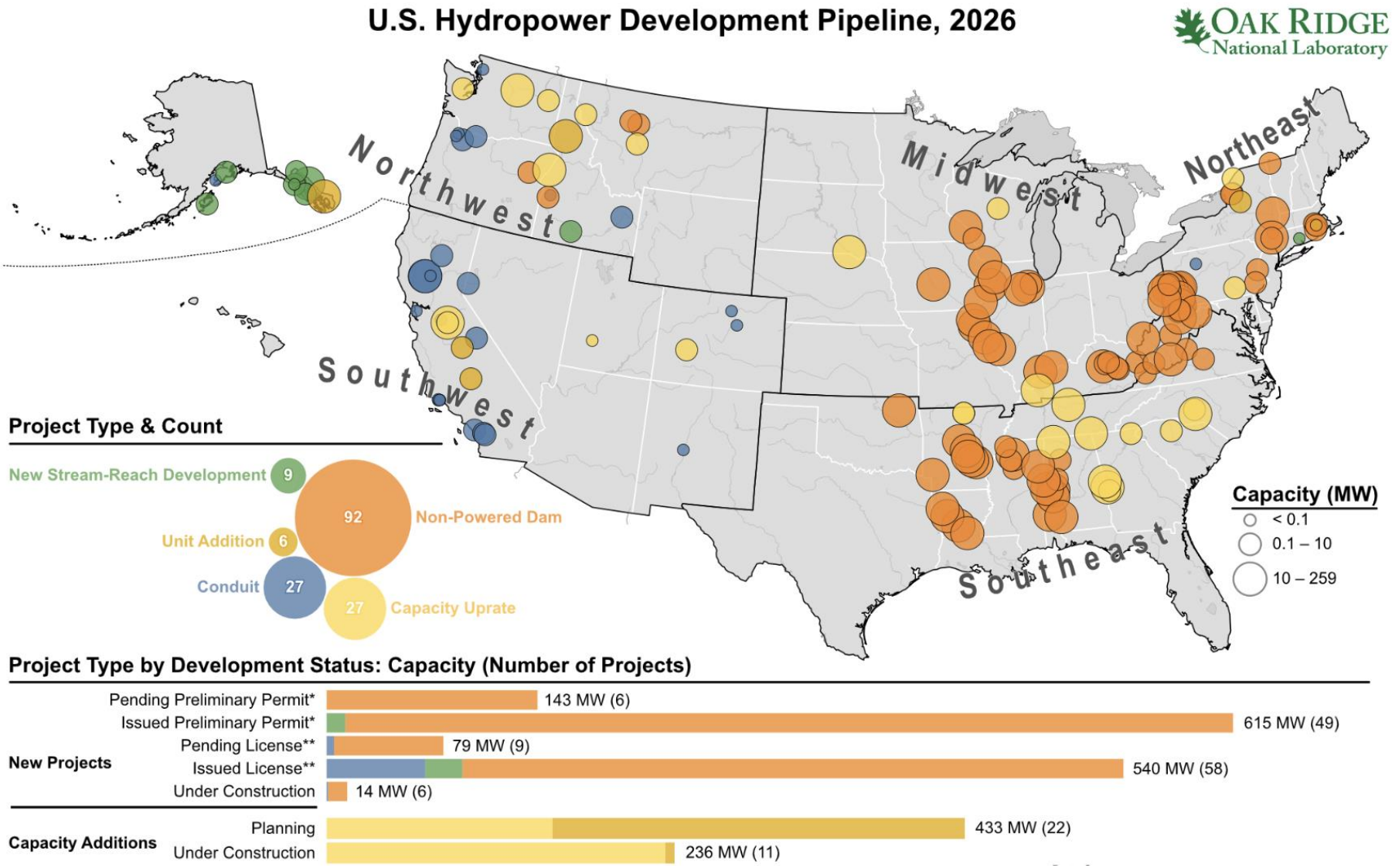
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https://hydrosource.ornl.gov/data/maps/2026-national-hydropower-map/

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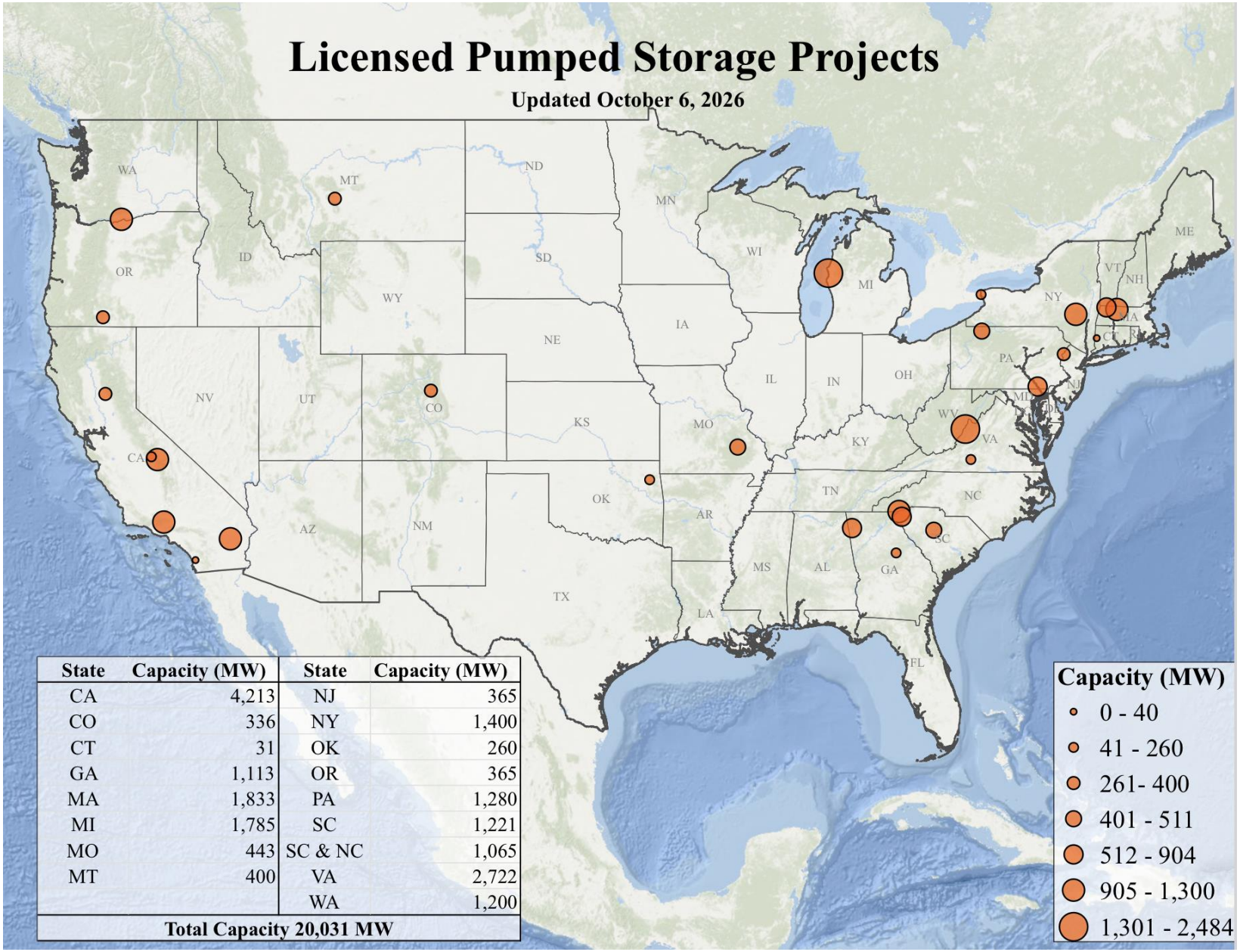
https://hydrosource.ornl.gov/data/datasets/us-hydropower-development-pipeline-data-2026/

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Licensed Pumped Storage Projects

Updated October 6, 2026



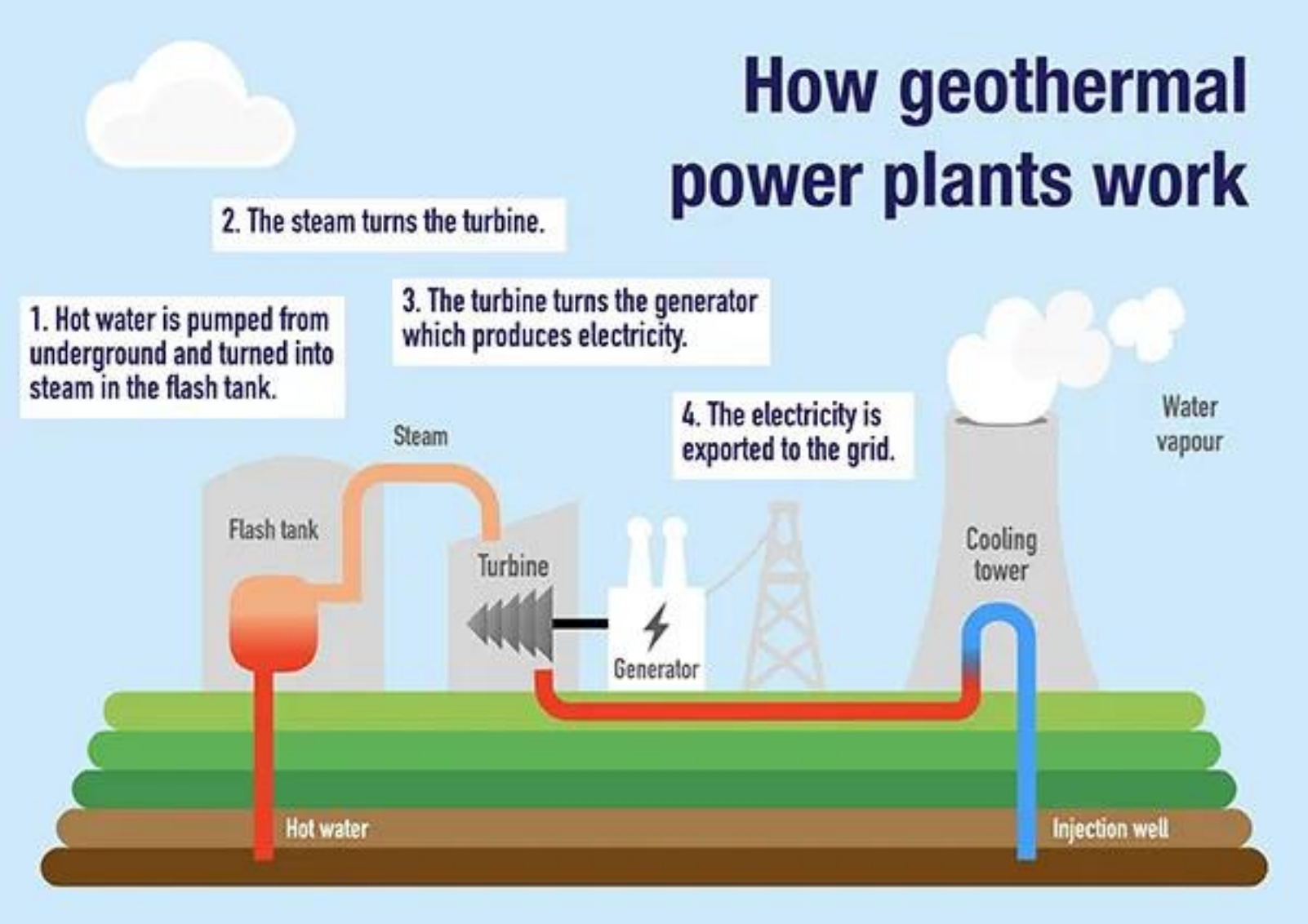
State	Capacity (MW)	State	Capacity (MW)
CA	4,213	NJ	365
CO	336	NY	1,400
CT	31	OK	260
GA	1,113	OR	365
MA	1,833	PA	1,280
MI	1,785	SC	1,221
MO	443	SC & NC	1,065
MT	400	VA	2,722
		WA	1,200
Total Capacity 20,031 MW			

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

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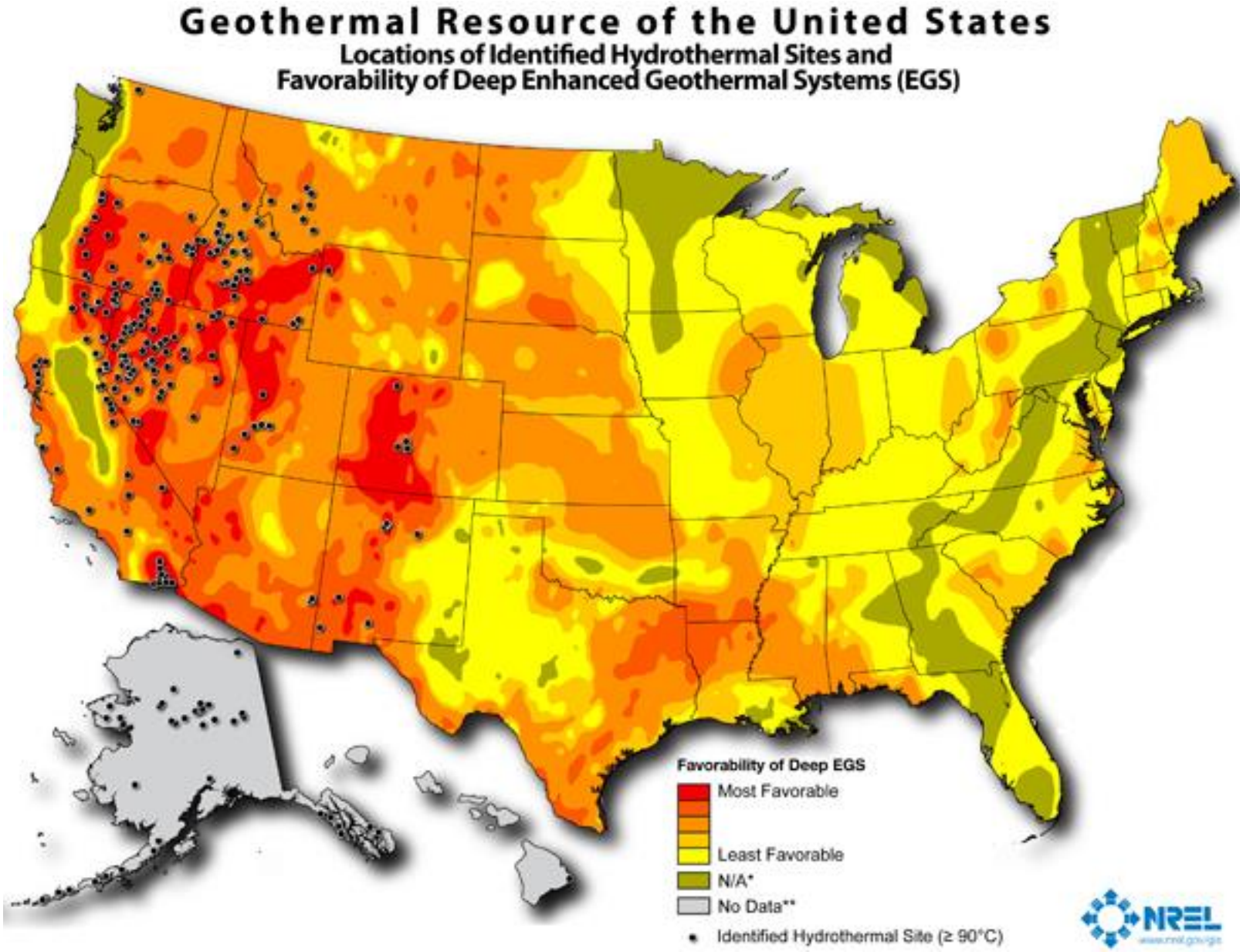
GEOTHERMAL POWER PLANTS



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

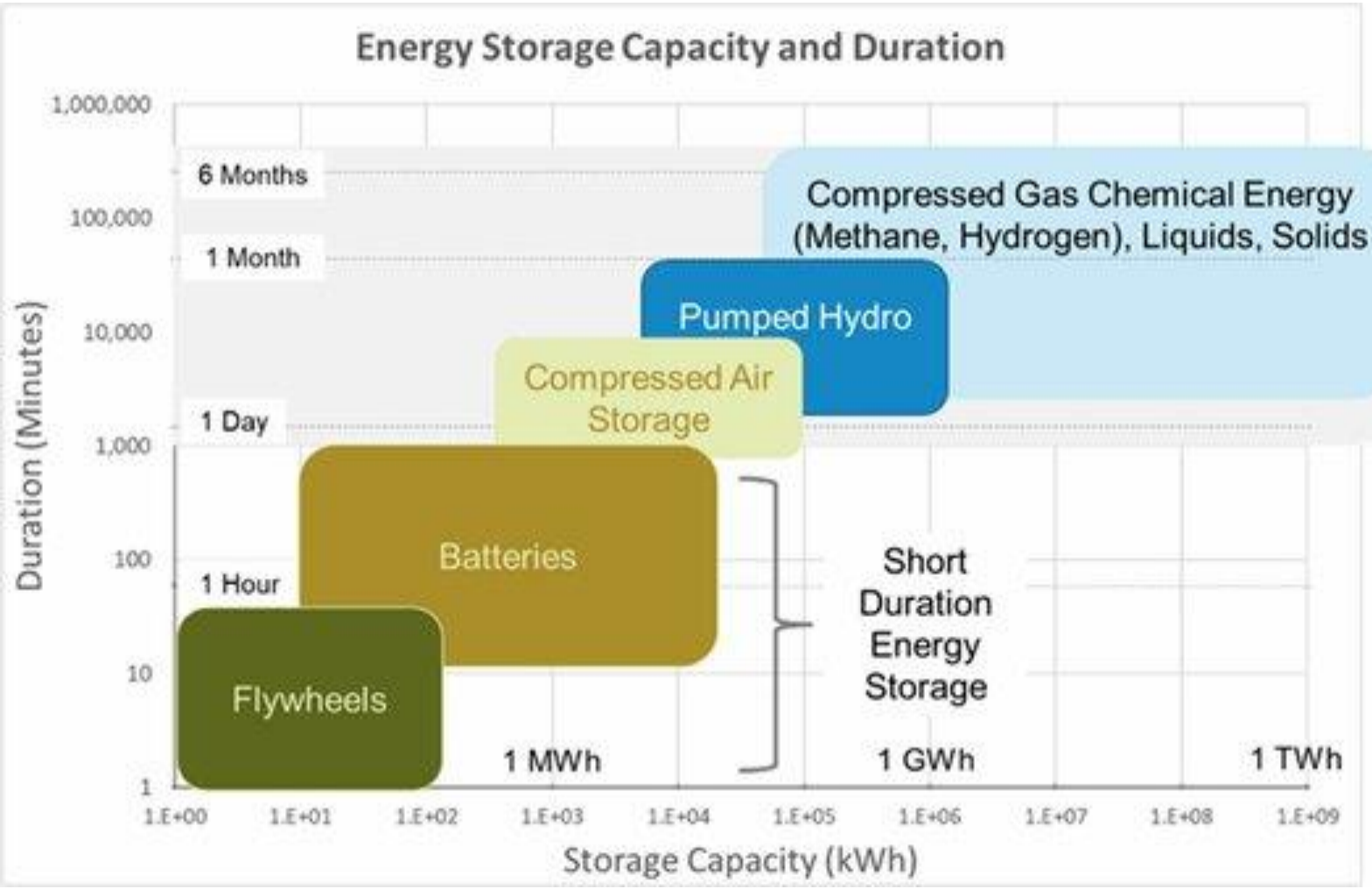
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https://www.eia.gov/todayinenergy/detail.php?id=3970

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

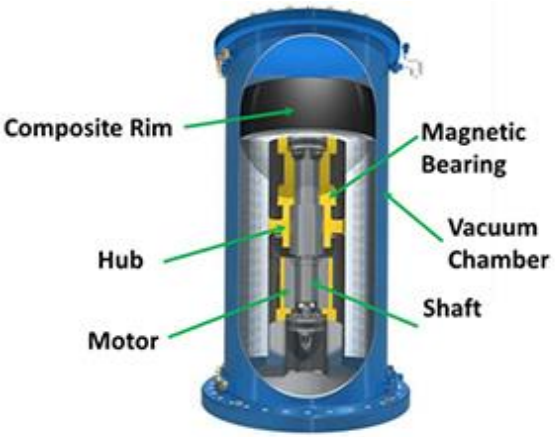
U.S. Department of Energy defines long-duration energy storage as capable of delivering electricity for 10 or more hours

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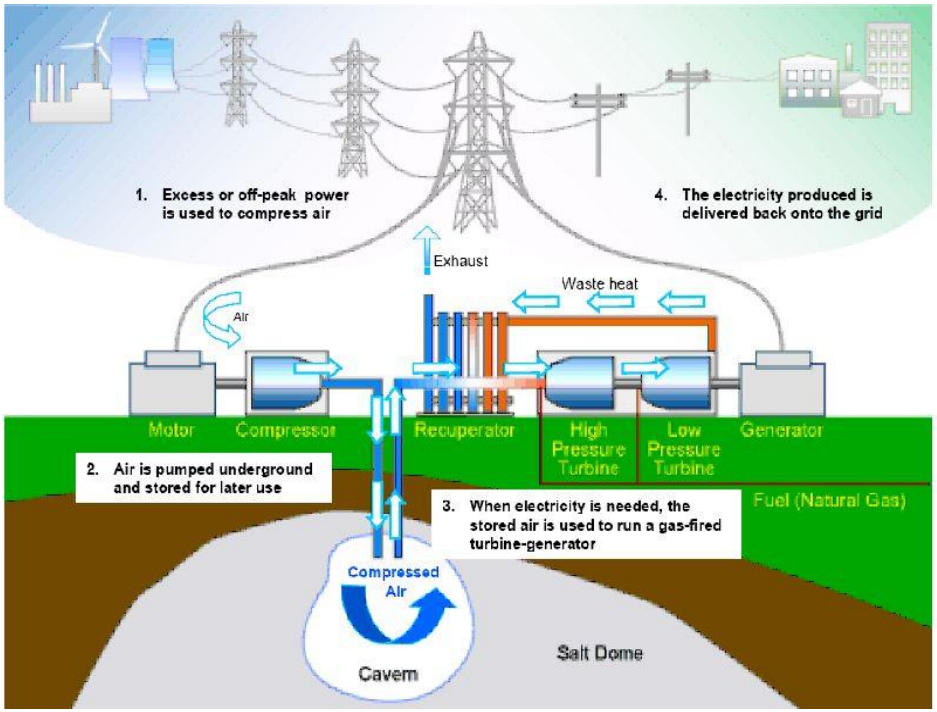
https://www.energy.gov/oced/long-duration-energy-storage

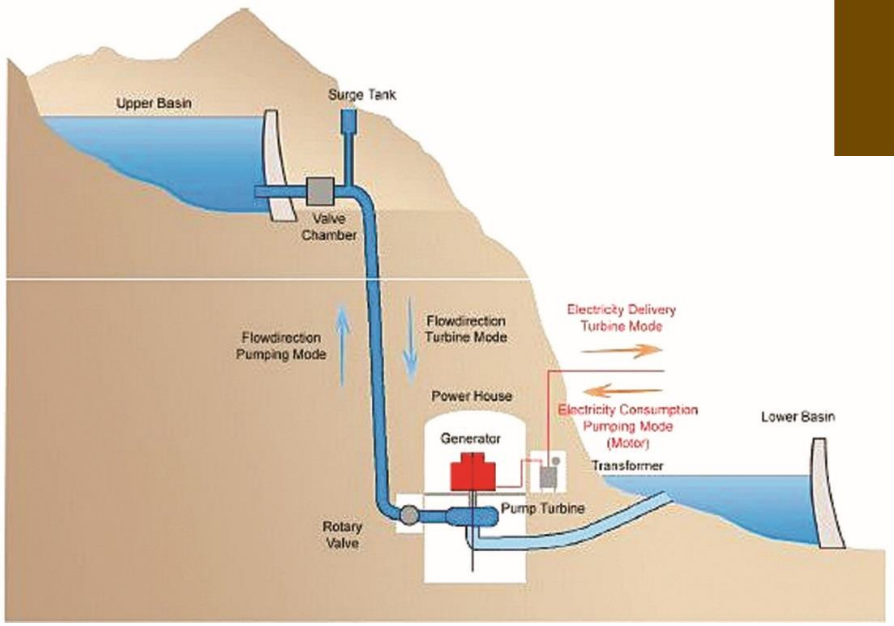
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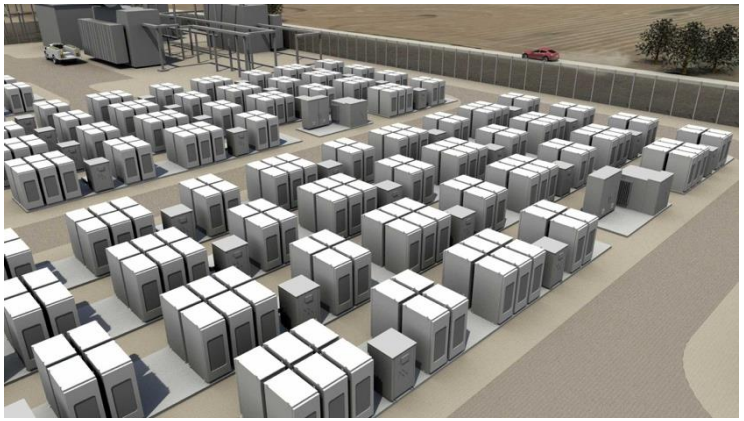
SOLUTIONS TO INTERMITTENCY



Source: Beacon Power, LLC



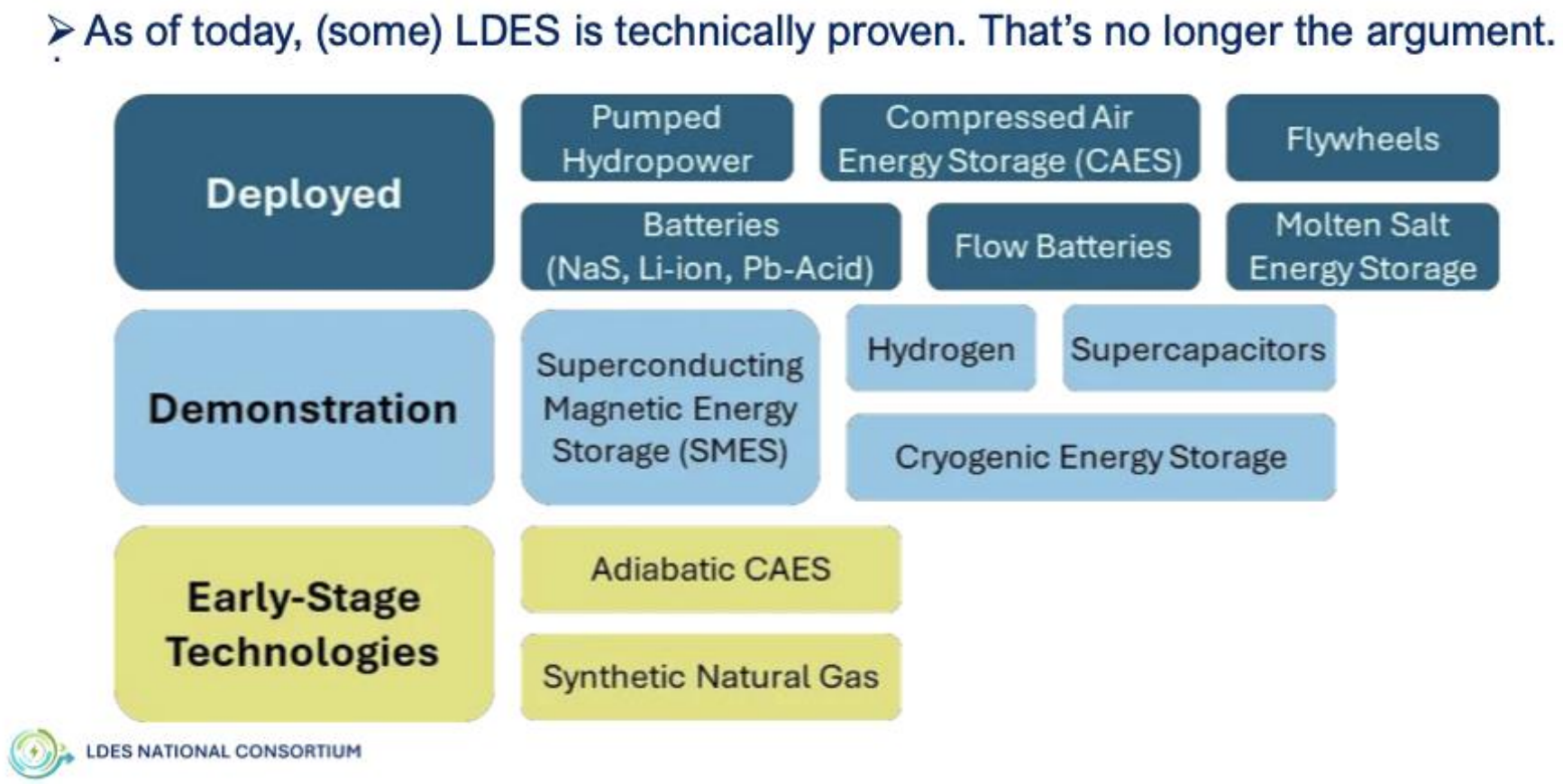




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LONG DURATION ENERGY STORAGE



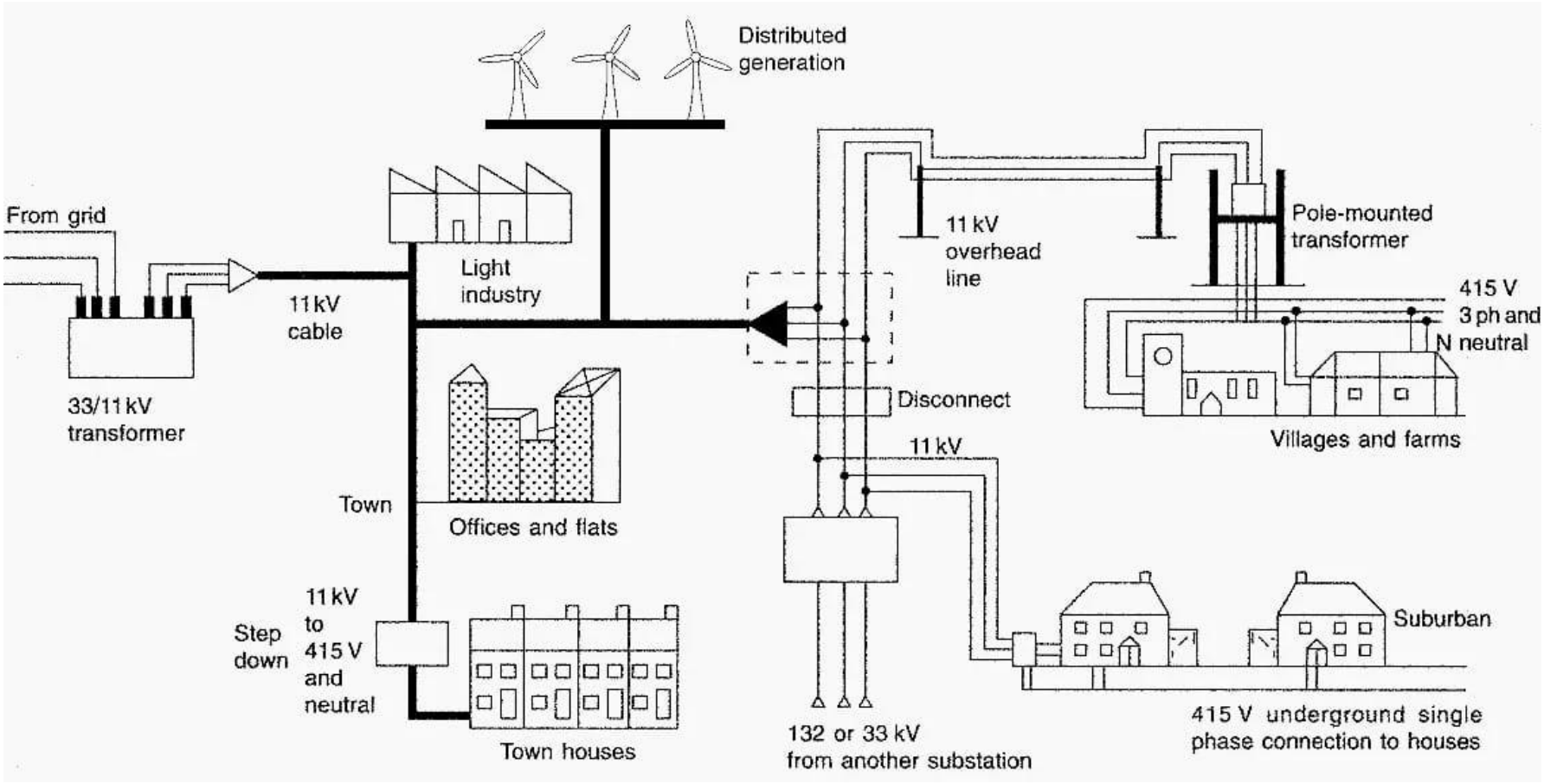
There is no clear 'winner' in the LDES sector. Different technologies ARE serving different customers in different geographies with different applications.

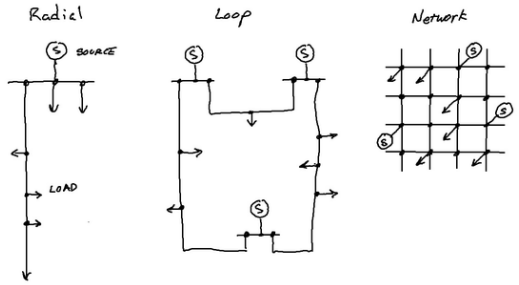
https://www.cleanegroup.org/webinar/the-road-forward-mdes-ldes/

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DISTRIBUTION SYSTEM

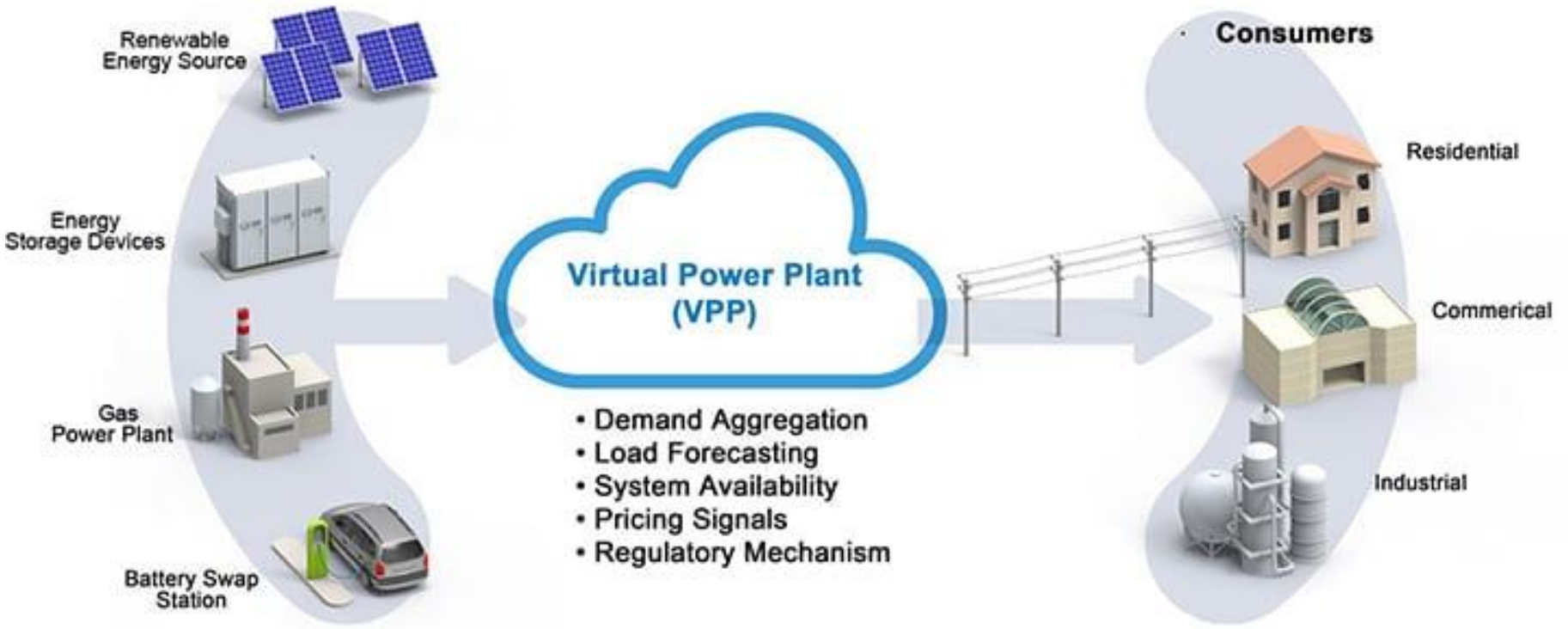




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VIRTUAL POWER PLANTS



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What is being Electrified?

DATA CENTERS

Transportation

- Public Charging Stations
- Electric Vehicles
- Fleet Electrification

Commercial and Industrial

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

Residential

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

Heavy Duty Off-Road

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

Aviation

- Pushbacks
- Belt Loaders
- Baggage Tugs

Agriculture

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

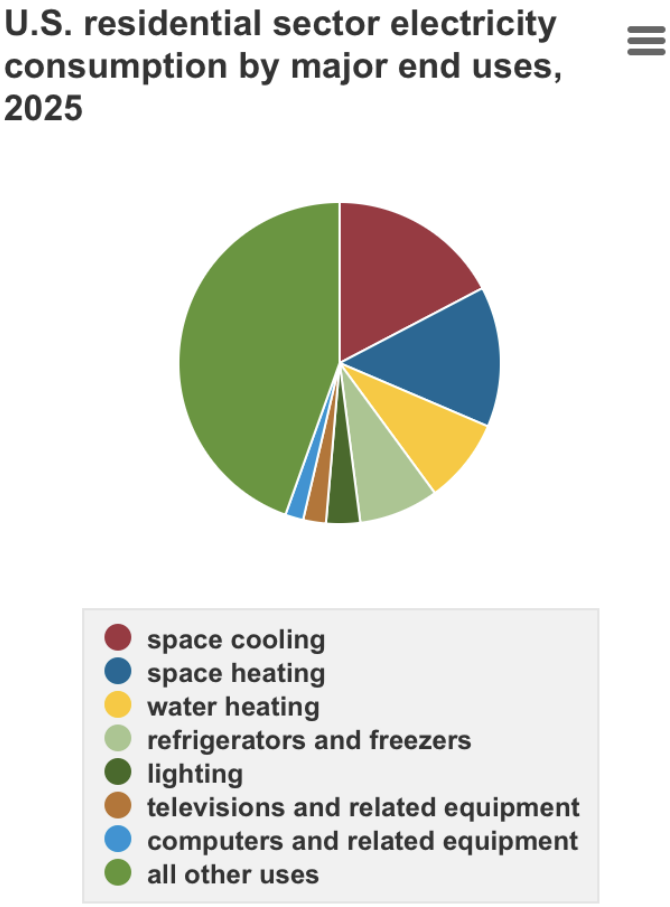


https://www.wtsenergy.com/glossary/electrification/

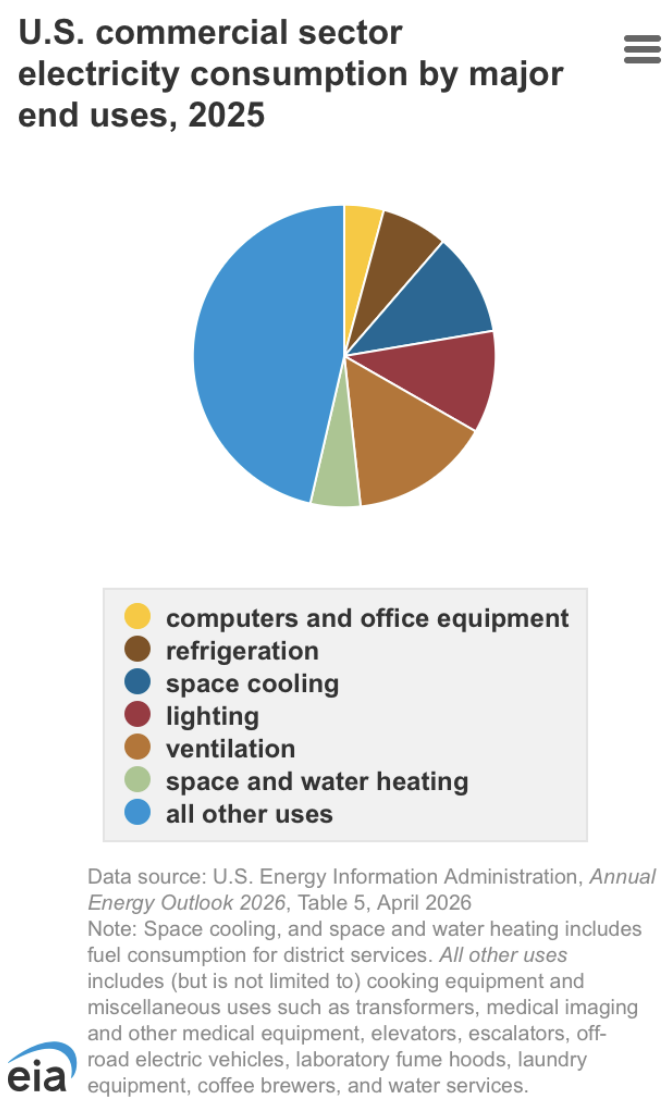
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END USES OF ELECTRICITY



Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2026*, Table 4, April 2026
Note: Space heating includes consumption for heat and for operating furnace fans and boiler pumps. *All other uses* includes clothes washers and dryers, dishwashers, cooking equipment, miscellaneous electric and electronic devices, heating elements, and motors not included in other uses.



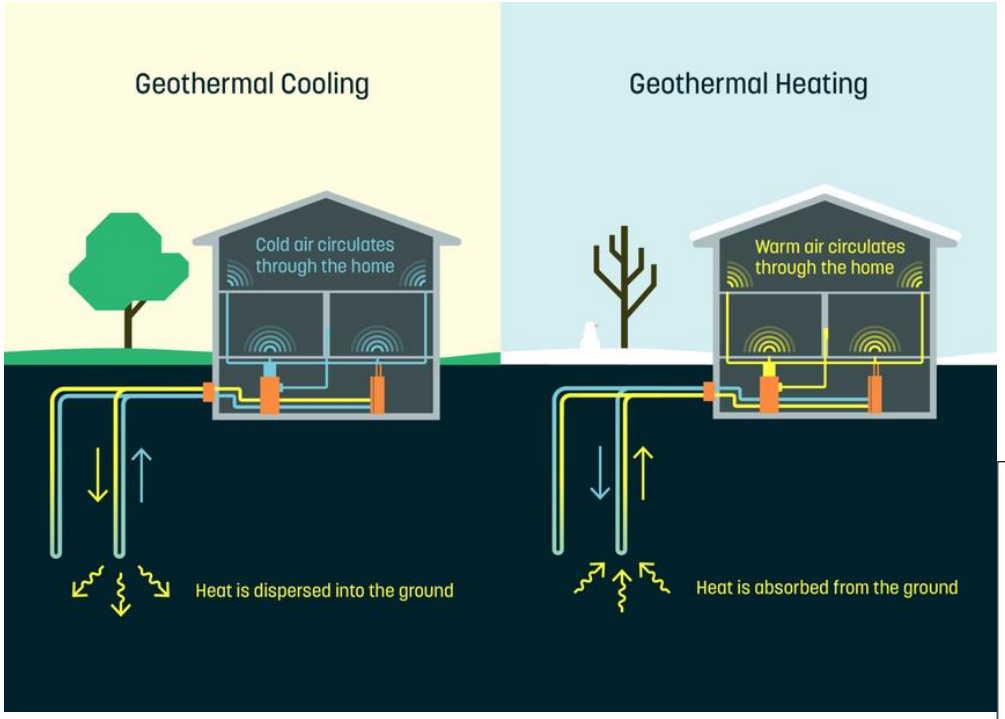
Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2026*, Table 5, April 2026
Note: Space cooling, and space and water heating includes fuel consumption for district services. *All other uses* includes (but is not limited to) cooking equipment and miscellaneous uses such as transformers, medical imaging and other medical equipment, elevators, escalators, off-road electric vehicles, laboratory fume hoods, laundry equipment, coffee brewers, and water services.

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https://www.eia.gov/energyexplained/electricity/use-of-electricity.php

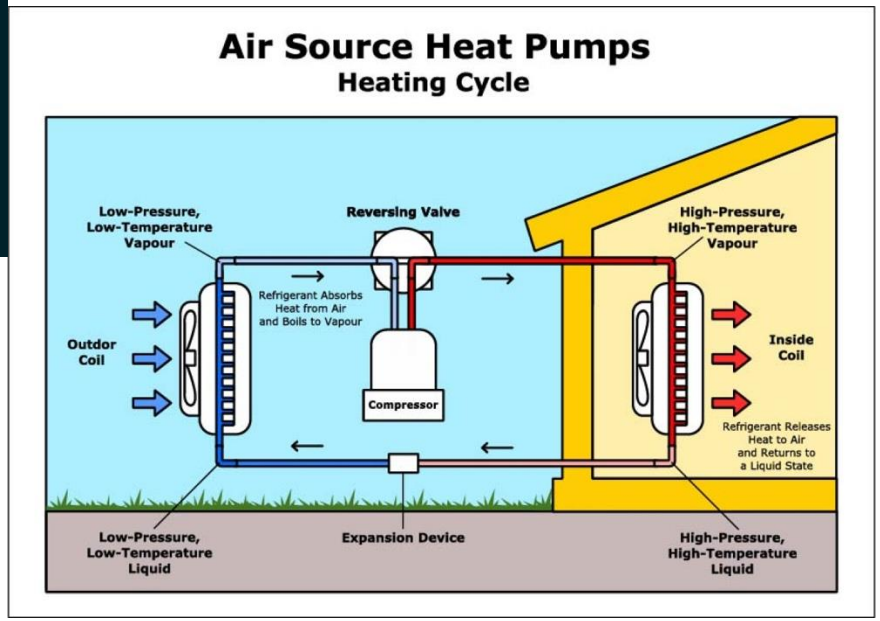
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HEAT PUMPS



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

Can provide both heating and cooling

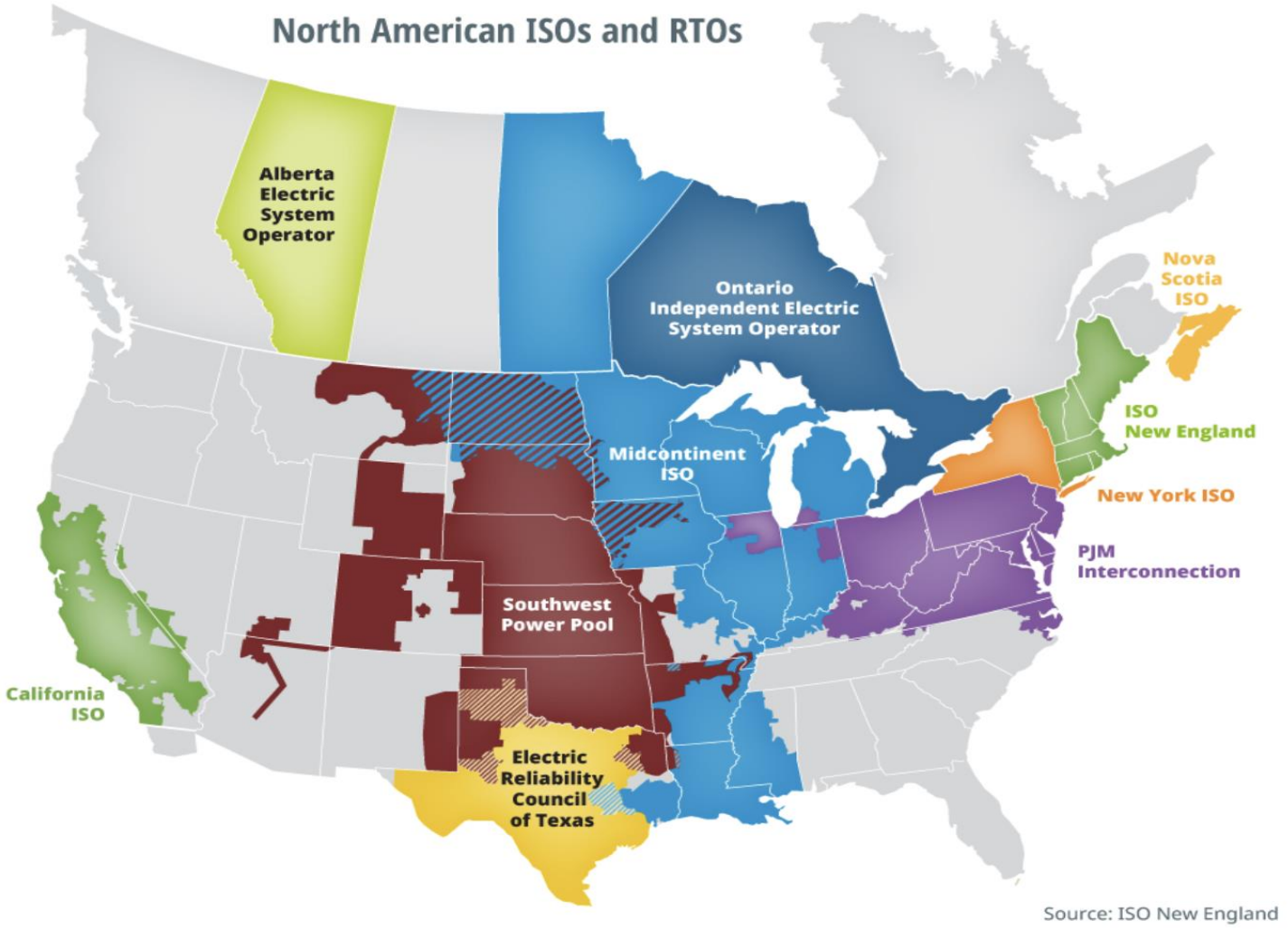


https://www.energy.gov/energysaver/air-source-heat-pumps

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REGIONAL TRANSMISSION ORGANIZATIONS (RTO)/INDEPENDENT SYSTEM OPERATORS (ISO)



https://www.iso-ne.com/about/key-stats/maps-and-diagrams#isos-rtos

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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?

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TERMINOLOGY AND ABBREVIATIONS CHECK

IPPs

ESCO/Load Aggregators

LSEs

GenCo

TransCo

RTO/ISO

PUC/PSC

FERC

Utilities

Capacity

Energy

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Session 2
Power System Fundamentals

Public

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

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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

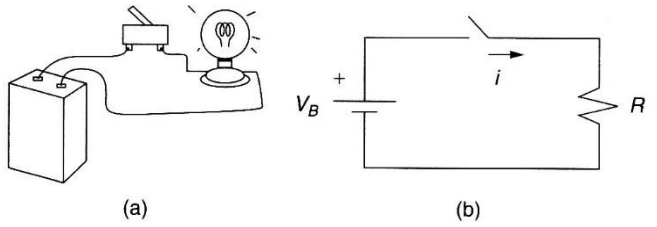
OHM'S LAW

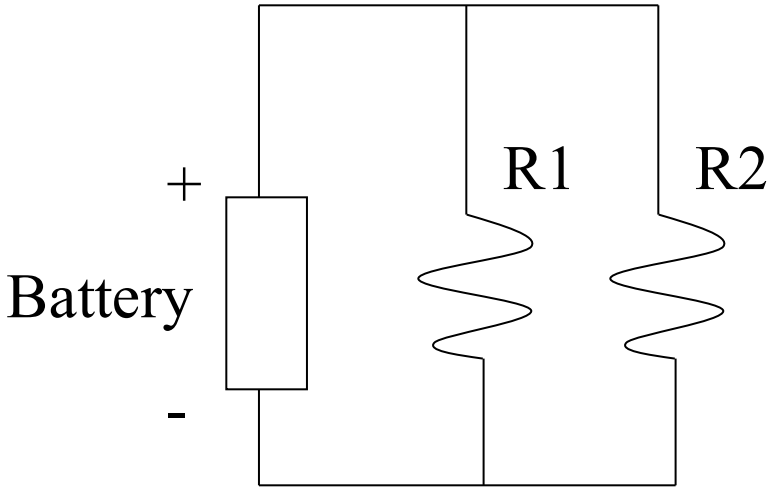
- V = IR

  V is voltage (Volts)

  I is current (Amps)

  R is resistances (Ohms)



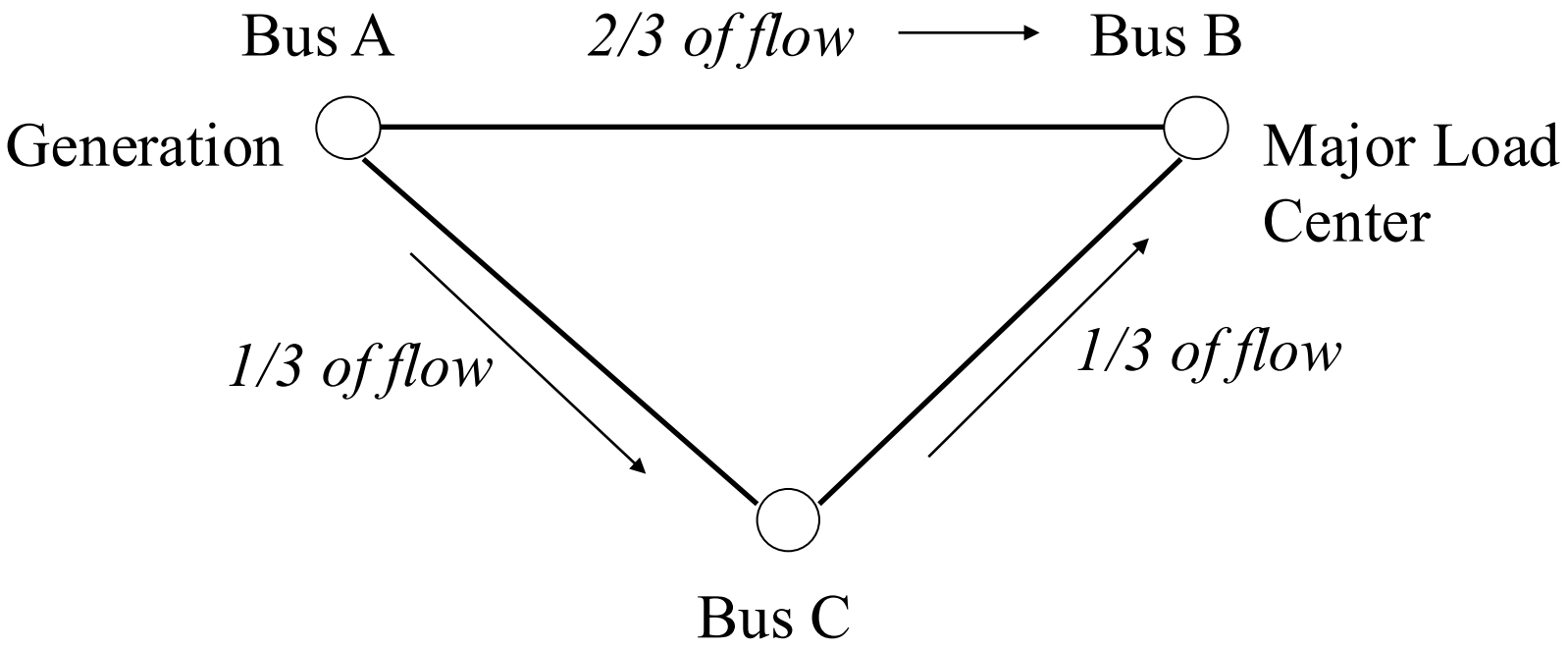


R1 and R2 are resistors, e.g., light bulbs in a flashlight

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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

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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")

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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

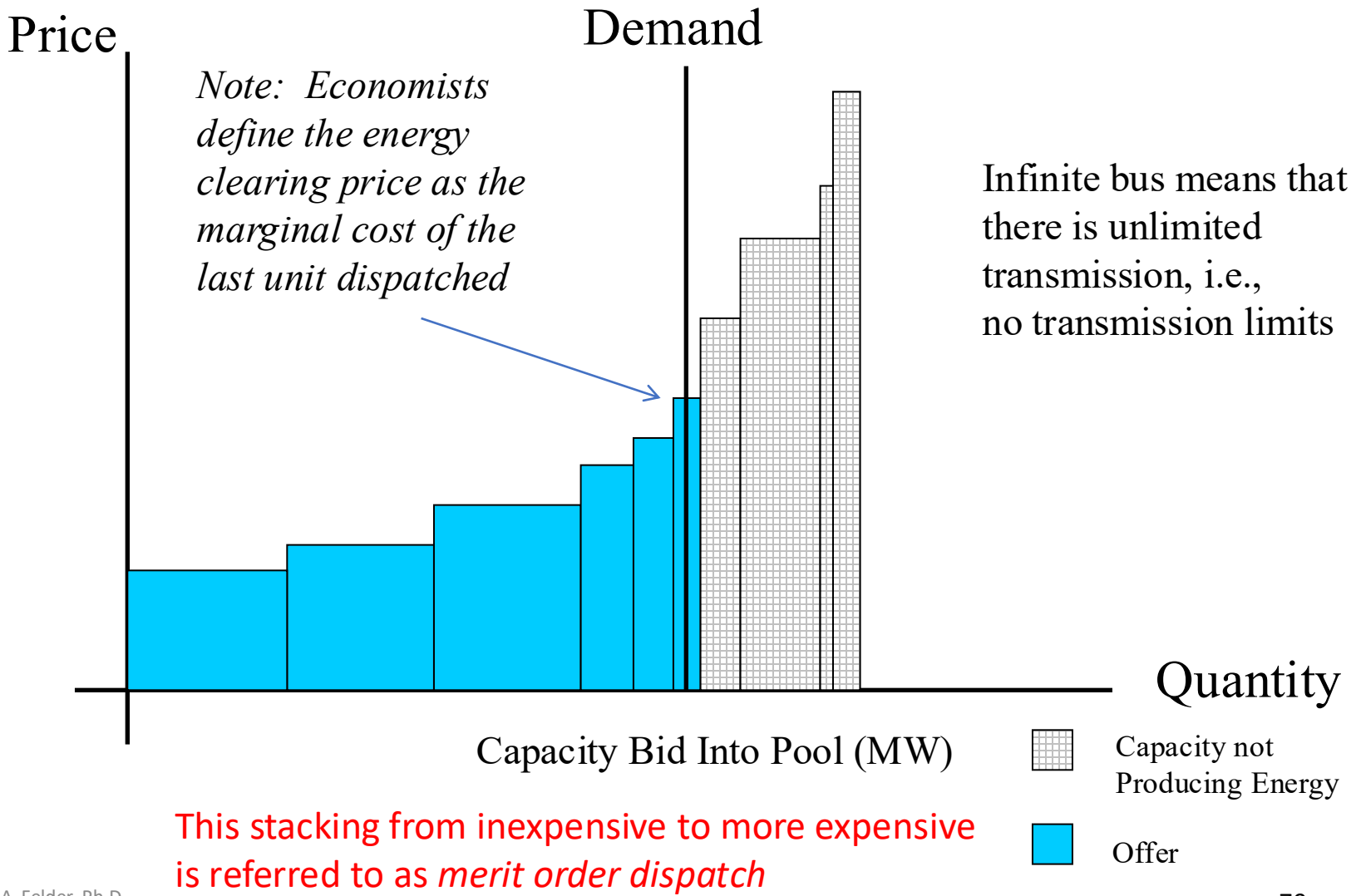
Nodal price (t) = marginal fuel cost + variable maintenance cost + transmission constraints + transmission losses

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

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INFINITE BUS SOLUTION (NO TRANSMISSION CONSTRAINTS)



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

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LOOP FLOW PROBLEM

No Transmission Constraints

3 Bus Example

- Lines have identical impedances
- No transmission losses

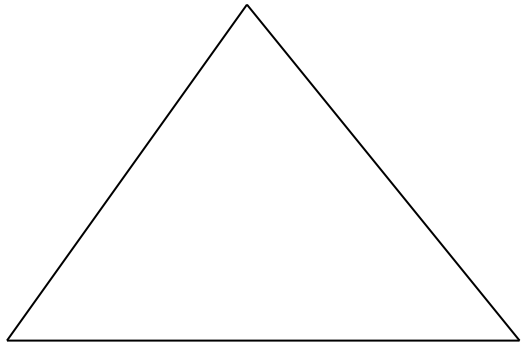
What is the least-cost dispatch?

- 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

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LOOP FLOW PROBLEM

Transmission Constraint

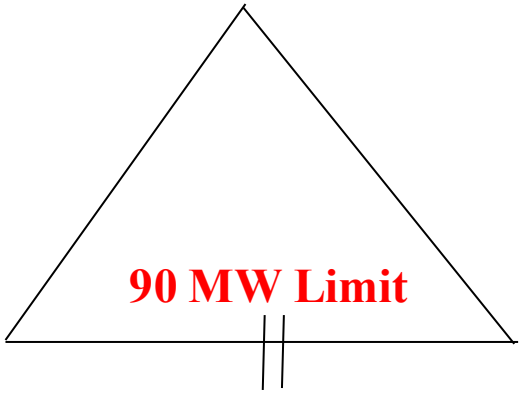
3 Bus Example

- Lines have identical impedances
- No transmission losses

What is the least-cost dispatch?

- With a 90 MW transmission constraint

G1 = 90 MW capacity at $50/MWh



G2 = 150 MW capacity at $30/MWh

Load= 150 MW

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LOOP FLOW SOLUTION

3 Bus Example

- Lines have identical impedances
- No transmission losses

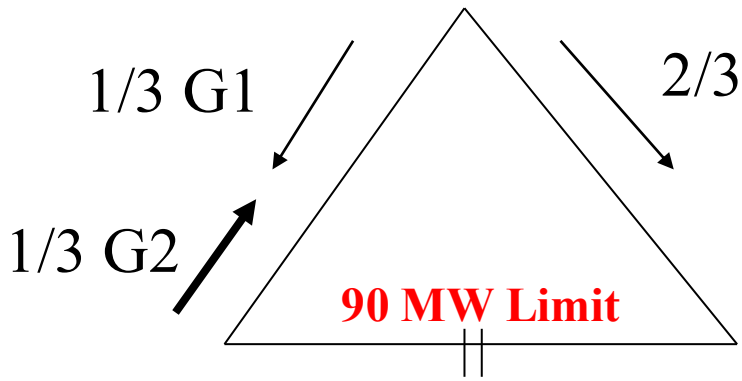
What is the least-cost dispatch?

- With a 90 MW transmission constraint

=> Solution

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

G1 = 90 MW max capacity at $50/MWh



G2 = 150 max Capacity MW At $30/MWh

L= 150 MW

1/3 G1=10 MW

2/3 G2=80 MW

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TRANSMISSION EXPANSION

Reconductor existing lines

Add new transmission lines

Add capacitors

Add power system stabilizers

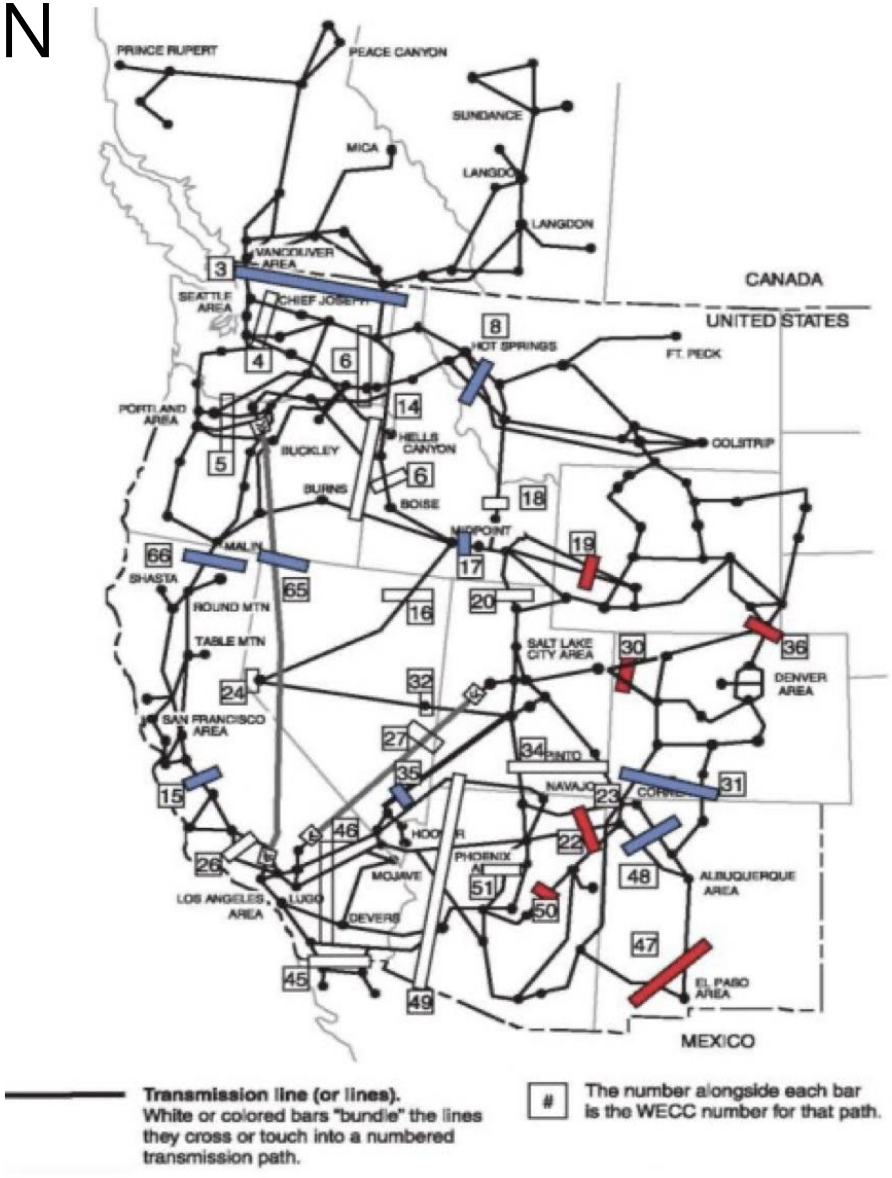
Add FACTS (aka phase angle regulators)

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.

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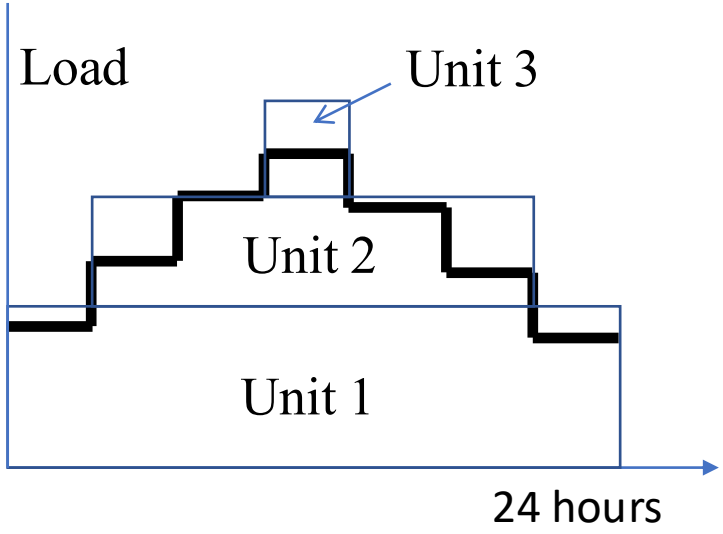
UNIT COMMITMENT

Unit Commitment: 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.

Dispatch: 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.

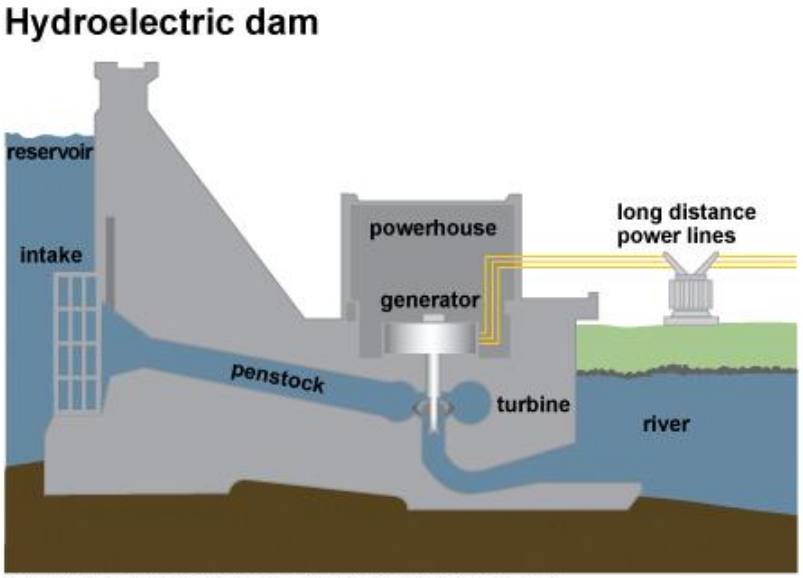


Note: Unit commitment is much more complicated than dispatching and requires a more sophisticated algorithm and longer run time.

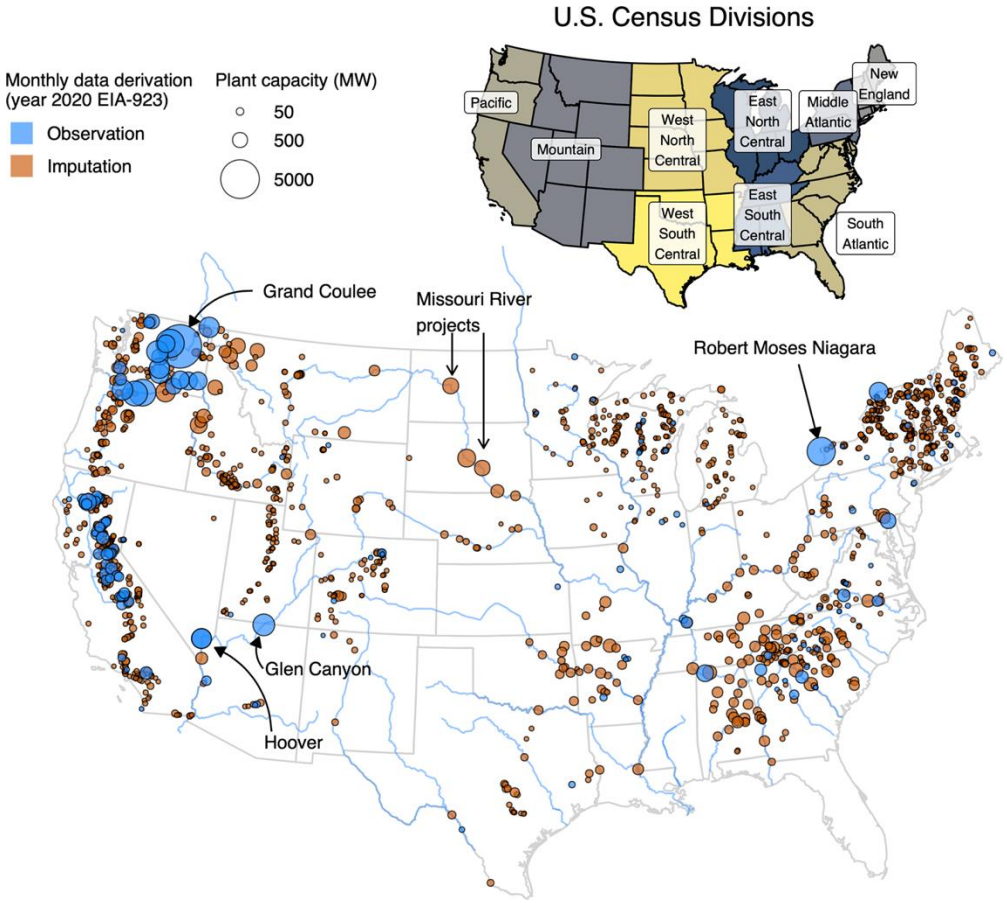
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HYDROELECTRIC SCHEDULING



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

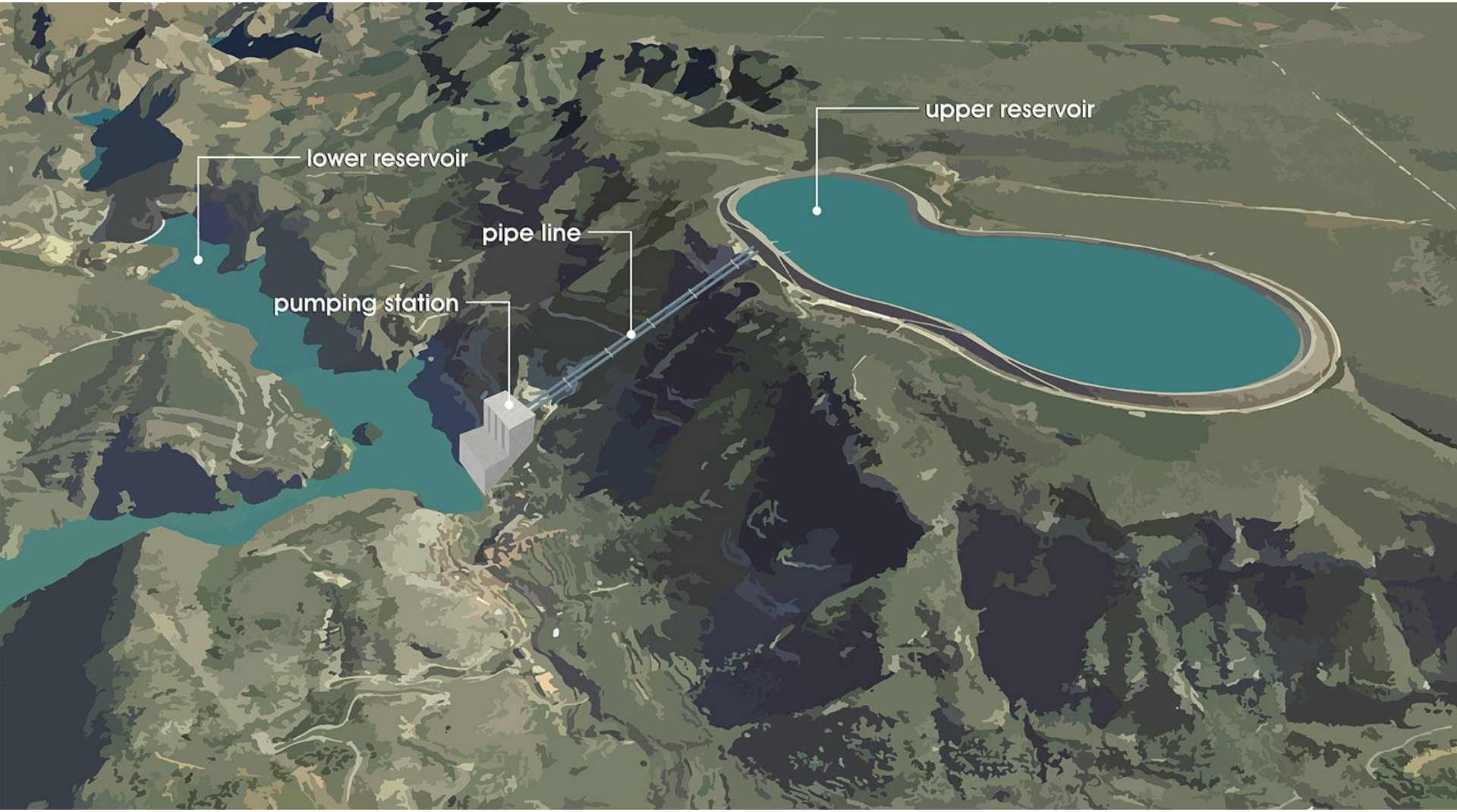


- Upstream plans affect downstream
- Different time periods for scheduling, seasonal, daily
- Hydro unit constraints: recreational, flooding, irrigation, fishing, waterway navigation

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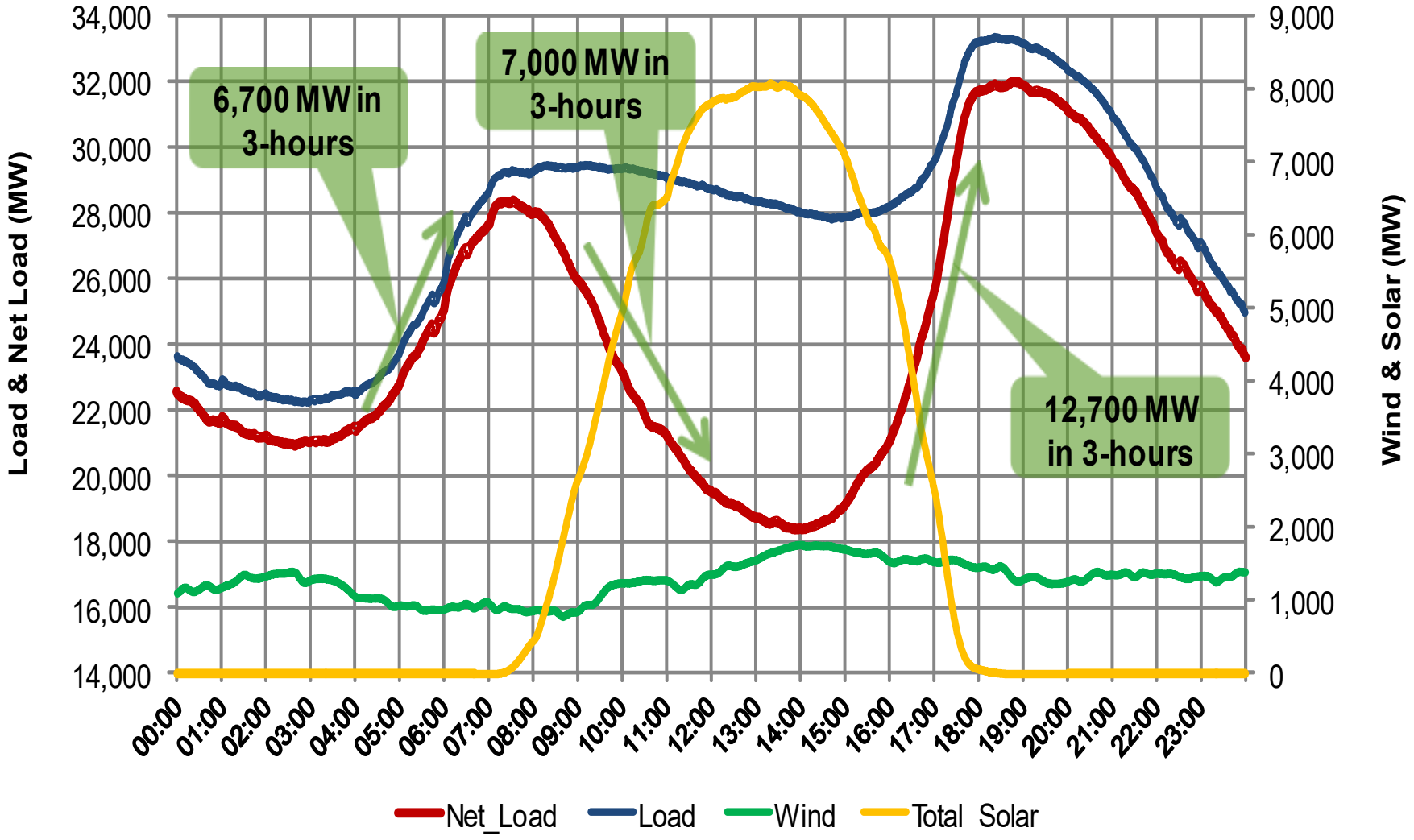
PUMP STORAGE



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"DUCK DIAGRAM"



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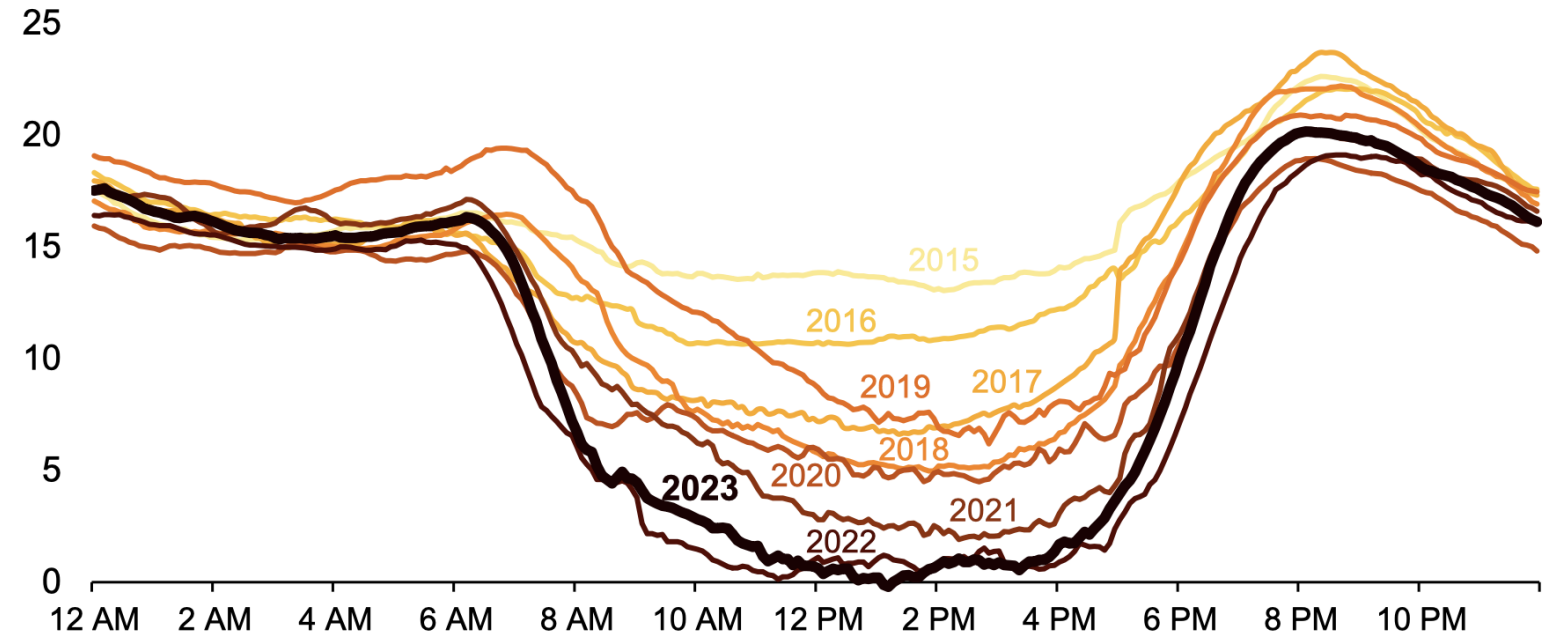
"DUCK DIAGRAM" AND NET LOAD

JUNE 21, 2023

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

California's duck curve is getting deeper

CAISO lowest net load day each spring (March–May, 2015–2023), gigawatts



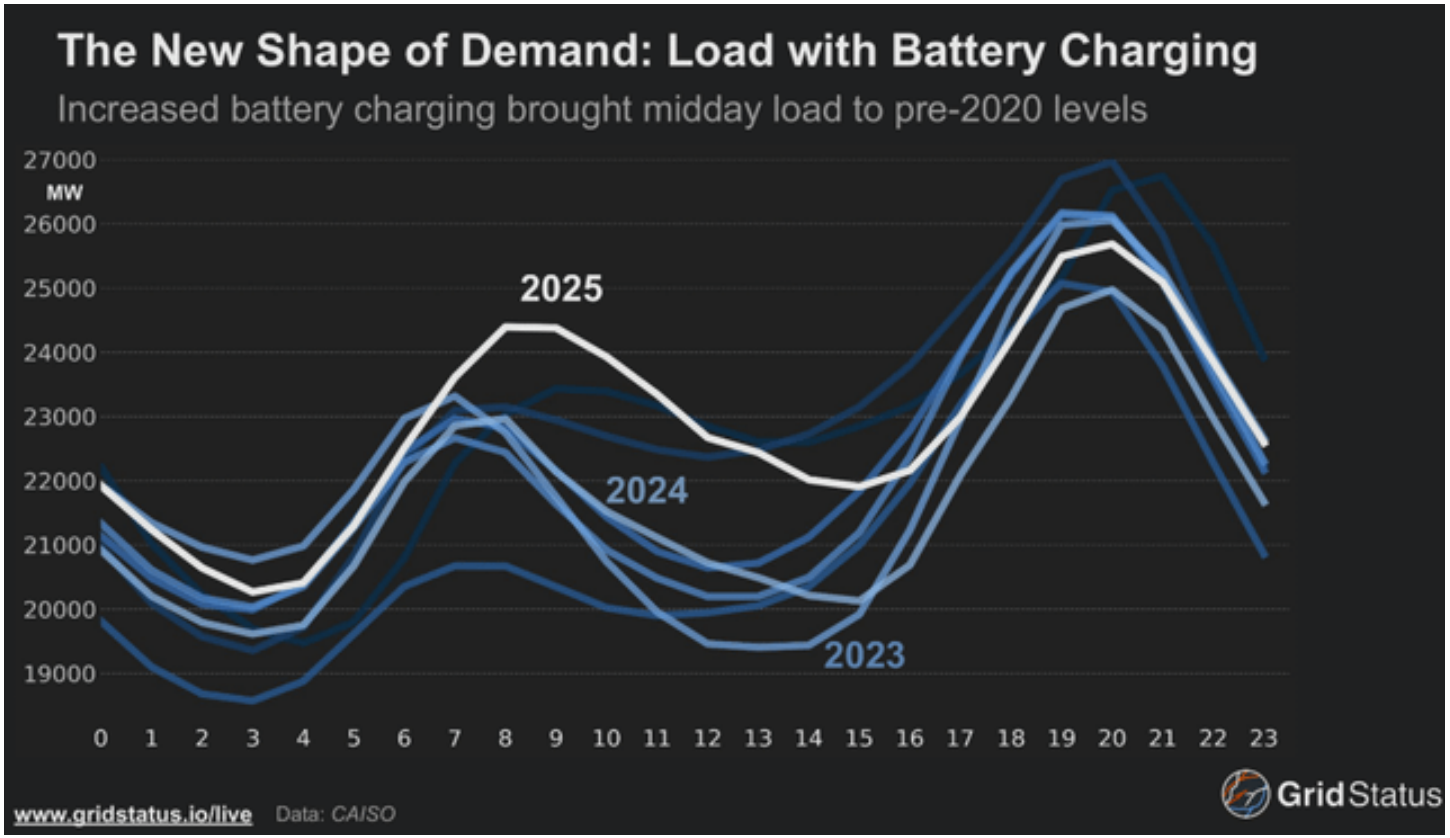
Data source: California Independent System Operator (CAISO)

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

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BATTERY ENERGY STORAGE IS CHANGING THE DUCK DIAGRAM



The most significant operational change to the diagram is the introduction of utility-scale and residential **battery energy storage systems (BESS)**. By charging batteries during the midday solar surplus (absorbing the "belly") and discharging that electricity when the sun sets (shaving off the "head"), grid operators are actively **"flattening the duck.**

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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 transmis-sion 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

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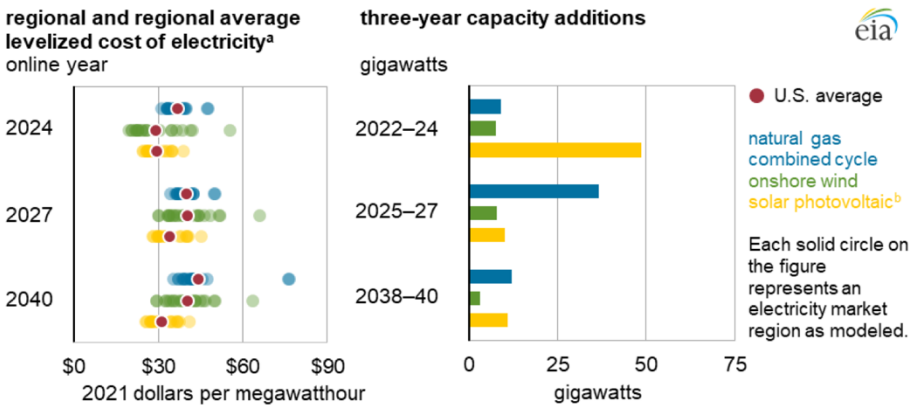
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LEVELIZED COST OF ELECTRICITY LIMITATIONS

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

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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>

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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

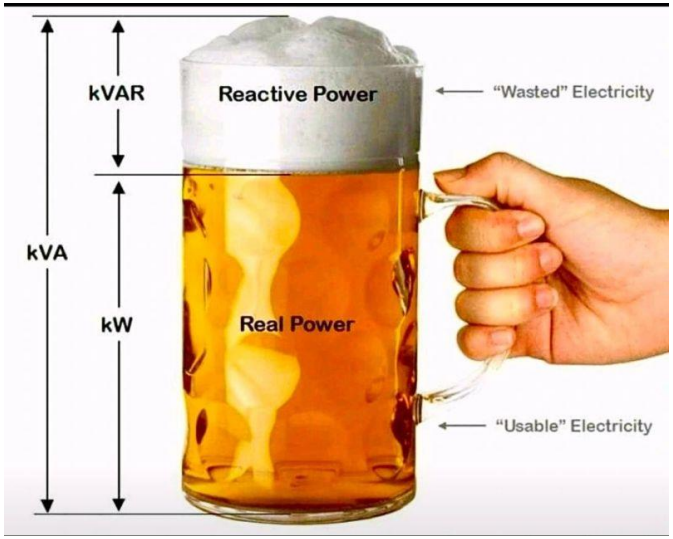
POWER is the rate at which energy is used or supplied (analogous to speed)

- 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

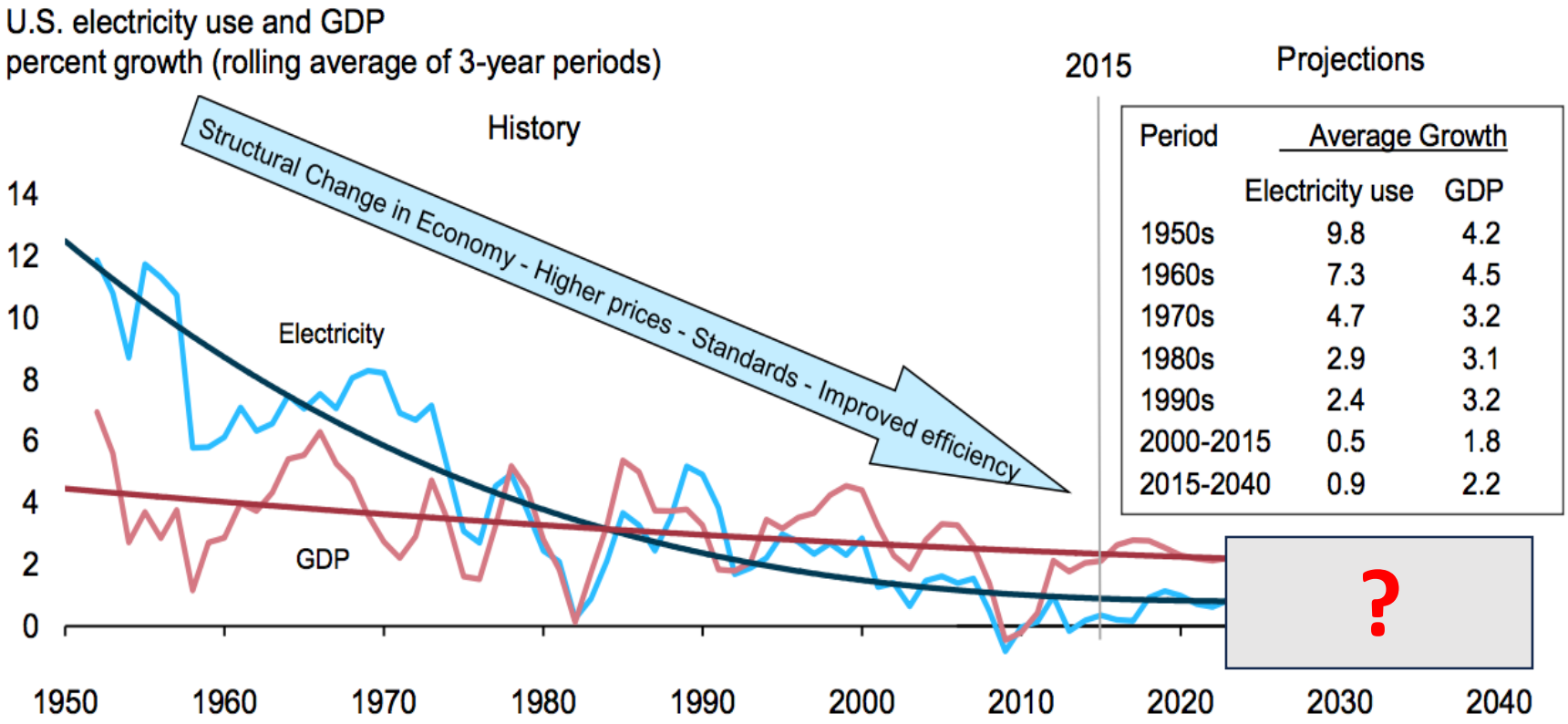
See the FERC Staff Report (2005) *Principles for Efficient and Reliable Reactive Power Supply and Consumption*



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GDP & ELECTRICITY DEMAND GROWTH RATE



Period	Average Growth	
	Electricity use	GDP
1950s	9.8	4.2
1960s	7.3	4.5
1970s	4.7	3.2
1980s	2.9	3.1
1990s	2.4	3.2
2000-2015	0.5	1.8
2015-2040	0.9	2.2

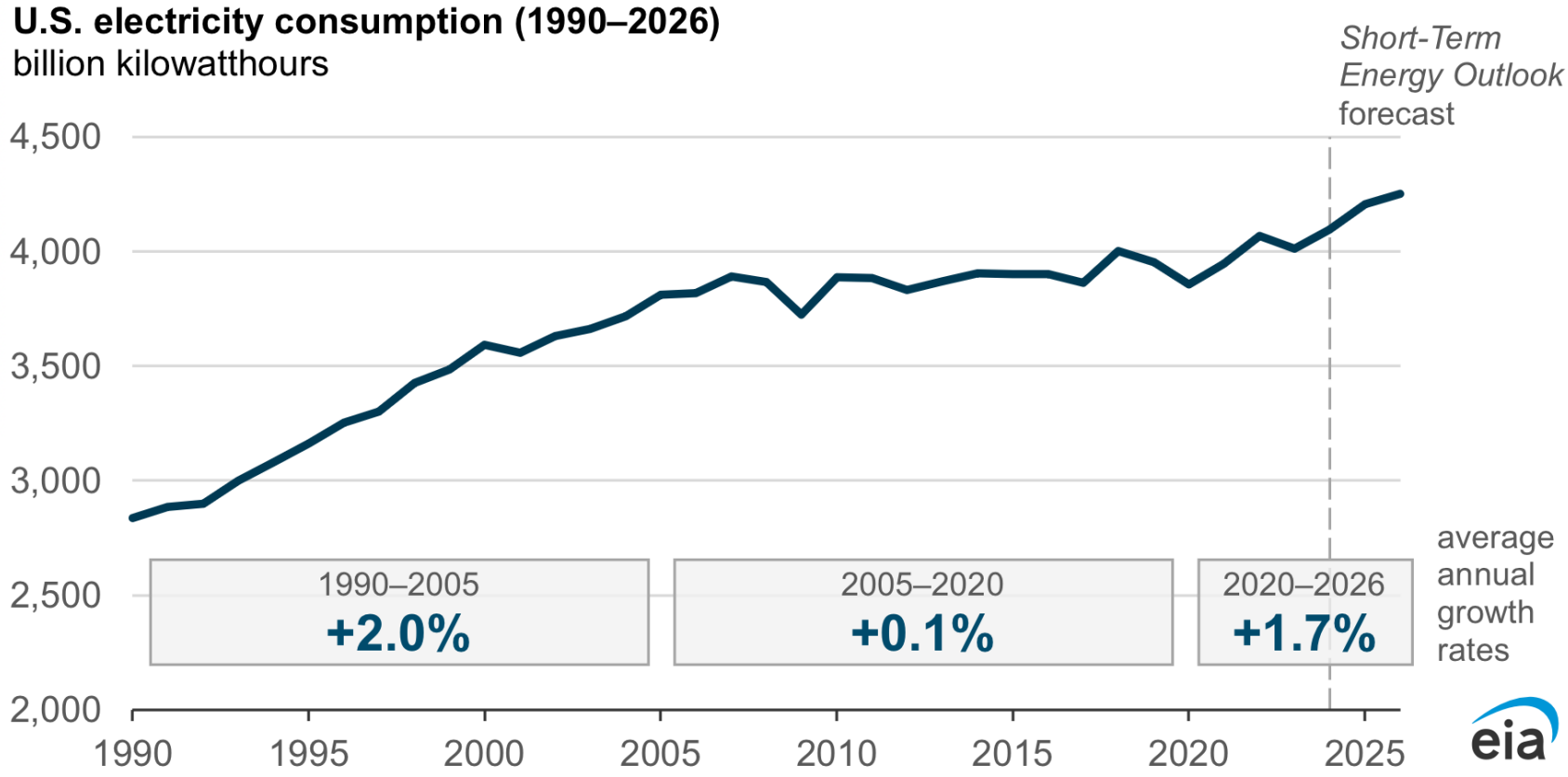
Source: EIA, Annual Energy Outlook 2016

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

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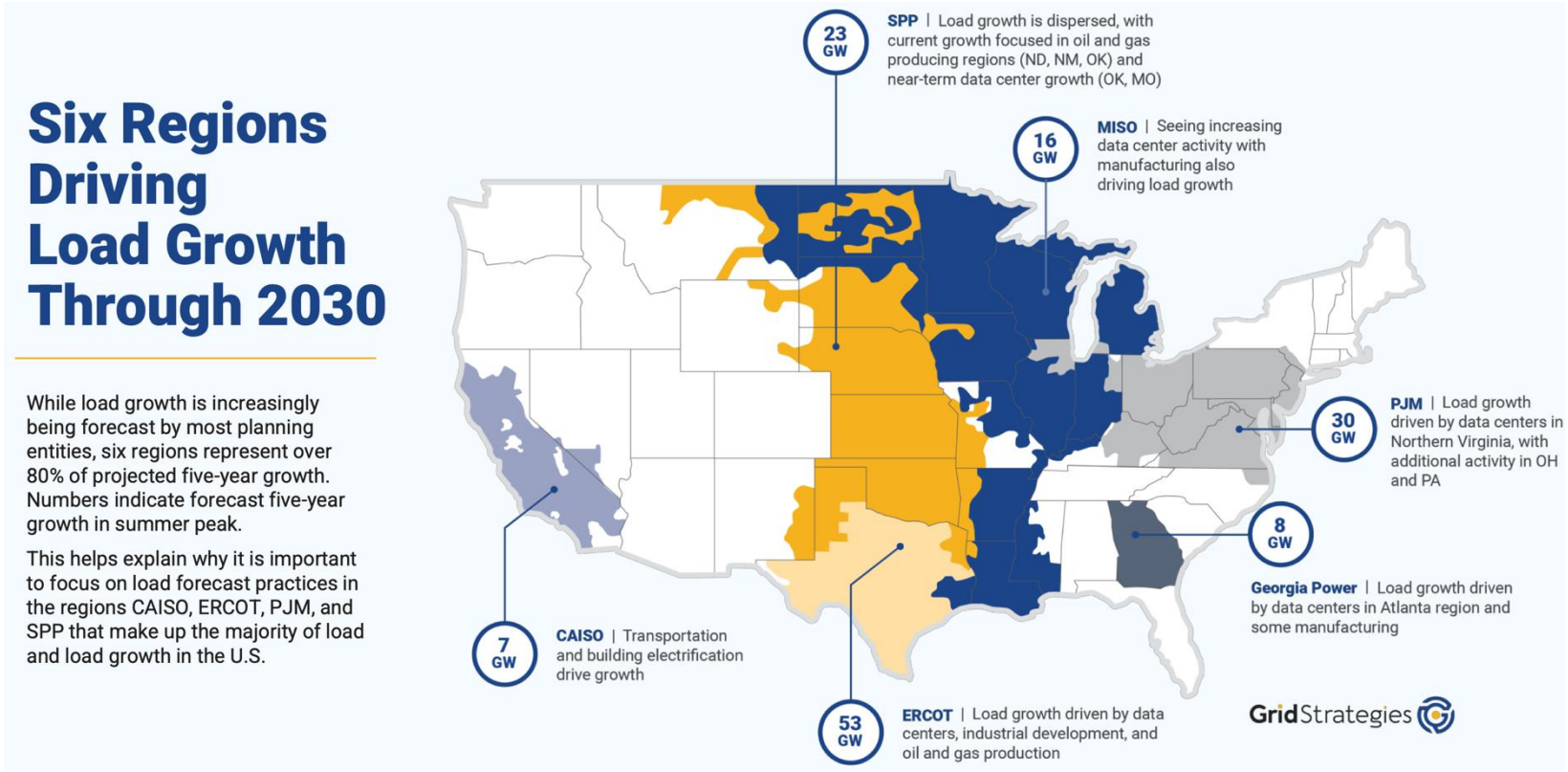
After more than a decade of little change, U.S. electricity consumption is rising again



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)

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

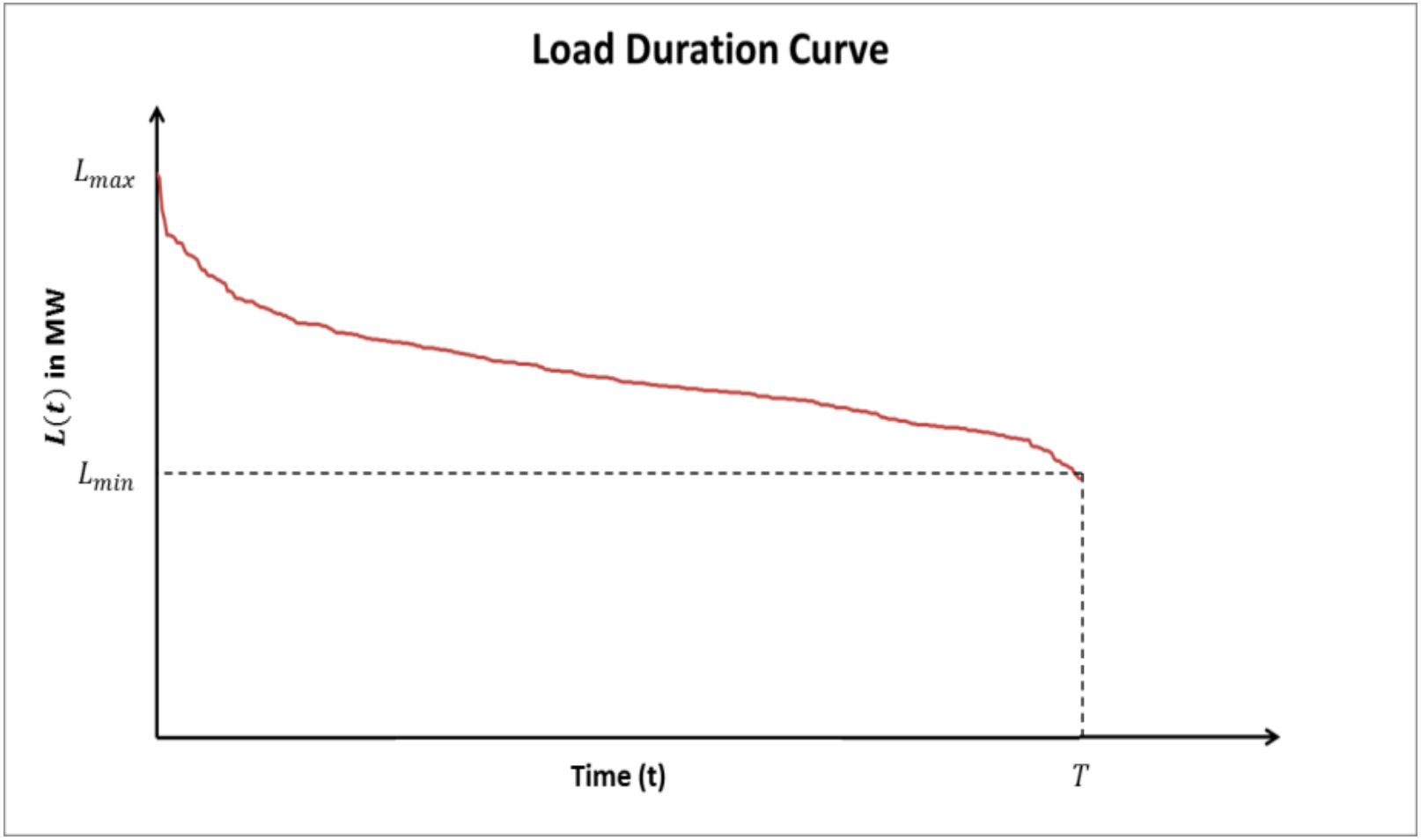
Powering the US Data Center Boom: Why Forecasting Can Be So Tricky

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

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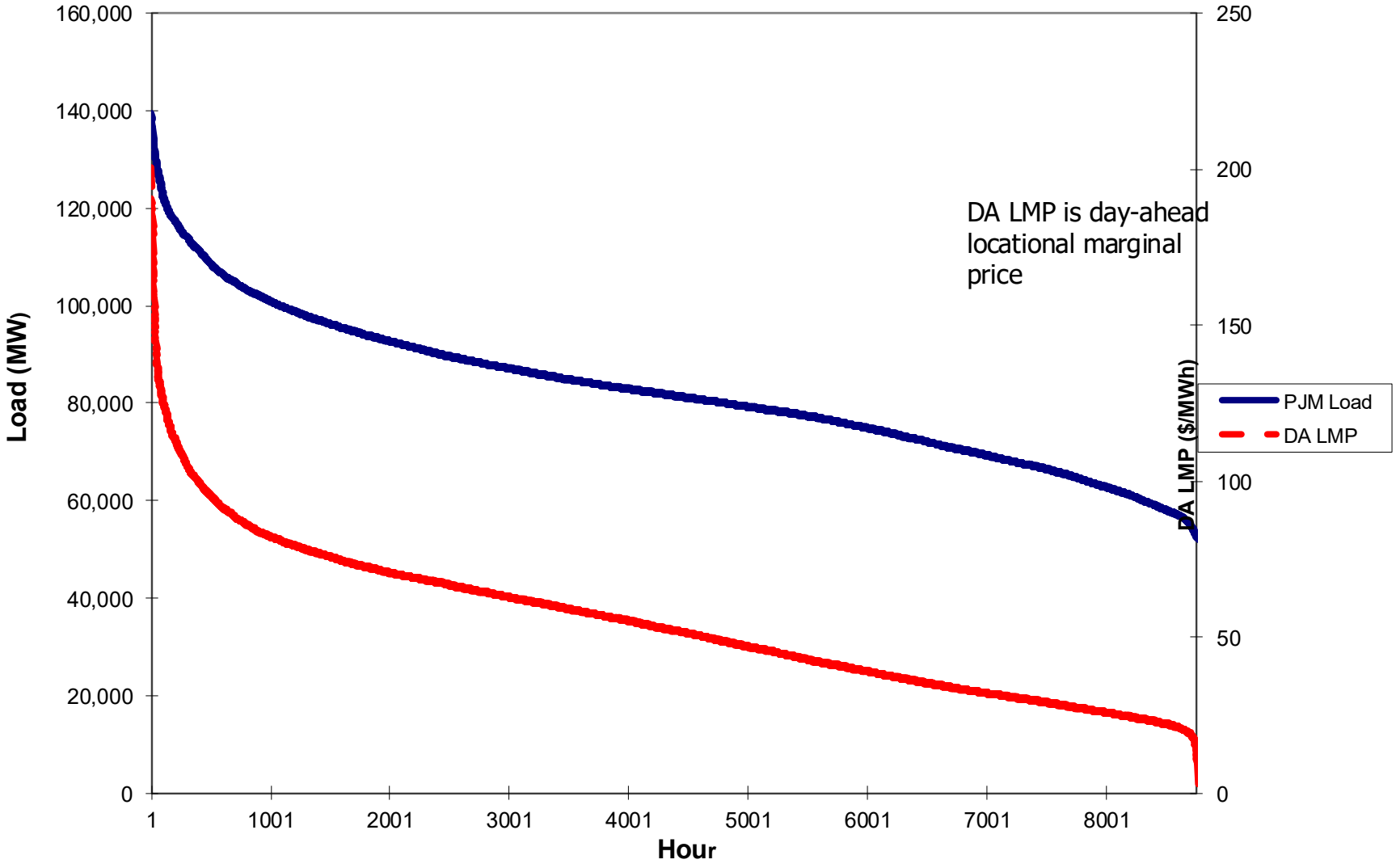
LOAD DURATION CURVE (LDC)



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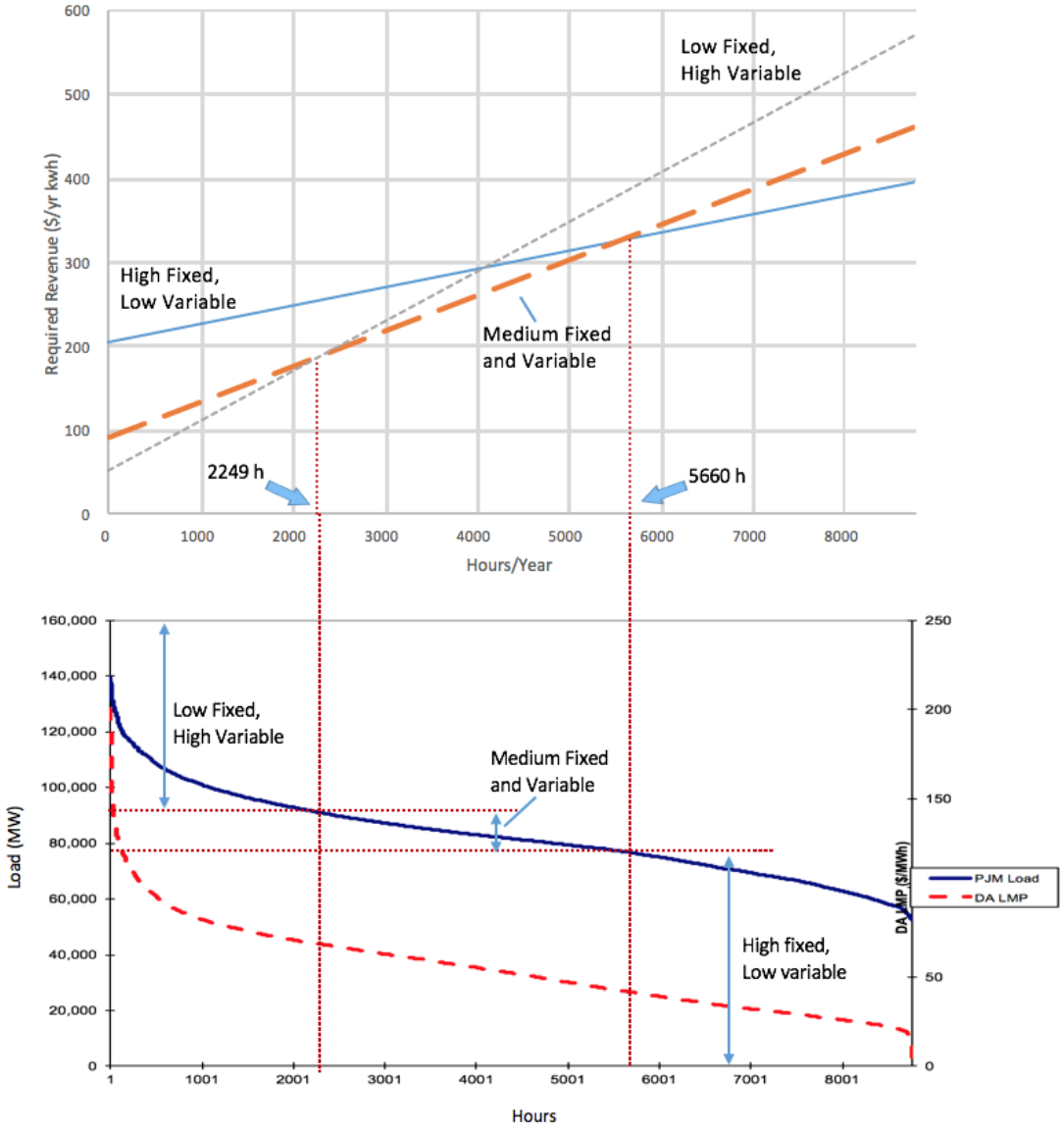
ANNUAL LOAD DURATION CURVE



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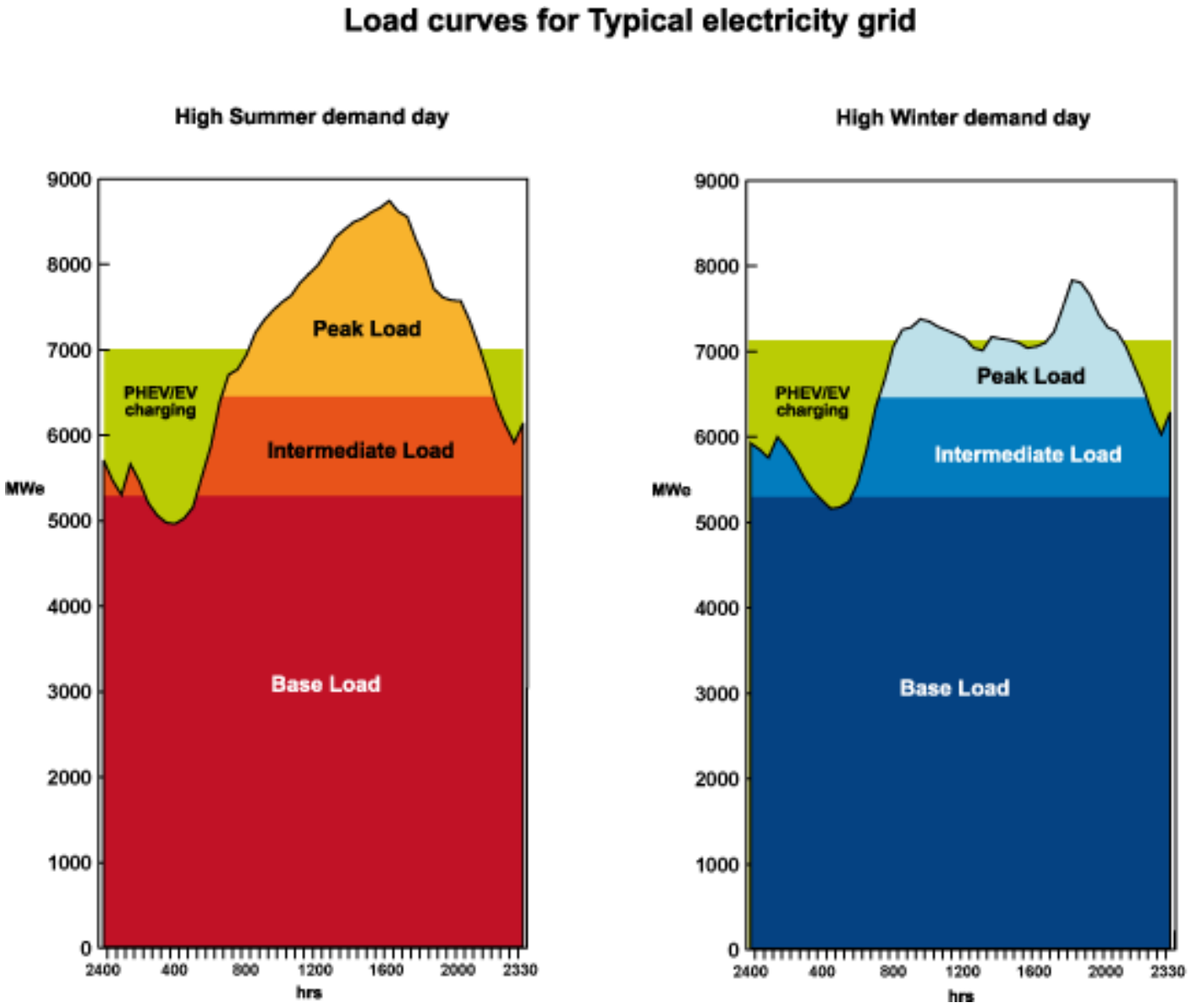
GENERATION INVESTMENT



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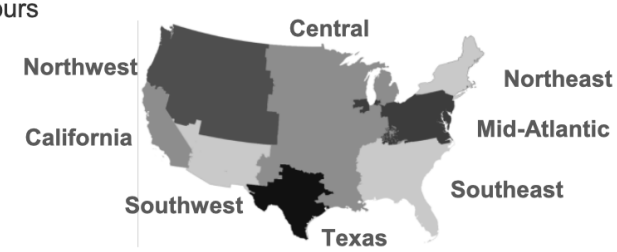
WEEKLY ELECTRICITY DEMAND



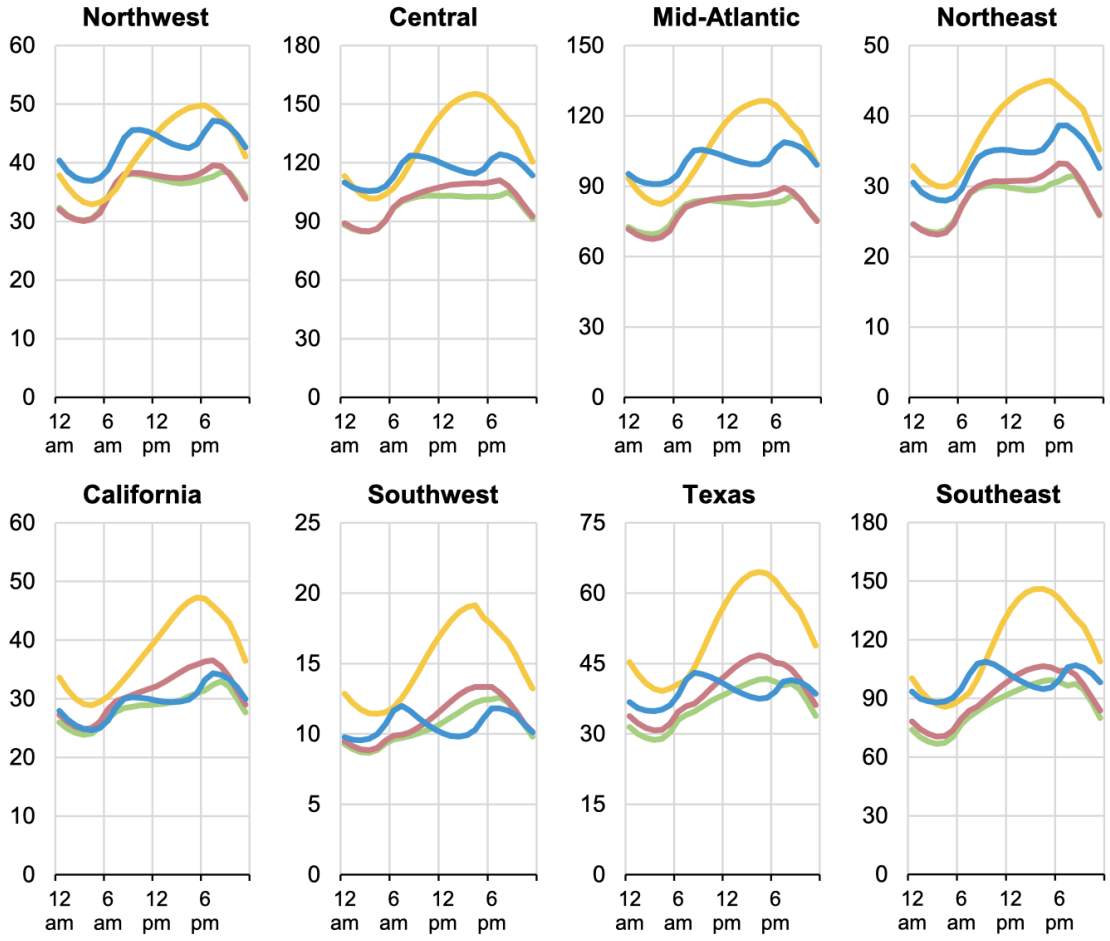
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Average hourly electricity load during typical day by region, selected months
million kilowatthours



January
April
July
October



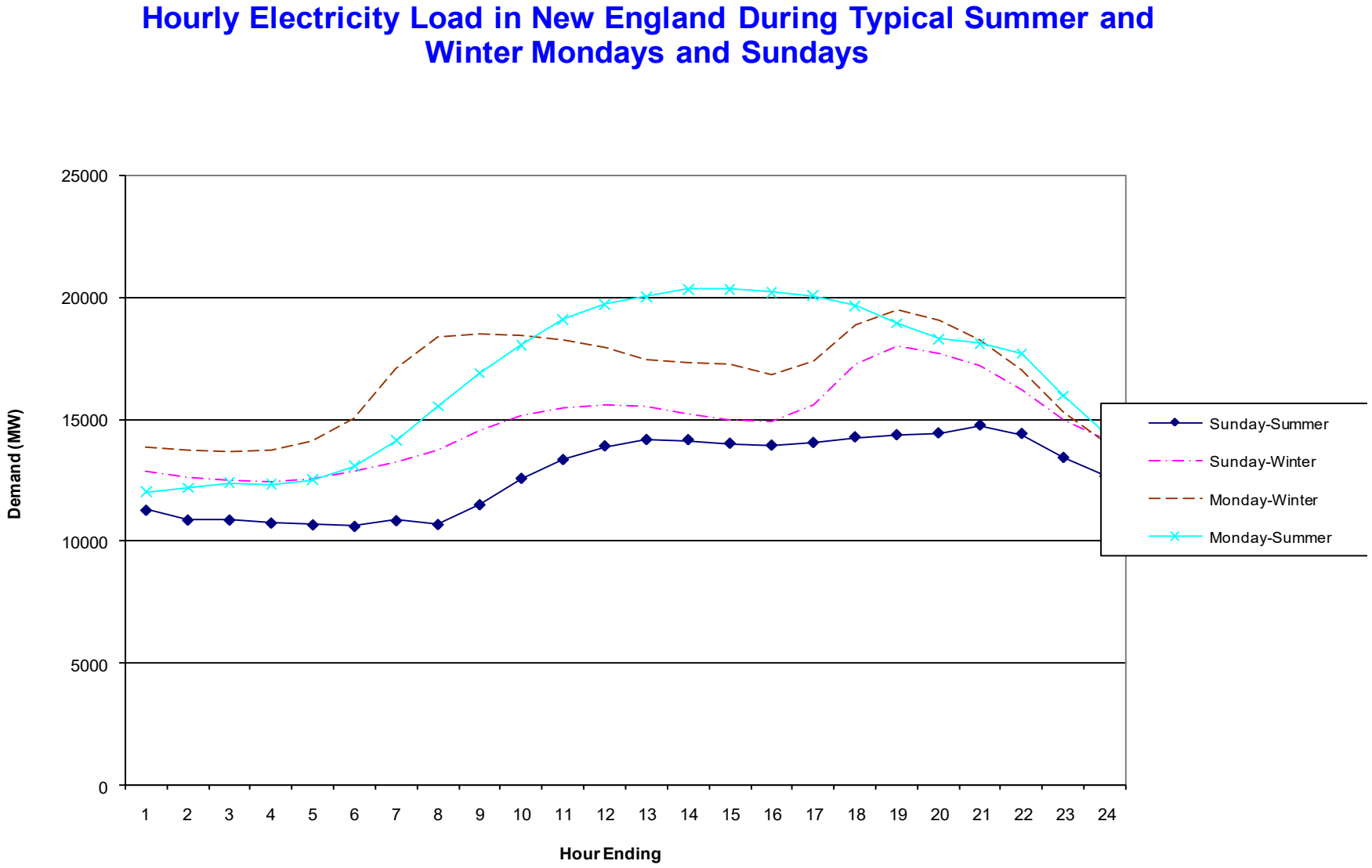
Source: U.S. Energy Information Administration, *U.S. Hourly Electric Grid Monitor*
Note: Hourly load shown is displayed for each region's local time zone.

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

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HOURLY ELECTRICITY DEMAND



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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

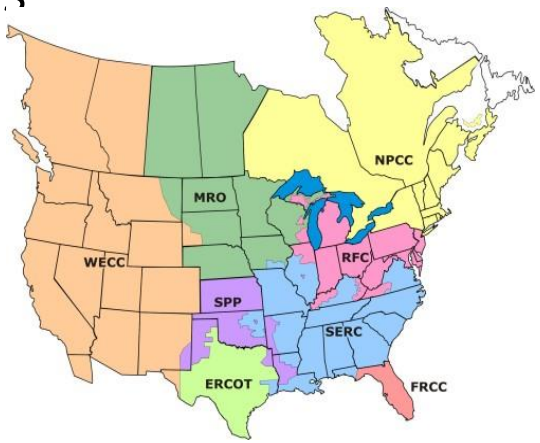
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NERC RELIABILITY CRITERIA

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



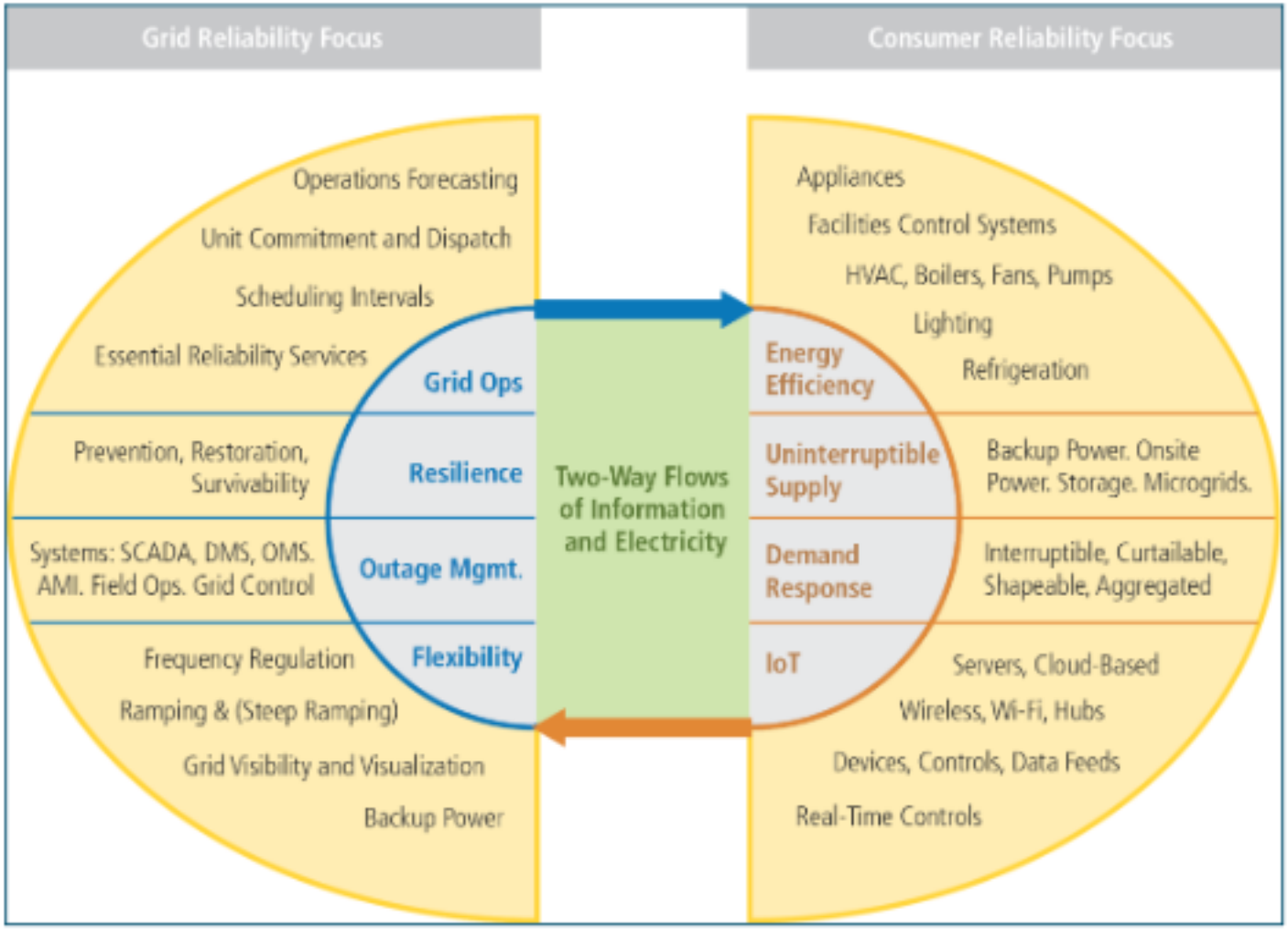
NERC Regions

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RELIABILITY

Electric Service Reliability Increasingly Interactive between Grid and Consumer



Source: Department of Energy, 2016

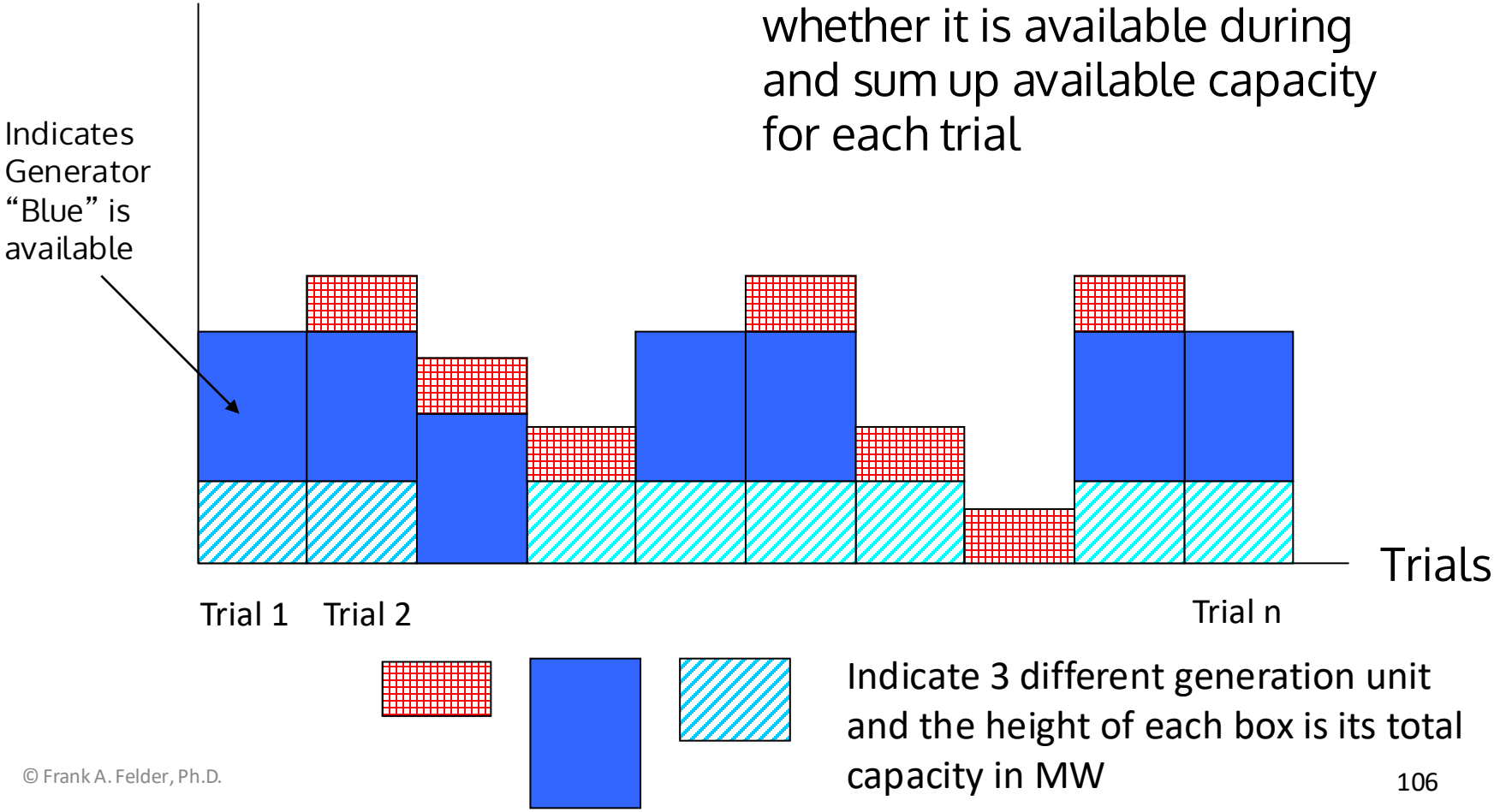
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GENERATION CAPACITY ADEQUACY

Available Capacity (MW)

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

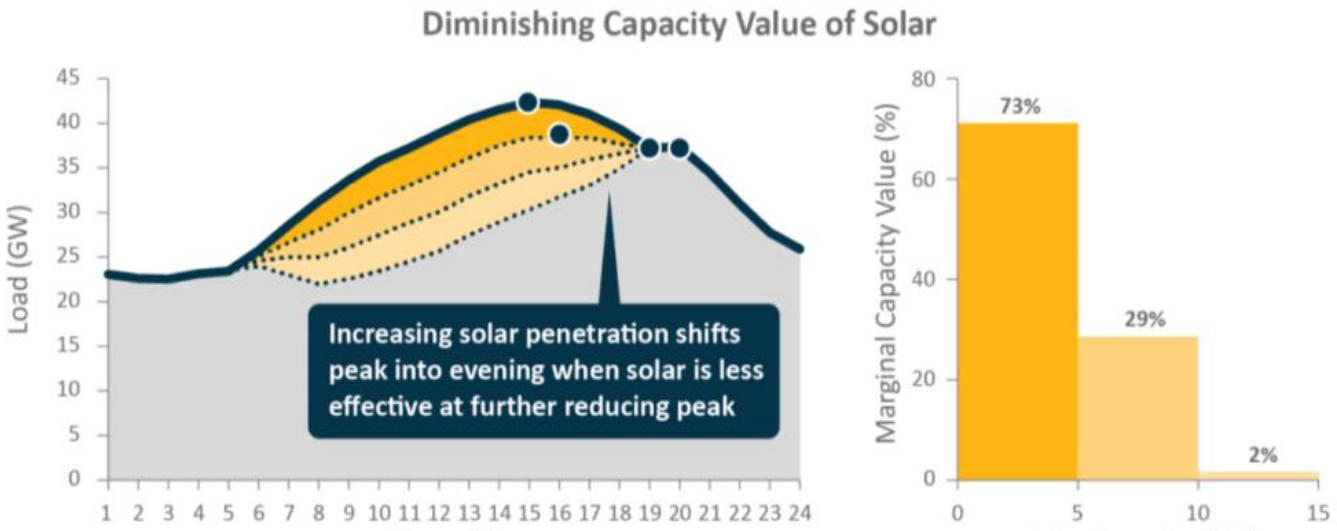


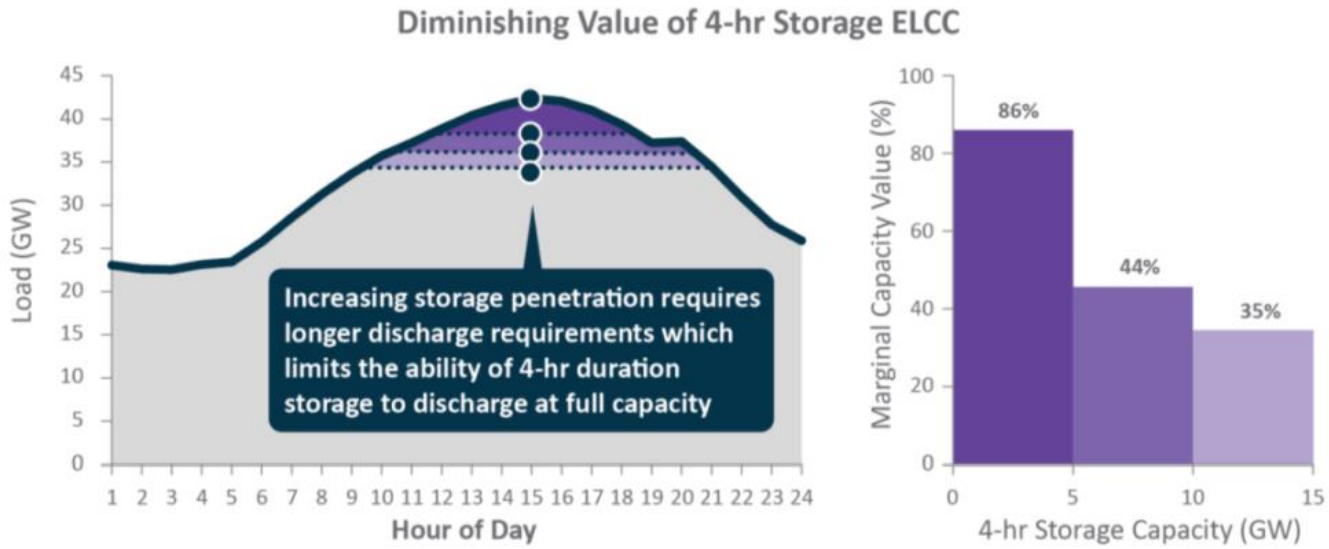
Indicate 3 different generation unit and the height of each box is its total capacity in MW

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EFFECTIVE LOAD CARRYING CAPABILITY (ELCC)





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

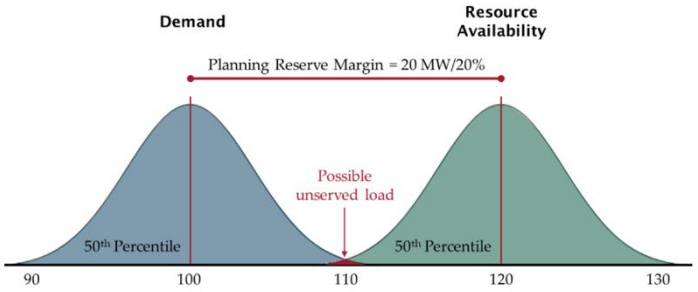
MRI is marginal reliability impact is another way to determine the capacity value of a resource

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

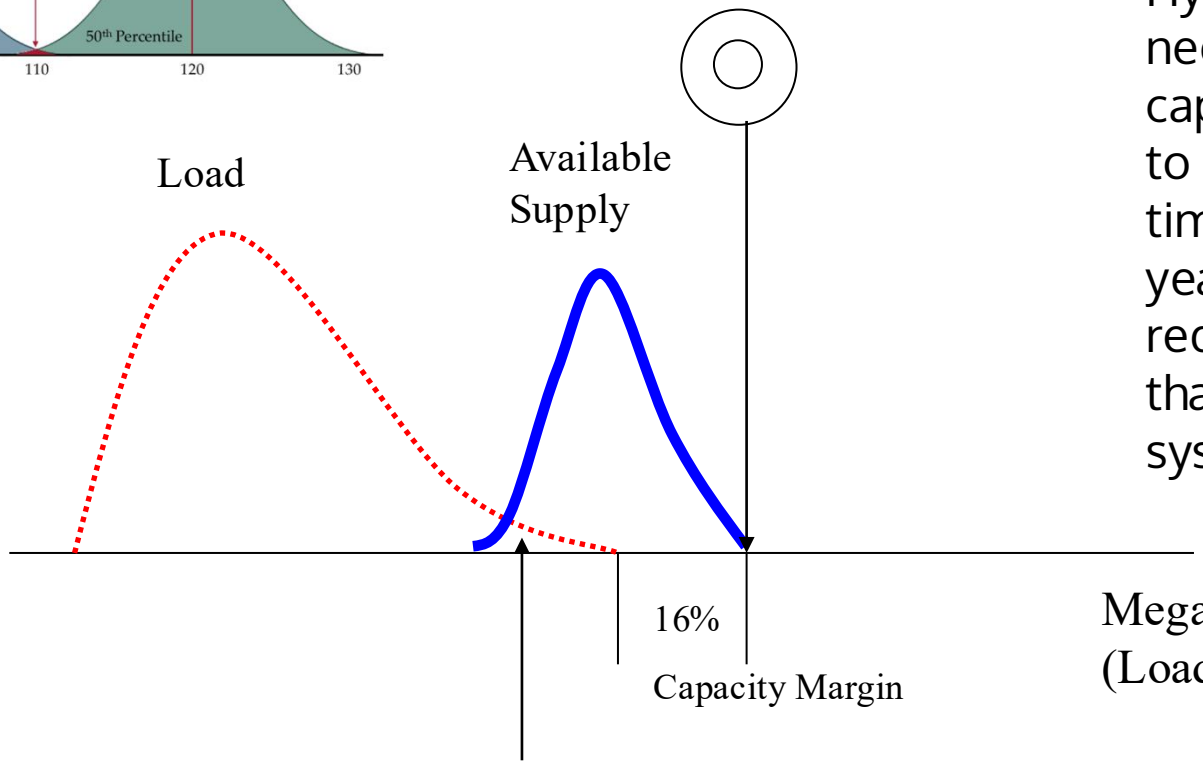
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GENERATION CAPACITY ADEQUACY



Installed Capacity is the Control Variable ("knob")



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

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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)

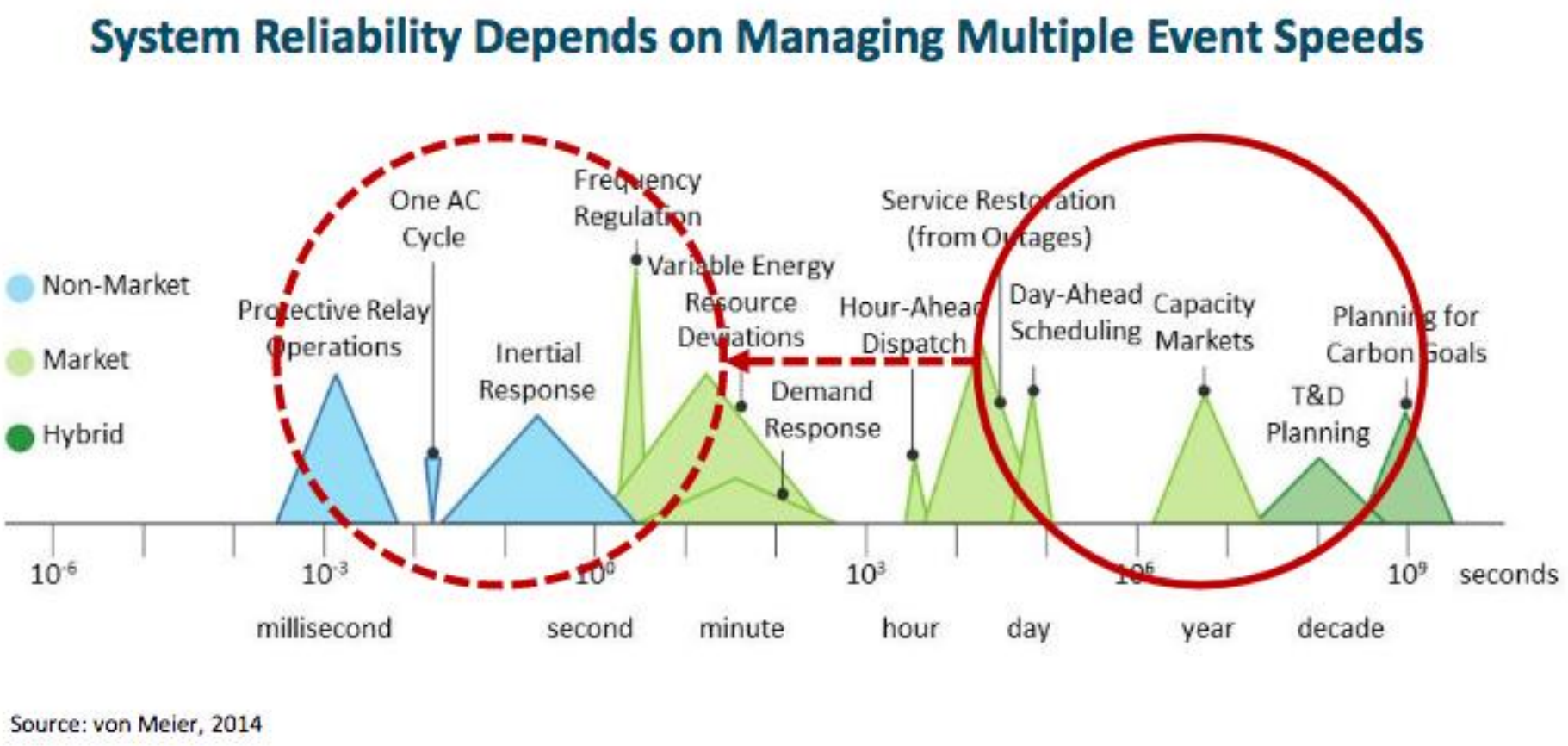
Black Start Service, Voltage Control (VARs) aka Reactive Power, …

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

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TIMELINE

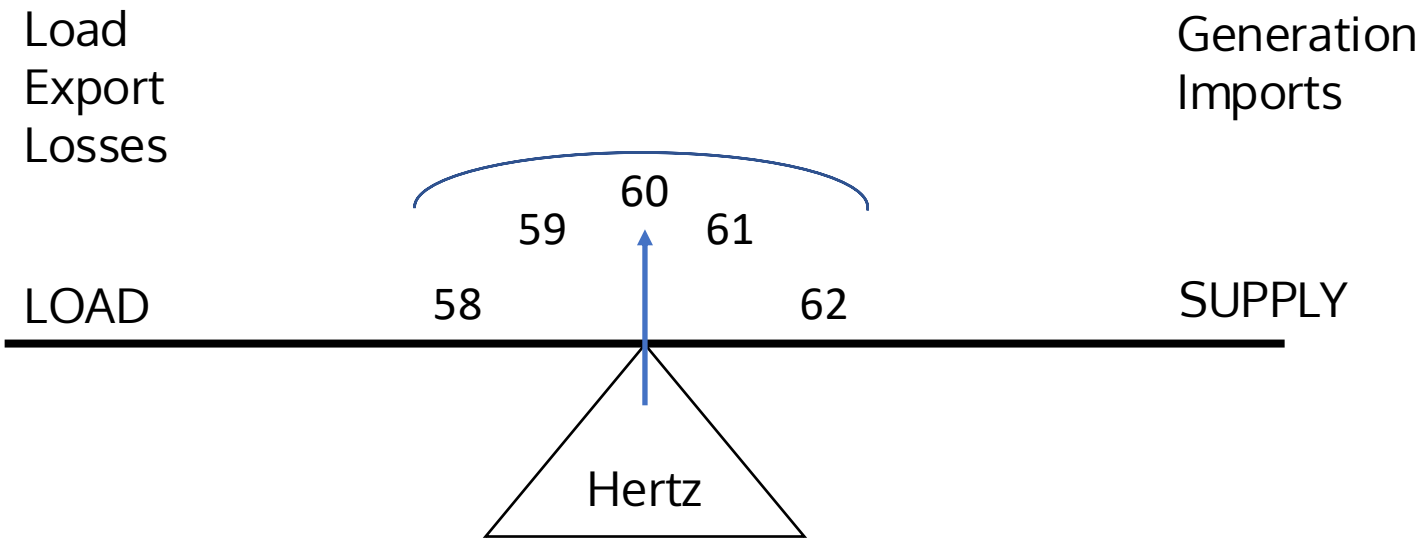


http://energyoutlook.naseo.org/Data/Sites/13/media/presentations/Battershell--QER-1.2-Briefin.PDF

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BALANCING SUPPLY & DEMAND



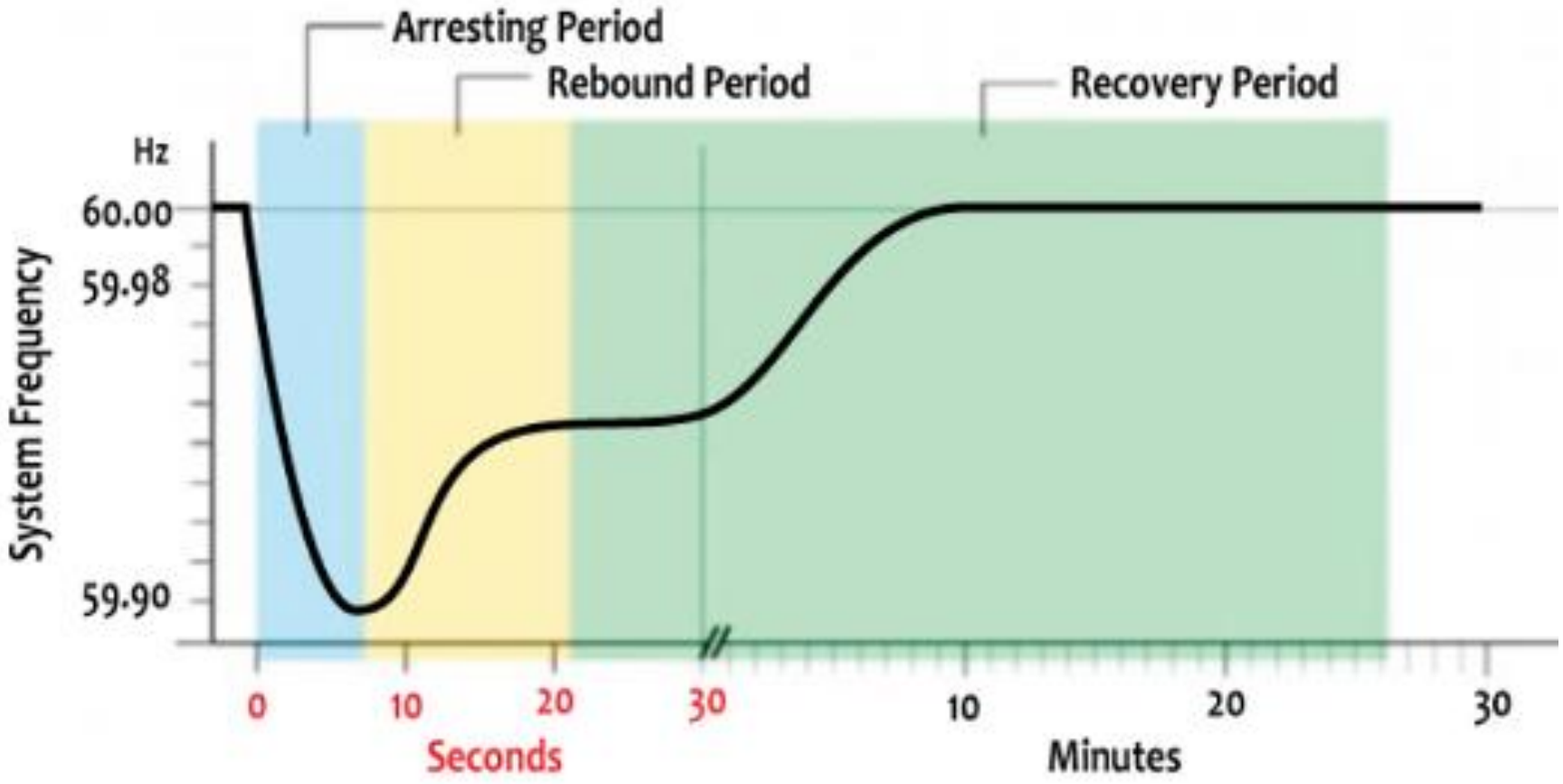
Load (demand) and supply must be in balance at (almost) all times

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

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BALANCING SUPPLY & DEMAND

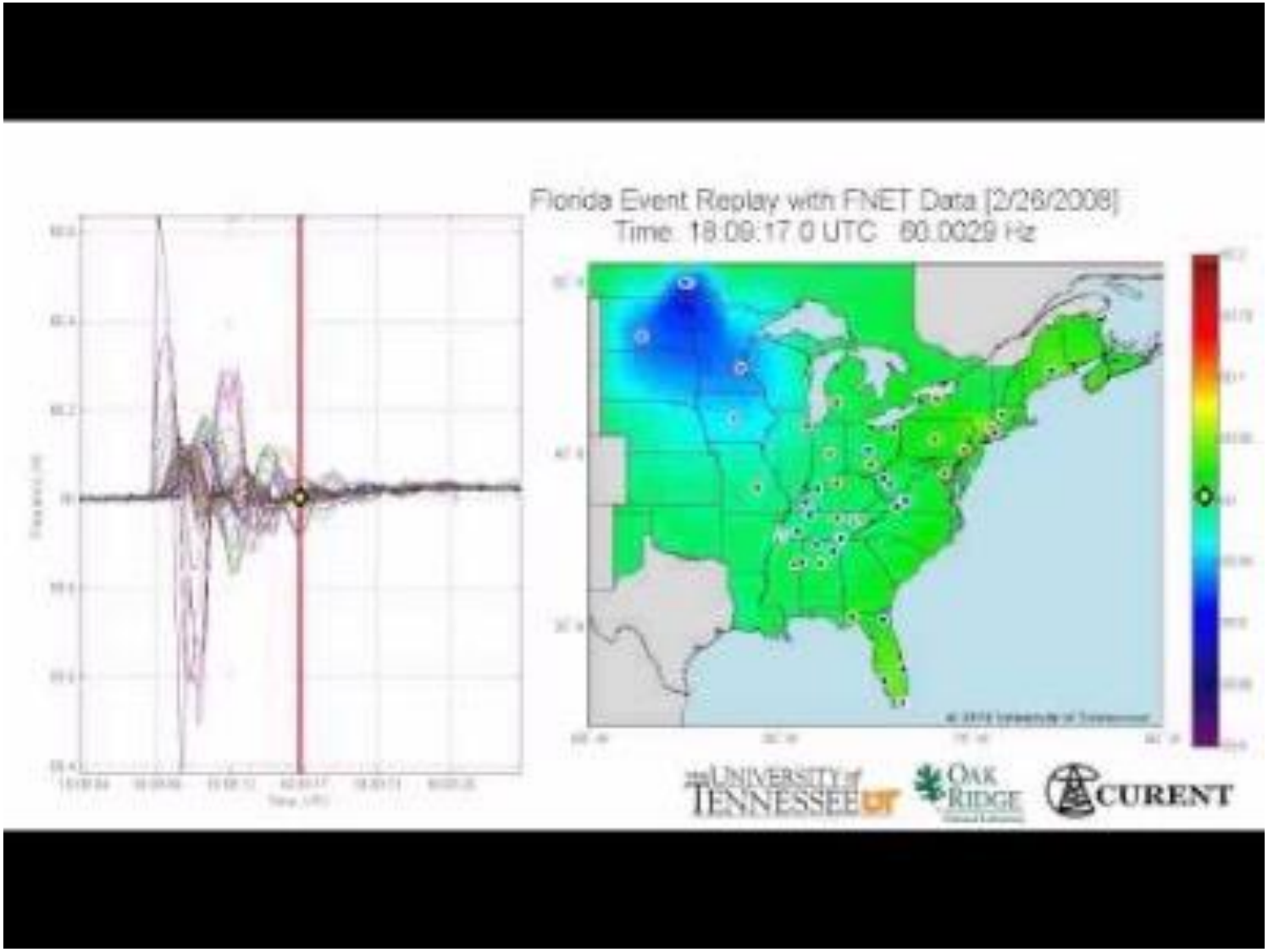


http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERS%20Abstract%20Report%20Final.pdf

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VIDEO OF POWER PLANT TRIPPING OFFLINE



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

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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?

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TERMINOLOGY AND ABBREVIATIONS CHECK

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

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Session 3:
Electricity Markets

Public

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

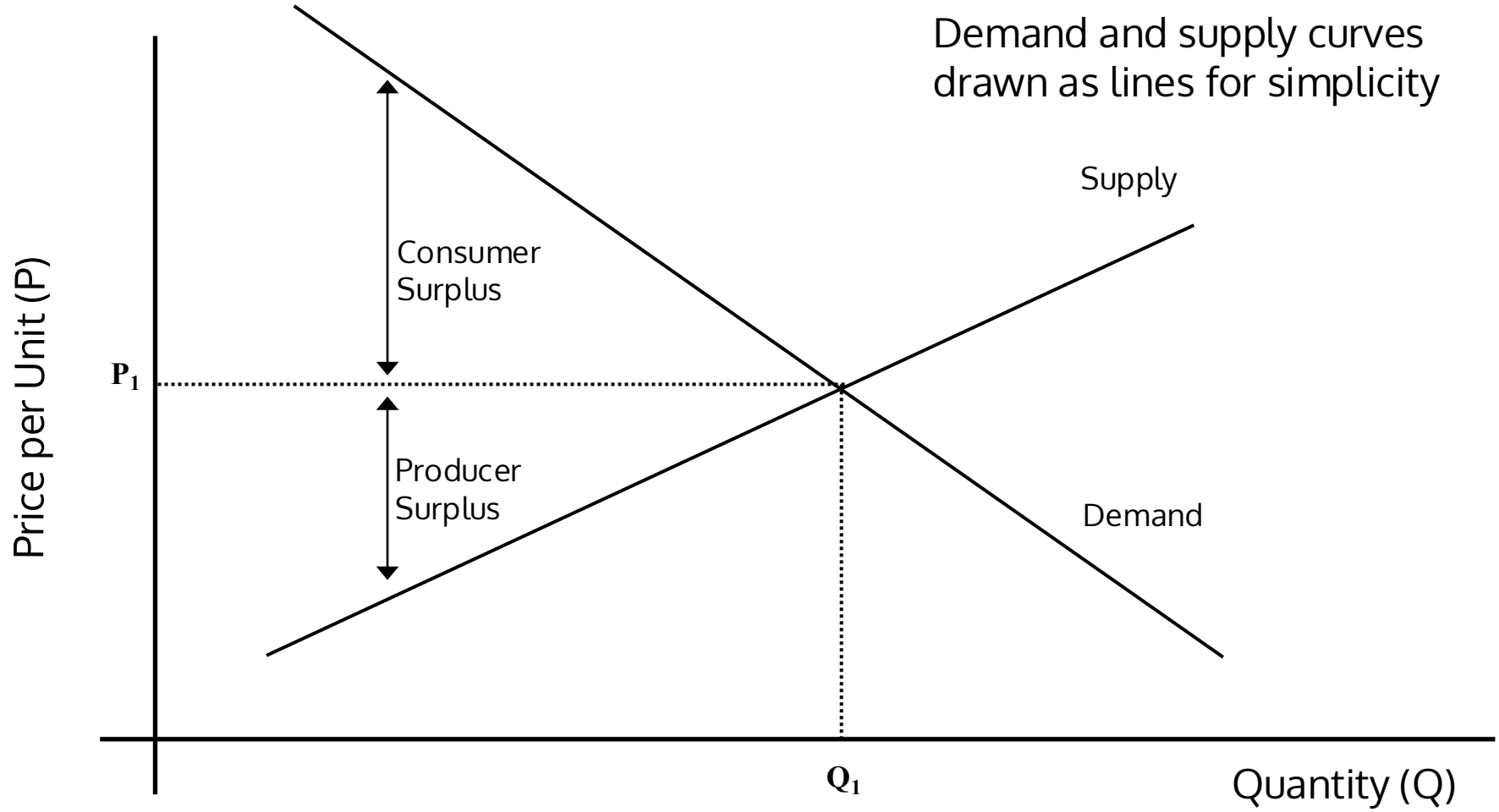
Key Questions

- 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?

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EFFICIENT PRICING - MICROECONOMICS

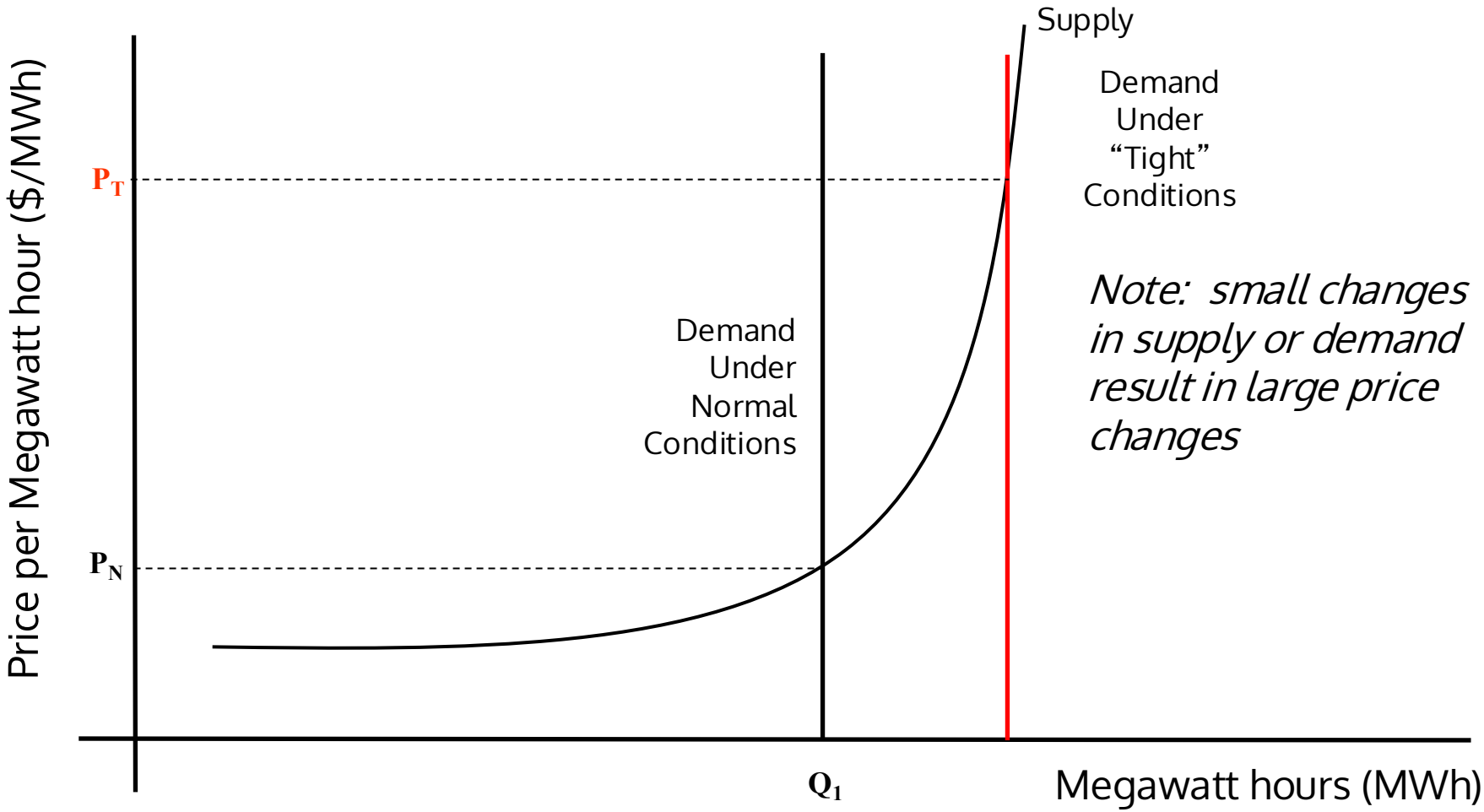


Social Welfare = Consumer Surplus + Producer Surplus

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ELECTRICITY SUPPLY & DEMAND

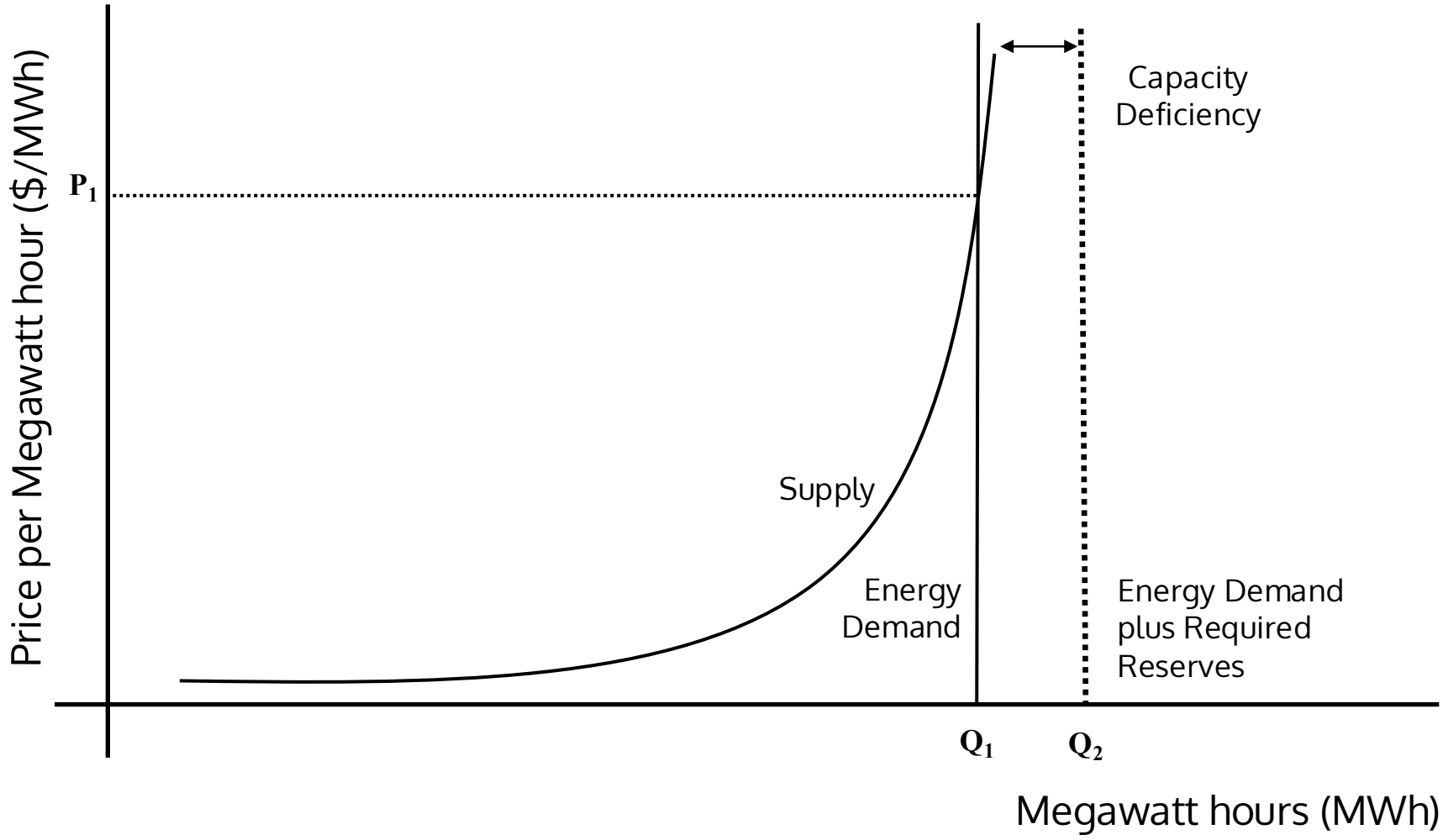


Sometimes the electricity supply curve is characterized as a "hockey stick"

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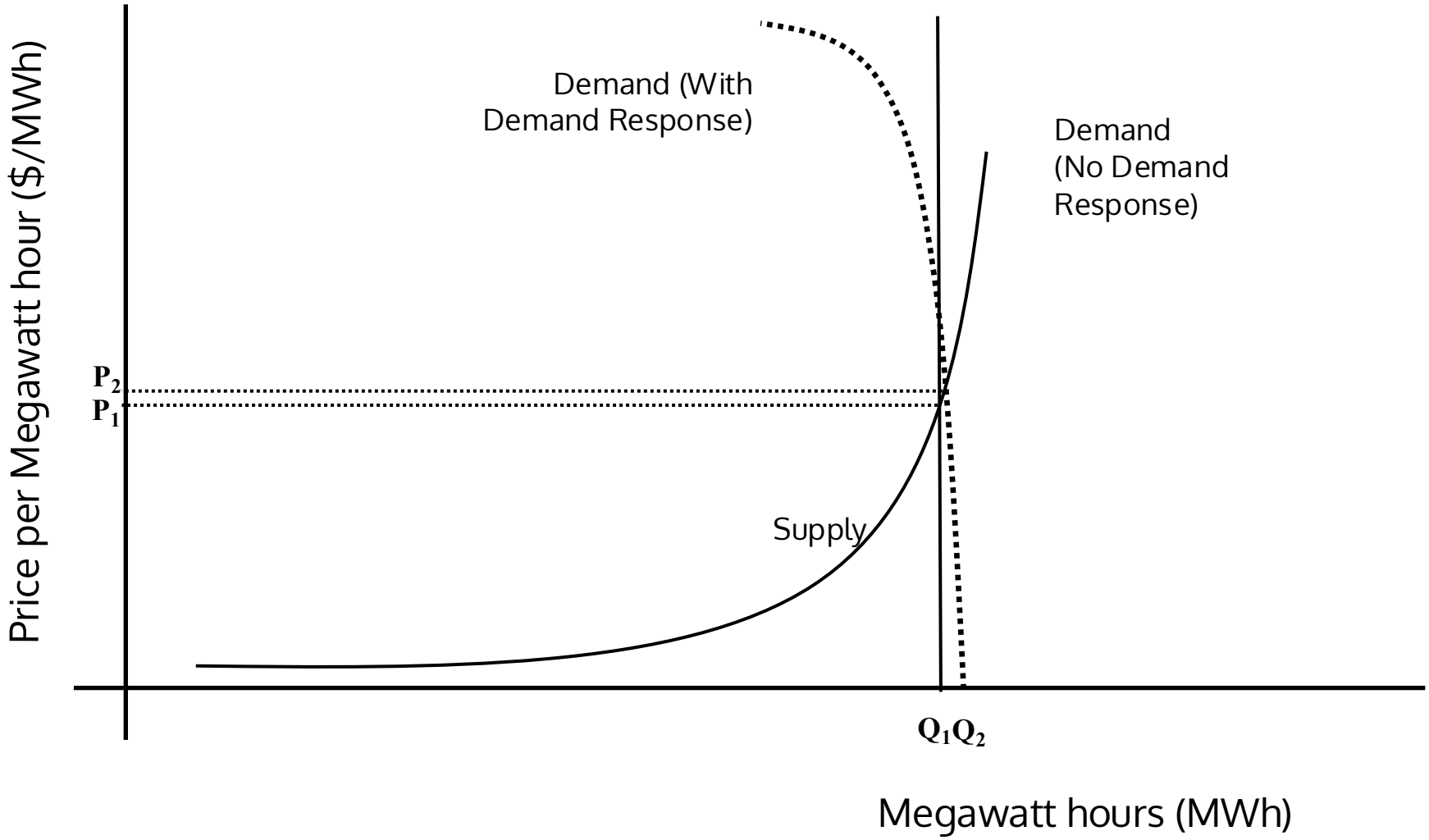
DEMAND PLUS RESERVES



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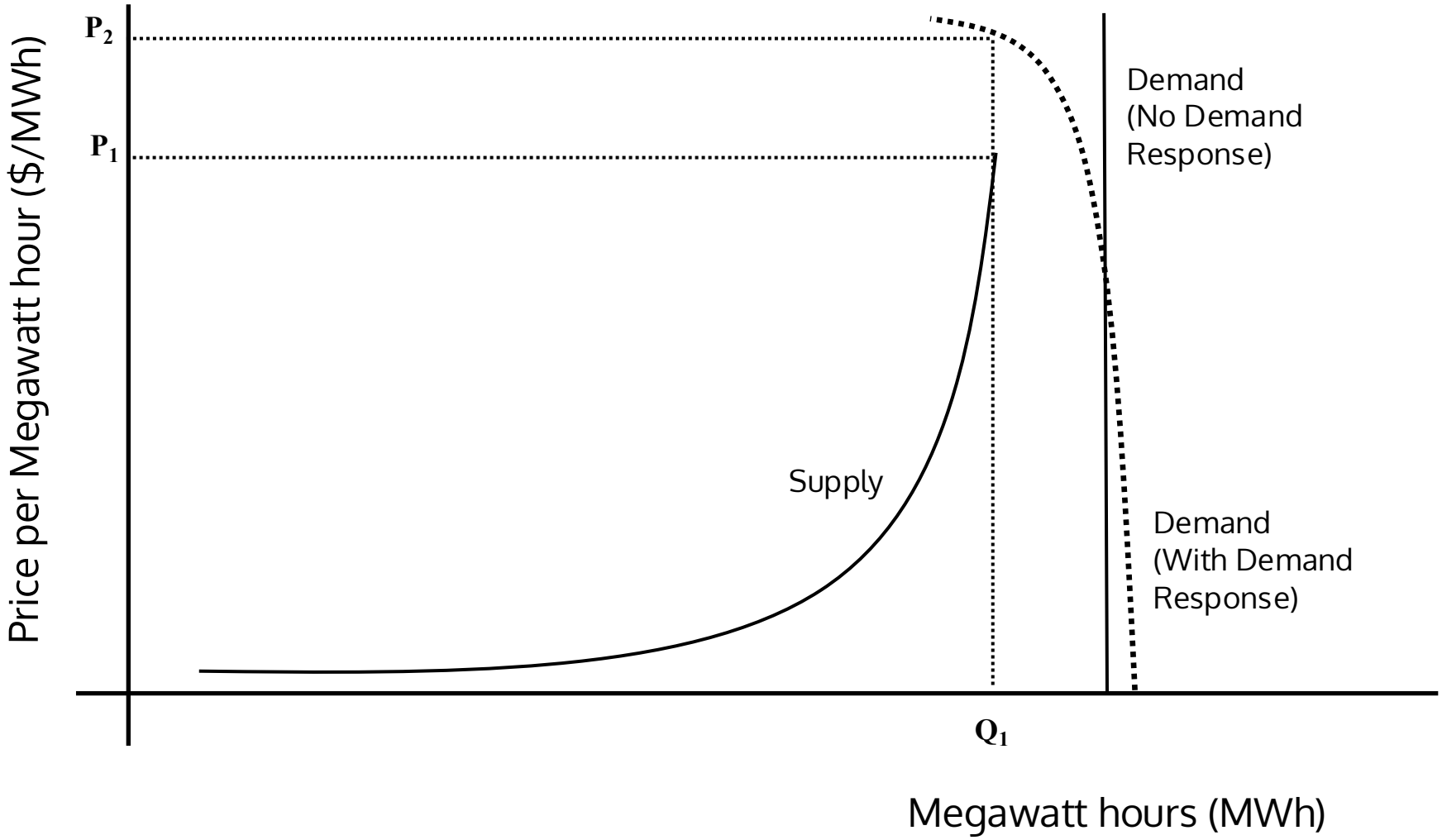
EFFICIENT PRICING DURING SURPLUS



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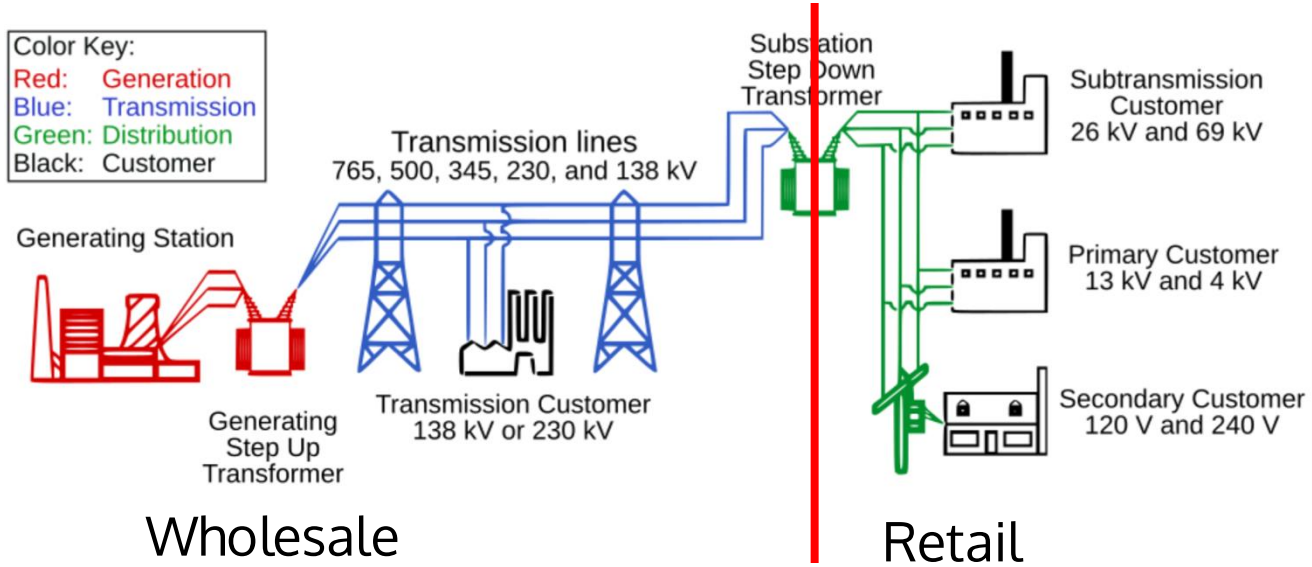
EFFICIENT PRICING DURING SHORTAGES



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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.

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Recall the US Federal-State Jurisdictional Split

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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

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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

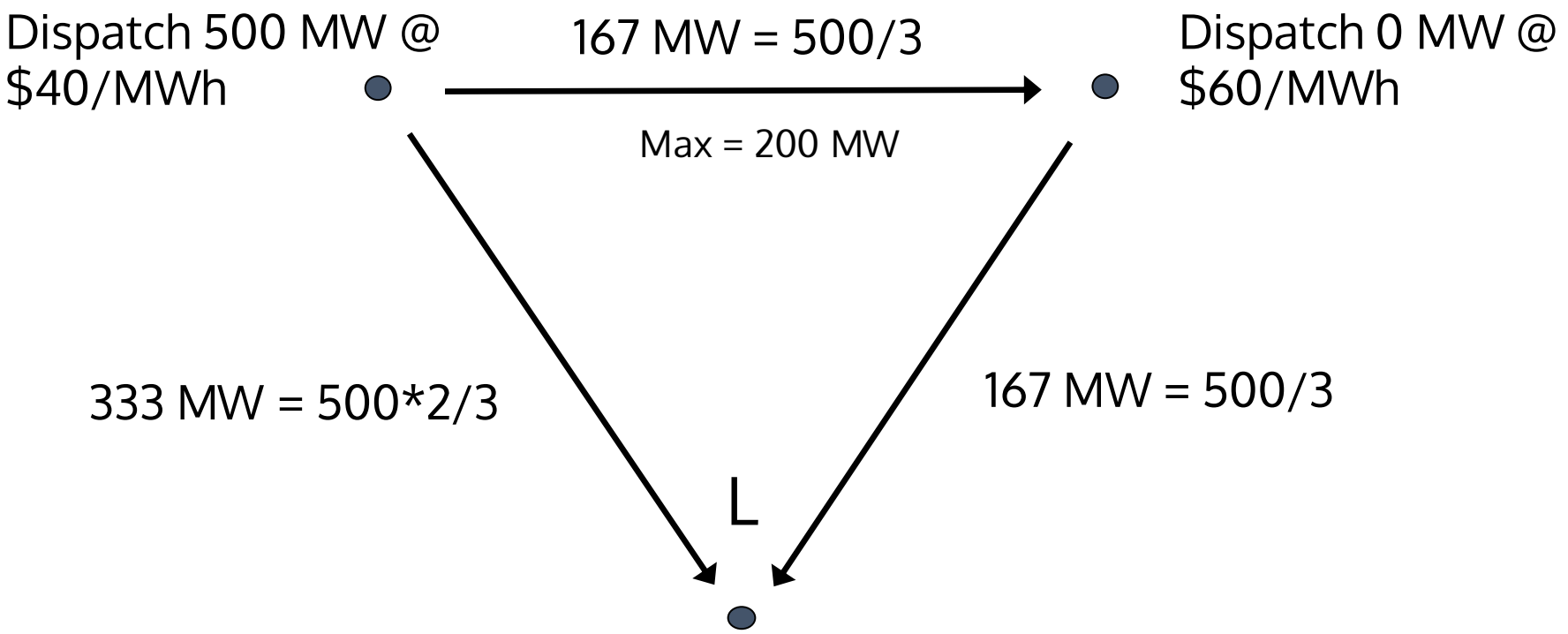
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LMPs: NO BINDING CONSTRAINT

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

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

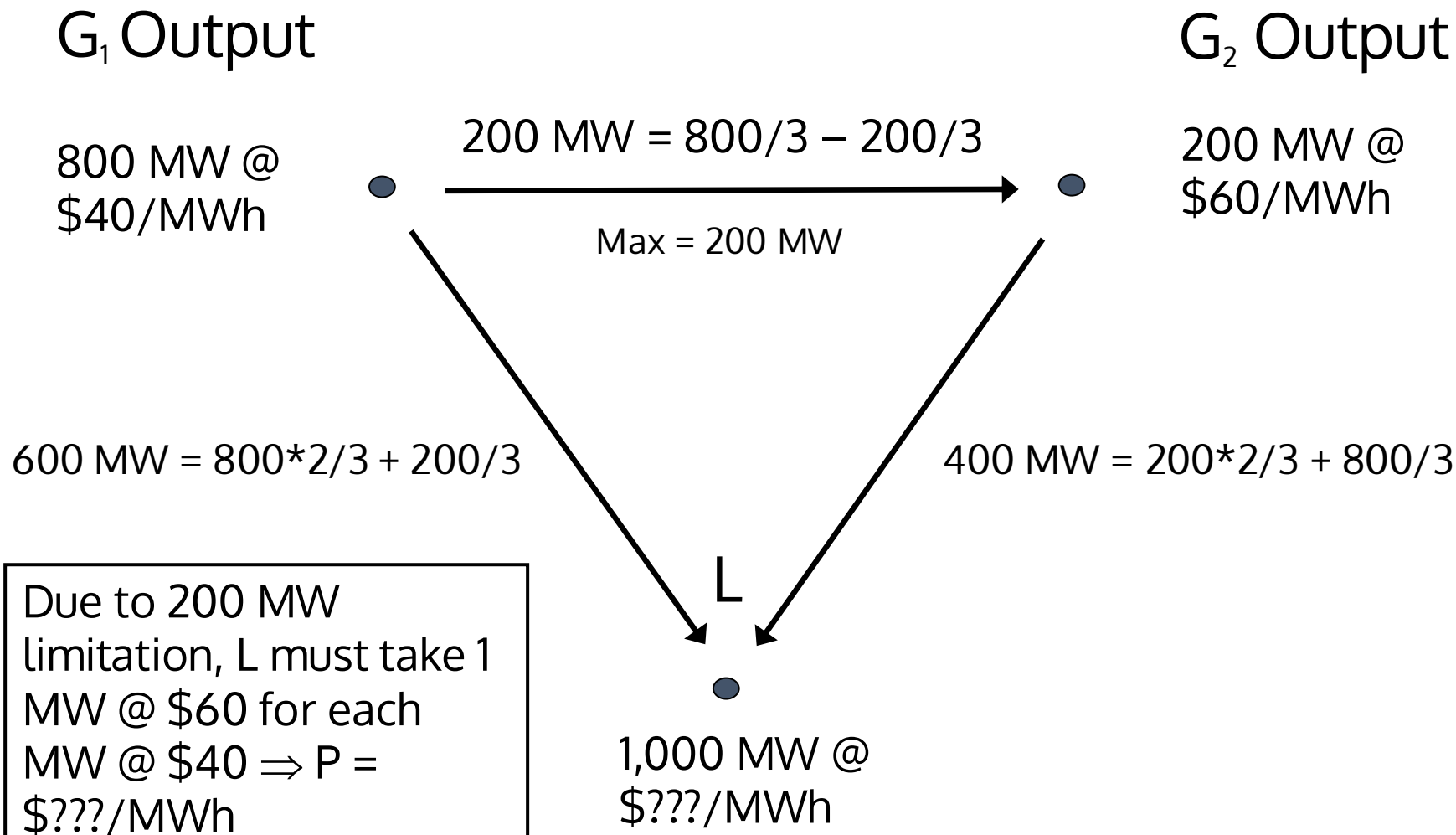


Unrestricted flow from G1 to L @ $40/MWh

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LMPs: BINDING CONSTRAINTS

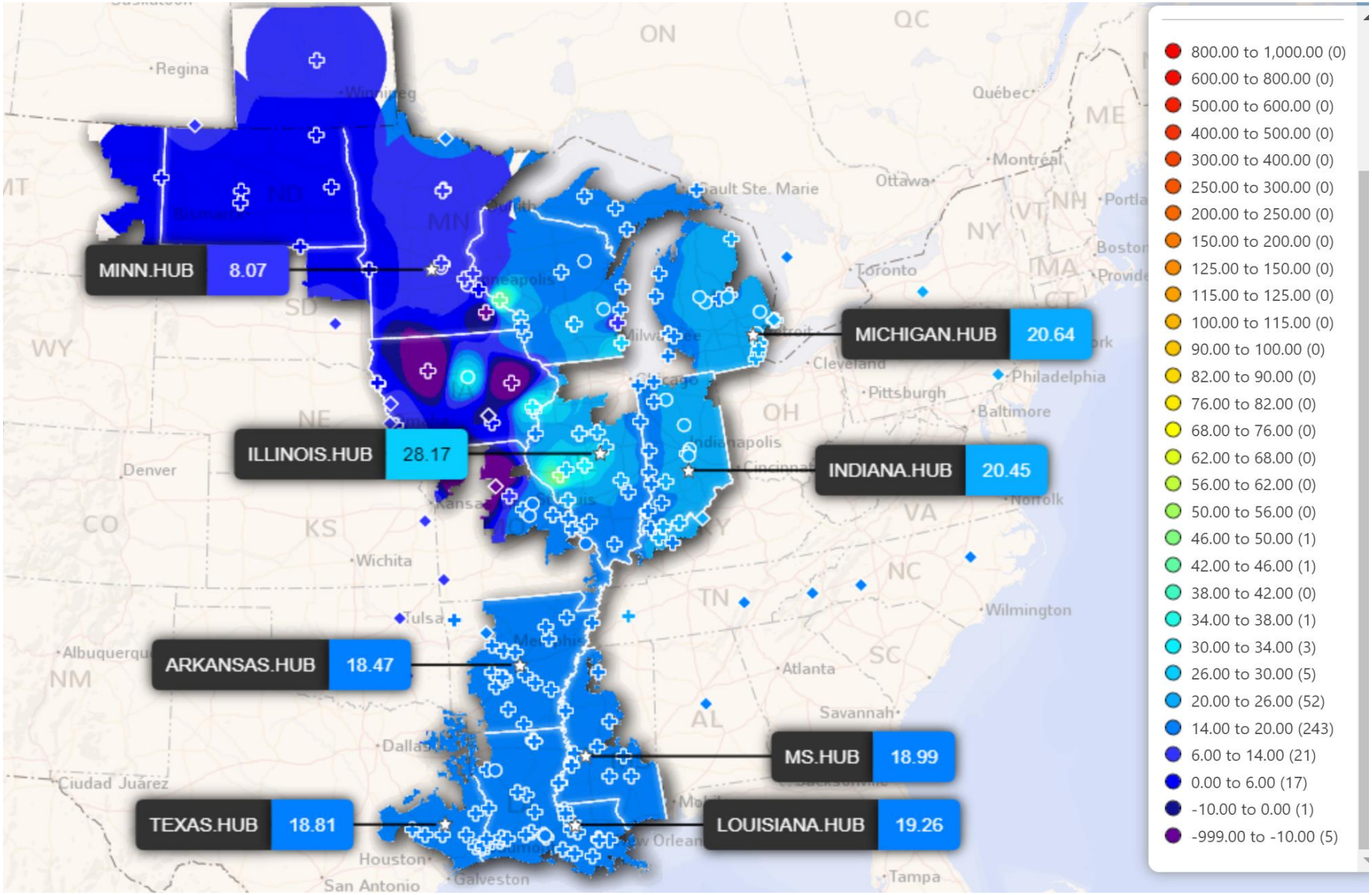


Due to 200 MW limitation, L must take 1 MW @ $60 for each MW @ $40 ⇒ P = $???/MWh

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MISO LMPs CONTOUR MAP

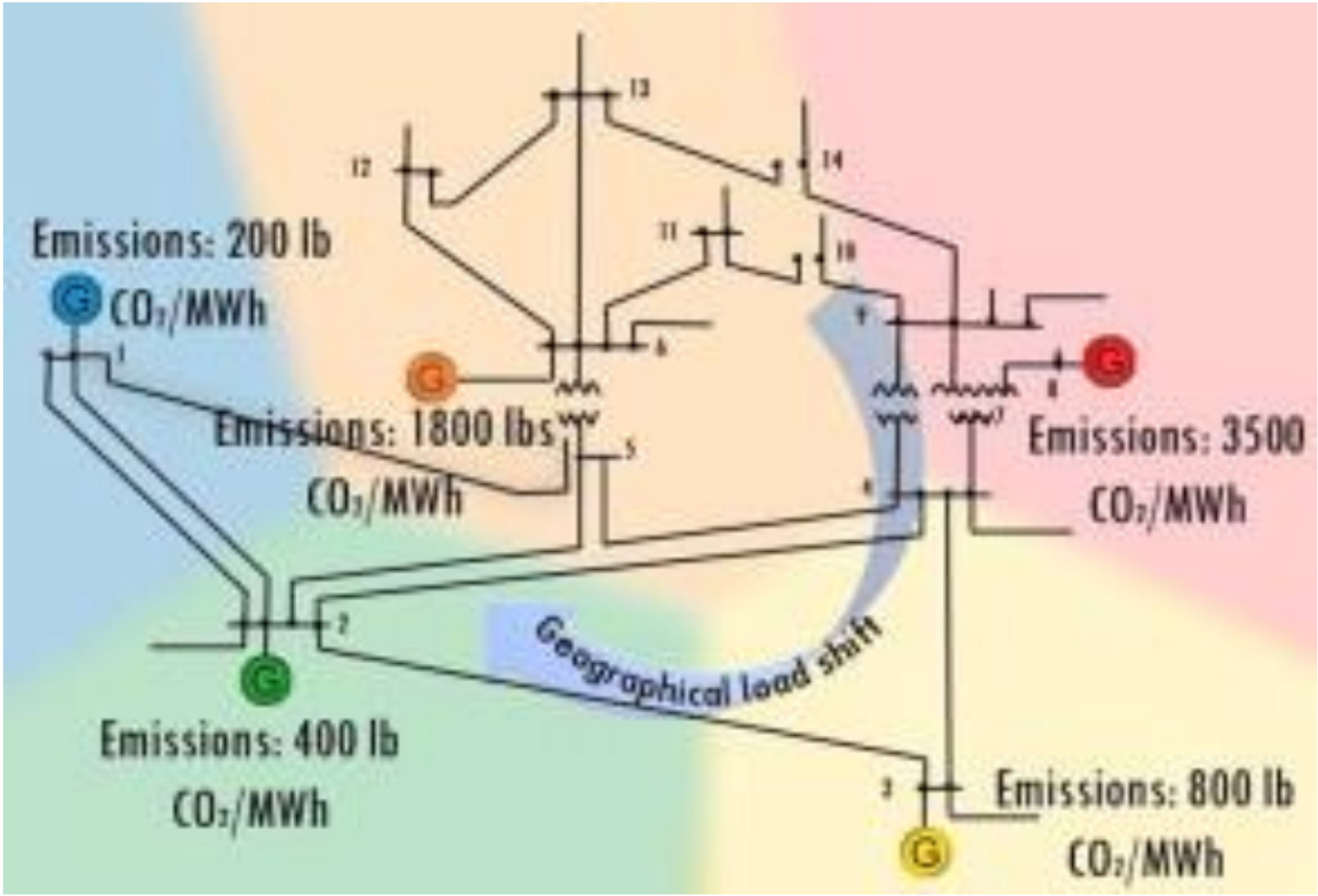


https://api.misoenergy.org/MISORTWD/lmpcontourmap.html

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LOCATIONAL MARGINAL EMISSIONS

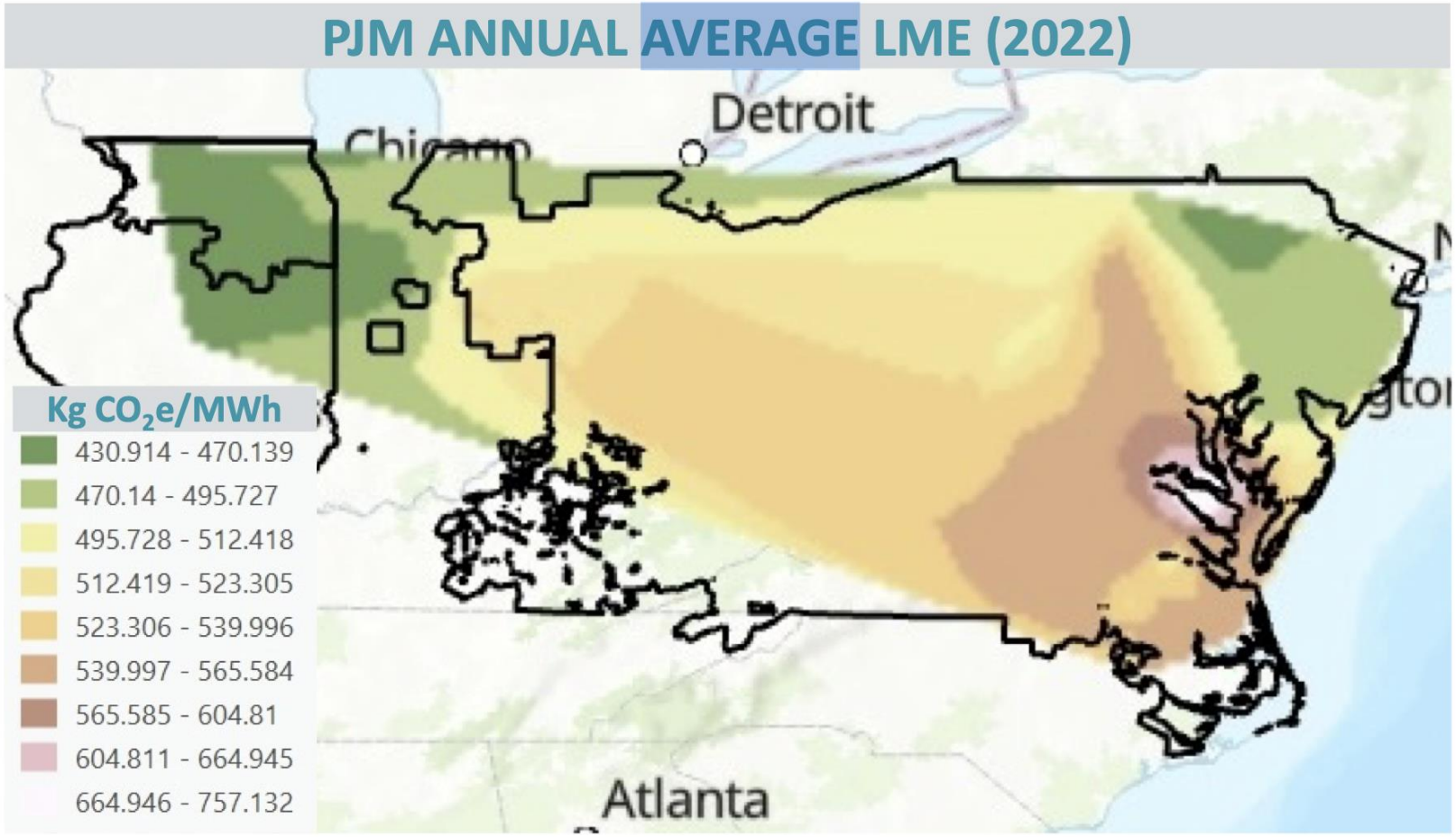


https://www.sciencedirect.com/science/article/abs/pii/S0306261913010611

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LOCATIONAL MARGINAL EMISSIONS – PJM DATA



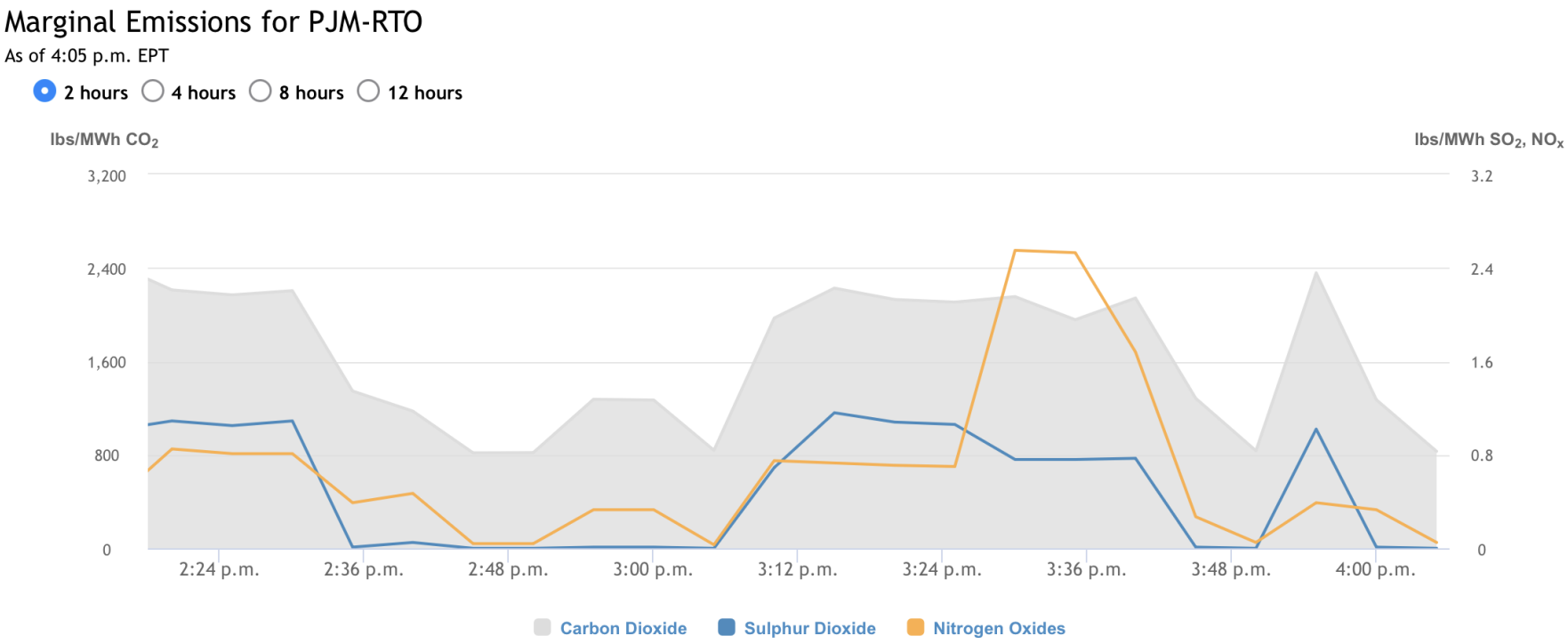
Source: Contour map developed using interpolation from generation node data. Data from ReSurety LME data product, derived from PJM Interconnection 5-minute, nodal LME data.

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

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PJM.COM PAGE VISUALIZES MARGINAL EMISSION RATES FOR ITS FOOTPRINT

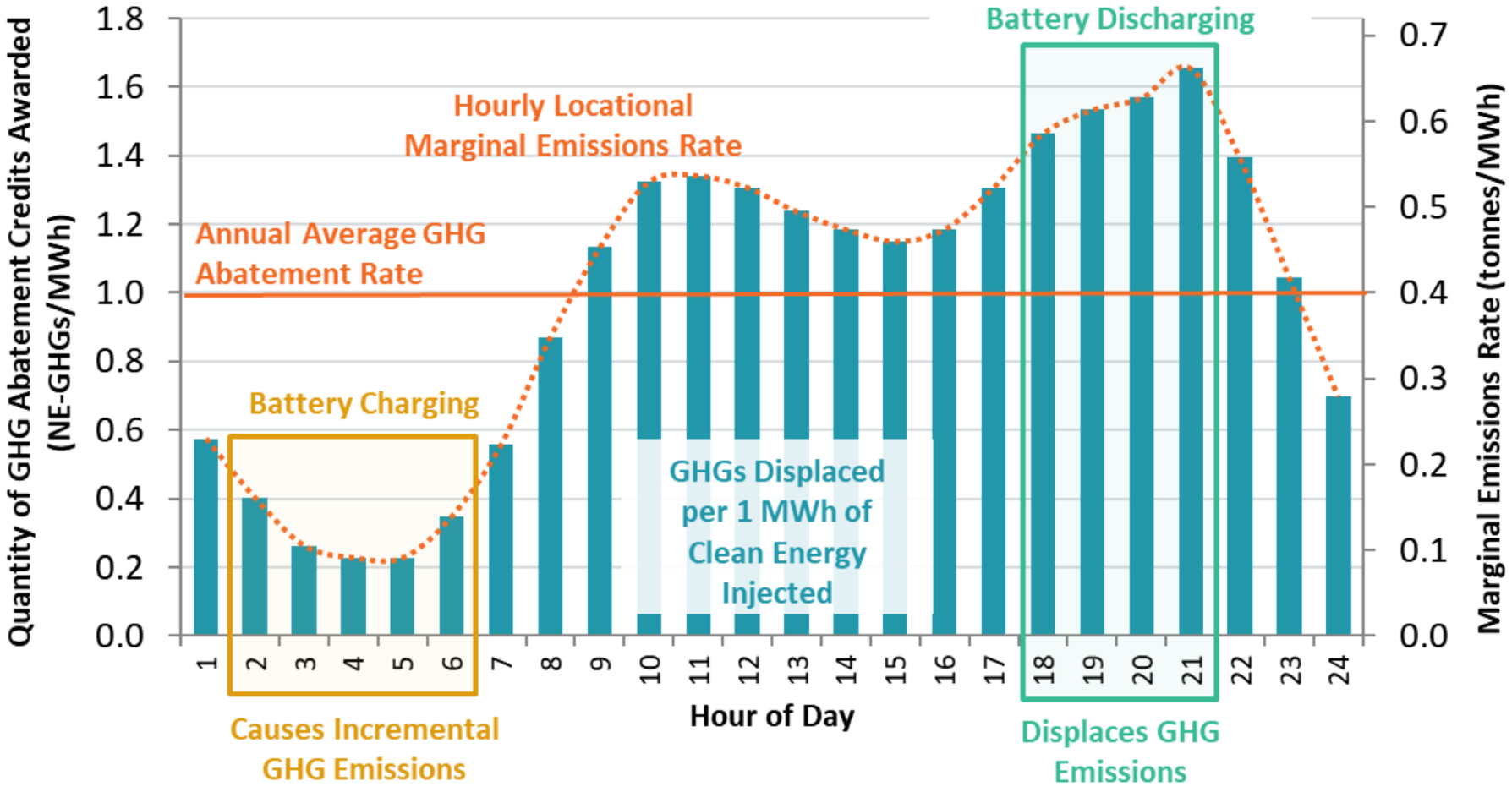


https://www.pjm.com/markets-and-operations/m/emissions

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MARGINAL EMISSIONS OVER TIME

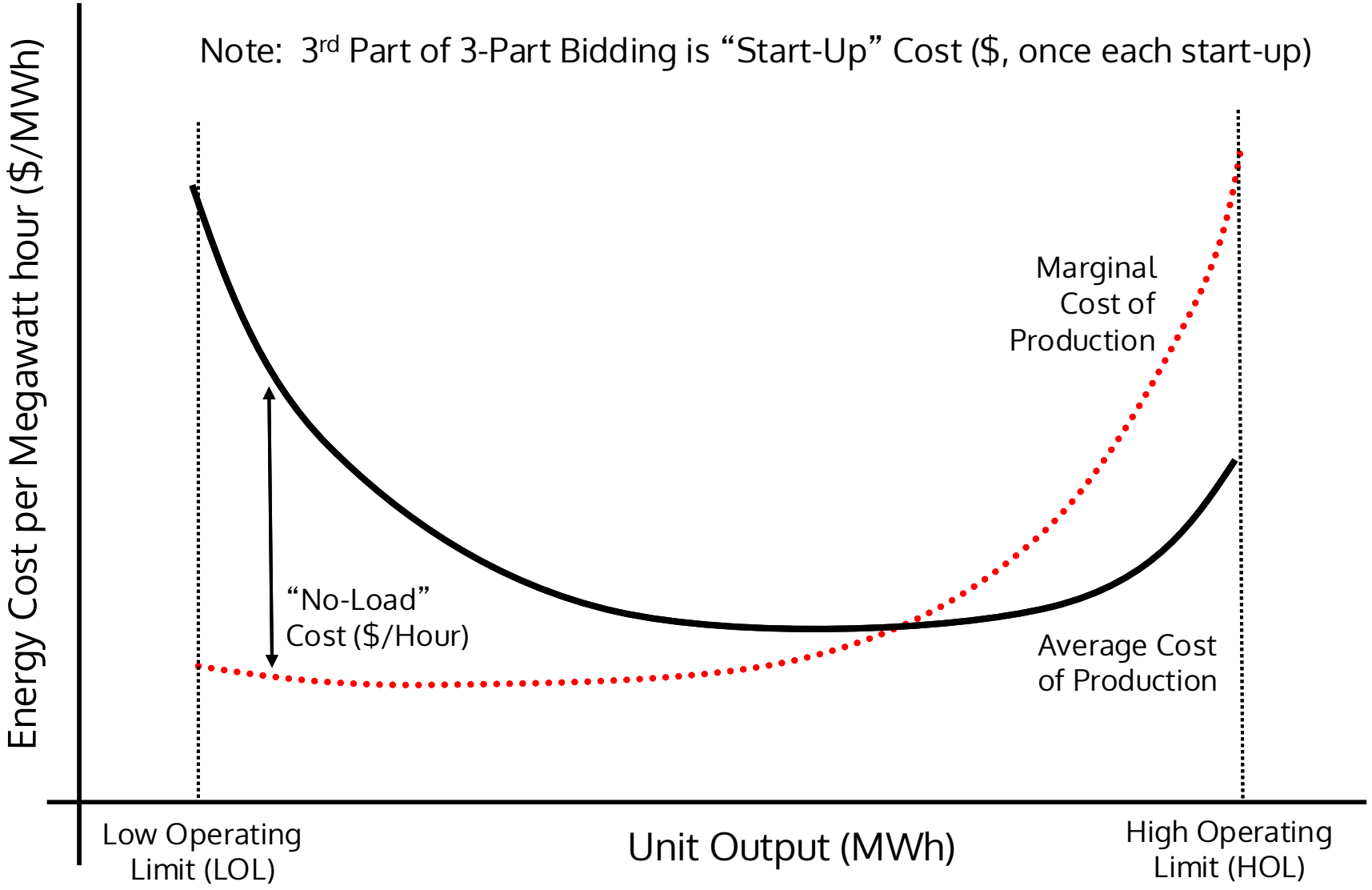


https://www.brattle.com/wp-content/uploads/2023/01/Locational-Marginal-Emissions.pdf

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GENERATION UNIT COSTS



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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

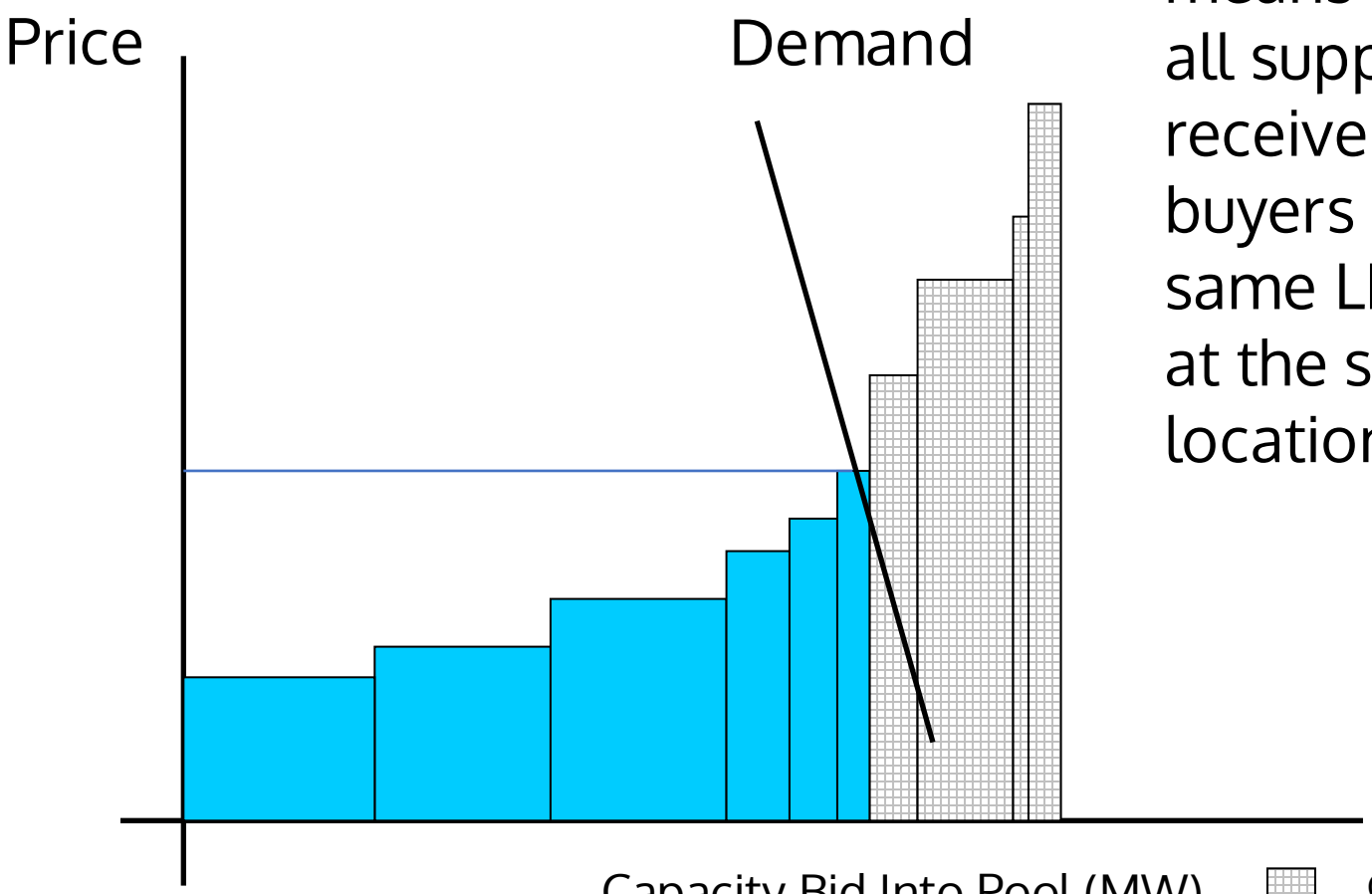
- Any Market Participant (Virtual Offers and Bids or Convergence Bidding)
  Submit offers and/or bids even if not planning to supply power or serve load

- 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

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UNIFORM AUCTION

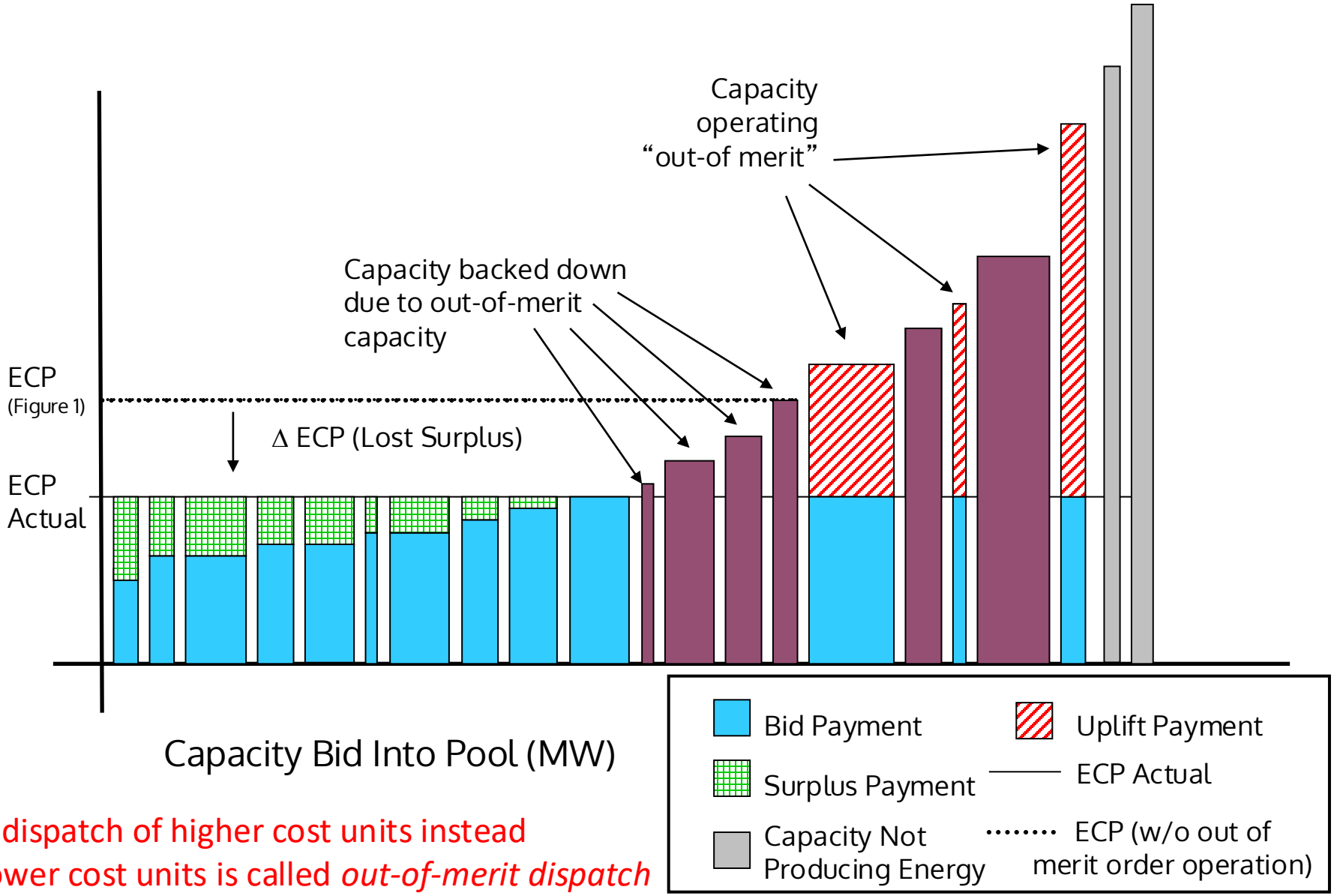


Uniform auction means that all suppliers receive and all buyers pay the same LMP at the same location and time

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WHY LMPs ARE NEEDED



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

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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

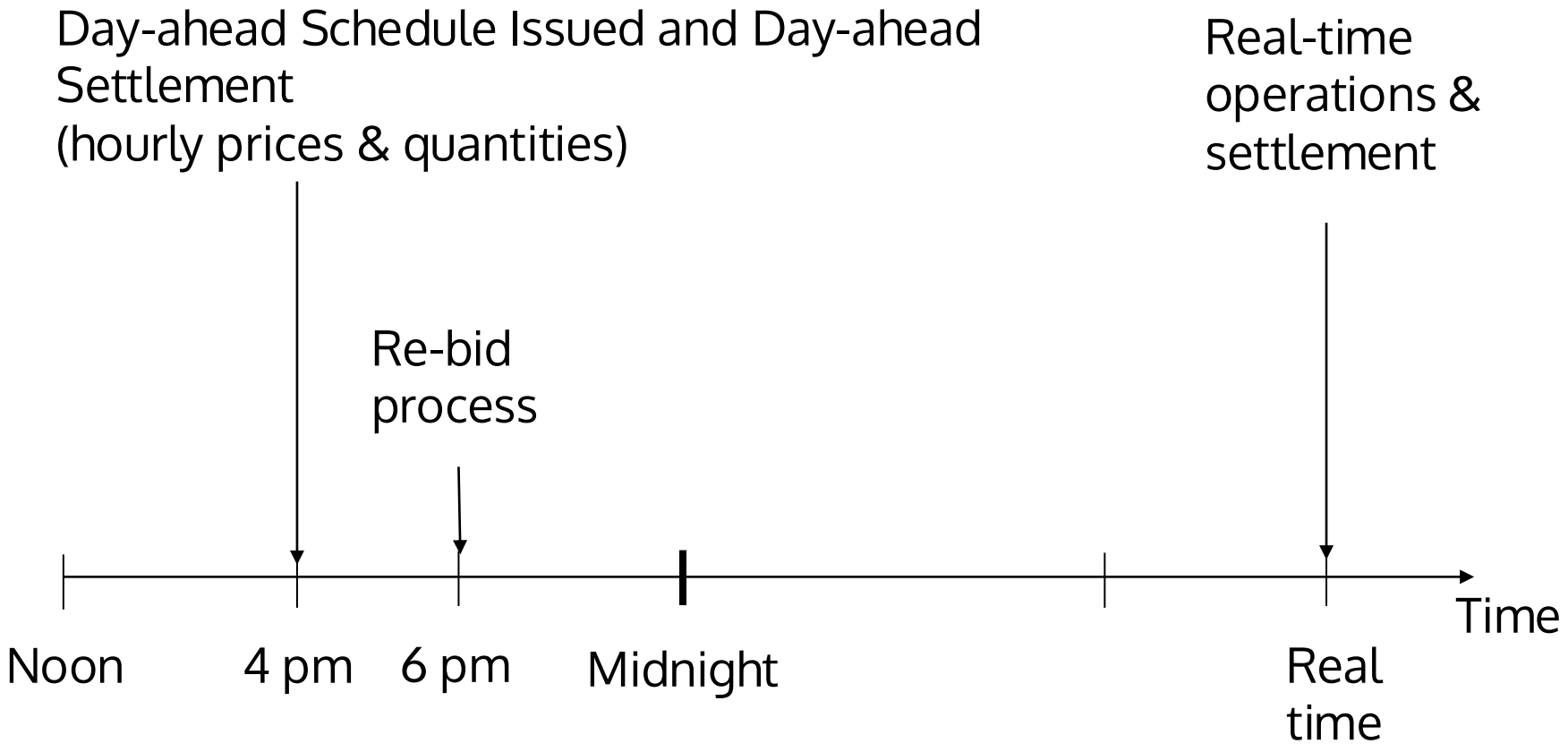
- Based on actual dispatch of system
- Settlement based on deviations from day-ahead settlement
- More volatile than day-ahead markets
- More important in shaping overall pricing (Day-ahead bidding shaped by expectations of real-time price)

=> Economic concept of arbitrage

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ISO MULTI-SETTLEMENT TIMELINE



Note: Actual schedule varies significantly across ISOs

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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:

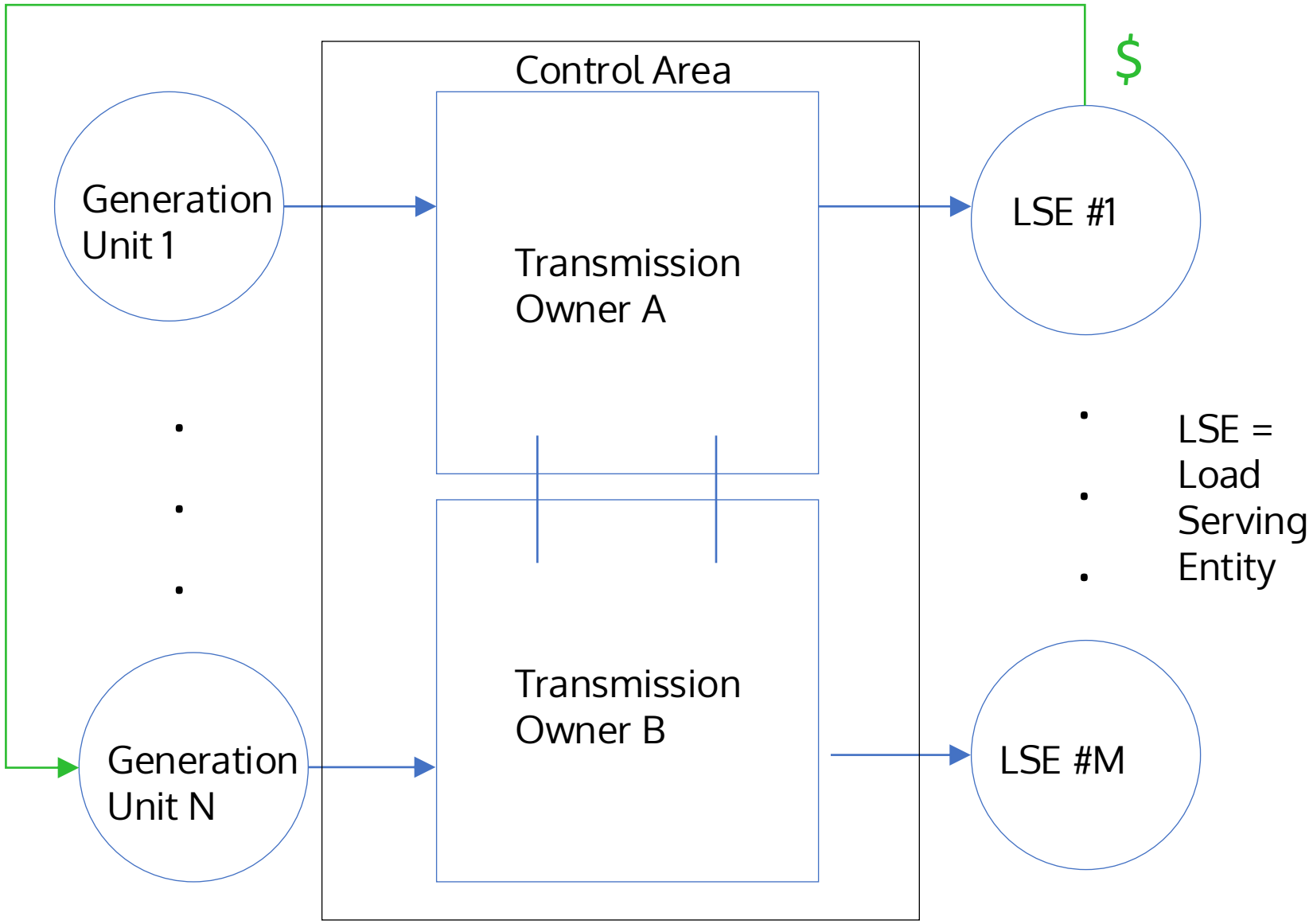
Sells 100MWh day-ahead in Hour 12 but only produces 90 MWh in real-time
Day-ahead price = $40/MWh & Real-time price = $50/MWh
Generator Hour 12 payment =
100 MWh*$40/MWh + [90 MWh – 100 MWh]*$50/MWh = $4,000 - $500 = $3,500

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

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BILATERAL CONTRACTS



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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

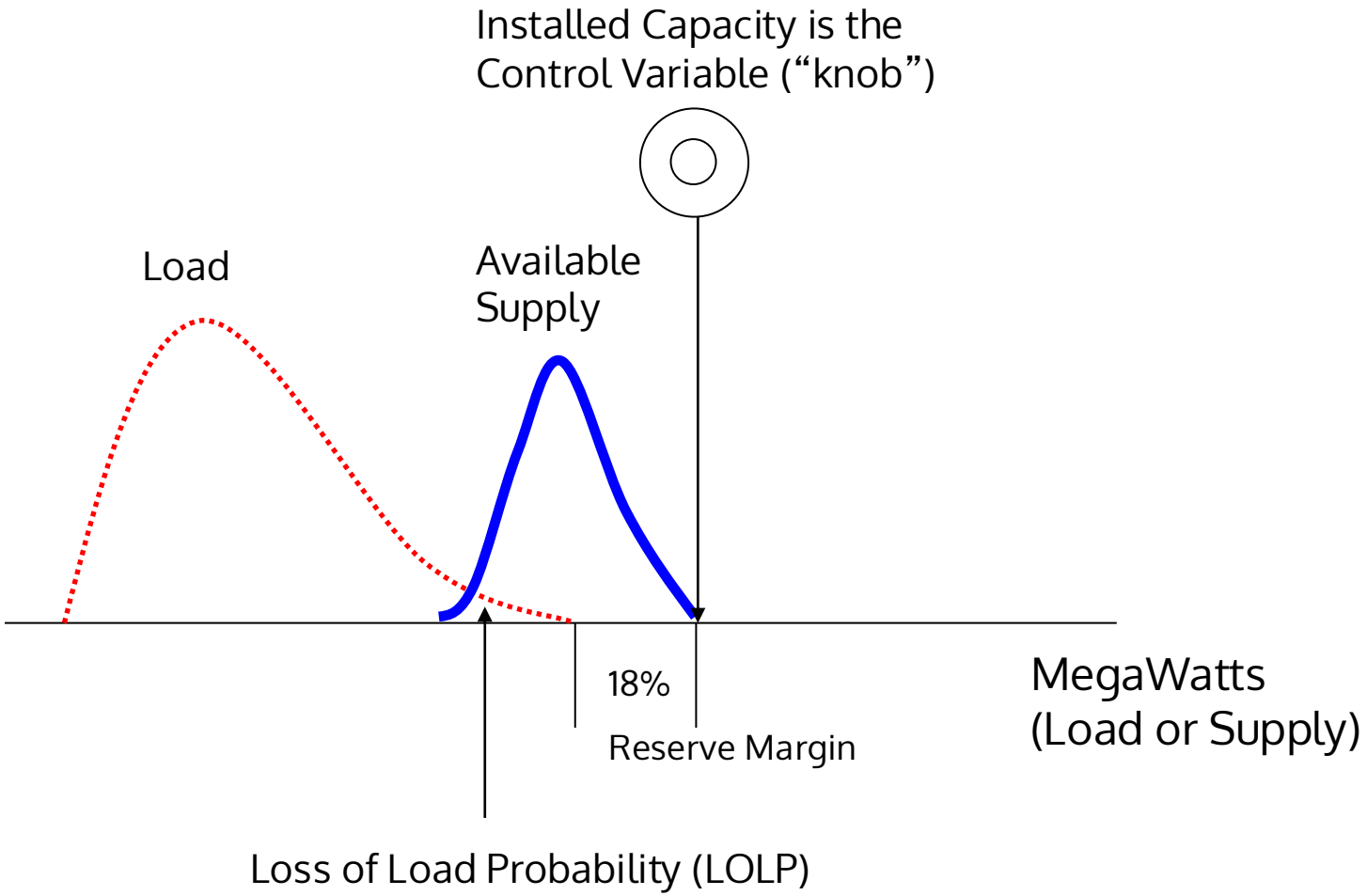


TCC for 1 MW = $50-$30/MWh = $20

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CAPACITY MARKETS



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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.

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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.

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ANCILLARY SERVICE CHARGES (PJM)

Table 1-9 Total cost per MWh by category: January through June, 2025 and 2026[66] [67] [68]

Category	2025 (Jan-Jun) $/MWh	2025 (Jan-Jun) ($ Millions)	2025 (Jan-Jun) Percent of Total	2026 (Jan-Jun) $/MWh	2026 (Jan-Jun) ($ Millions)	2026 (Jan-Jun) Percent of Total	Percent Change
Energy	$49.21	$19,431	64.6%	$72.68	$29,415	63.5%	47.7%
Day Ahead Energy	$49.09	$19,382	64.5%	$73.65	$29,808	64.3%	50.0%
Balancing Energy	$1.17	$461	1.5%	$2.11	$854	1.8%	80.6%
ARR Credits	($1.44)	($568)	(1.9%)	($3.13)	($1,268)	(2.7%)	117.7%
Self Scheduled FTR Credits	($1.26)	($499)	(1.7%)	($2.85)	($1,153)	(2.5%)	125.6%
Balancing Congestion	$0.76	$302	1.0%	$0.96	$388	0.8%	25.5%
Emergency Energy	$0.01	$6	0.0%	$0.05	$20	0.0%	244.8%
Inadvertent Energy	($0.01)	($6)	(0.0%)	$0.02	$10	0.0%	(267.7%)
Load Response - Energy	$0.04	$15	0.0%	$0.05	$21	0.0%	35.3%
Emergency Load Response	$0.00	$0	0.0%	$0.01	$2	0.0%	570.1%
Energy Uplift (Operating Reserves)	$1.44	$568	1.9%	$2.80	$1,133	2.4%	94.5%
Marginal Loss Surplus Allocation	($0.70)	($278)	(0.9%)	($1.28)	($517)	(1.1%)	81.6%
Market to Market Payments	$0.12	$47	0.2%	$0.29	$118	0.3%	144.3%
Capacity	$6.39	$2,522	8.4%	$19.61	$7,938	17.1%	207.1%
Capacity (Capacity Market and FRR)	$6.32	$2,497	8.3%	$19.75	$7,994	17.3%	212.4%
Capacity Part V (RMR)	$0.06	$25	0.1%	($0.14)	($57)	(0.1%)	(319.6%)
Load Response - Capacity	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Transmission	$18.82	$7,432	24.7%	$19.88	$8,048	17.4%	5.6%
Transmission Service Charges	$15.94	$6,294	20.9%	$17.18	$6,955	15.0%	7.8%
Transmission Enhancement Cost Recovery	$2.79	$1,101	3.7%	$2.61	$1,056	2.3%	(6.4%)
Transmission Owner (Schedule 1A)	$0.09	$37	0.1%	$0.09	$37	0.1%	(4.0%)
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	$1.06	$419	1.4%	$1.63	$660	1.4%	53.7%
Reactive	$0.46	$182	0.6%	$0.36	$144	0.3%	(22.9%)
Regulation	$0.32	$126	0.4%	$1.02	$412	0.9%	218.0%
Black Start	$0.07	$29	0.1%	$0.06	$22	0.0%	(24.4%)
Synchronized Reserves	$0.19	$74	0.2%	$0.17	$71	0.2%	(6.3%)
Secondary Reserves	$0.00	$2	0.0%	$0.02	$7	0.0%	236.1%
Non-Synchronized Reserves	$0.02	$6	0.0%	$0.01	$5	0.0%	(22.1%)
Day Ahead Scheduling Reserve (DASR)	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Administration	$0.67	$266	0.9%	$0.69	$280	0.6%	2.4%
PJM Administrative Fees	$0.63	$248	0.8%	$0.64	$259	0.6%	2.0%
NERC/RFC	$0.04	$17	0.1%	$0.05	$18	0.0%	6.2%
RTO Startup and Expansion	$0.00	$0	0.0%	$0.00	$0	0.0%	0.0%
Other	$0.00	$2	0.0%	$0.01	$2	0.0%	13.6%
Total Cost ($/MWh)	$76.16	$30,071	100.0%	$114.50	$46,340	100.0%	50.3%
Total Day Ahead Load (GWh)	388,687			397,264			2.2%
Total Balancing Load (GWh)	(6,155)			(7,446)			21.0%
Total Real Time Load (GWh)	394,842			404,710			2.5%
Total Cost ($ Billions)	$30.07			$46.34			54.1%

66 Note: The totals in this table include after the fact billing adjustments and may not match totals presented in past reports.
67 The total cost in this table does not match the PJM reported total billing due to differences in calculation methods. The total prices in this table are load-weighted average system prices per MWh by category, even if each category is not charged on a per MWh basis. The total cost is the total costs to load, whereas PJM's reported total billing are the total dollars (charges) that pass through the PJM settlement process.
68 The MMU publishes monthly detail of the total cost of wholesale power. See <https://www.monitoringanalytics.com/data/pjm_cost.shtml>.

PJM State of the Market, 2026, Table I-9, p. 20, Monitoring Analytics

https://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2026/2026q2-som-pjm-sec1.pdf

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EMISSION PERMIT (ALLOWANCE) MARKETS

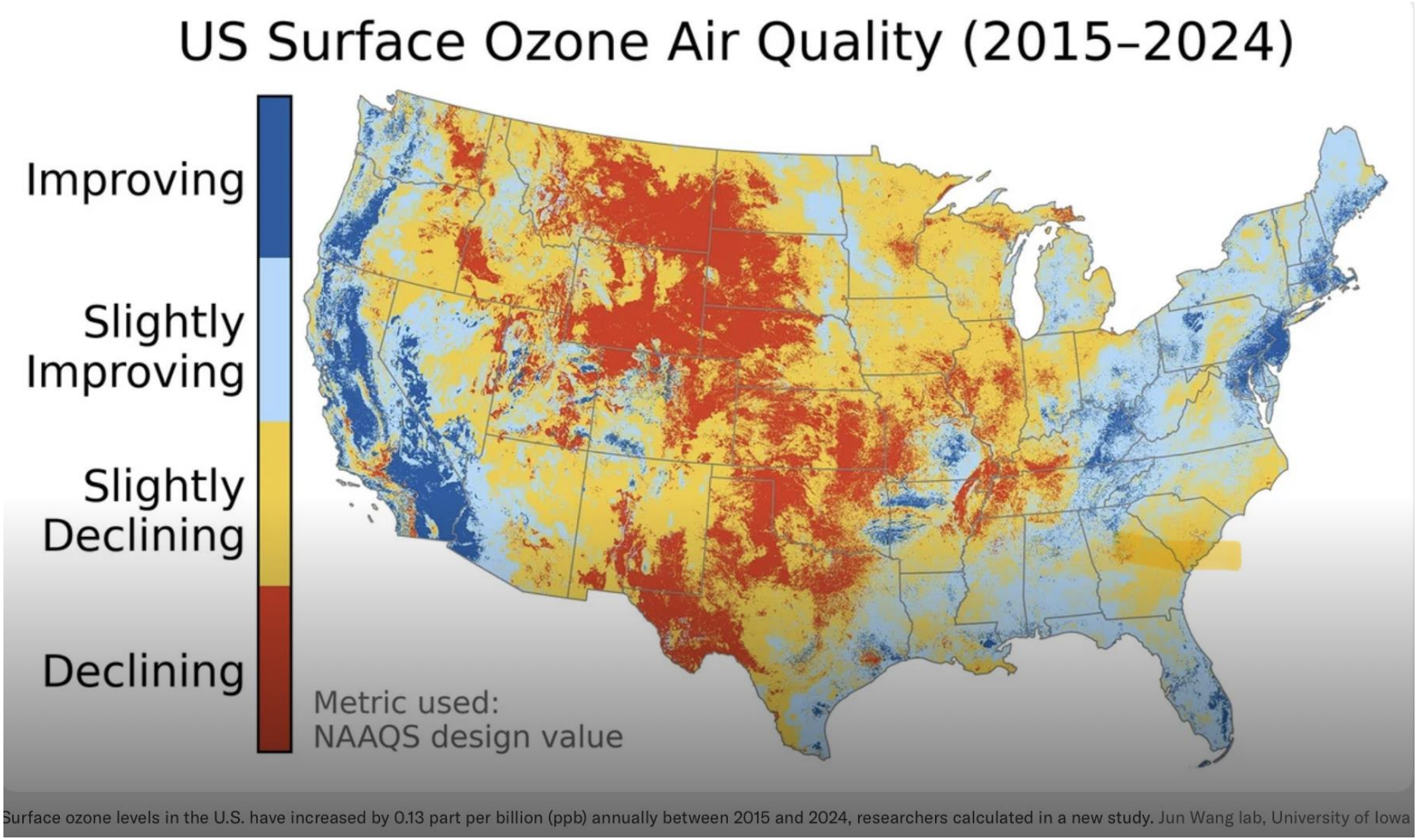
- For some emissions, e.g., SO_2 and NO_x, a permit, aka an allowance, is required per unit of emission

  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

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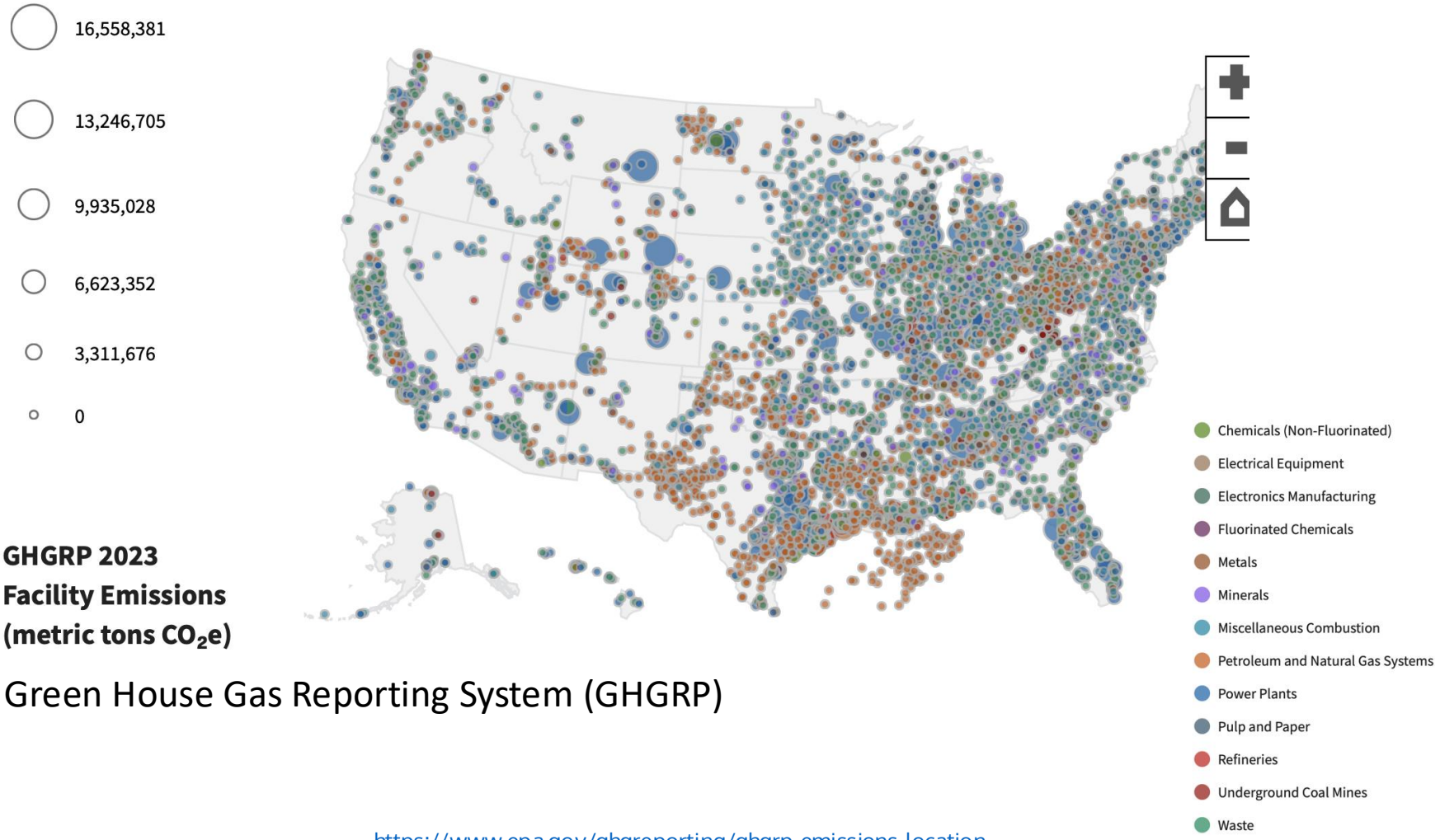


https://www.scientificamerican.com/article/increase-in-wildfire-driven-ozone-pollution-linked-to-premature-deaths-across-the-u-s/

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LOCATION & TOTAL REPORTED CO2 EMISSIONS FROM GHGRP FACILITIES



Green House Gas Reporting System (GHGRP)

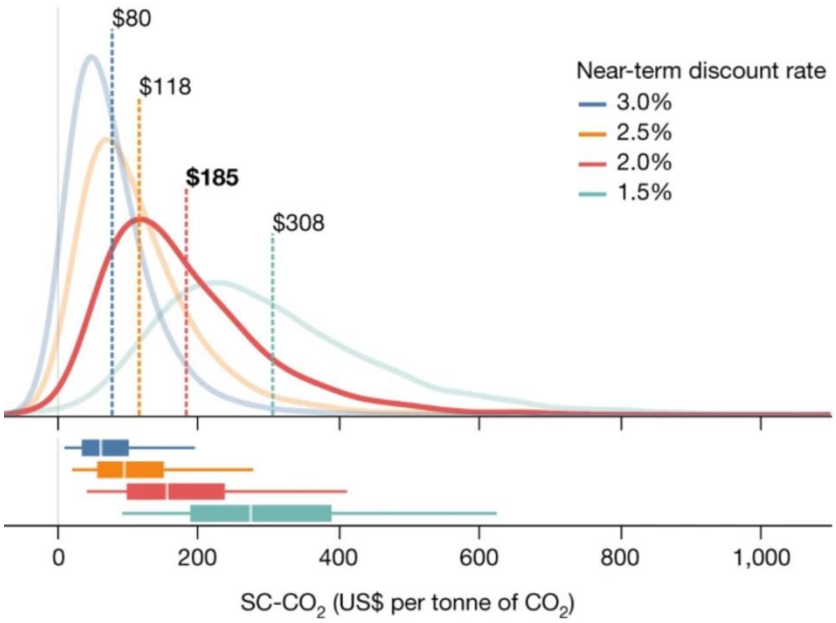
https://www.epa.gov/ghgreporting/ghgrp-emissions-location

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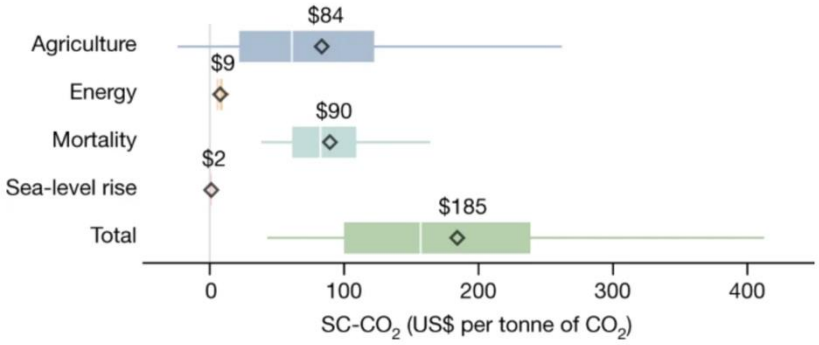
Social Cost of Carbon

SC-CO_2 distributions vary with the choice of near-term discount rates.



Distributions of the SC-CO_2 based on RFF-SP scenario samples, a stochastic, growth-linked discounting framework, uncertainty in the FaIR climate and BRICK sea-level models, and uncertainty in climate damage parameters. Colours correspond to near-term average discount rates of 3.0% (blue), 2.5% (orange), 2.0% (red, our preferred specification) and 1.5% (teal). Dashed vertical lines highlight mean SC-CO_2 values. Box and whisker plots along the bottom of the figure depict the median of each SC-CO_2 distribution (centre white line), 25%–75% quantile range (box width), and 5%–95% quantile range (coloured horizontal lines) values. All SC-CO_2 values are expressed in 2020 US dollars per metric tonne of CO_2.

Fig. 3: Partial SC-CO_2 estimates and uncertainty levels strongly differ across the four climate damage sectors.



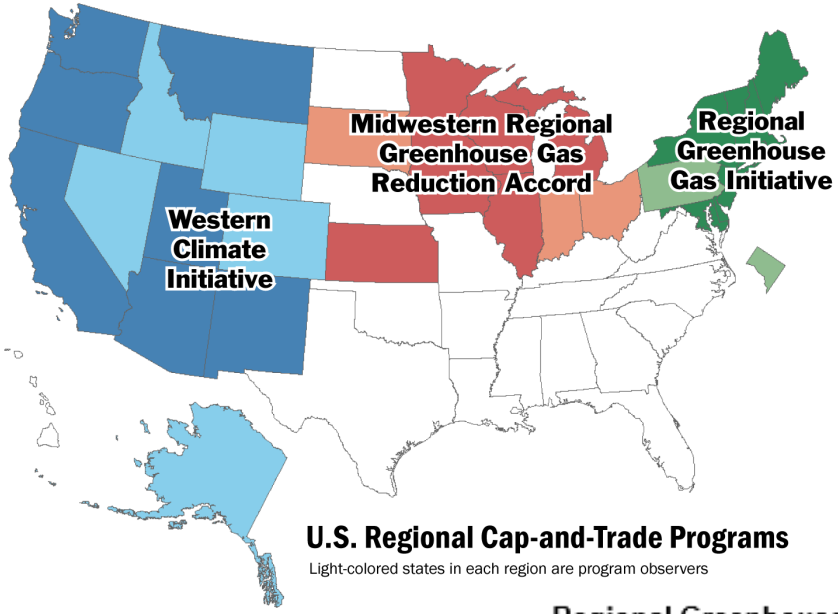
Box and whisker plots for the climate damage sectors included in the GIVE model, based on partial SC-CO_2 estimates for each sector. The figure depicts the median (centre white line), 25%–75% quantile range (box width), and 5%–95% quantile range (coloured horizontal lines) partial SC-CO_2 values. Black diamonds highlight each sector's mean partial SC-CO_2, with the numeric value written directly above. All SC-CO_2 values are expressed in 2020 US dollars per metric tonne of CO_2.

https://www.nature.com/articles/s41586-022-05224-9#Fig2

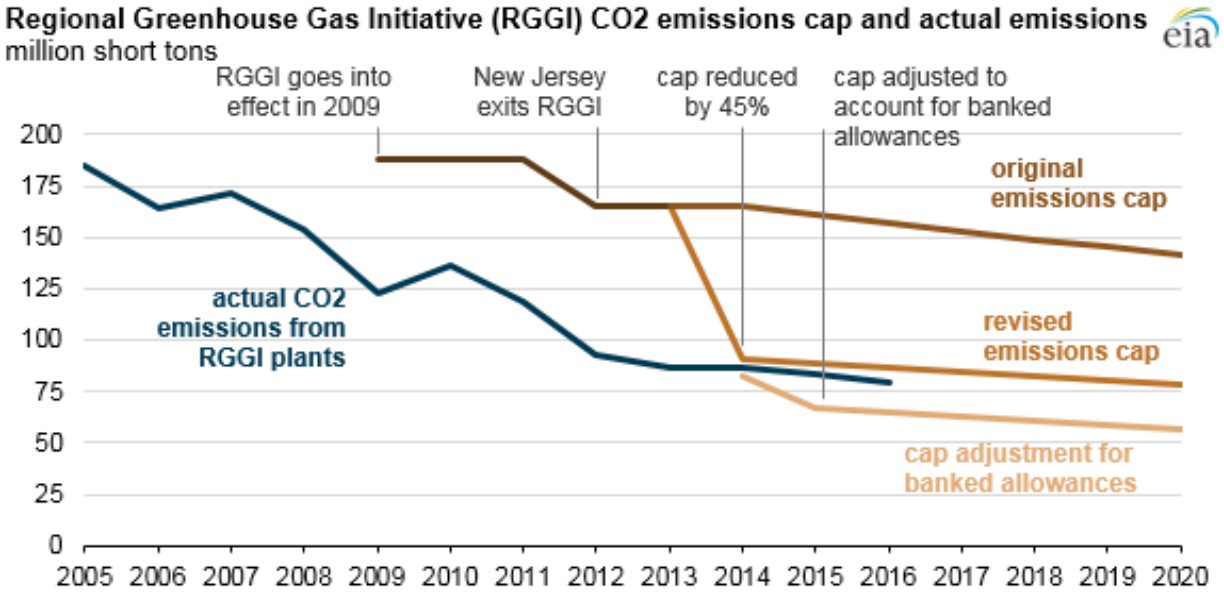
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GREEN HOUSE GAS MARKETS



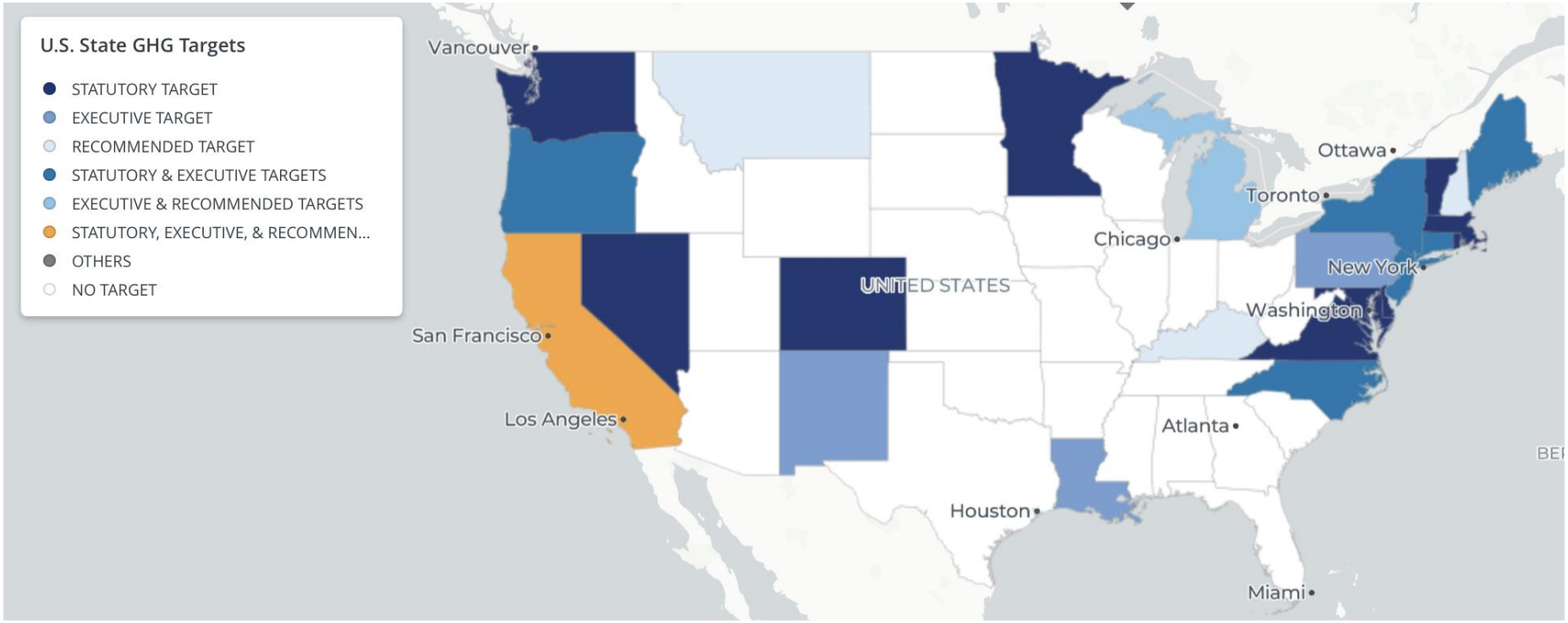
IL, NY, NJ, CT, OH, AND PA have implemented
Zero Emission Credit (ZECs) programs to prevent the retirement of nuclear units



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Greenhouse Gas Emission Targets

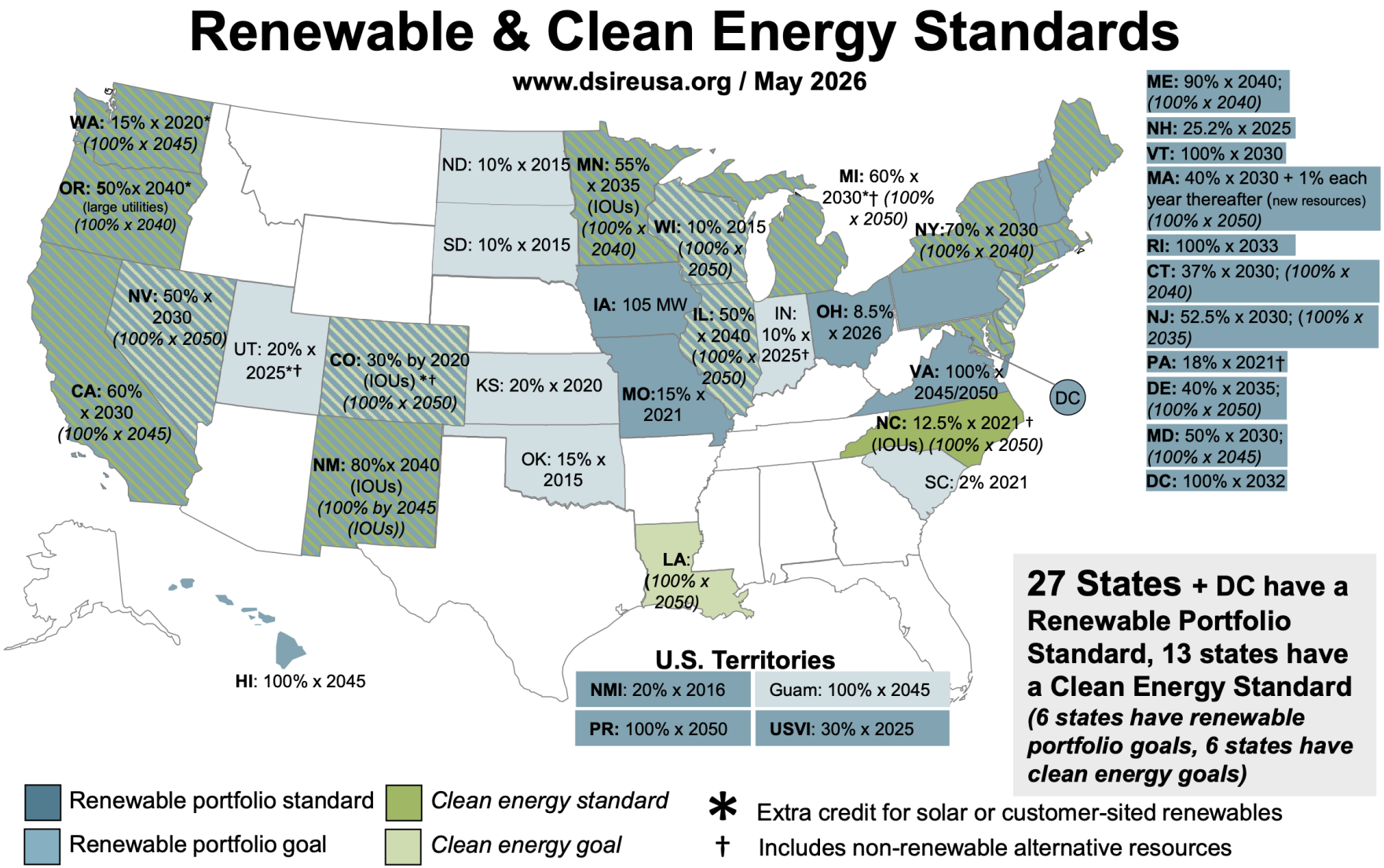


https://www.c2es.org/content/state-climate-policy/

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Renewable Markets

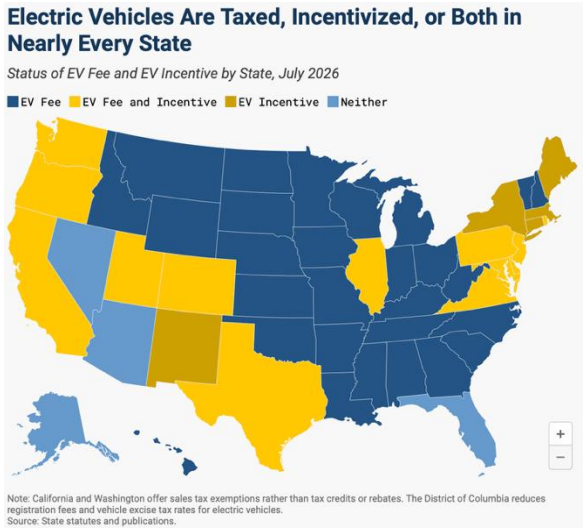


https://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2026/05/RPS-CES-May2026.pdf

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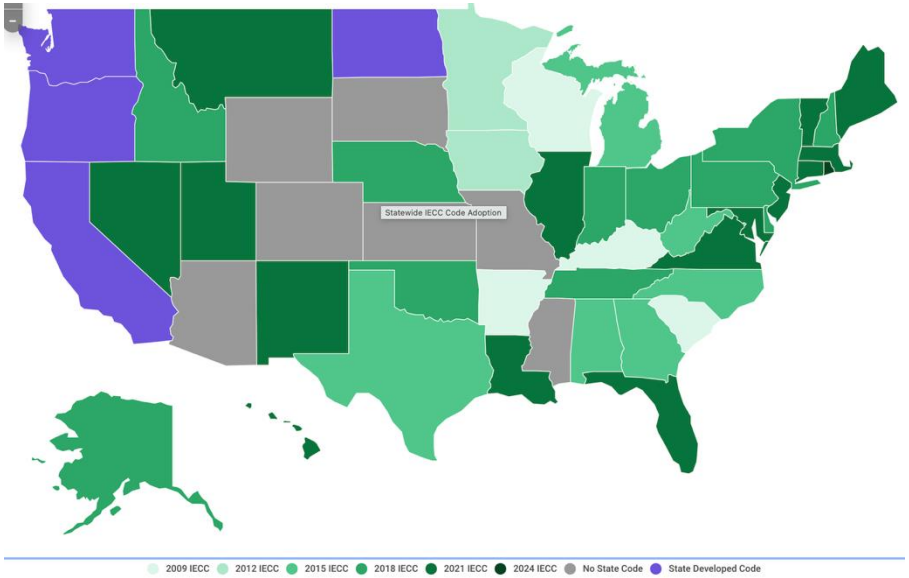
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STATE POLICIES



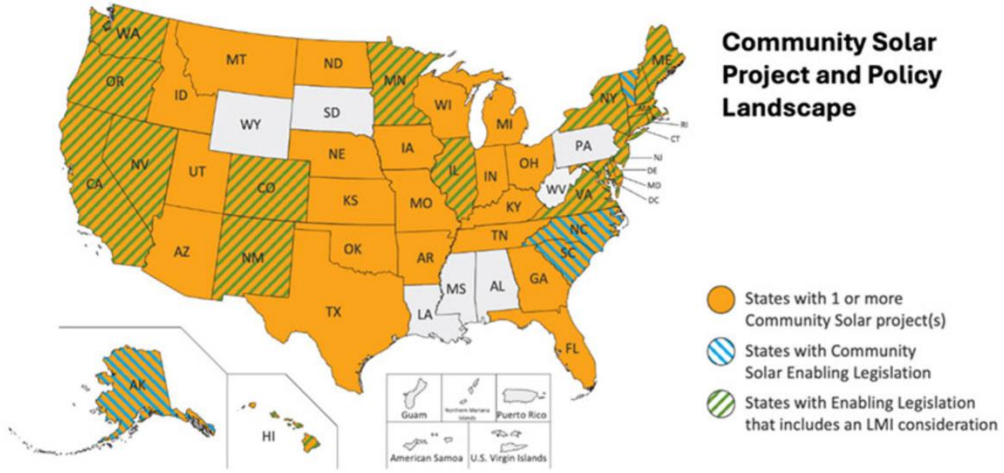
https://taxfoundation.org/data/all/state/electric-vehicle-ev-taxes/

State Energy Codes 2026



https://www.nahb.org/advocacy/top-priorities/building-codes/energy-codes/energy-code-adoption-by-state

States have major impacts on electricity supply and demand



https://www.nlr.gov/state-local-tribal/community-solar

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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

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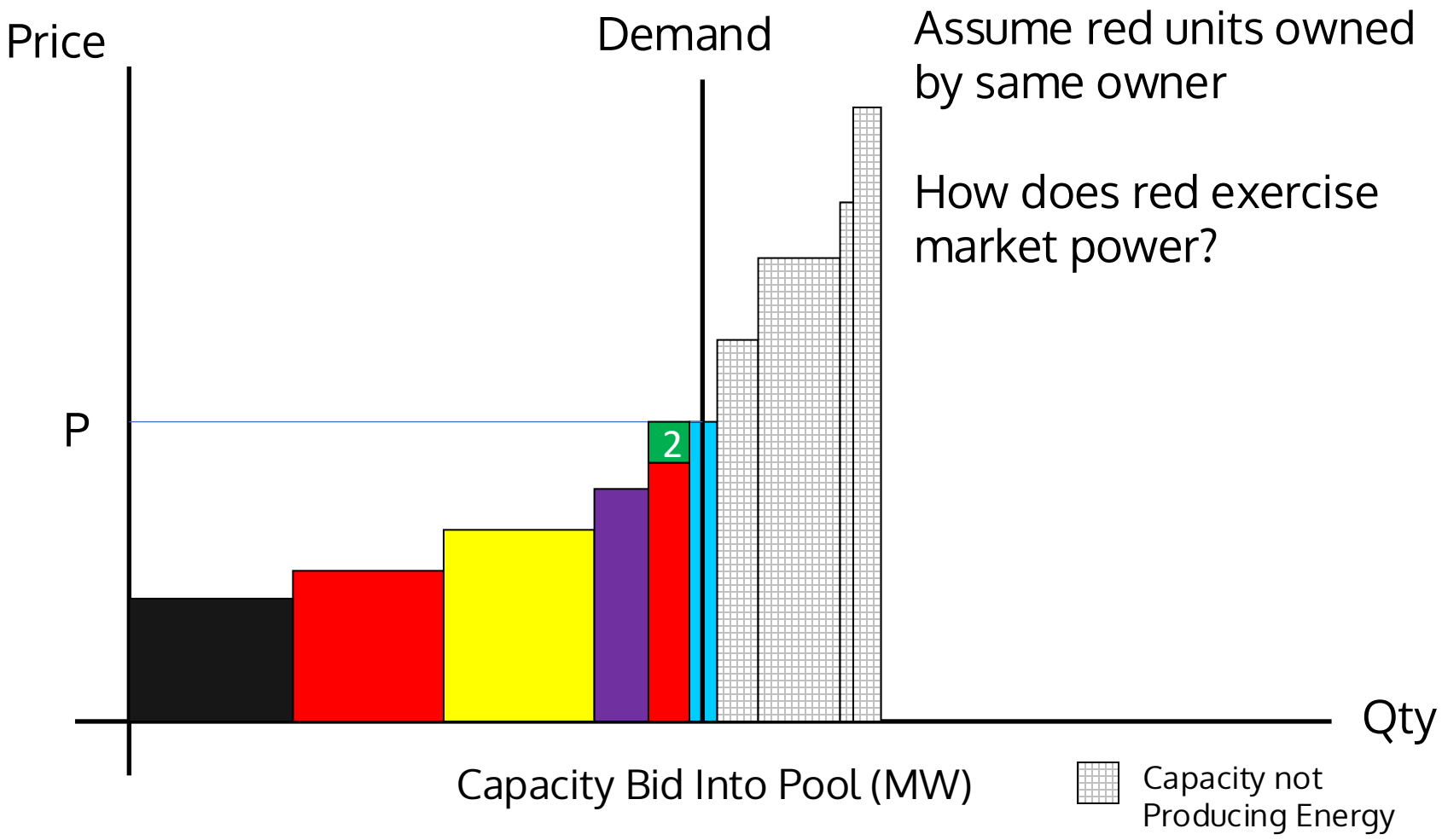
SUMMARY OF MARKET DESIGN CHOICES

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)

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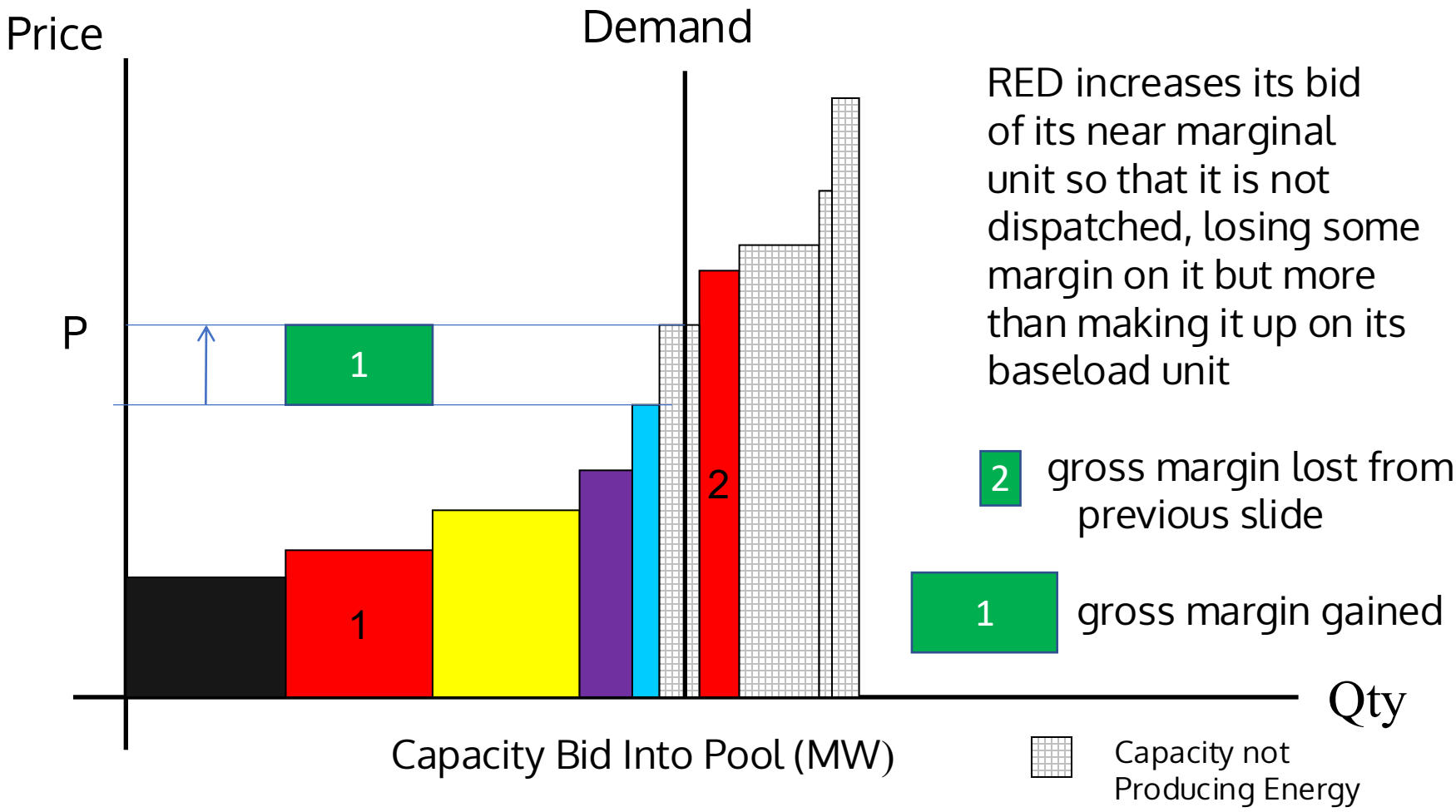
MARKET POWER EXAMPLE



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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

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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"

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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?

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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

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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

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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?

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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

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Session 4:
Political, Regulatory and Business Context

Public

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

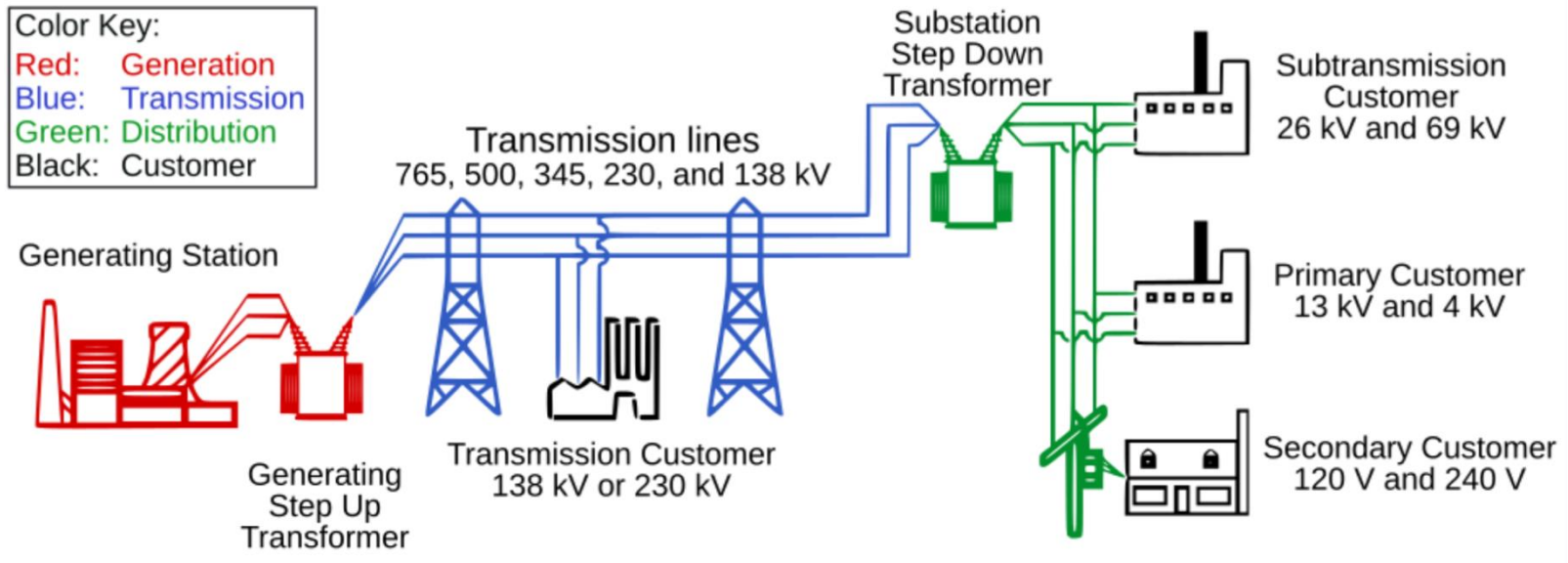
- What role has economies of scale played in the structure of the electric power industry?
- What portions of the industry remain economically regulated and why?
- What is ISO governance?
- What are the roles of the federal and state governments in the power sector?
- Why is transmission planning necessary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

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FORMER REGULATORY STRUCTURE

Investor-Owned Utilities (IOUs)- Integrated



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

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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

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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

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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)

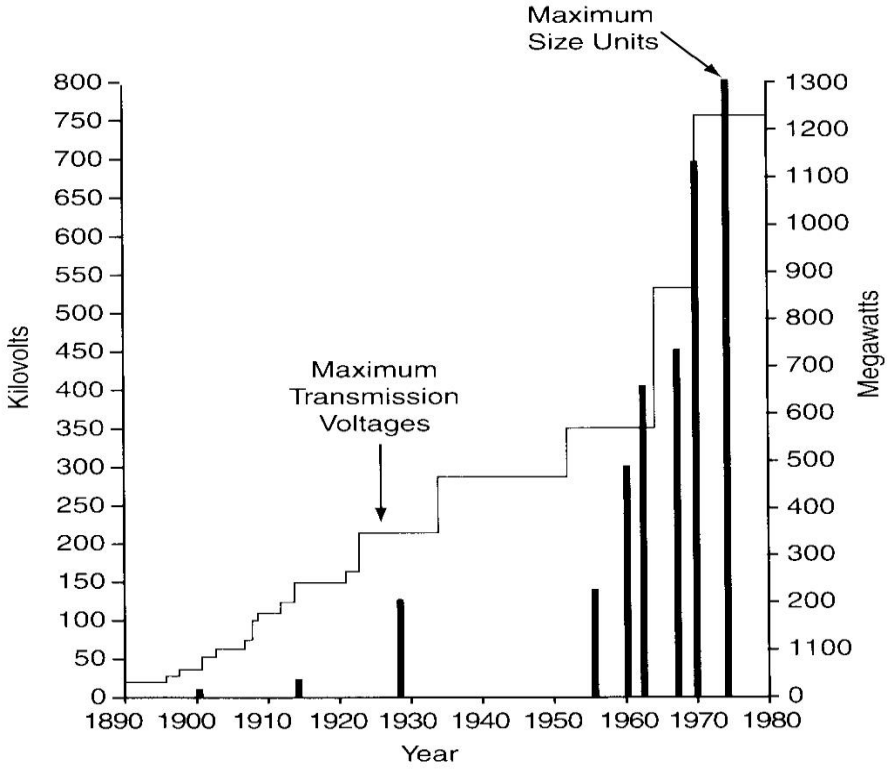
Ratebase

- Original-accumulated depreciation
- Replacement
- Fair market value

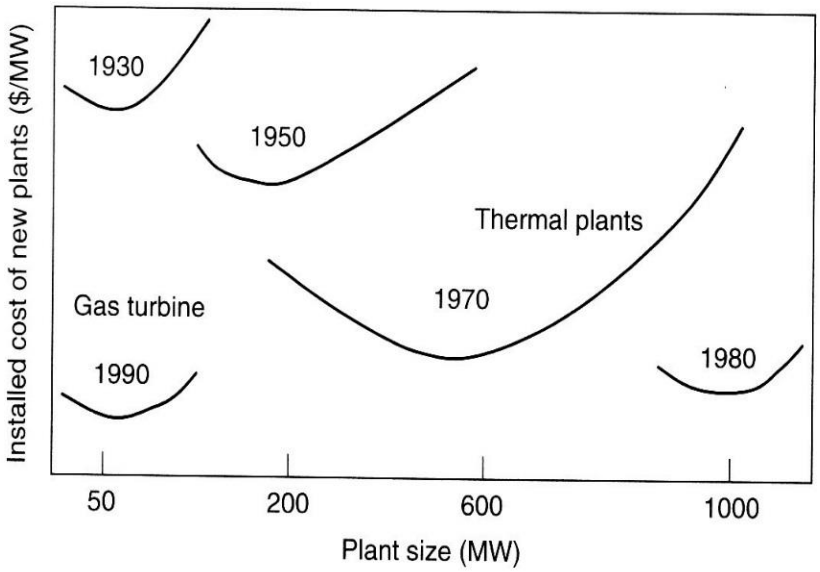
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ECONOMIES OF SCALE



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.

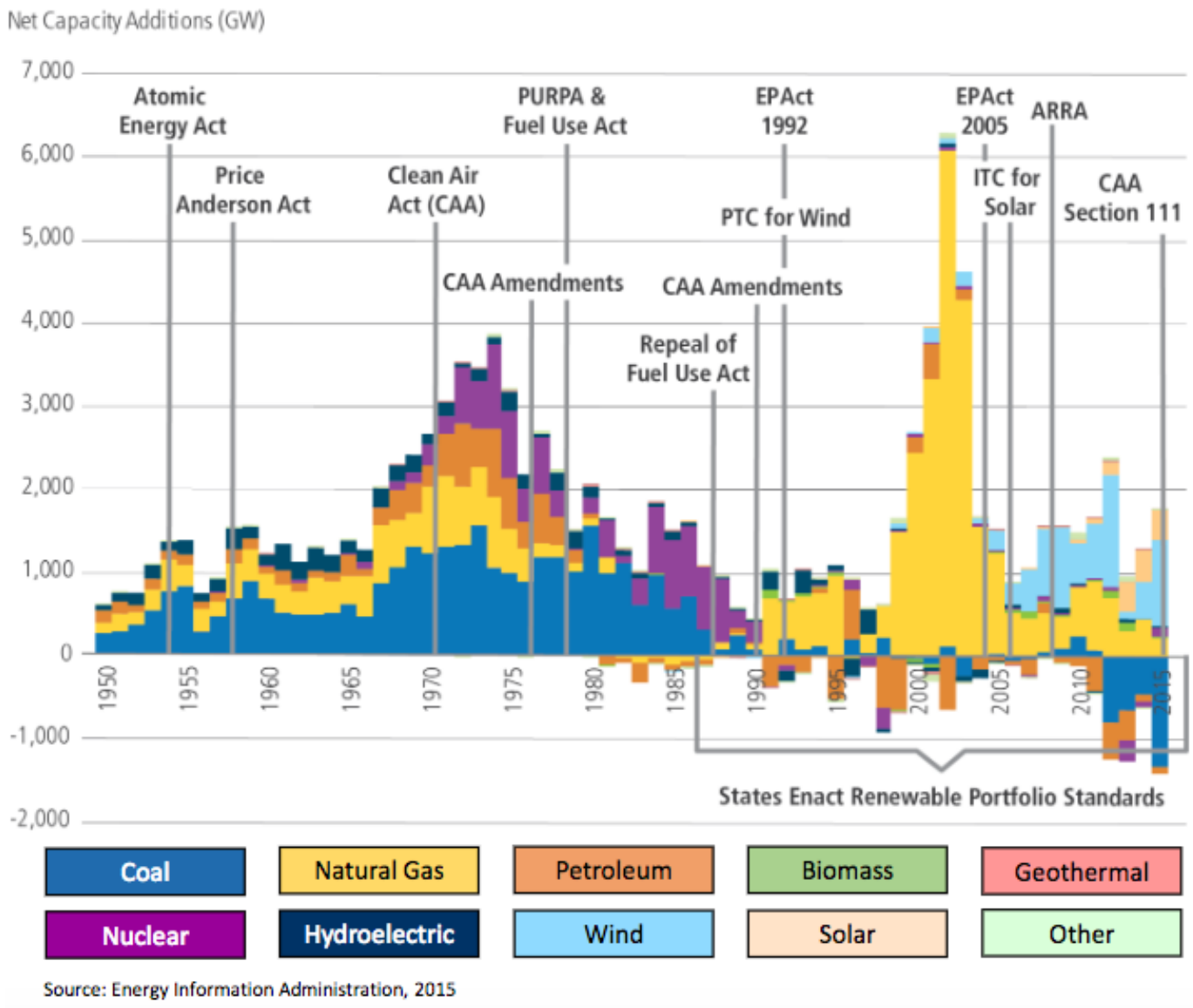
Historical Note: First workable electric system built by Edison at Pearl Street Station, Financial District, NYC



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FEDERAL ELECTRICITY POLICY

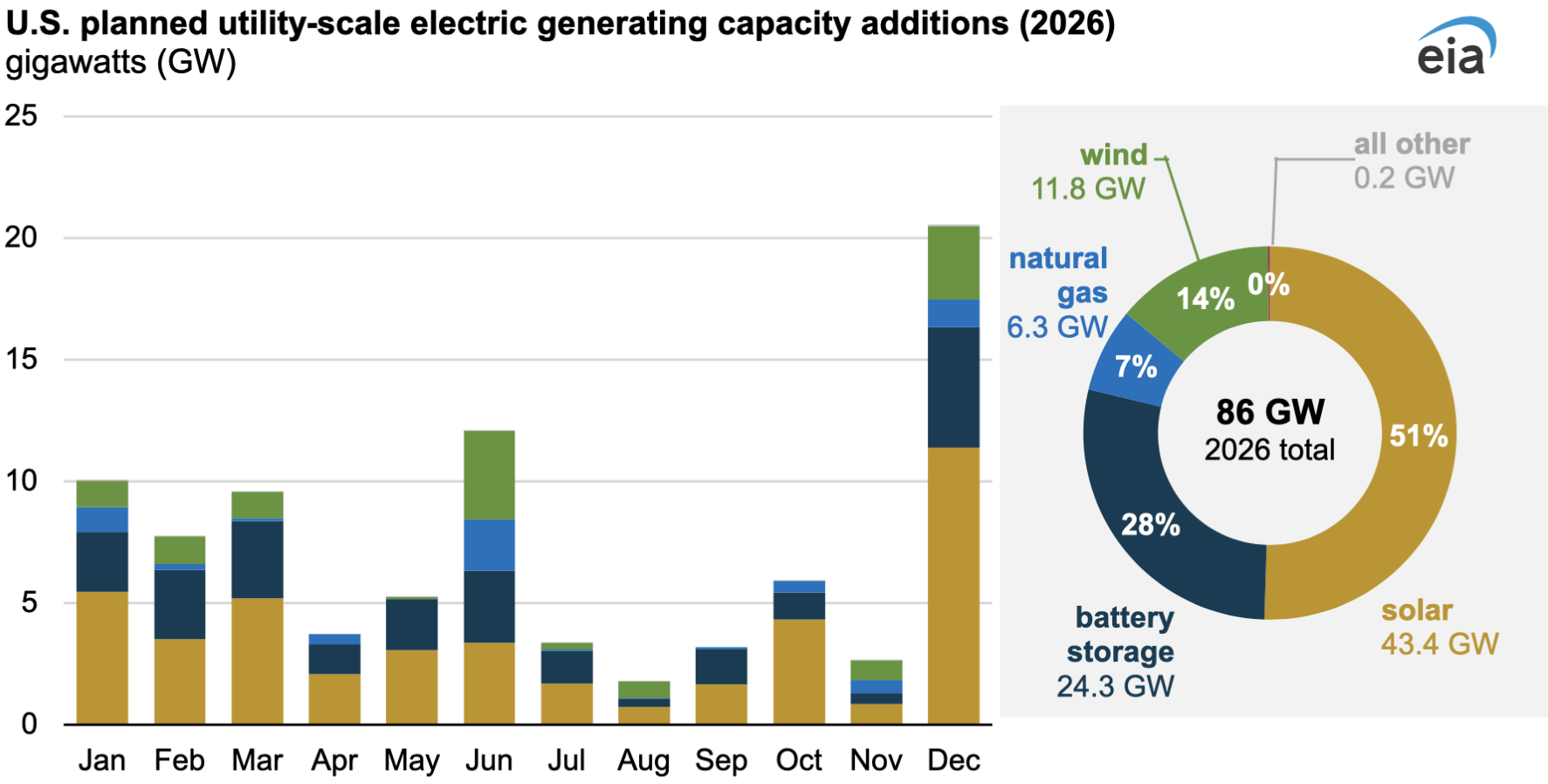


Also the US Inflation Reduction Act (2022) and the US Infrastructure Investment and Jobs Act (2021). One Big Beautiful Bill Act (2025)

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New U.S. electric generating capacity expected to reach a record high in 2026



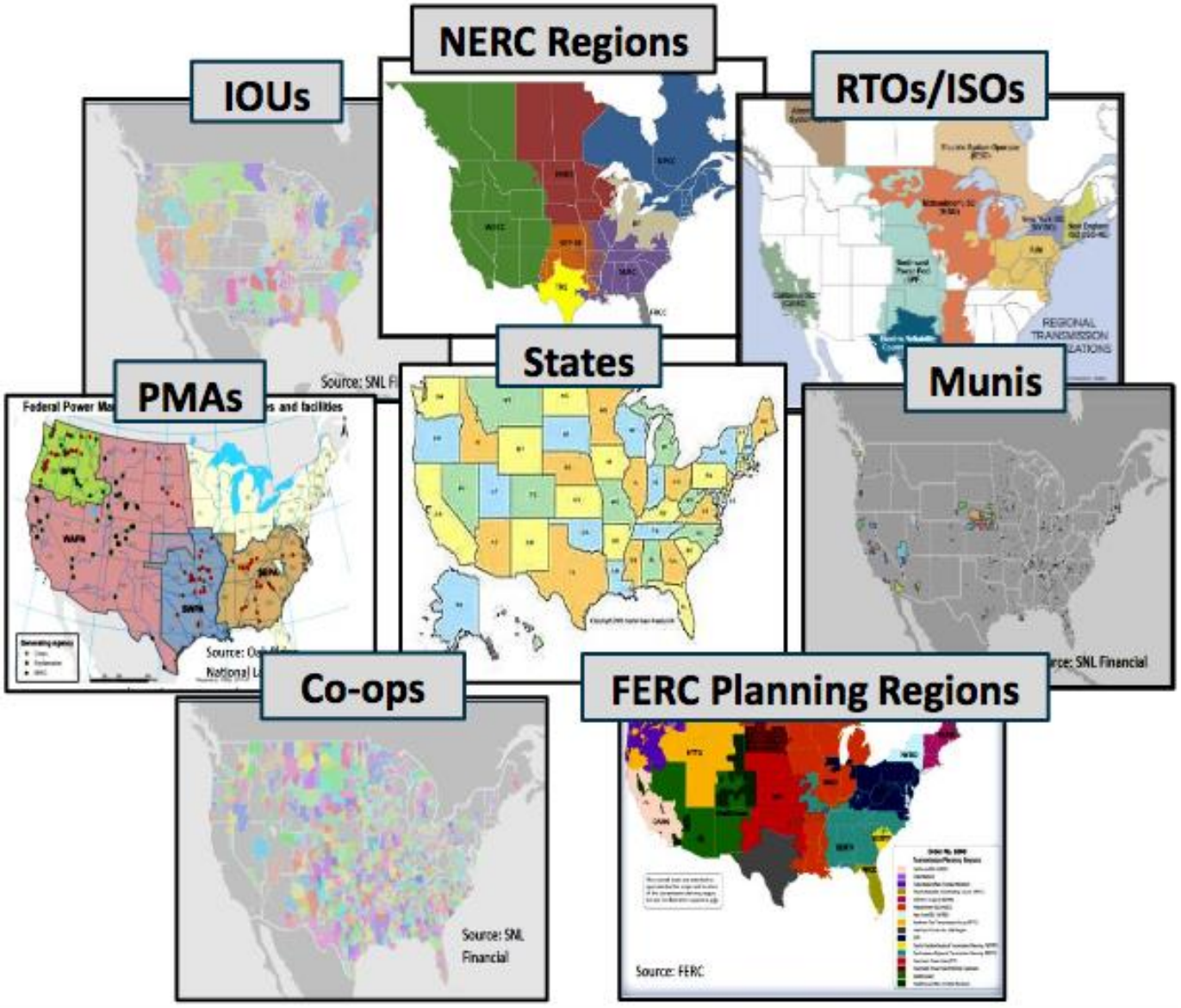
Data source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory*, December 2025

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https://www.eia.gov/todayinenergy/detail.php?id=67205

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ELECTRIC POWER SECTOR GOVERNANCE



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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

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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

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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

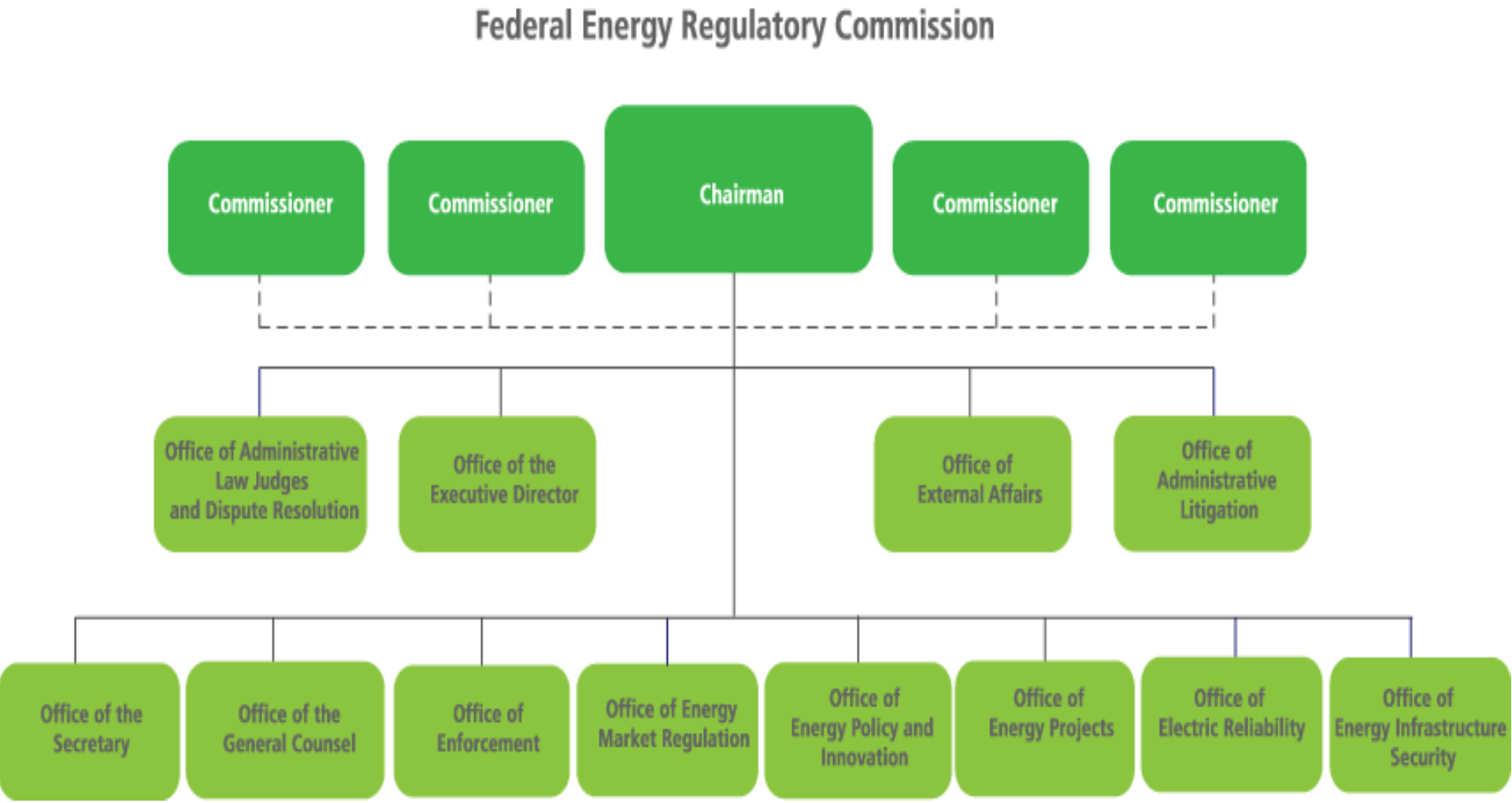
- Regulation at the state level started in 1907 in New York and Wisconsin

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

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FEDERAL ENERGY REGULATORY COMMISSION (FERC)



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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

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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)

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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

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RECENT FERC ELECTRICITY ORDERS

Order No.	Date	Title
AD26-10	July 16, 2026	FERC Orders Western Grid Operators to Deliver Joint Report on Grid Coordination
RM24-8-000 RM25-8-000 RD25-8-000	March 19, 2026	E-2 | E-3 | E-4 | FERC Action: New Reliability Safeguards for American Power Grid | News Release
EL25-49-000	December 18, 2025	E-1 | PJM Co-location Proceeding | News Release | Presentation | Fact Sheet
RM25-8-000 RM24-8-000 RD25-7-000 RM24-4-000	September 18, 2025	Reliability Standard Updates: Items E-1 through E-4 | News Release | Presentation
RM25-3-000	July 24, 2025	E-1 | Reliability Standards for Frequency and Voltage Protection Settings and Ride-Through for Inverter-Based Resources| News Release

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

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RECENT FERC ELECTRICITY ORDERS

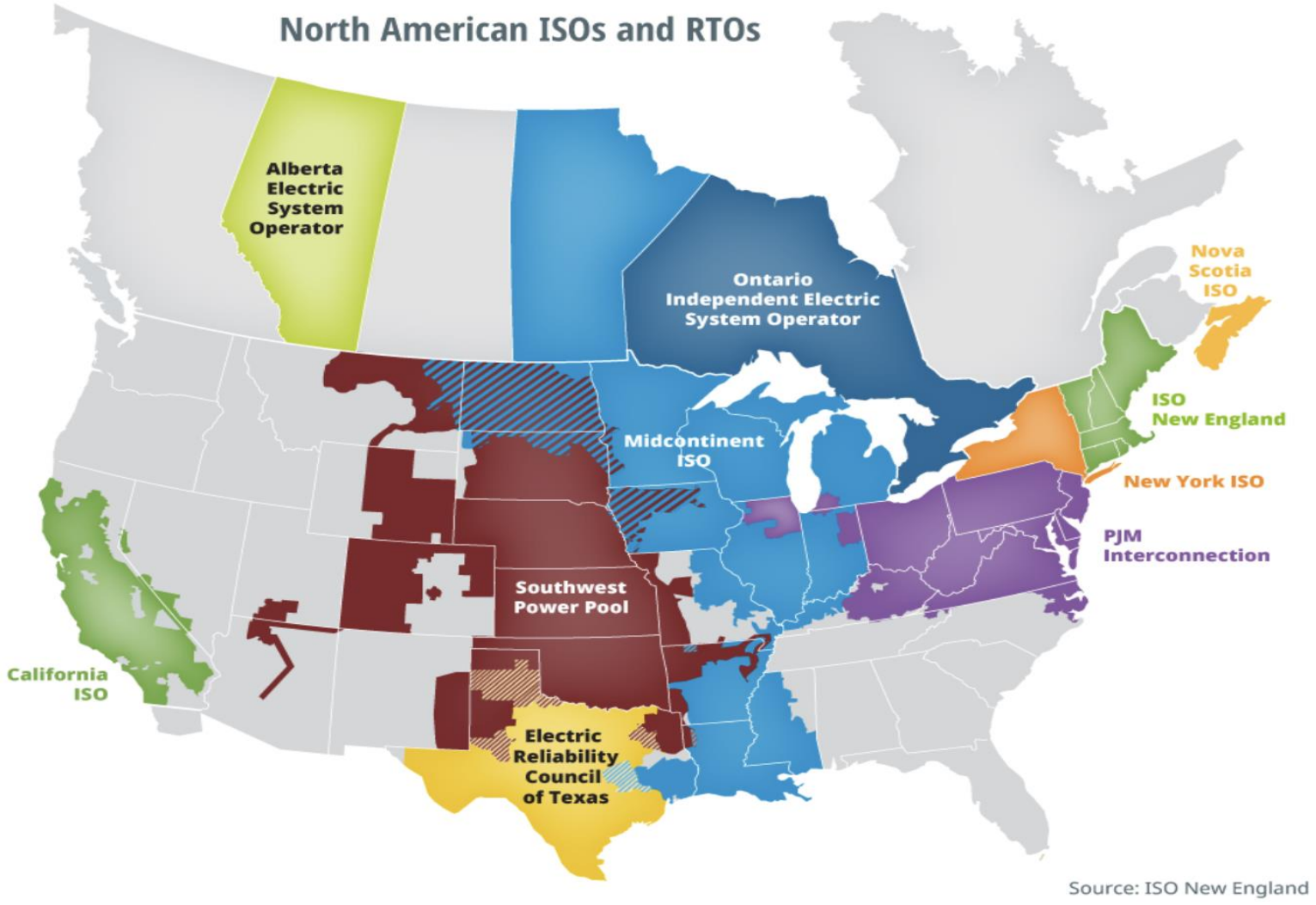
Order No.	Date	Title
EL26-67-000 EL26-70-000 EL26-68-000 EL26-71-000 EL26-72-000 EL26-69-000	June 18, 2026	Order Instituting Proceeding Under Section 206 of the Federal Power Act | News Release | Fact Sheet | Presentation
Order No. 1920 Guidance	June 17, 2025	Compliance Filings Schedule
Order 1920-B	April 11, 2025	Order on Rehearing and Clarification: Building for the Future Through Electric Regional Transmission Planning and Cost Allocation | Explainer
Order No. 1920-A	November 21, 2024	Building for the Future Through Electric Regional Transmission Planning and Cost Allocation | Presentation | News Release
Order 1977-A	October 17,2024	Applications for Permits to Site Interstate Electric Transmission Facilities Rehearing | Item E-1 | News Release

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

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RTO/ISO MAP

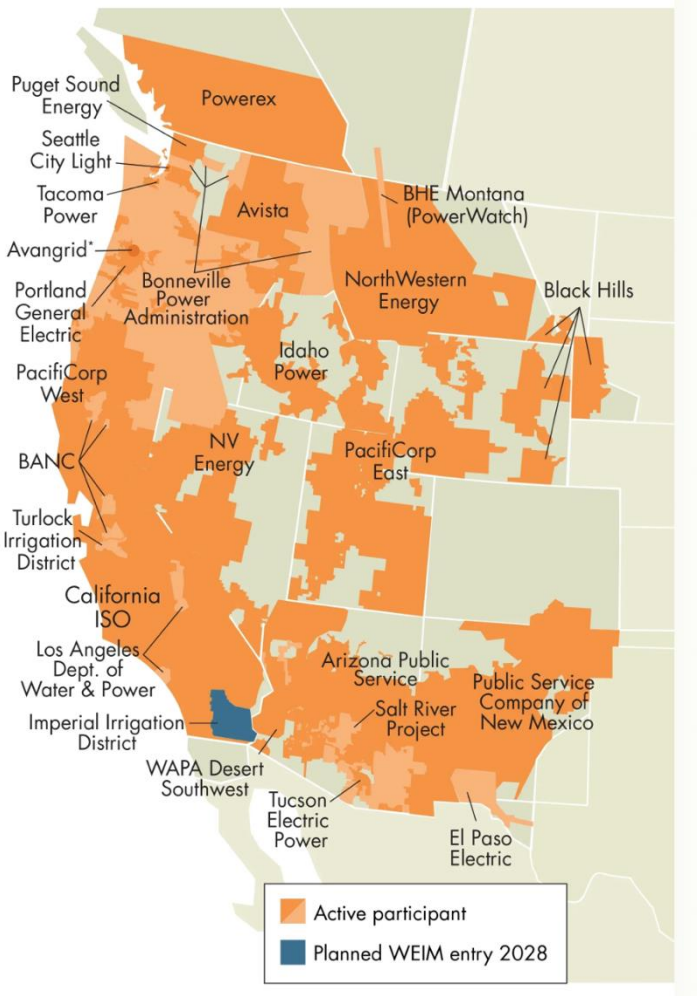


https://www.iso-ne.com/about/key-stats/maps-and-diagrams#isos-rtos

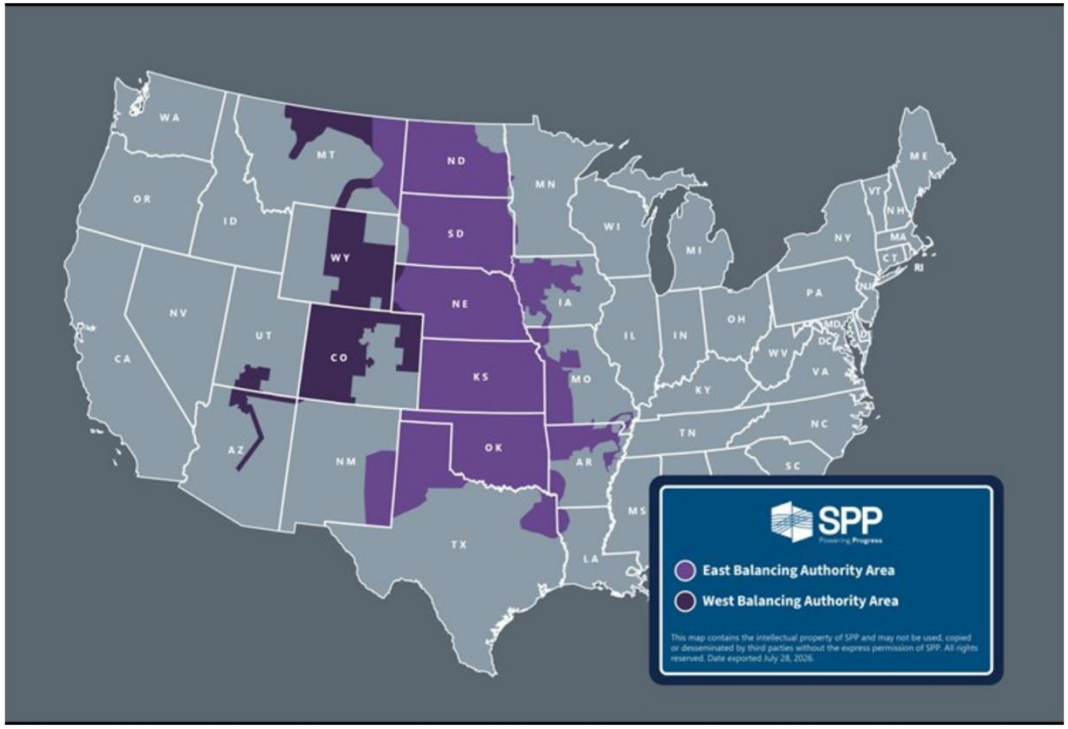
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WESTERN MARKETS



https://www.westernenergymarkets.com/western-energy-imbalance-market-weim

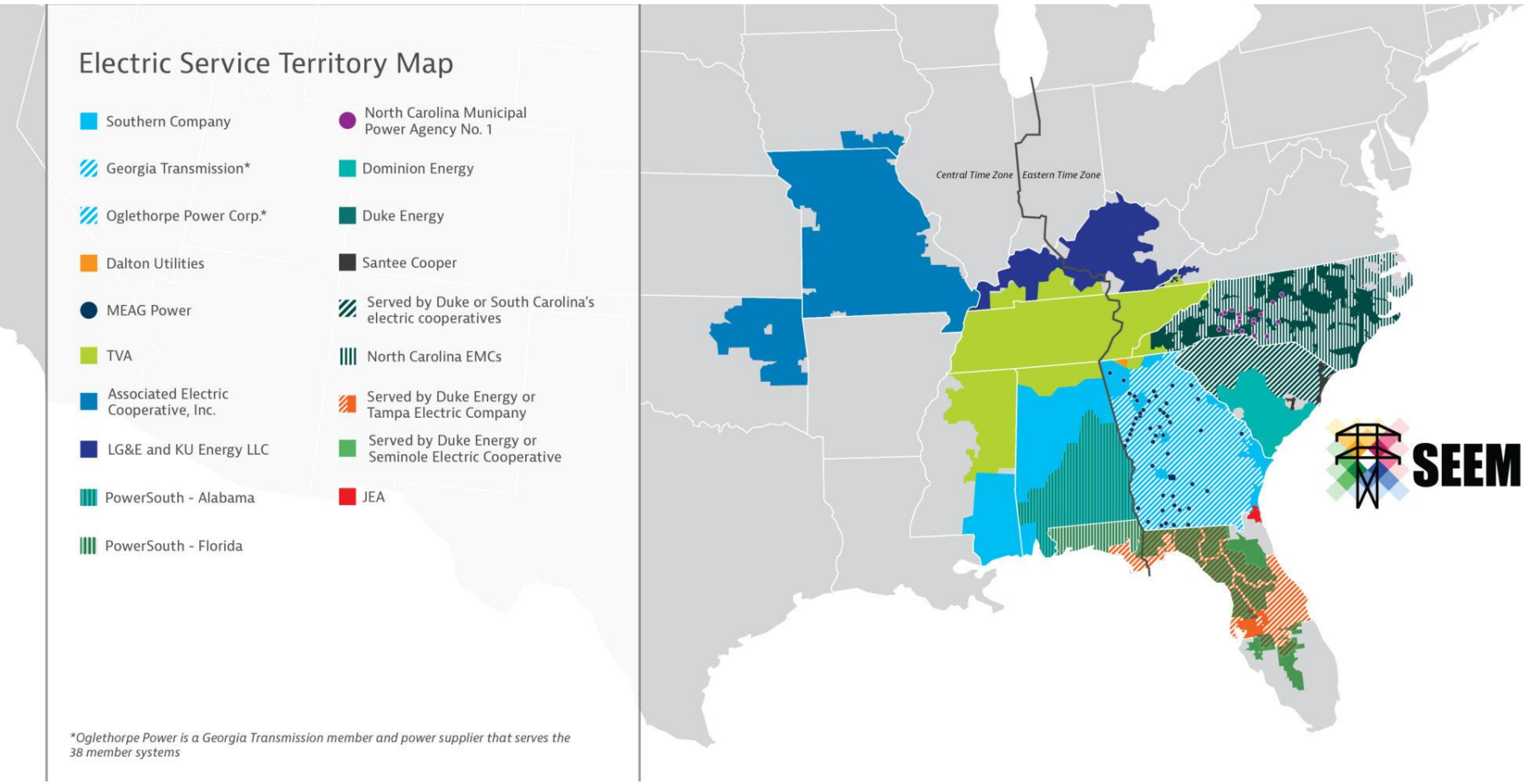


https://spp.org/markets-operations/current-grid-conditions/

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U.S. SOUTHERN ELECTRICITY MARKETS

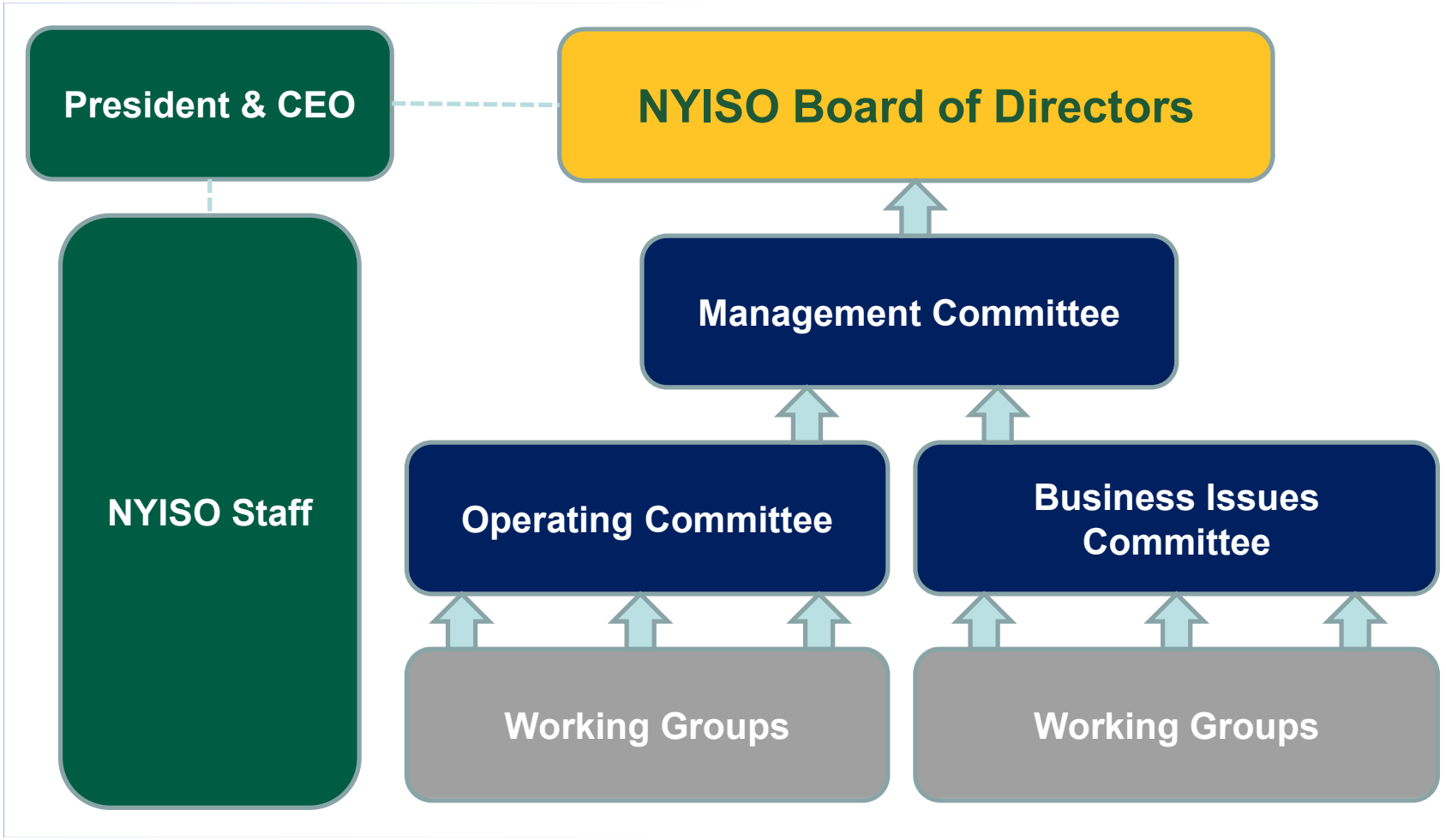


https://southeastenergymarket.com

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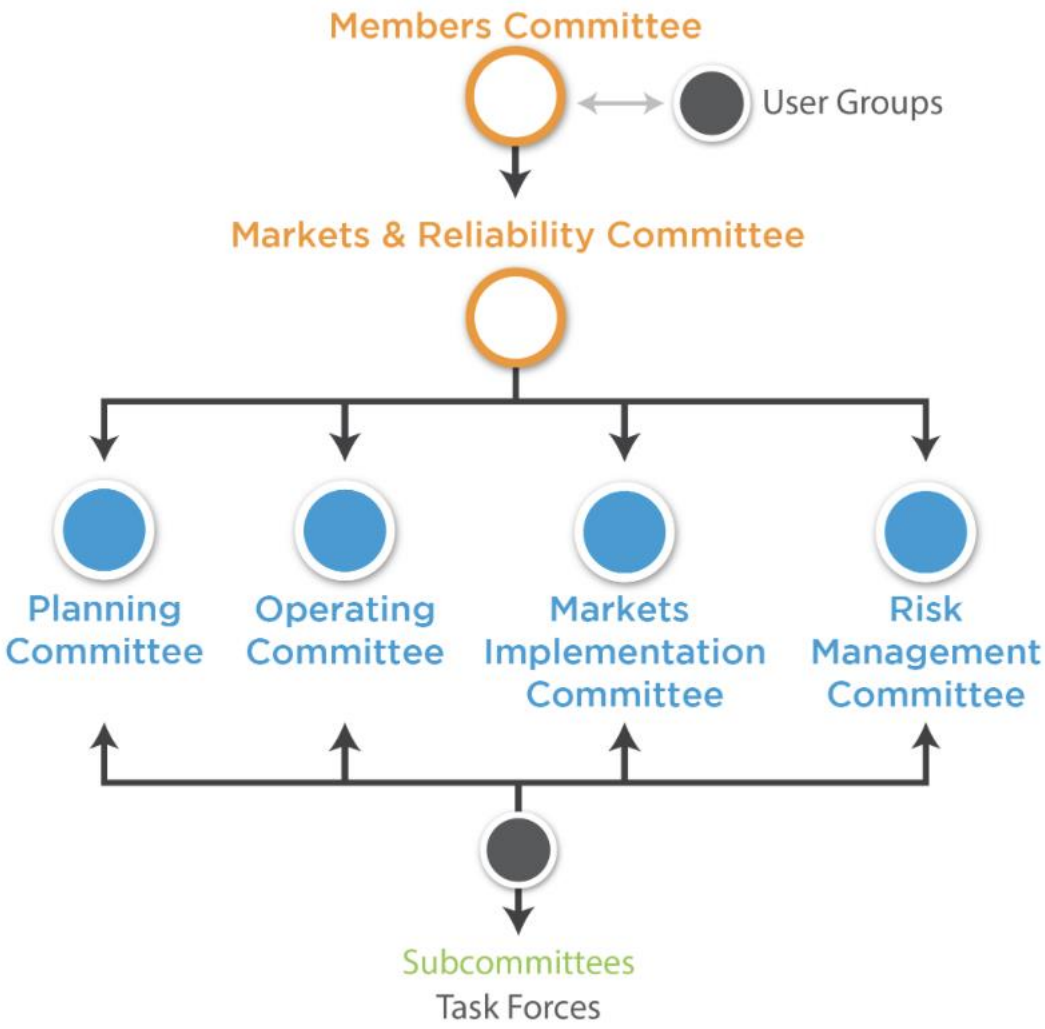
NYISO GOVERNANCE



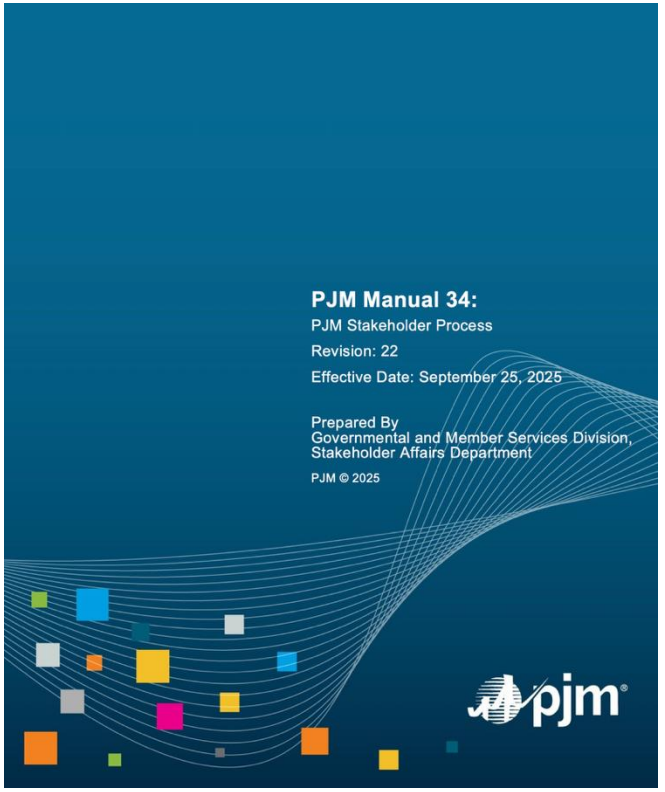
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PJM GOVERNANCE



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



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

187

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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

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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?

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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

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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

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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

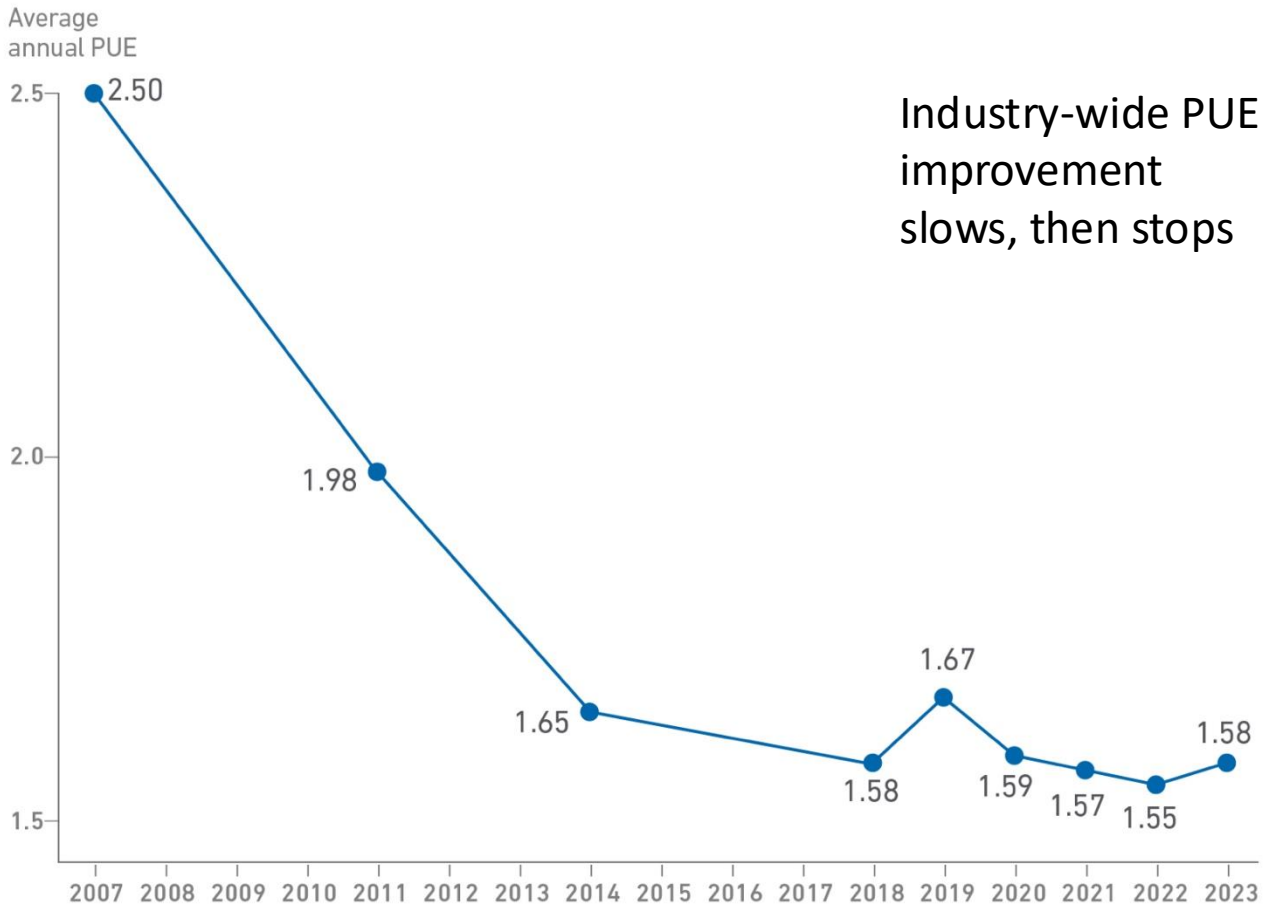
https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/investing-in-the-rising-data-center-economy

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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/

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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

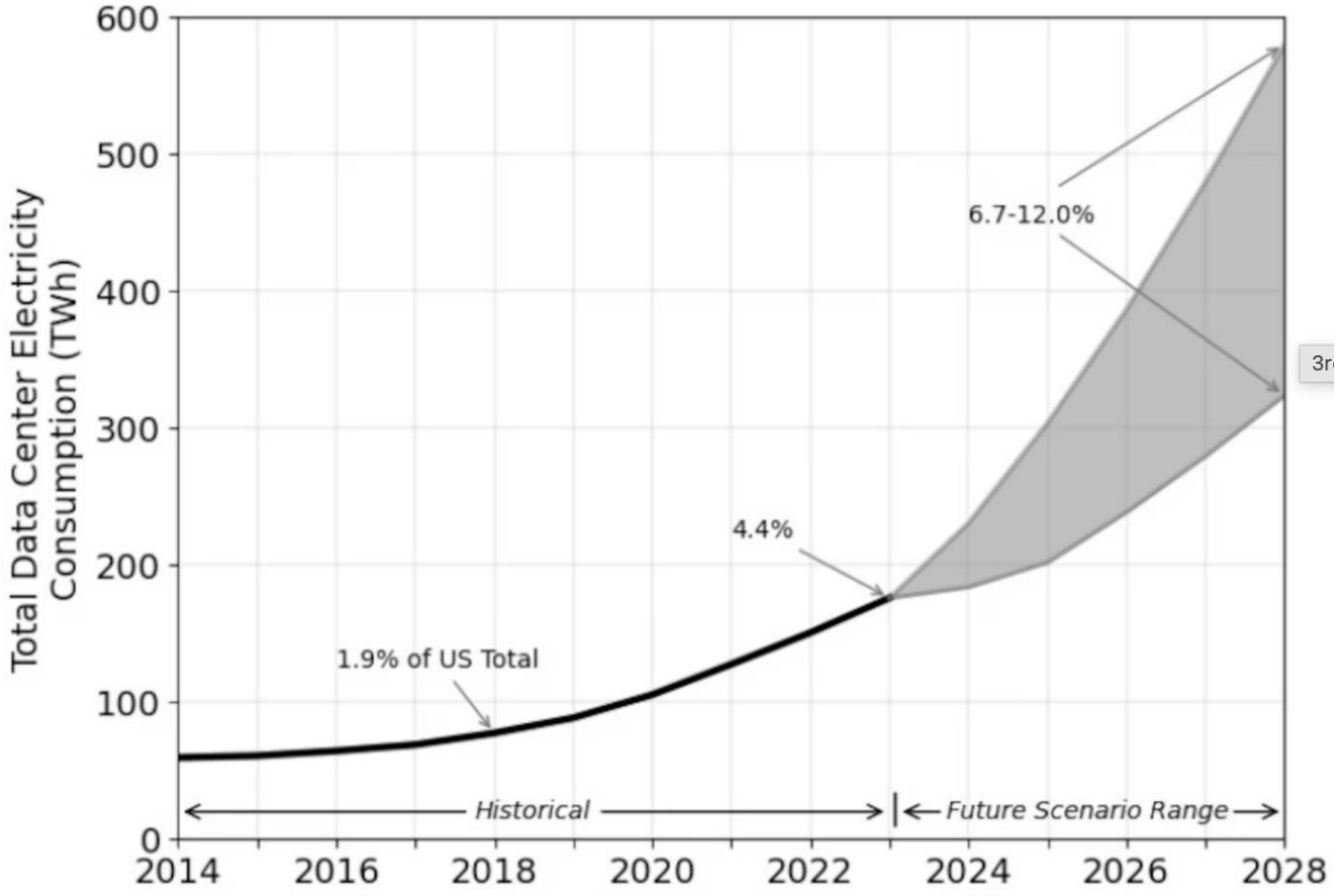
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DATA CENTERS PROJECTED GROWTH

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

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

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US FIBER OPTICS MAP

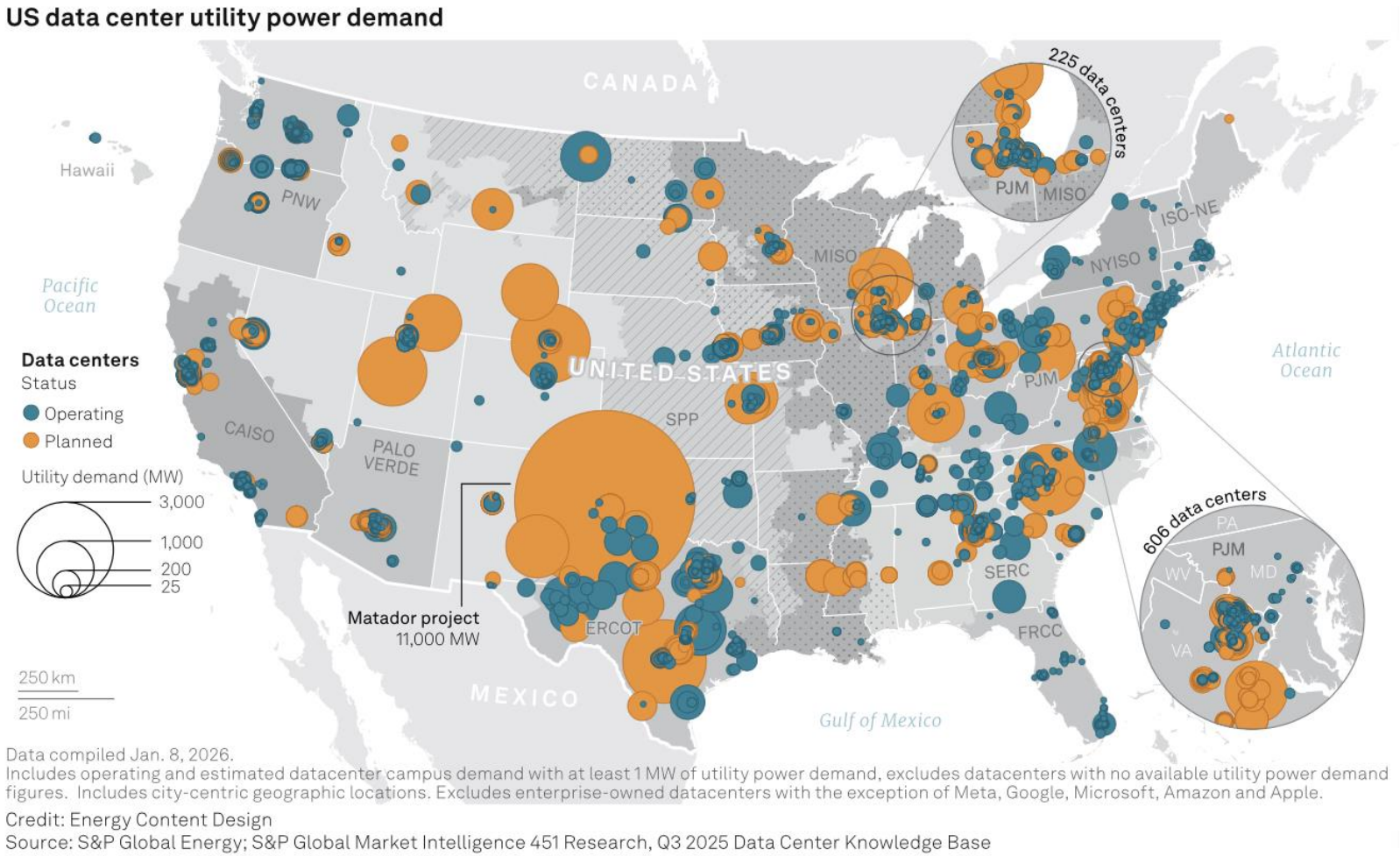


https://www.landgate.com/news/unlocking-the-potential-of-data-centers-and-fiber-optics

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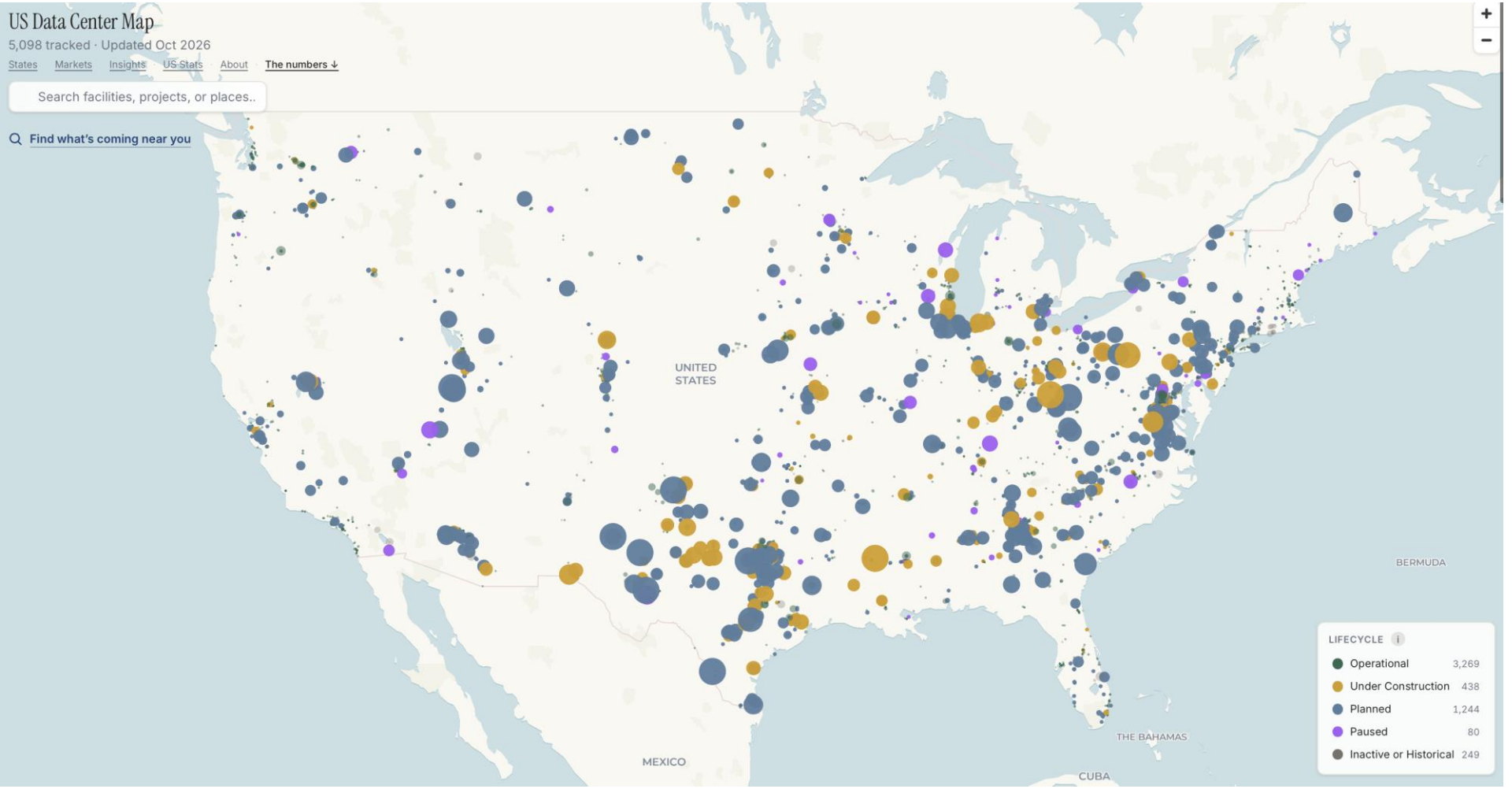


https://www.spglobal.com/energy/en/news-research/latest-news/electric-power/012926-data-center-opposition-gains-momentum-as-power-demand-spikes

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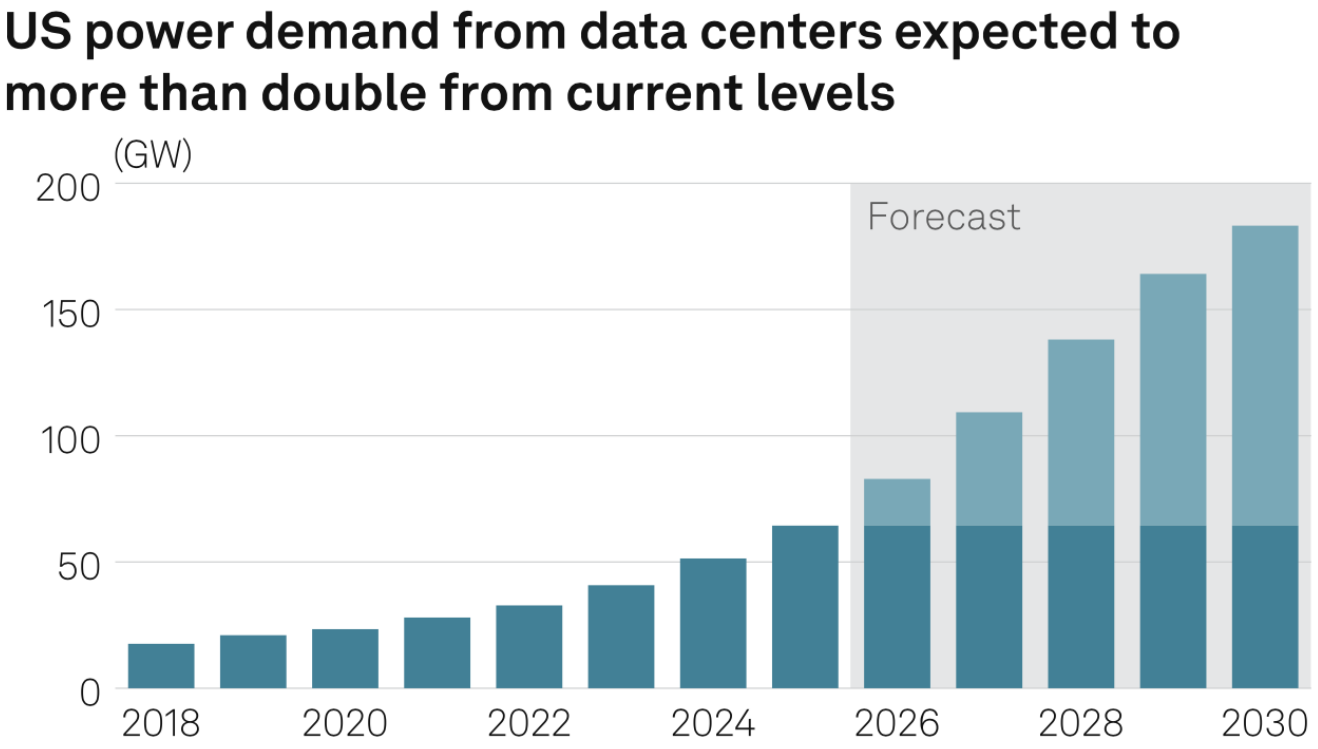
This website also has a map of data centers by capacity

https://dcmap.us/?view=pipeline&c=38.0915%2C-97.7818%2C3.99

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DATA CENTERS



Notes: Data compiled April 13, 2026. Excludes enterprise-owned data centers. Utility power represents actual and forecasted total electricity supplied to data centers from the power grid, including IT equipment, cooling, lighting, offices and security systems as of the market monitor release date.

Source: S&P Global Energy Horizons; latest 451 Research Datacenter Services & Infrastructure Market Monitor & Forecast: US focused

https://www.spglobal.com/energy/en/news-research/latest-news/electric-power/050626-surging-us-data-center-power-demand-tests-sustainability-targets

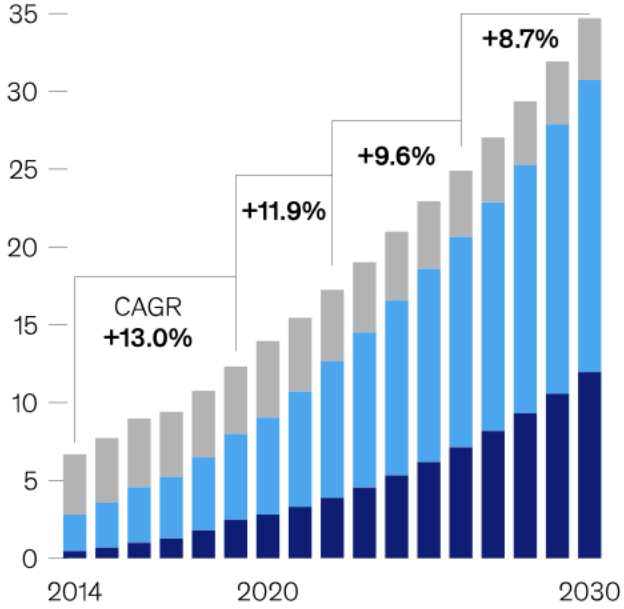
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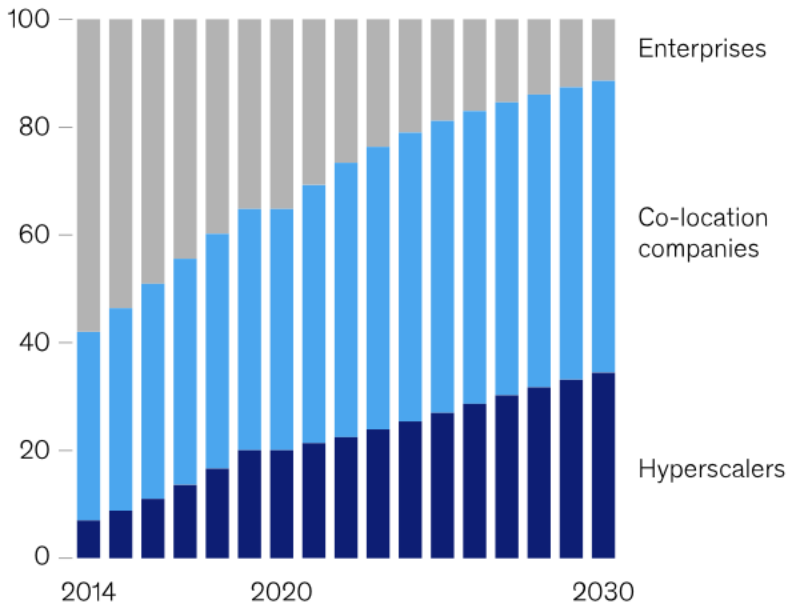
DATA CENTERS

US data center demand is forecast to grow by some 10 percent a year until 2030.

Data center power consumption, by providers/enterprises,[1] gigawatts



Data center power consumption, by providers/enterprises,[1] % share



[1]Demand is measured by power consumption to reflect the number of servers a data center can house. Demand includes megawatts for storage, servers, and networks.

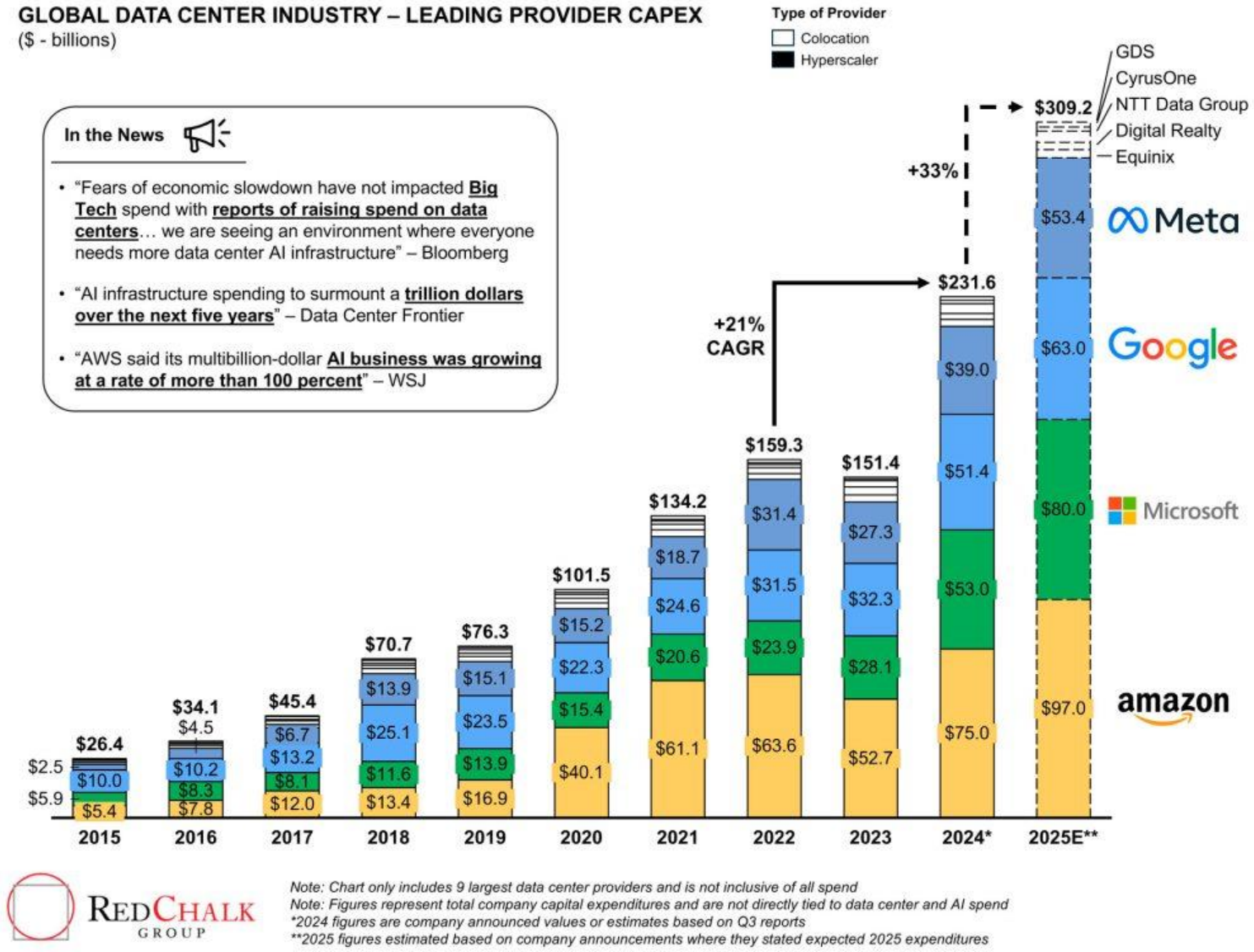
McKinsey & Company

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

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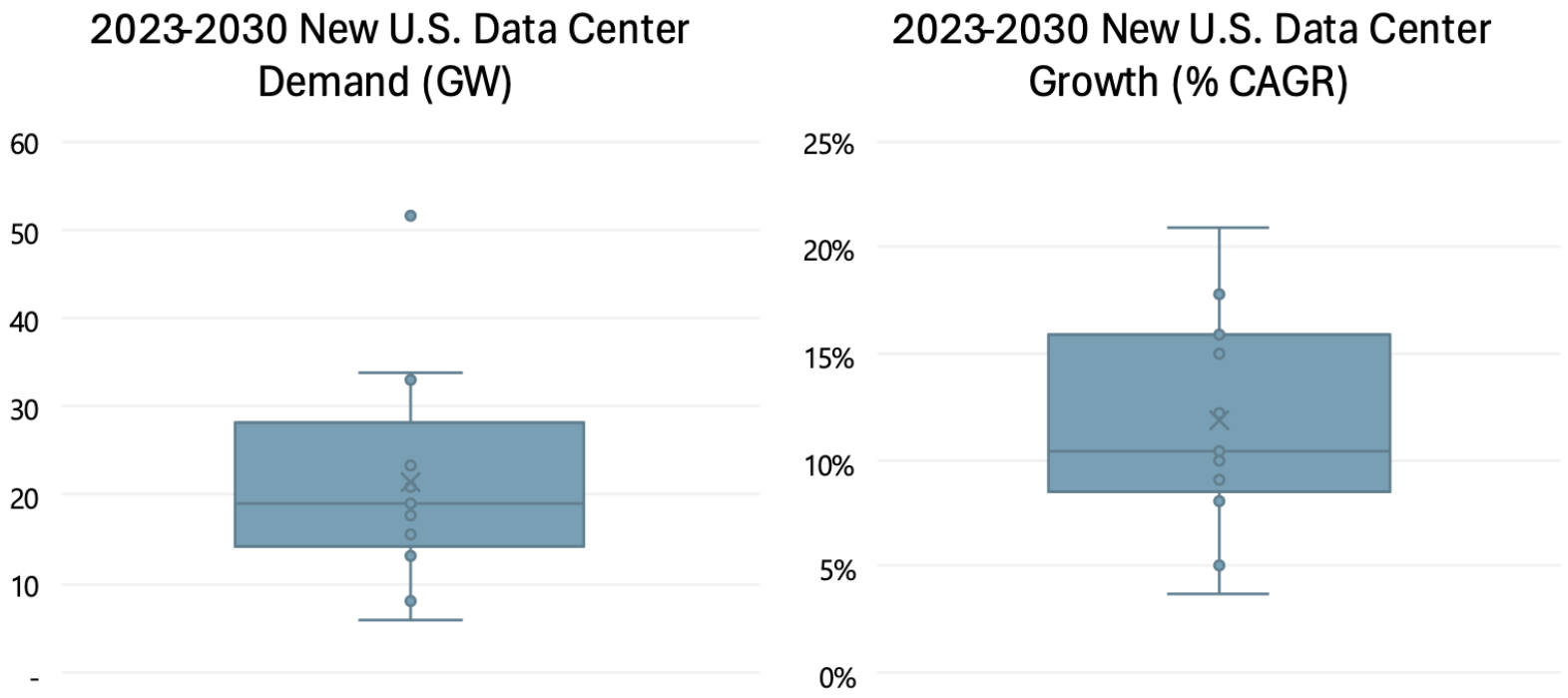


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https://www.redchalk.com/the-new-gold-rush-the-data-center-investment-boom/

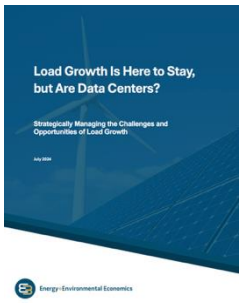
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DATA CENTERS



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

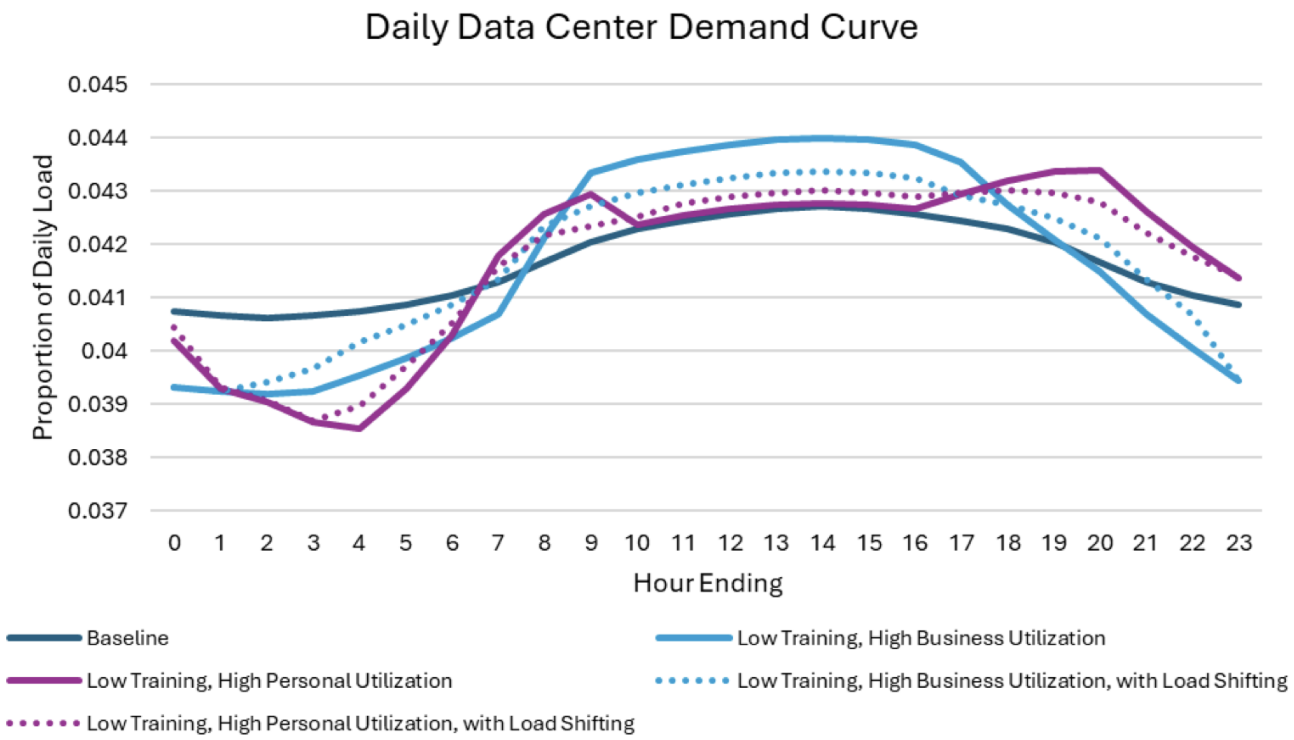


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DATA CENTERS HOURLY LOAD PROFILES

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.

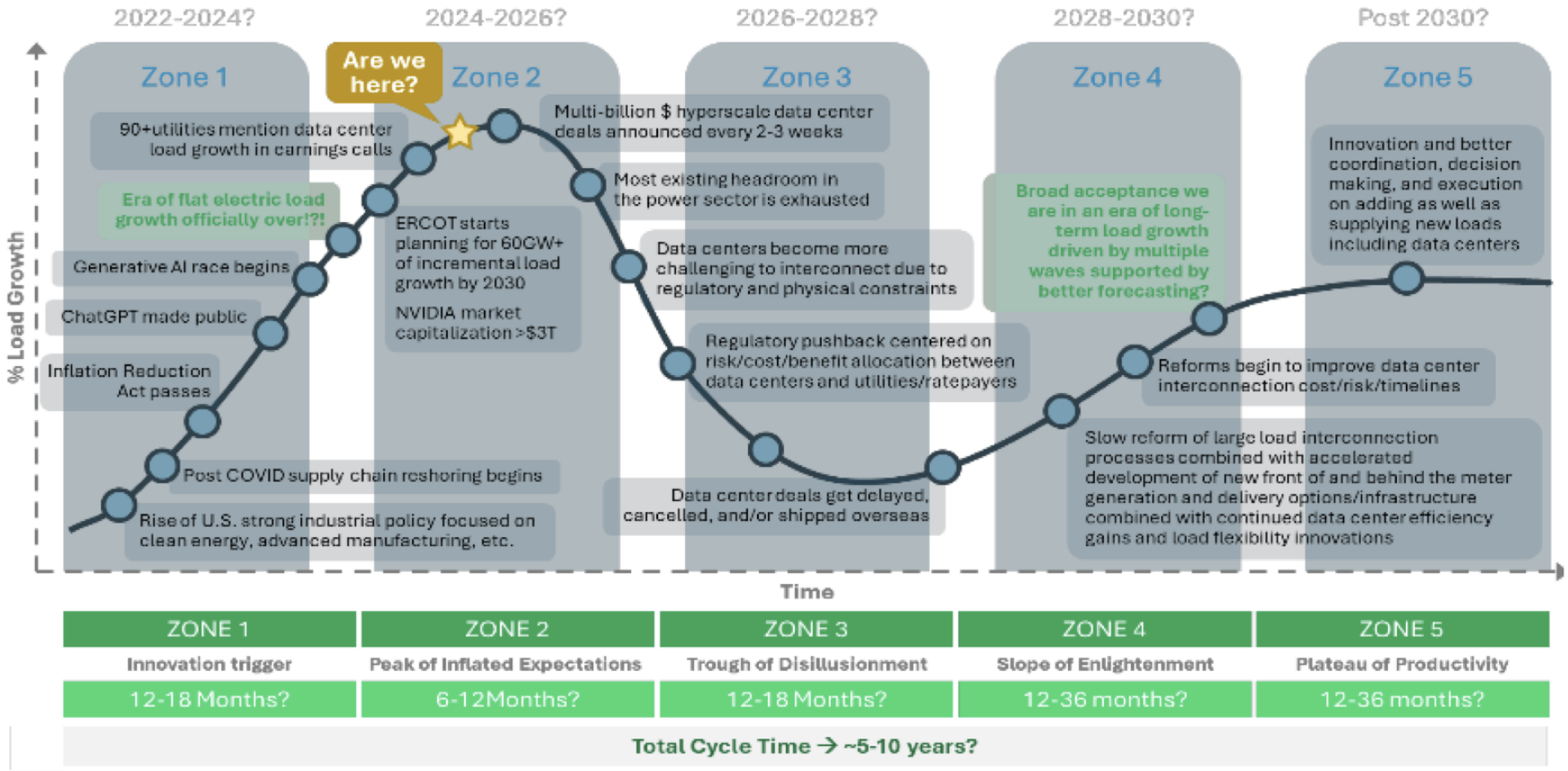
https://www.ethree.com/wp-content/uploads/2024/07/E3-White-Paper-2024-Load-Growth-Is-Here-to-Stay-but-Are-Data-Centers-2.pdf

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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

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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.

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

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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.

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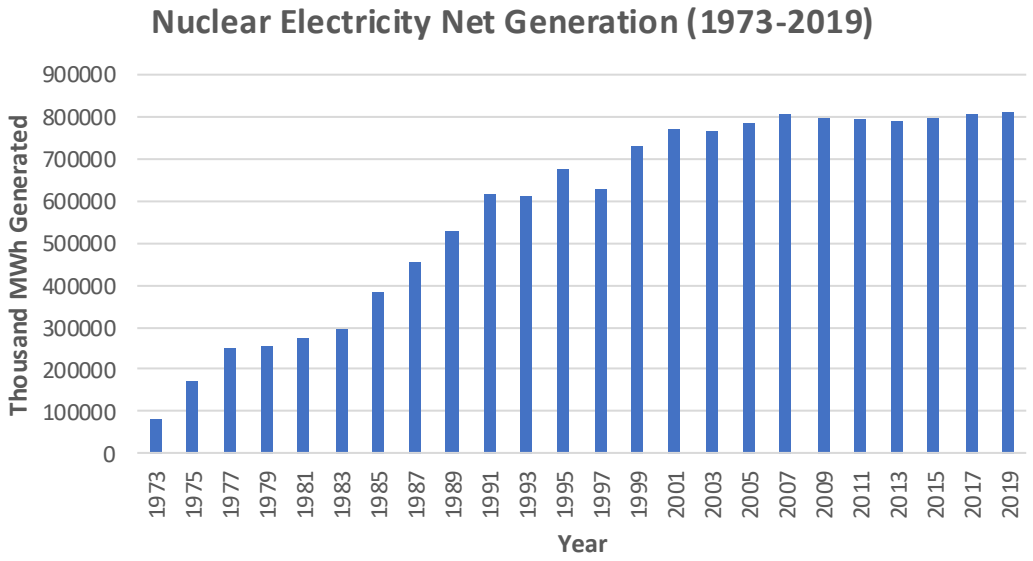
NUCLEAR GENERATION

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

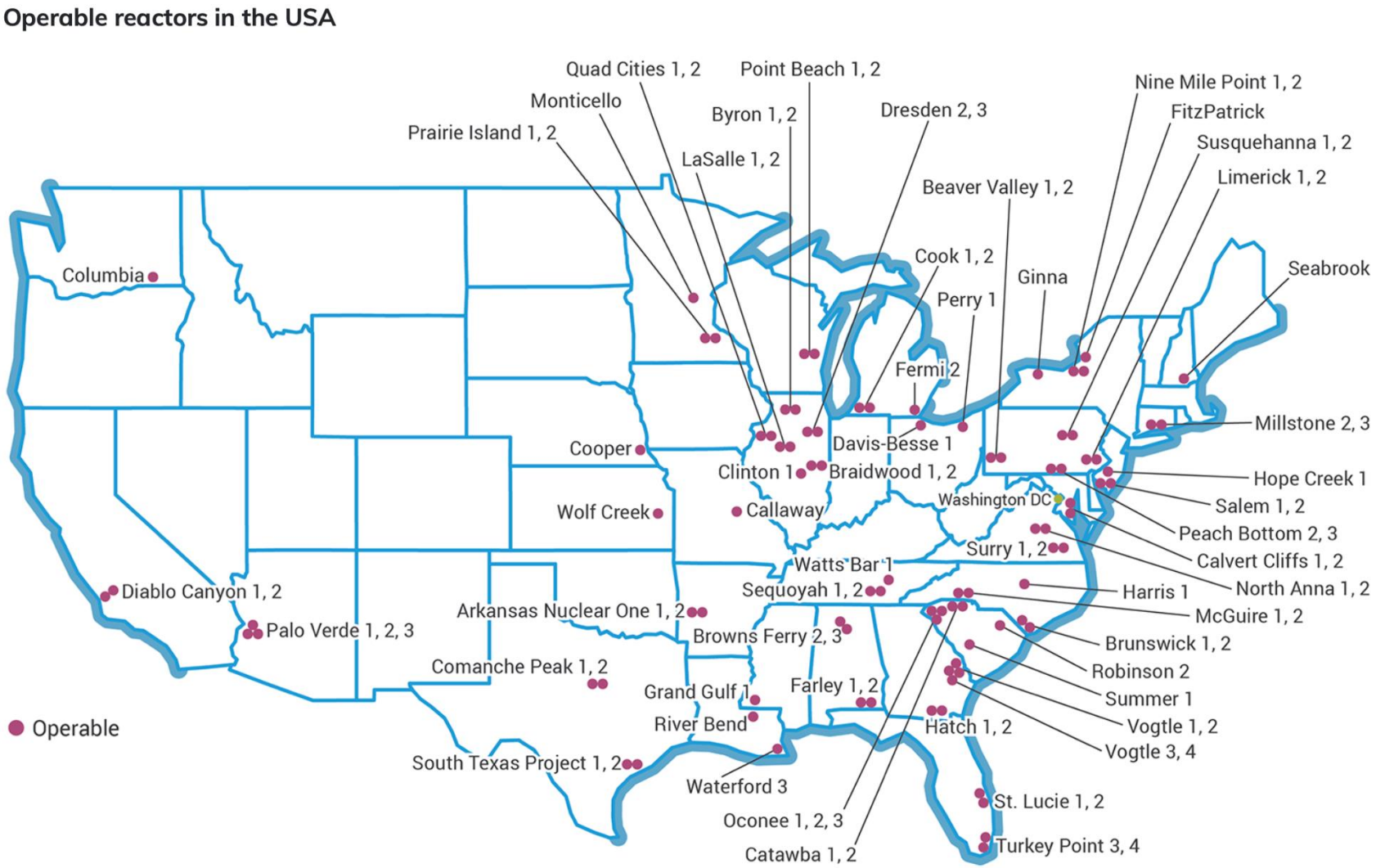


Source: EIA- *May 2020 Monthly Energy Review*

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NUCLEAR GENERATION



https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power

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NUCLEAR GENERATION

Nuclear power reactors restarting

Site	MWe net	Proponent/utility	Licensing status	Loan guarantee; restart date	Licence expiration, once restored
Palisades	805	Holtec	January 2023: Request filed to restore operational status July 2025: Authorized to receive fresh nuclear fuel	$1.52 billion; 2026	March 2031
Crane Clean Energy Center (Three Mile Island 1)	819	Constellation	November 2024: Request filed to restore operational status June 2026: Draft environmental assessment issued September 2026: Final environmental assessment issued	$1 billion; 2027	April 2034
Duane Arnold	601	NextEra	January 2025: Request filed to restore operational status July 2026: Draft environmental assessment issued	$1.9 billion; early 2029	February 2034

Subtotal restarting: 2225 MWe

Proposed nuclear reactors

Site	Technology	MWe gross	Proponent/utility	Licensing status
Kemmerer 1, Wyoming	Natrium	345	US SFR Owner (a TerraPower subsidiary)	Construction permit application March 2024; issued March 2026. Non-nuclear plant construction under way from April 2026
Seadrift, Texas	Xe-100	4x80	X-energy, Long Mott Energy (a Dow subsidiary)	Construction permit application March 2025; environmental assessment completed May 2026.
Clinch River, Tennessee	BWRX-300	1 x 300	TVA	ESP application May 2016, issued December 2019. Construction permit application April 2025; safety evaluation completed June 2026; Construction licence issued September 2026.
Adjacent to Columbia Generating Station, Washington	Xe-100	12 x 80	X-energy, Energy Northwest	
Palisades, Michigan	SMR-300	2 x 300	Holtec	Partial construction permit application submitted December 2025; accepted for review February 2026; preliminary safety analysis report submitted September 2026.
Idaho National Laboratory, Idaho	Aurora	75	Oklo	DOE issued site use permit in 2019. In July 2025 Oklo completed a pre-application readiness assessment for Phase 1 of a COL application. In June 2026 the DOE approved the preliminary documented safety analysis for the first unit.
Fermi America 1-4, Carson County, Texas	AP1000	4 x 1250	Fermi America	COL application submitted in parts, June and August 2025; accepted for review September 2025.

Subtotal proposed: 21 small (2600 MWe) and 4 large (5000 MWe)

https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power

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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)

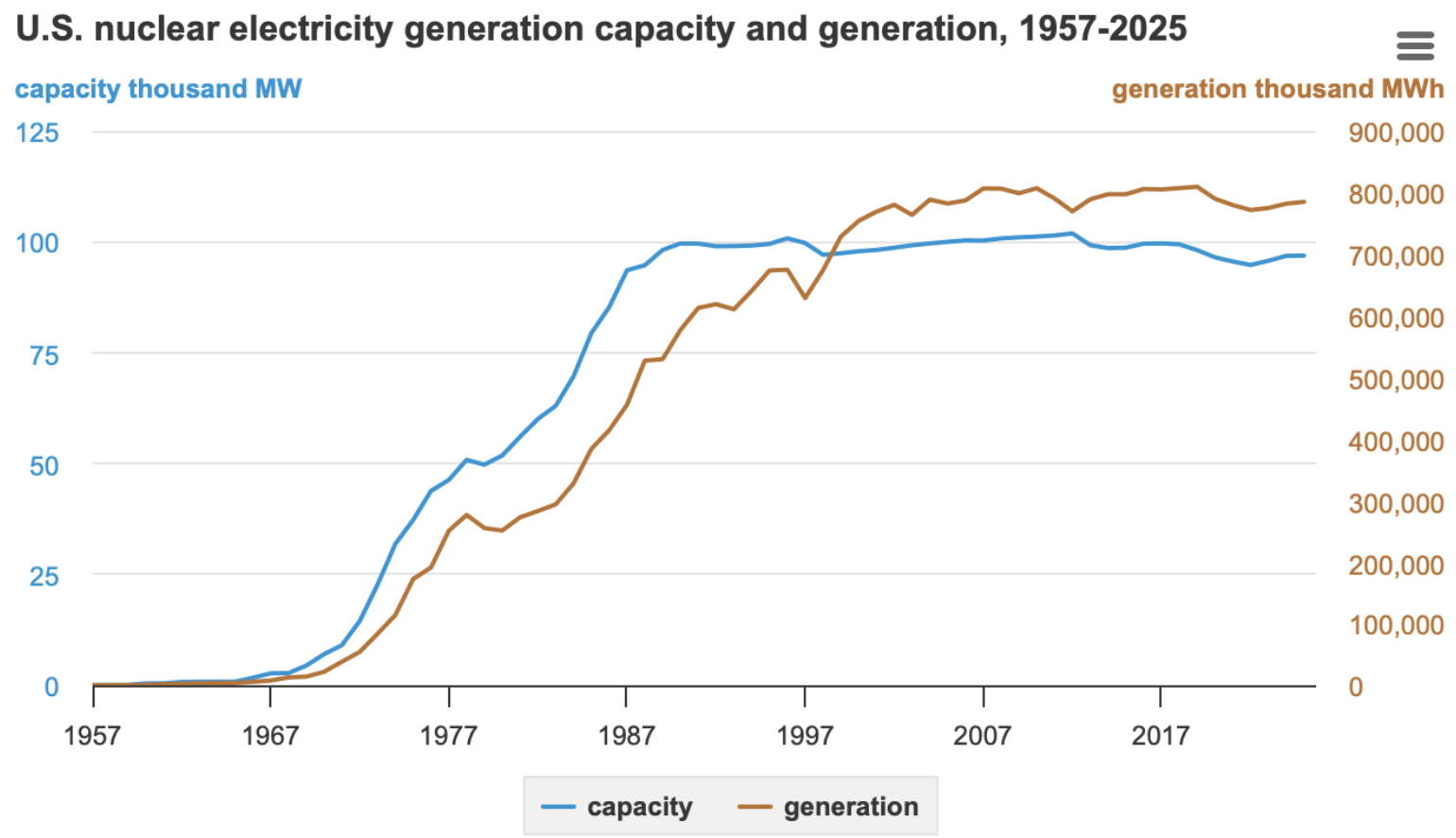


https://www.statista.com/statistics/191201/capacity-factor-of-nuclear-power-plants-in-the-us-since-1975/

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NUCLEAR GENERATION



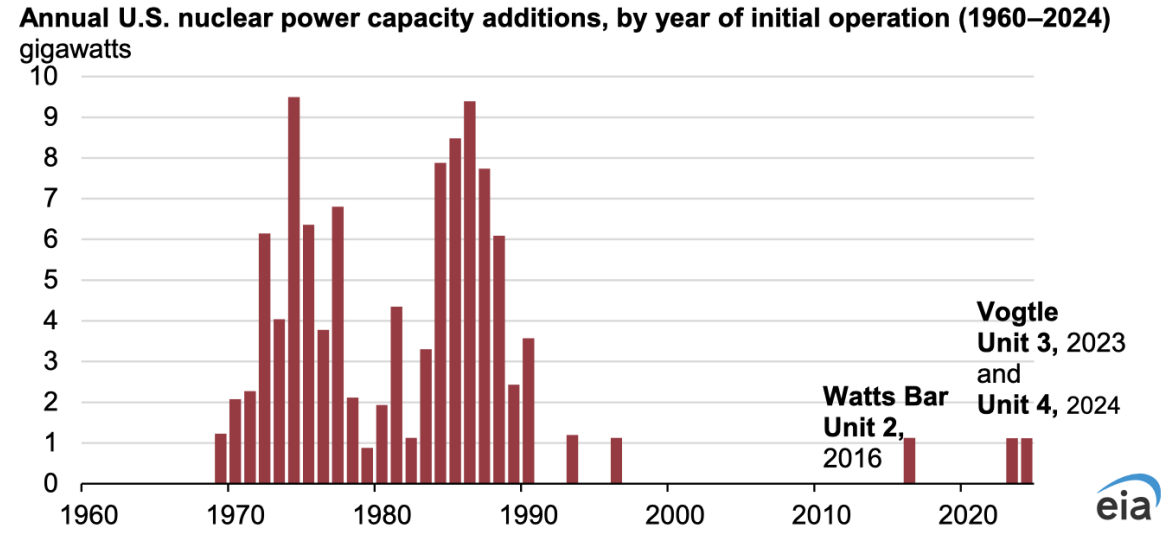
Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 8.1, March 2026, preliminary data for 2025
Note: Capacity is net summer; MW is megawatts; MWh is megawatthours.

https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php

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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

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

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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

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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

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

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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

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RENEWABLE DEVELOPER CORE FUNCTIONS

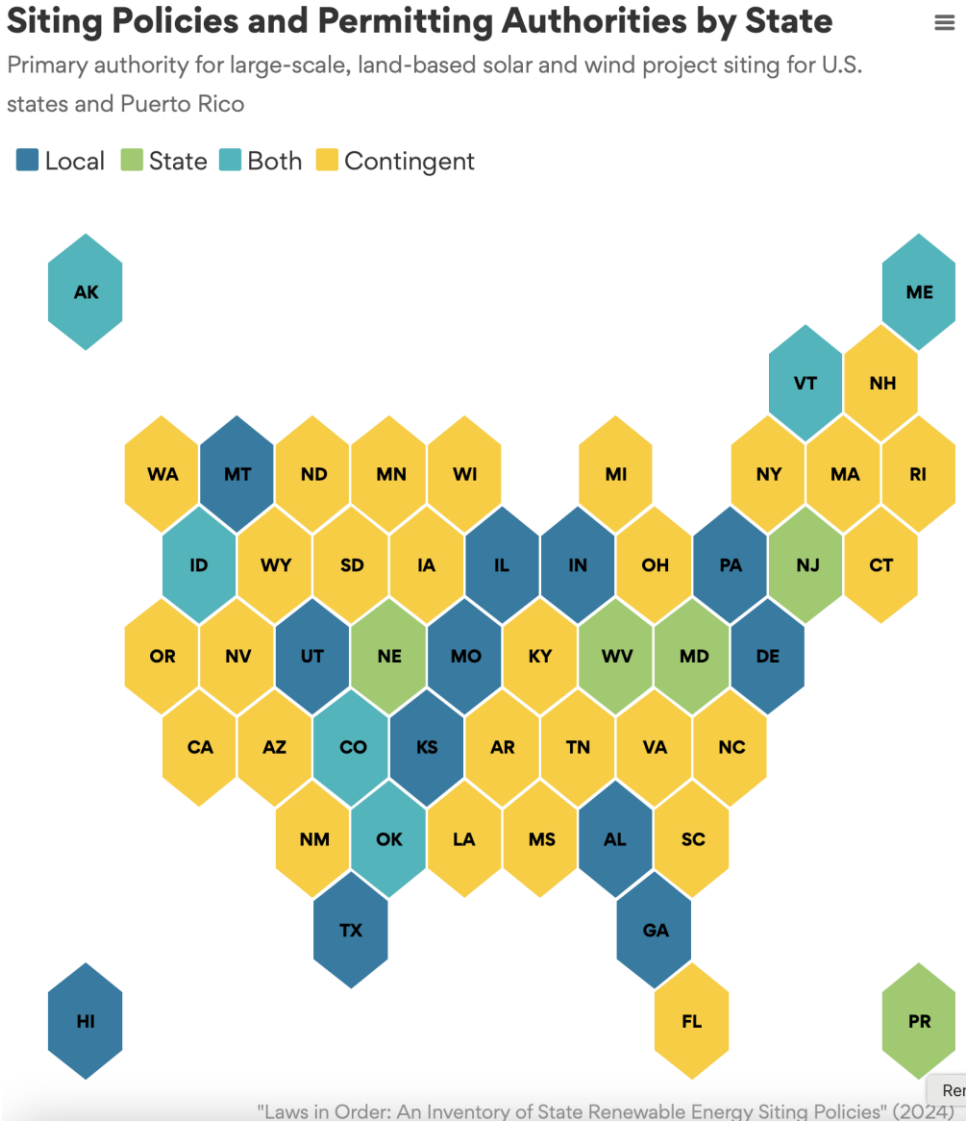
- Site evaluation and selection
- Land acquisition and permitting
- Project feasibility analysis
- Investor engagement
- Community outreach and engagement
- Technology selection and optimization
- Supply chain management
- Grid integration and interconnection
- Marketing and branding
- Public advocacy

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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

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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

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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?

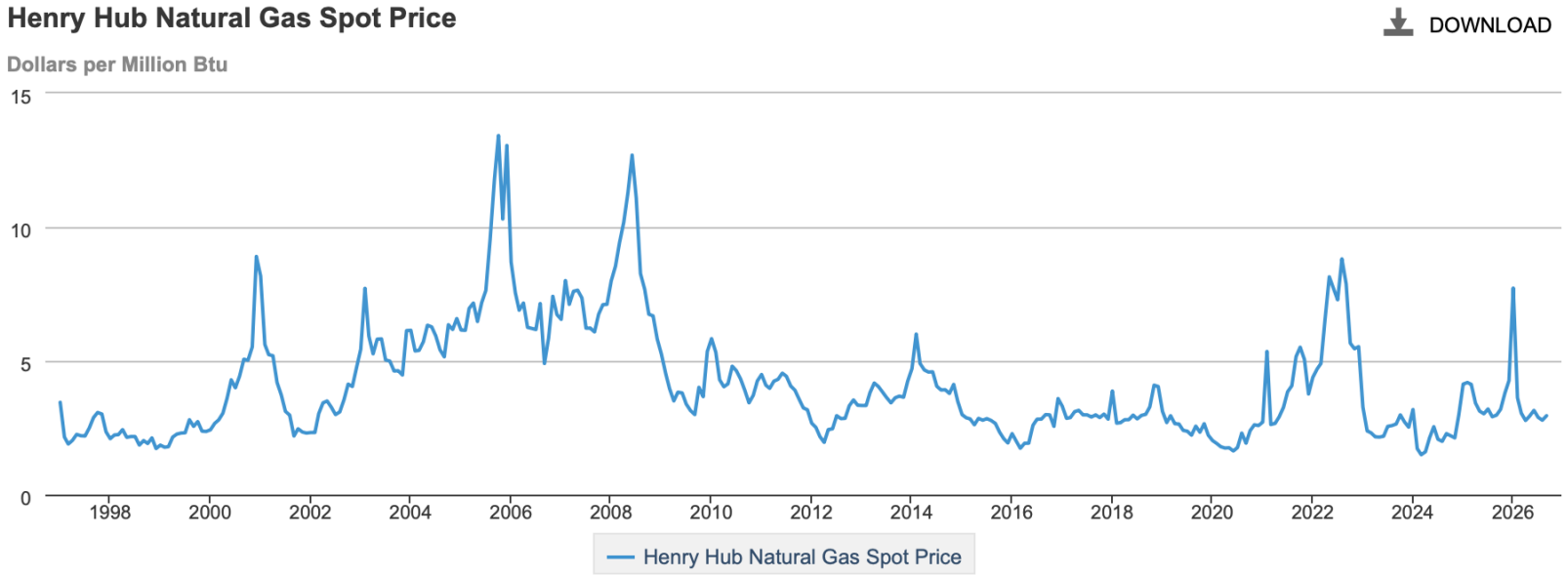
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IMPORTANCE OF RISK MANAGEMENT

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

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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.

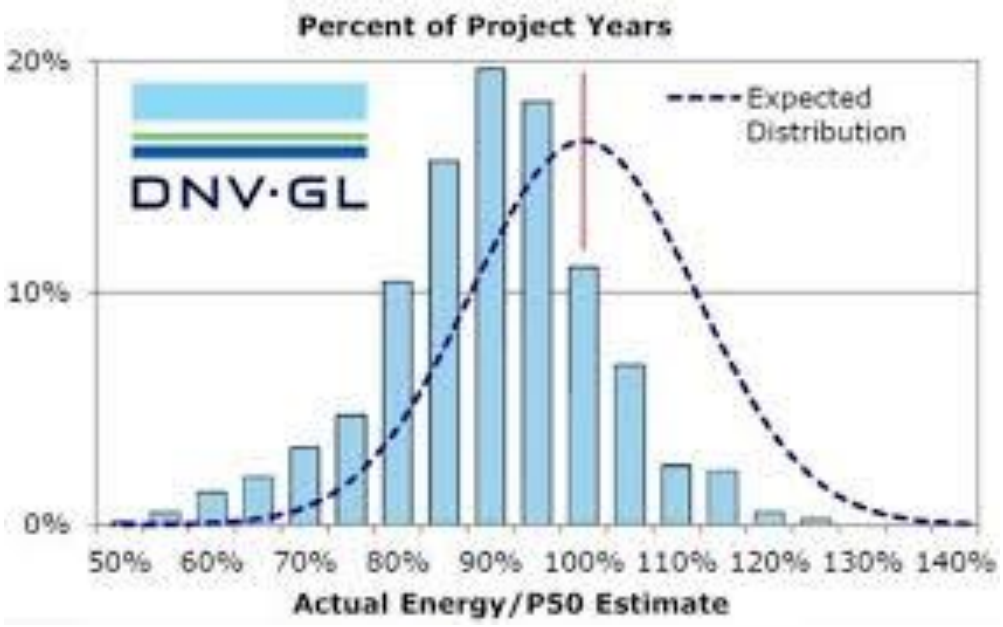
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FORECASTING AND PROBABILITIES

- 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.



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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

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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

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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)….

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POWER PURCHASE AGREEMENTS (PPAs)

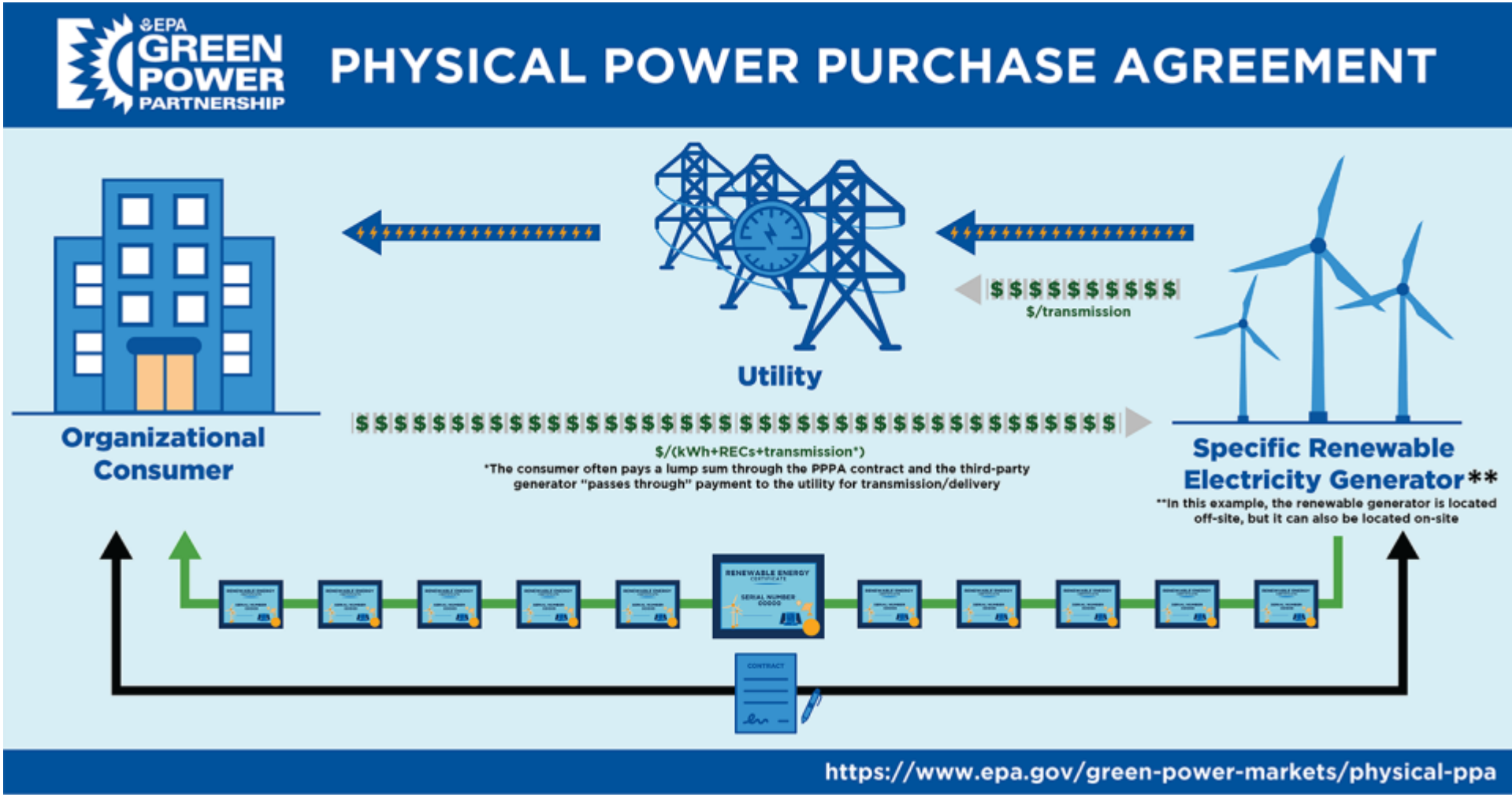
- PPA is a contract for the purchase of power from a specific power plant
- If the generator is renewable, the PPA includes the purchase of the associated renewable energy credits (RECs)
- Typically, 10-30-year agreements that define all the commercial terms for the sale of electricity including start 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

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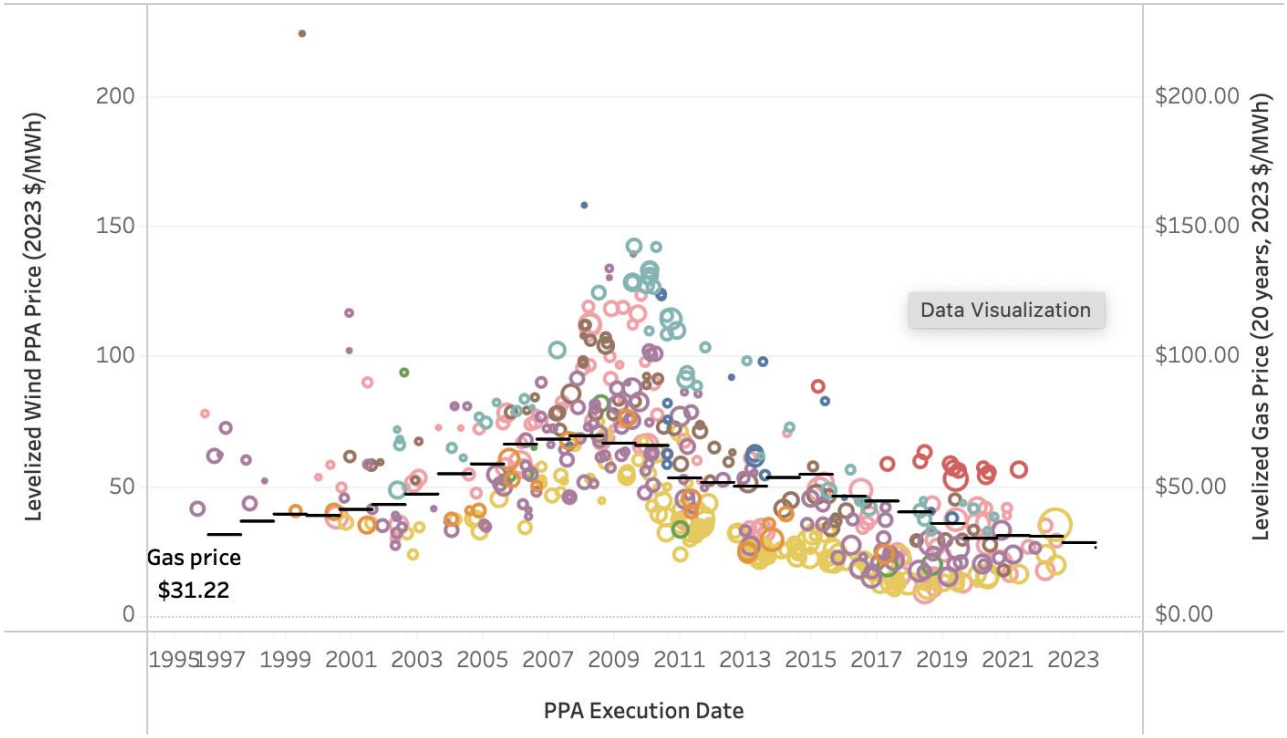
POWER PURCHASE AGREEMENTS (PPAs)


EPA GREEN POWER PARTNERSHIP
PHYSICAL POWER PURCHASE AGREEMENT
Organizational Consumer
Utility
$$$$$$$$$$
$/transmission
$$$$$$$$$$

Wind Power Purchase Agreement (PPA) Prices

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

BERKELEY LAB



Select range of years
1996 2024

Select range of project capacity (MW)
1.0 643.4

Click region to highlight
- CAISO
- ERCOT
- Gas
- ISO-NE
- MISO
- NYISO
- PJM
- Southeast (non-ISO)
- SPP
- West (non-ISO)

- 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

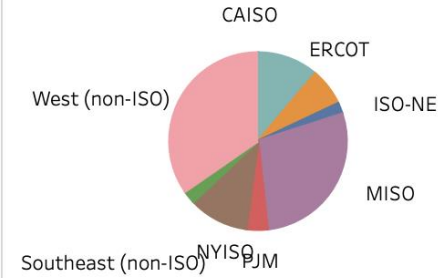


For more information on US wind energy from Berkeley Lab see the *Land Based Wind Market Report: 2024* at windreport.lbl.gov

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Share of MW by region

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



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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

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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

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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

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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

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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

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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

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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

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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

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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

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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.

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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

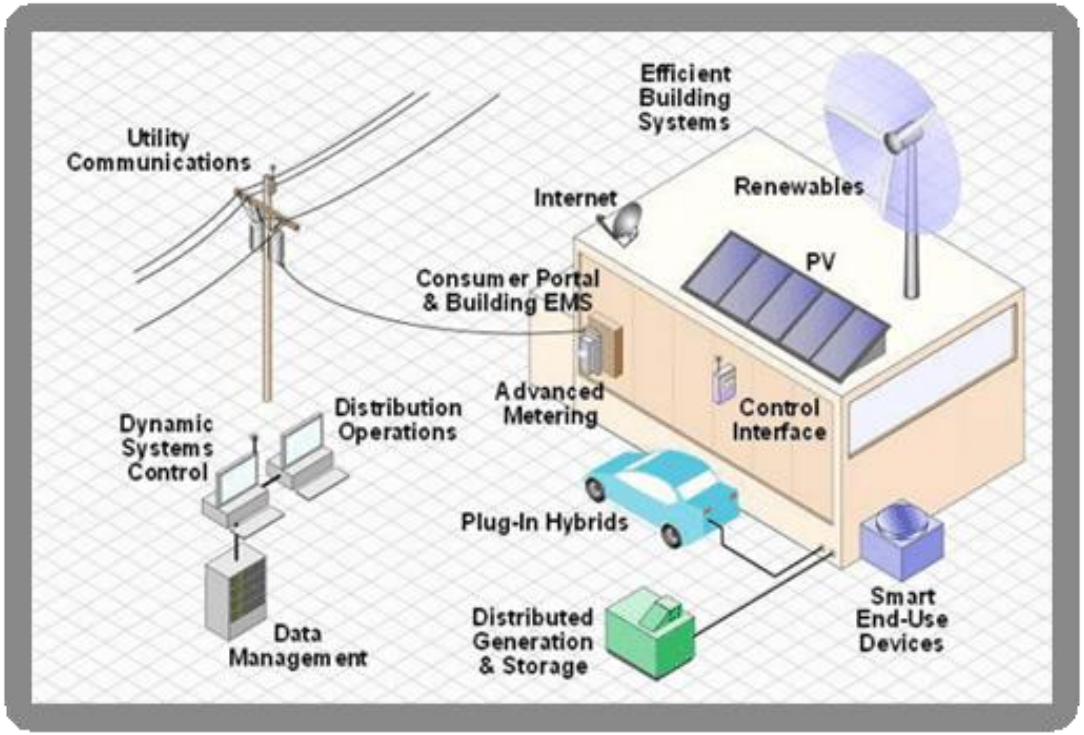
- Also referred to as Third Party Providers, Energy Service Companies (ESCo's), and Retail Aggregators

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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

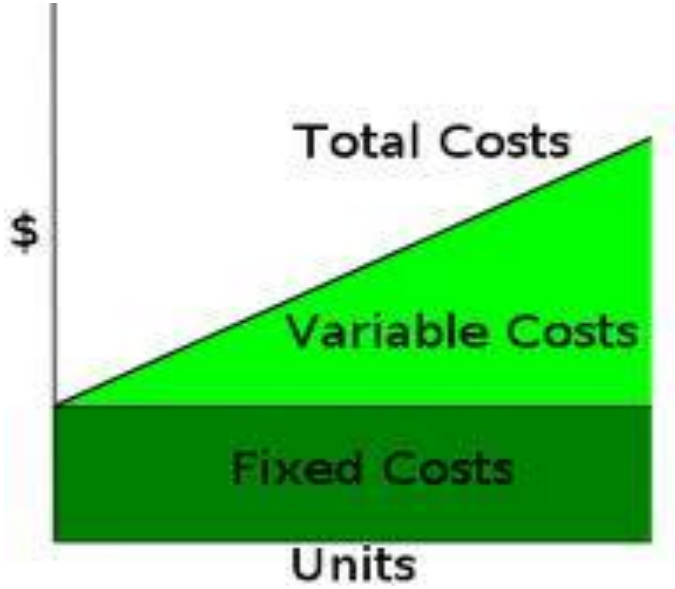




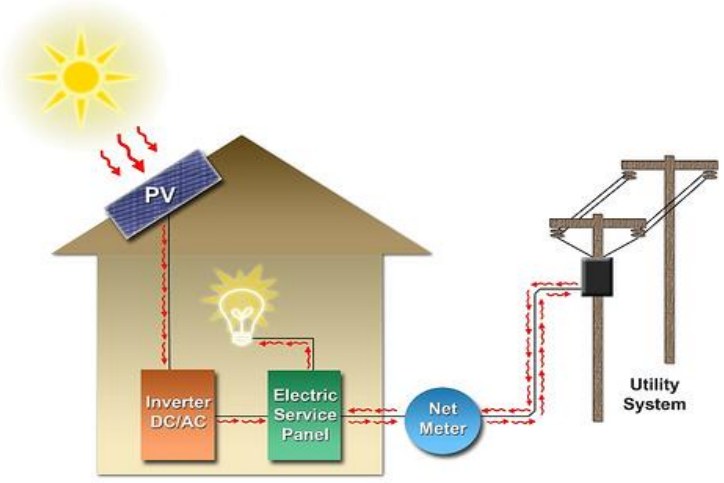
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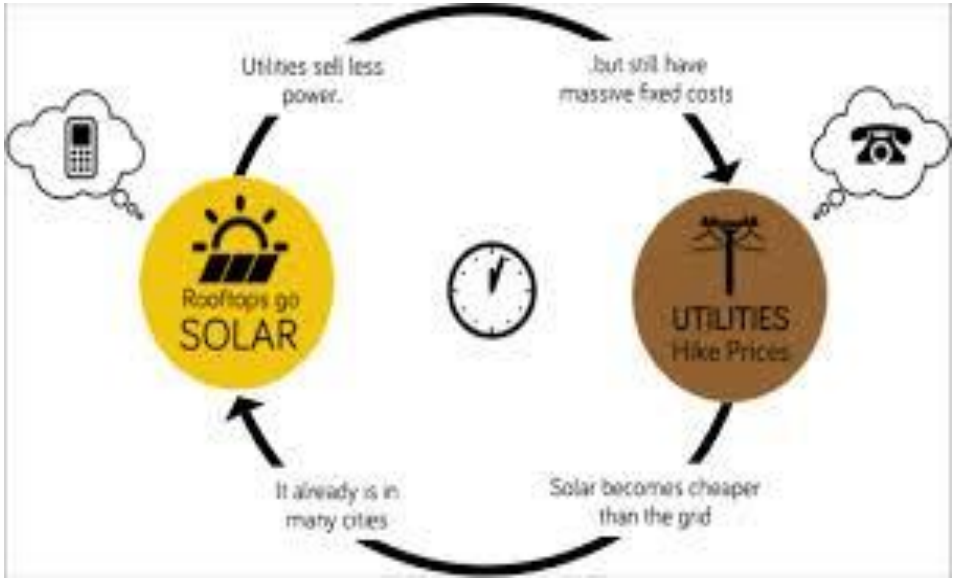
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NET METERING & DEATH SPIRAL



Rate = (Total Cost)/Quantity
= Average Cost

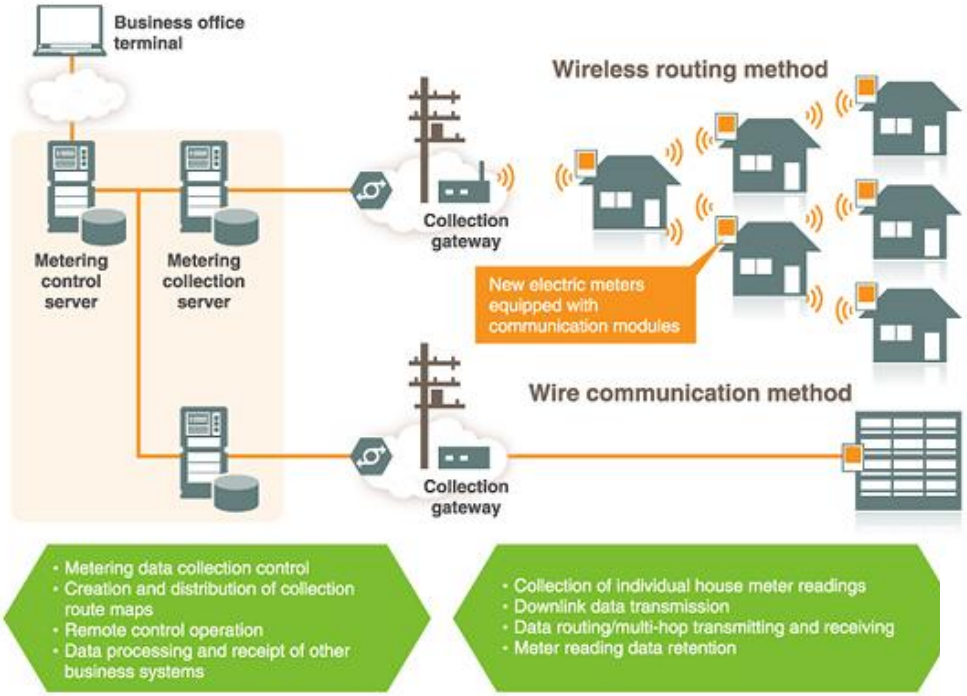




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SMART GRID DISTRIBUTION SYSTEM





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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?

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TERMINOLOGY AND ABBREVIATIONS CHECK

Revenue requirement

WACC

Ratebase

Economies of scale

FPA

NOPR

OATT

Order 888

Derivatives

Options

Net metering

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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

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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

FERC State of the Market Report, 2022, https://www.ferc.gov/sites/default/files/2023-03/2022_State-of-the-market.pdf

Other Sources

Harvard Electricity Policy Group: http://www.hks.harvard.edu/hepg/

The Electricity Journal: http://www.journals.elsevier.com/the-electricity-journal/

Federal Energy Regulatory Commission: http://www.ferc.gov

Steven Stoft, Power System Economics: Designing Markets for Electricity

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

Video course on Locational Marginal Prices: https://users.ece.utexas.edu/~baldick/classes/394V/EE394V.html

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MORE INFORMATION

Primers on Topics Related to Electricity

Federal Energy Regulatory Commission (FERC), Energy Primer: A Handbook for Energy Market Basics, April 2020.

MIT CEEPR, Regulation of Access, Pricing, and Planning of High Voltage Transmission in the U.S., February 2024.

National Regulatory Research Institute (NRRI), Transmission Investment, Commissioner Primer, July 2006.

National Conference of State Legislatures, Electricity Markets: A Primer for State Legislators, January 2022.

National Council on Electricity Policy, Electricity Transmission: A Primer, June 2004.

Resources for the Future: https://www.rff.org/publications/explainers/us-electricity-markets-101/

U.S. Department of Energy, United States Electricity Industry Primer, July 2015.

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MORE INFORMATION

IEA Electric Grid and Secure Energy Transitions, 2023

Market Monitors

Monitoring Analytics, PJM
Potomac Economics, ERCO, MISO, ISO-NE, NYISO, RGGI
Market Monitor, CAISO
Market Monitor, SPP

General Books

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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MORE INFORMATION

Data Centers

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

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

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