ECEN 615
Methods of Electric Power Systems Analysis

Lecture 2: Power Systems Overview

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Announcements

- Start reading Chapters 1 to 3 from the book (mostly background material)
- We'll be using PowerWorld Simulator fairly extensively in this class, both the educational and professional versions
- Download the free 42 bus educational versions of PowerWorld Simulator at

  https://www.powerworld.com/gloveroverbyesarma

Electric Frequencies and Residential Voltages Worldwide

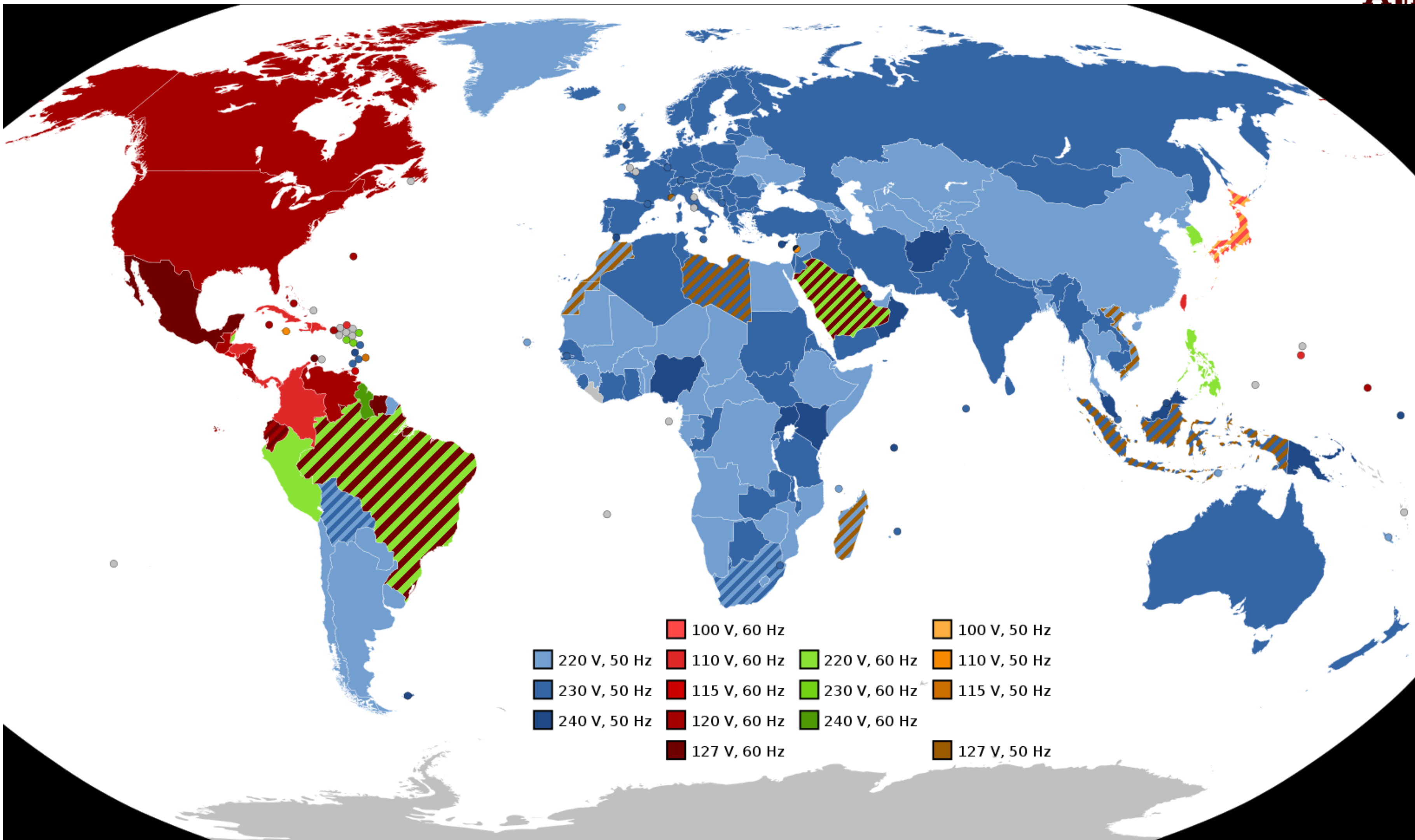
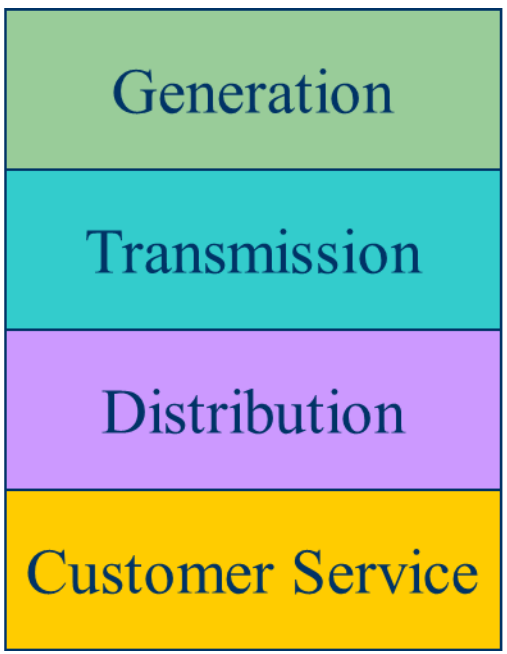


Image Source: en.wikipedia.org/wiki/Mains_electricity_by_country#/media/File:World_Map_of_Mains_Voltages_and_Frequencies,_Detailed.svg

Historical Electric Utility Organization

- Traditionally electric utilities were vertical monopolies; within a particular geographic market, they had an exclusive franchise
  - This has changed in many places around the country



In return for this exclusive franchise, the utility had the obligation to serve all existing and future customers at rates determined jointly by utility and regulators.

Generation

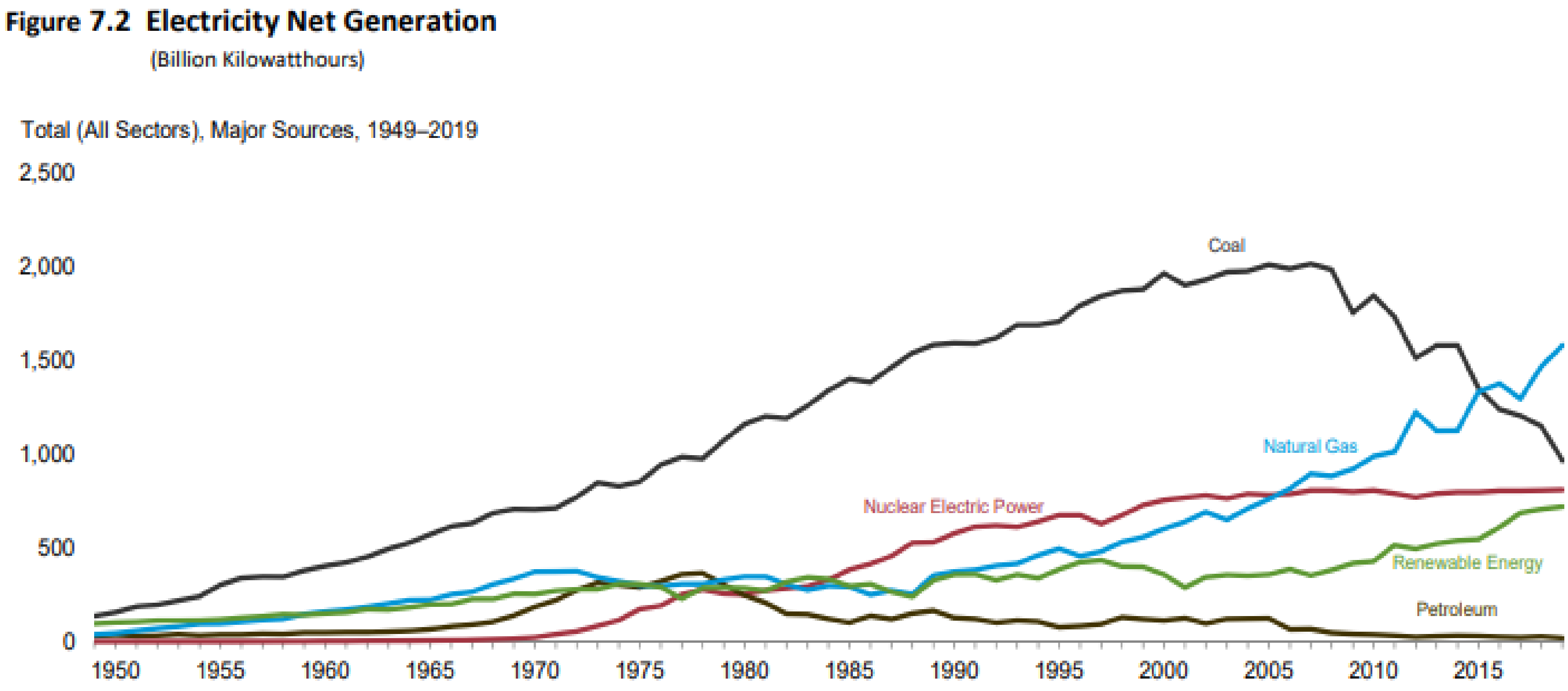
- Large plants have predominated, up to 1500 MW
- Natural Gas (40%) and coal (21%) are most common sources, followed by nuclear (20%), wind (7.6%), hydro (6.6%), and solar (2.7%)
  - Wood is 1.0%, geothermal 0.4%

Coal was at least 50% of the total up to 2007

- New construction mostly wind, solar and natural gas (with wind and solar energy costs now quite low)

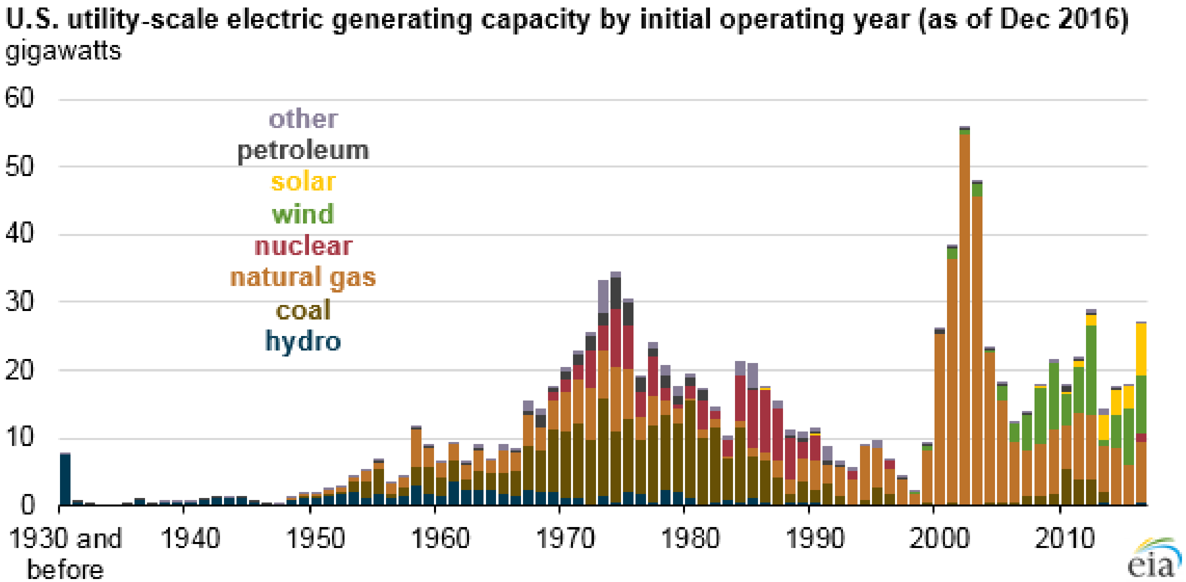
Sources are by energy (not capacity), 5/2019-4/2020; source US EIA

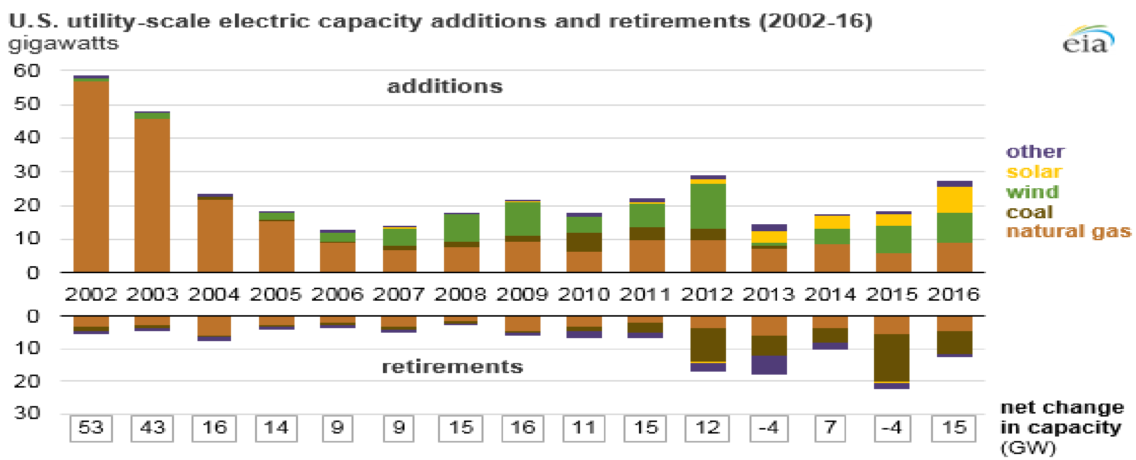
US Electricity Generation



Source: EIA Monthly Energy Review, July 2020

US Generator Capacity Additions



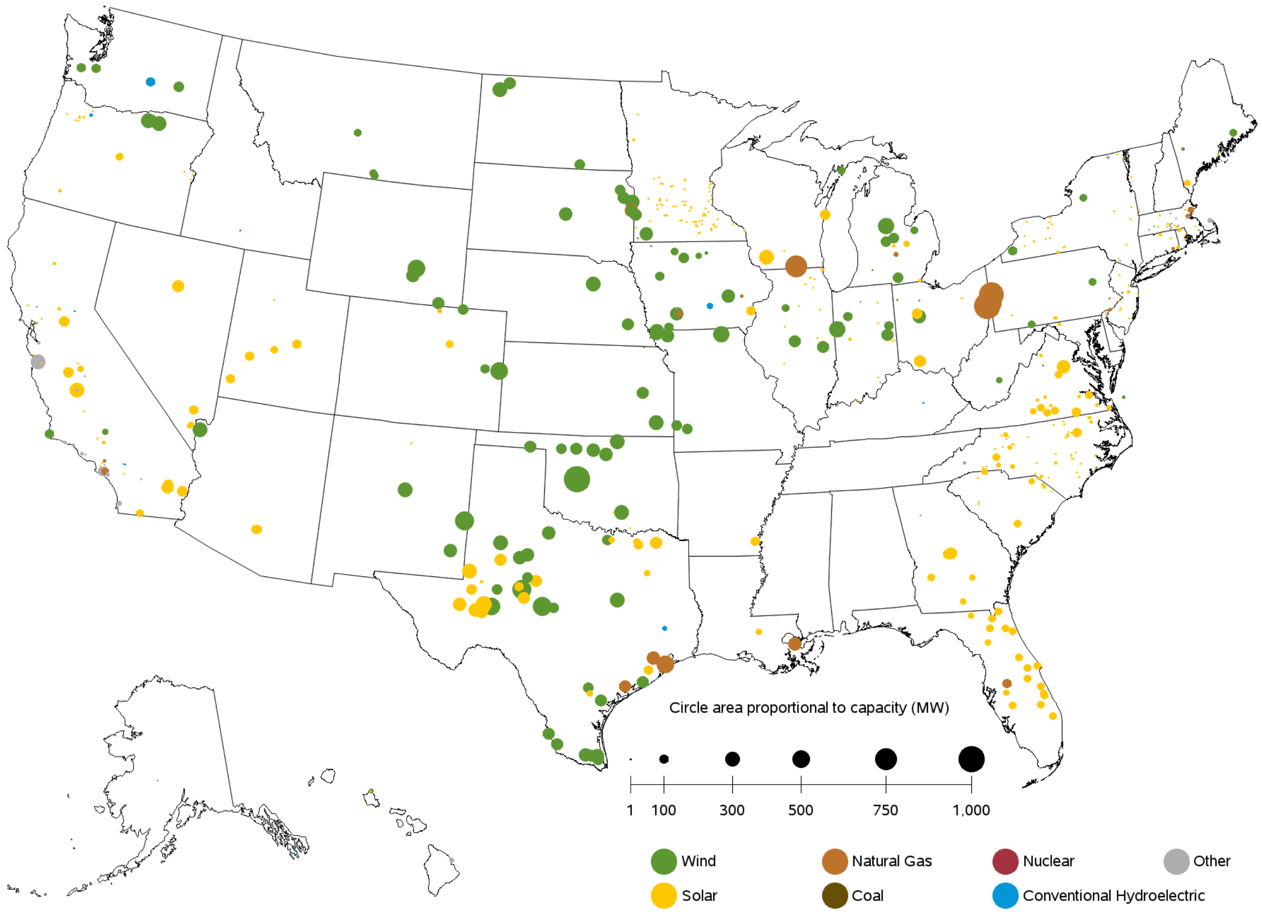


Natural gas and wind generation additions in the last decade dwarfed all other technologies, but with solar rapidly growing. The gas generation, and low natural gas prices were partially responsible for the recent decrease in carbon dioxide emissions

Sources: www.eia.gov/todayinenergy/detail.php?id=25432

New Generation May 2020 to April 2021

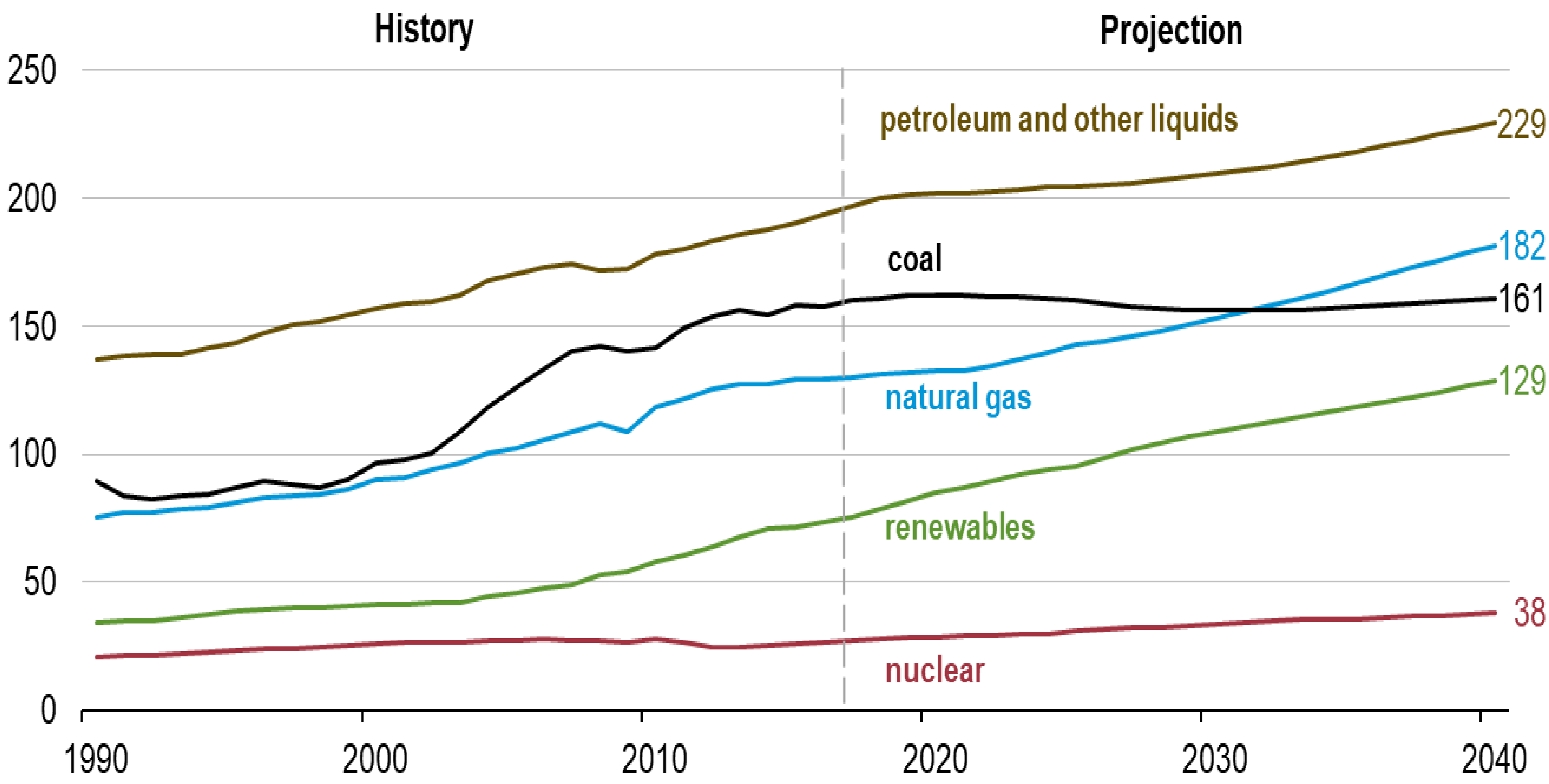
Figure 6.1.C. Utility-Scale Generating Units Planned to Come Online from May 2020 to April 2021



Sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

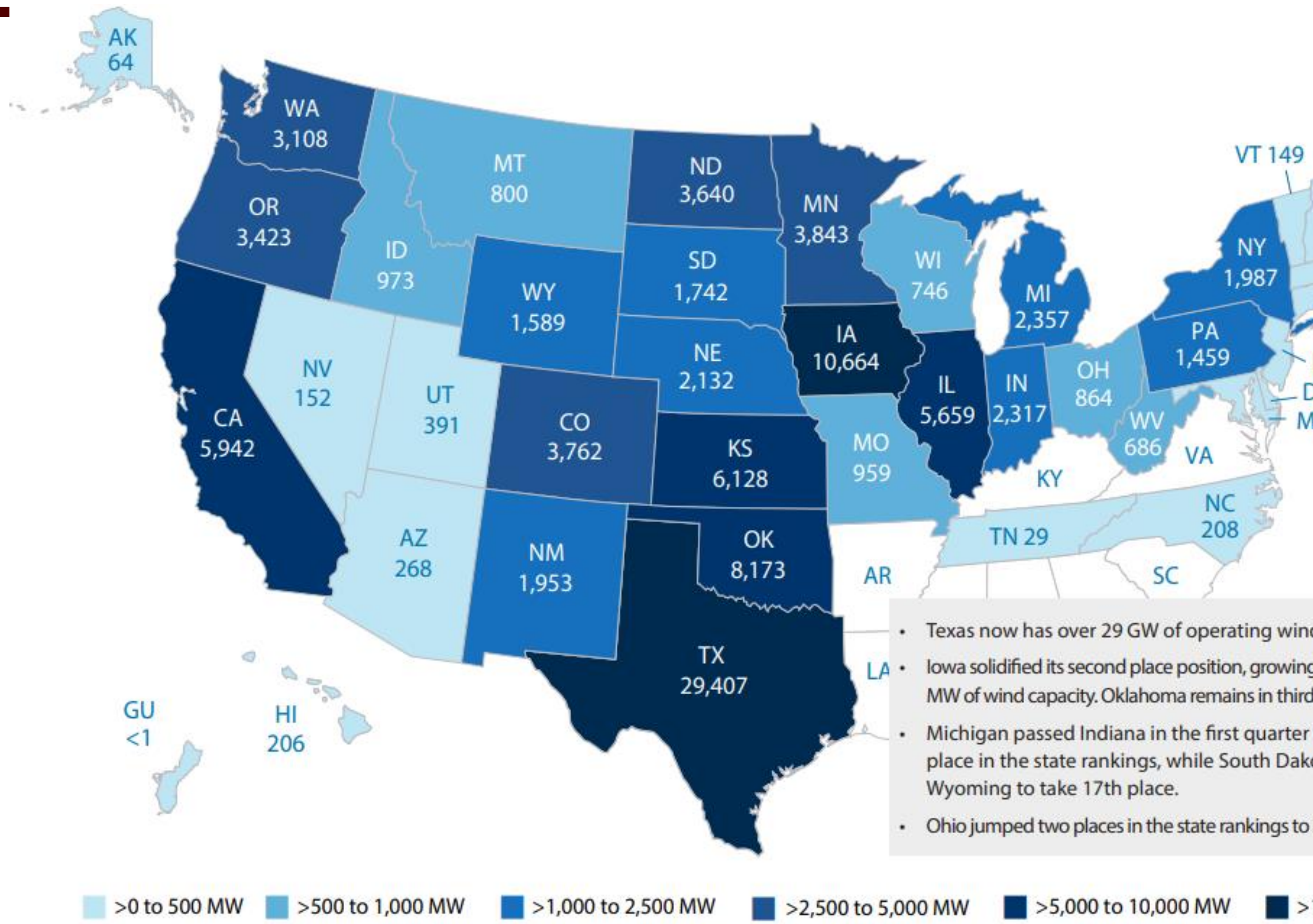
Sources: EIA Electricity Monthly, May 2020

The World: Energy Consumption by Source



Source: EIA, International Energy Outlook 2018

US Wind Capacity by State



Total wind capacity is now 107 GW (compared to a total US capacity of about 1000 GW)

Source: AWEA 1st Quarter 2020 Market Report

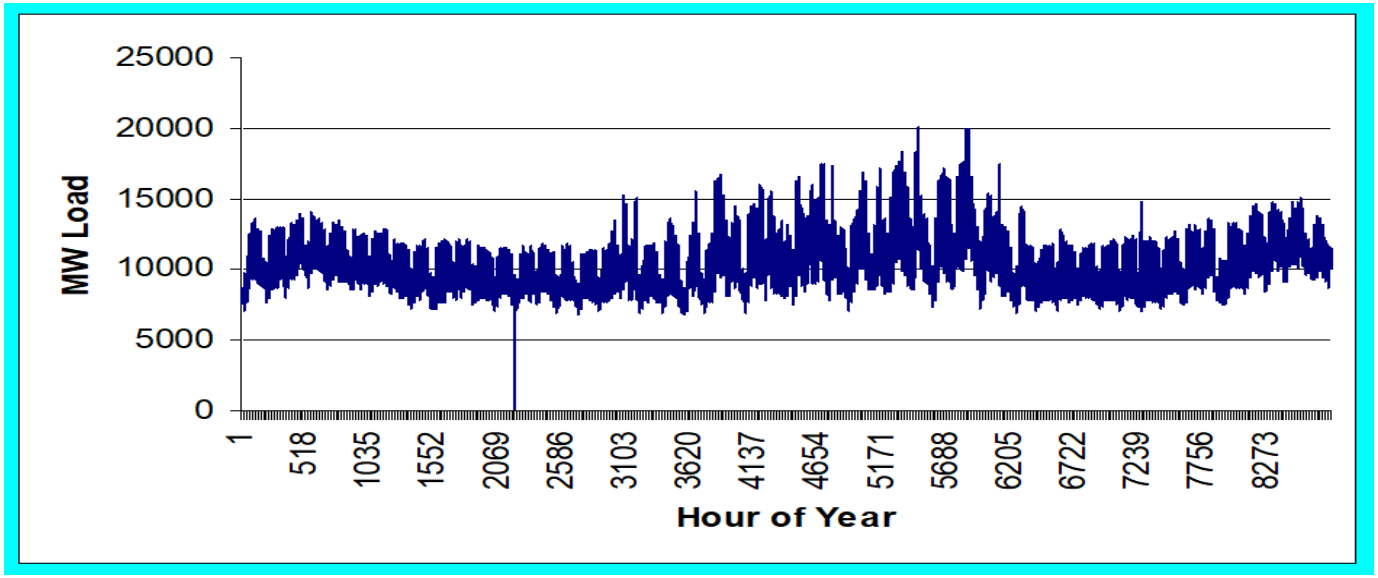
Texas Electricity Sources

- In 2018 the Texas top five fuel sources for electricity were Natural Gas (50%), Coal (23%), Wind (15.7%), Nuclear (8.7%), Solar (0.6%), other (the rest)
  - **Average retail price is 8.48 cents/kWh**
- In 2018 the California top five fuel sources for electricity were Natural Gas (46%), Solar (13.8), Hydro (13.5%), Nuclear (9.3%), Wind (7.2%), Geo (5.9%)
  - **Average retail price is 16.58 cents/kWh**
- In 2018 Kentucky was 75% coal, while Washington was 69% hydro; highest retails costs are 29.1 cents/kWh in Hawaii, 19.3 in Alaska and 18.4 in Connnecticut

Source: www.eia.gov/electricity/state

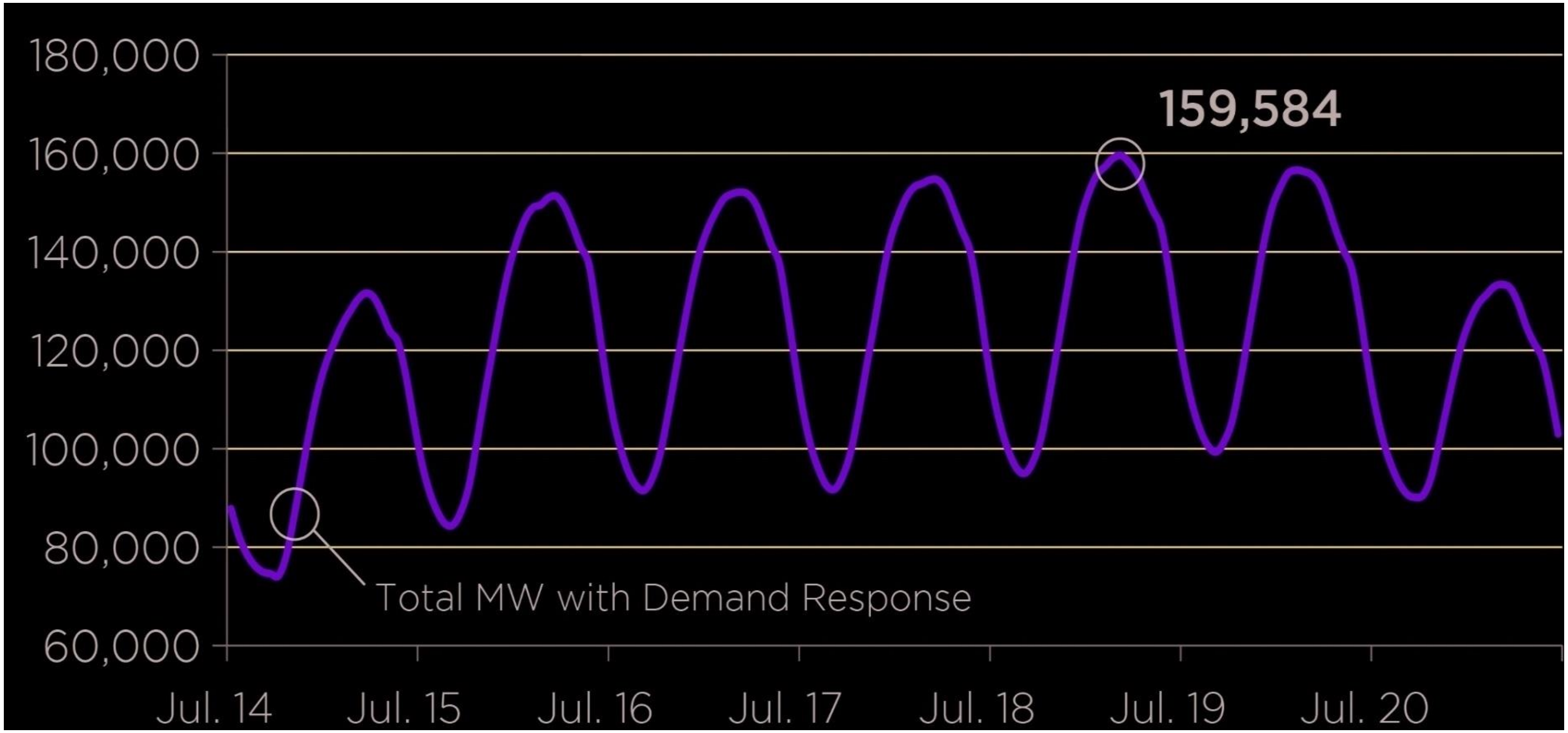
Loads

- Can range in size from less than one watt to 10's of MW.
- Loads are usually aggregated.
- The aggregate load changes with time, with strong daily, weekly and seasonal cycles.

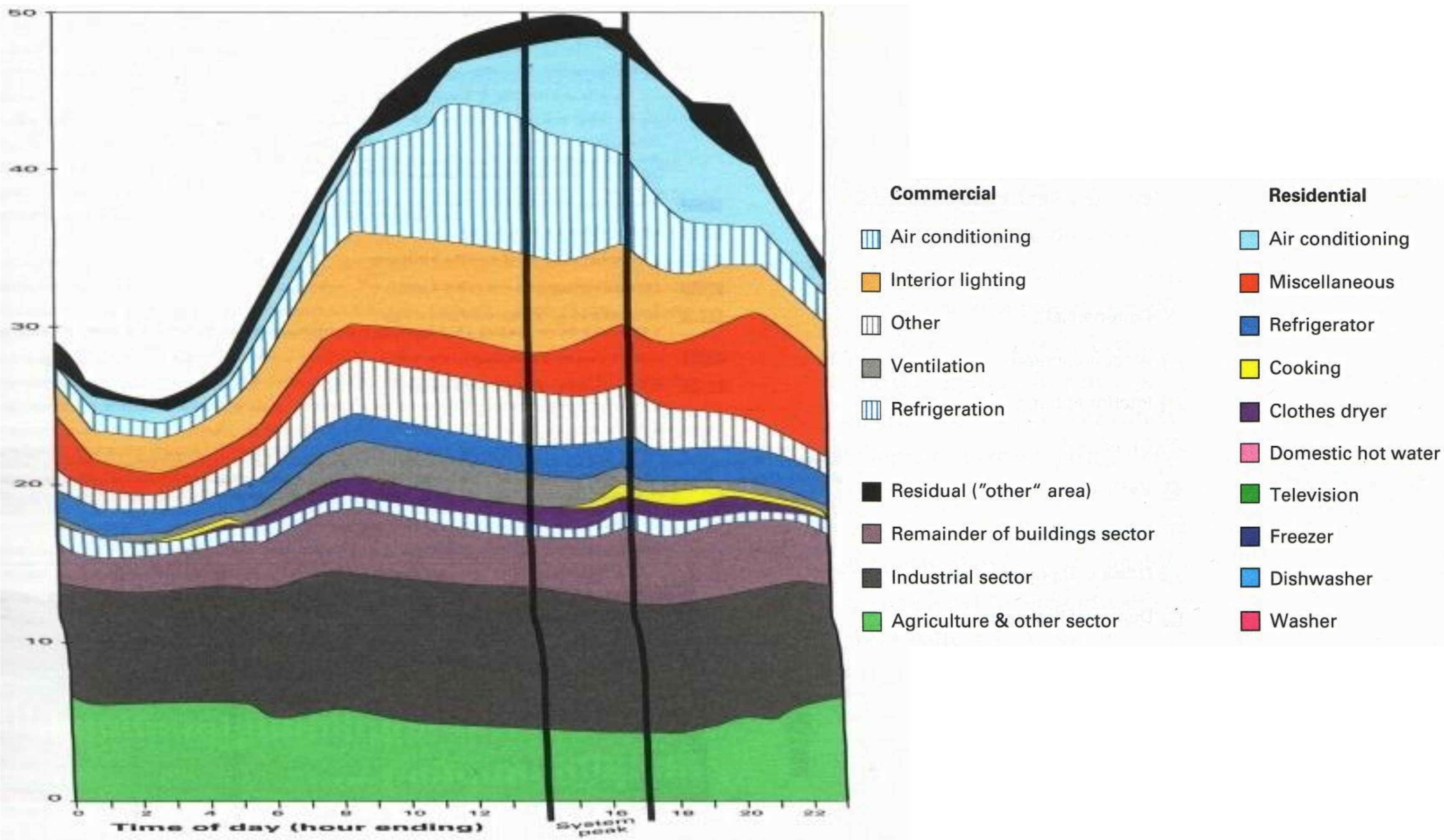


ComEd Yearly Load

Example: PJM Weekly Summer Load Variation, July 2013



Example Daily Load Variation: Very Location Specific



Transmission and Distribution

- Goal is to move electric power from generation to load with low losses.
- Less losses at higher voltages ($S=VI^*$ and I^2R losses), but more difficult to insulate.
- Typical high voltage transmission voltages are 765, 500, 345, 230, 161, 138 and 69 kV.
- Lower voltage lines are used for distribution (12.4 or 13.8 kV).
- Typical losses are about 3 to 5% in transmission and 10 to 15% in the distribution system.

Transmission & Distribution

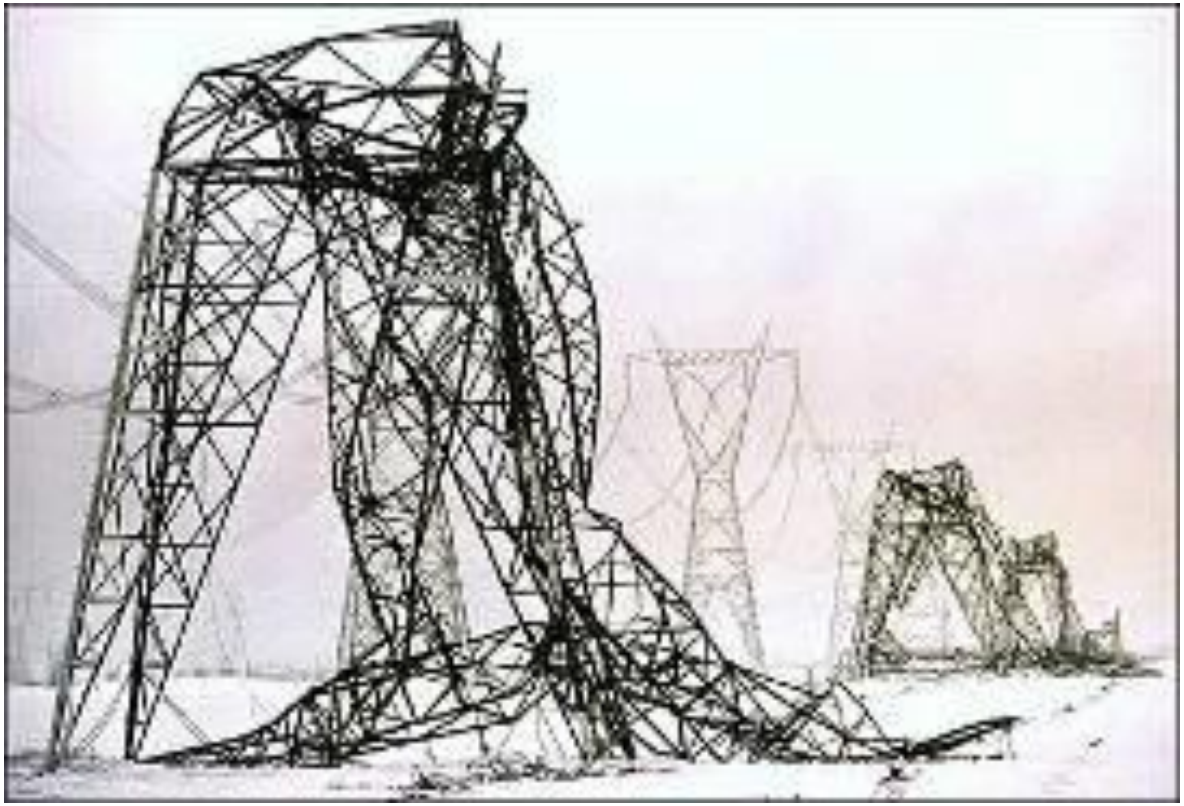
- Transmission
  - networked connections
  - power can be supplied from multiple sources
  - typically higher voltages, above 100 kV
  - mostly overhead, with some underground in urban areas
  - Often source of large-scale blackouts

- Distribution
  - radial connections
  - power moves in one direction only
  - typically lower voltages, below 100 kV
  - the source of most black-outs, but these are local
  - Most new construction is underground, especially in suburban and urban locations

Three Phase Transmission Line

Transmission Lines and the Elements

Ike in Beaumont, Tx

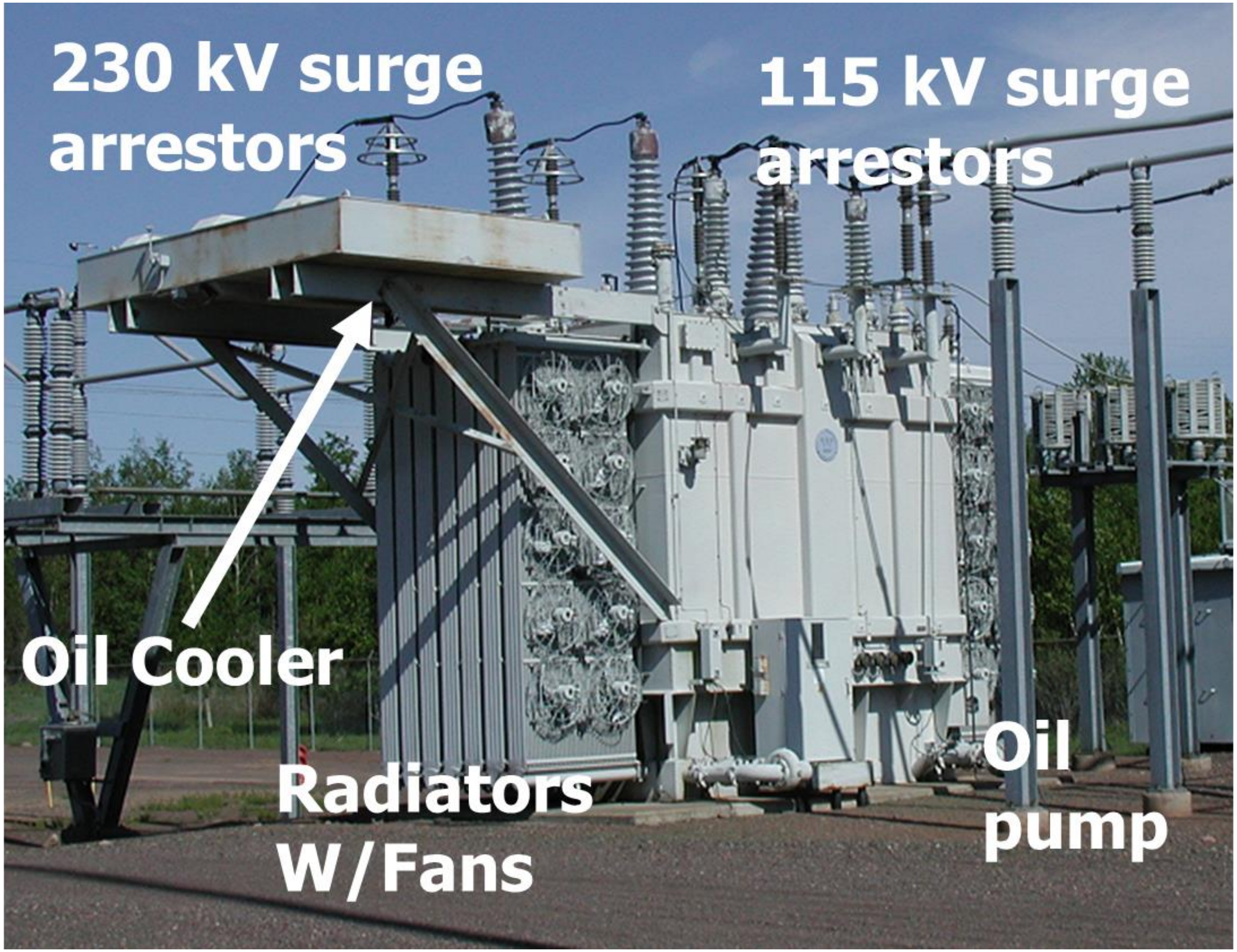


Quebec Ice Storm

Transformers

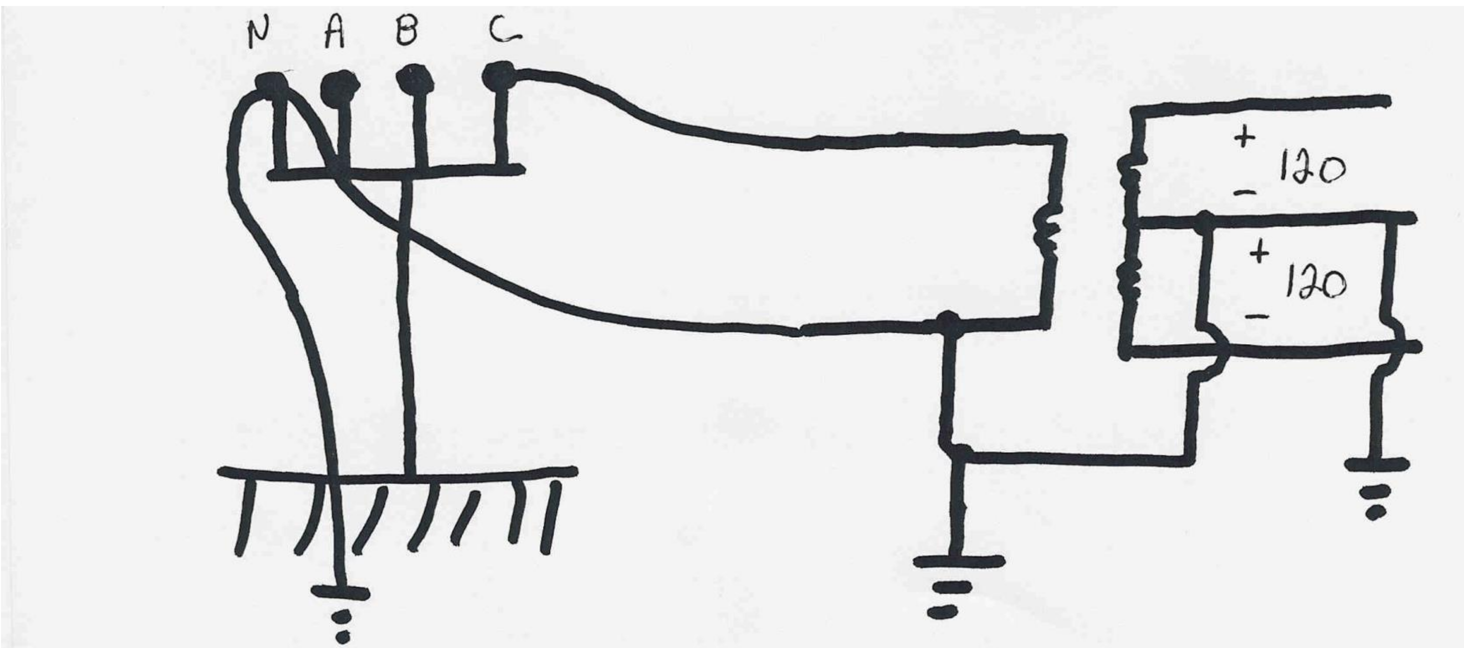
- Transformers provide an easily means for changing ac voltage levels
  - Power flow through transformers is bi-directional
- Heating is a major concern that can quickly lead to loss of transformer life (and occasionally explosions!)
- High voltage transformers (say 230 kV and up) are large, heavy, and difficult to replace

A 230/115 kV Transformer



Residential Distribution Transformers

- Residential single phase electric service uses a center tapped transformer to provide 240/120 volt service; a separate ground is used for safety



Per Unit Calculations

- A key problem in analyzing power systems is the large number of transformers.
  - It would be very difficult to continually have to refer impedances to the different sides of the transformers
- This problem is avoided by a normalization of all variables.
- This normalization is known as per unit analysis

$$\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

Components Join Together at a Bus

Energy Economics

- Electric generating technologies involve a tradeoff between fixed costs (costs to build them) and operating costs
  - Nuclear and solar high fixed costs, but low operating costs (though cost of solar has decreased substantially recently)
  - Natural gas/oil have low fixed costs but can have higher operating costs (dependent upon fuel prices)
  - Coal, wind, hydro are in between
- Also the units capacity factor is important to determining ultimate cost of electricity

Estimated Energy Costs for New Generation, 2019 Edition

Table 1b. Estimated levelized cost of electricity (unweighted average) for new generation resources entering service in 2023 (2018 $/MWh)

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmis-sion cost	Total system LCOE	Levelized tax credit[1]	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS[2]	85	61.3	9.7	32.2	1.1	104.3	NA	104.3
Coal with 90% CCS[2]	85	50.2	11.2	36.0	1.1	98.6	NA	98.6
Conventional CC	87	9.3	1.5	34.4	1.1	46.3	NA	46.3
Advanced CC	87	7.3	1.4	31.5	1.1	41.2	NA	41.2
Advanced CC with CCS	87	19.4	4.5	42.5	1.1	67.5	NA	67.5
Conventional CT	30	28.7	6.9	50.5	3.2	89.3	NA	89.3
Advanced CT	30	17.6	2.7	54.2	3.2	77.7	NA	77.7
Advanced nuclear	90	53.8	13.1	9.5	1.0	77.5	NA	77.5
Geothermal	90	26.7	12.9	0.0	1.4	41.0	-2.7	38.3
Biomass	83	36.3	15.7	39.0	1.2	92.2	NA	92.2
Non-dispatchable technologies								
Wind, onshore	41	39.8	13.7	0.0	2.5	55.9	-6.1	49.8
Wind, offshore	45	107.7	20.3	0.0	2.3	130.4	-12.9	117.5
Solar PV[3]	29	47.8	8.9	0.0	3.4	60.0	-14.3	45.7
Solar thermal	25	119.6	33.3	0.0	4.2	157.1	-35.9	121.2
Hydroelectric[4]	75	29.9	6.2	1.4	1.6	39.1	NA	39.1

Source: www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf (February 2019)

Estimated Energy Costs for New Generation, 2020 Edition

Table 1a. Estimated levelized cost of electricity (LCOE, capacity-weighted[1]) for new generation resources entering service in 2025 (2019 dollars per megawatthour)

Plant type	Capacity factor (percent)	Levelized capital cost	Levelized fixed O&M[2]	Levelized variable O&M	Levelized transmis-sion cost	Total system LCOE	Levelized tax credit[3]	Total LCOE including tax credit
Dispatchable technologies								
Ultra-supercritical coal	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Combined cycle	87	7.48	1.59	26.40	1.13	36.61	*NA*	36.61
Combustion turbine	30	16.10	2.65	46.51	3.44	68.71	*NA*	68.71
Advanced nuclear	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Geothermal	90	20.36	14.50	1.16	1.45	37.47	-2.04	35.44
Biomass	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*	*NB*
Non-dispatchable technologies								
Wind, onshore	40	23.51	7.51	0.00	3.08	34.10	*NA*	34.10
Wind, offshore	45	84.00	27.89	0.00	3.15	115.04	*NA*	115.04
Solar photovoltaic[4]	30	24.12	5.77	0.00	2.91	32.80	-2.41	30.39
Hydroelectric[5,6]	73	28.89	7.64	1.39	1.62	39.54	*NA*	39.54

[1]The capacity-weighted average is the average levelized cost per technology, weighted by the new capacity coming online in each region. The capacity additions for each region are based on additions from 2023 to 2025. Technologies for which capacity additions are not expected do not have a capacity-weighted average and are marked as *NB*, or not built.

[2]O&M = operations and maintenance.

[3]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 2025 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 calculations. See text box on page 2 for details on how the tax credits are represented in the model.

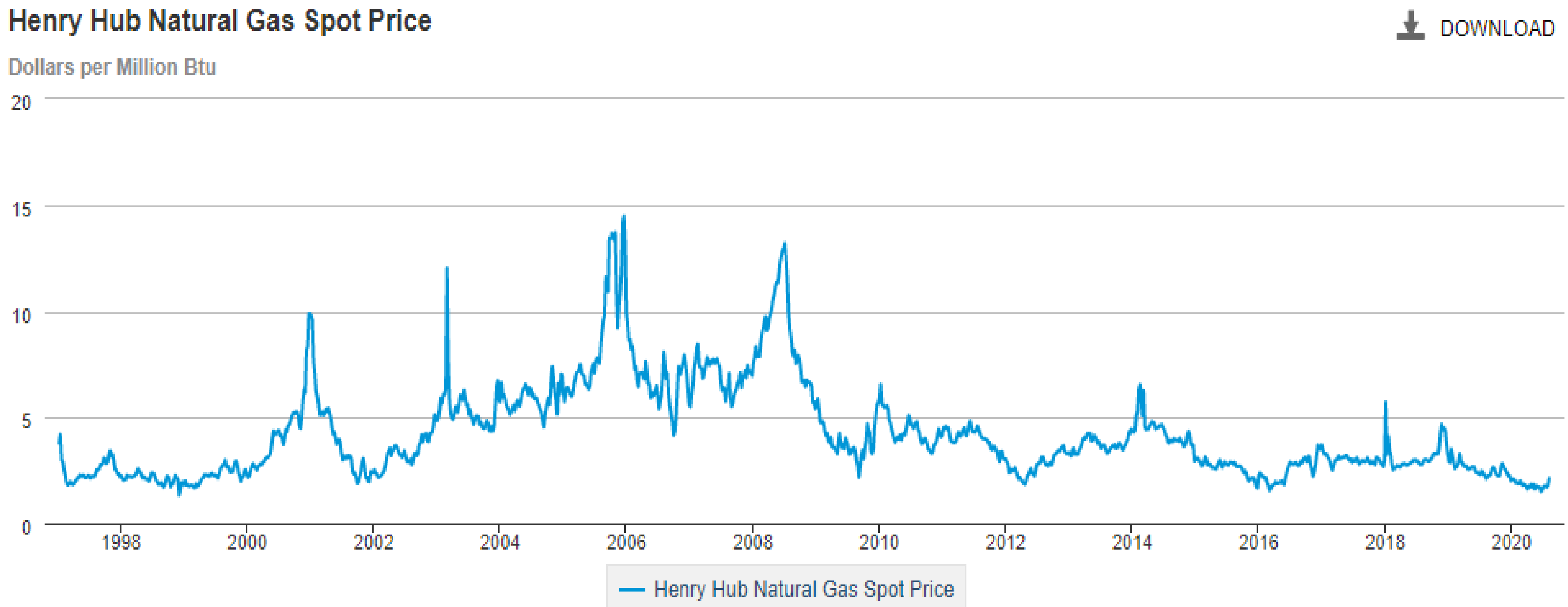
[4]Costs are expressed in terms of net AC (alternating current) power available to the grid for the installed capacity.

[5]As modeled, EIA assumes that hydroelectric generation has seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

[6]Costs are for 2023 online year. See page 6 for details on the exception.

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2020*

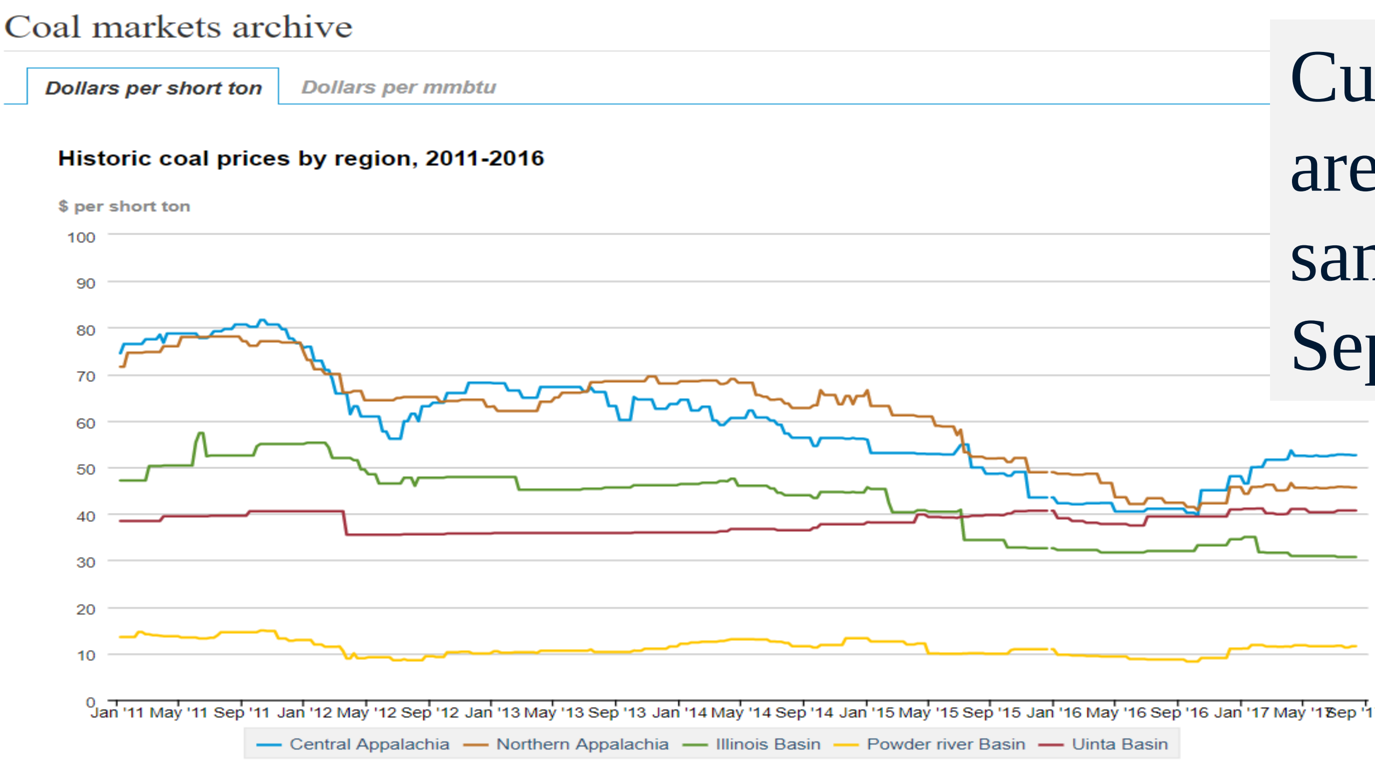
Natural Gas Prices 1997 to 2020



Marginal cost for natural gas fired electricity price in $/MWh is about 7-10 times gas price; Henry Hub is a gas pipeline located in Erath, Louisiana.

Source: http://www.eia.gov/dnav/ng/hist/rngwhhdW.htm

Coal Prices had Fallen But Are Now Back to Values from Five Years Ago



Current prices are about the same as in Sept. 2017

BTU content per pound varies between about 8000 and 15,000 Btu/lb, giving costs of around $1 to 2/Mbtu

Source: eia.gov/coal

Average Cost of Solar Systems, 2019

Average cost of solar panels based on system size

SYSTEM SIZE	AVERAGE SOLAR PANEL SYSTEM COST (BEFORE TAX CREDITS)	AVERAGE SOLAR PANEL SYSTEM COST (AFTER TAX CREDITS)
2 kW	$5,960	$4,172
3 kW	$8,940	$6,258
4 kW	$11,920	$8,344
5 kW	$14,900	$10,430
6 kW	$17,880	$12,516
7 kW	$20,860	$14,602
8 kW	$23,840	$16,688
10 kW	$29,800	$20,860
12 kW	$35,760	$25,032
15 kW	$44,700	$31,290
20 kW	$59,600	$41,720
25 kW	$74,500	$52,150

These prices reflect the cost of a solar energy system both *before AND after* deducting the federal solar tax credit (known as the ITC), which reduces your solar system cost by 30 percent. Some states, local governments, and utilities also offer rebates and other tax incentives that can further reduce the solar system costs in your quotes from solar installers.

For the cost for a 10 kW system is $2.98 per watt before the tax credit and $ 20.86 after

Source news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/

Brief History of Electric Power

- First real practical uses of electricity began with the telegraph (1860's) and then arc lighting in the 1870's
- Early 1880's – Edison introduced Pearl Street dc system in Manhattan supplying 59 customers
- 1884 – Sprague produces practical dc motor
- 1885 – invention of transformer
- Mid 1880's – Westinghouse/Tesla introduce rival ac system
- Late 1880's – Tesla invents ac induction motor
- 1893 – Three-phase transmission line at 2.3 kV

History, cont'd

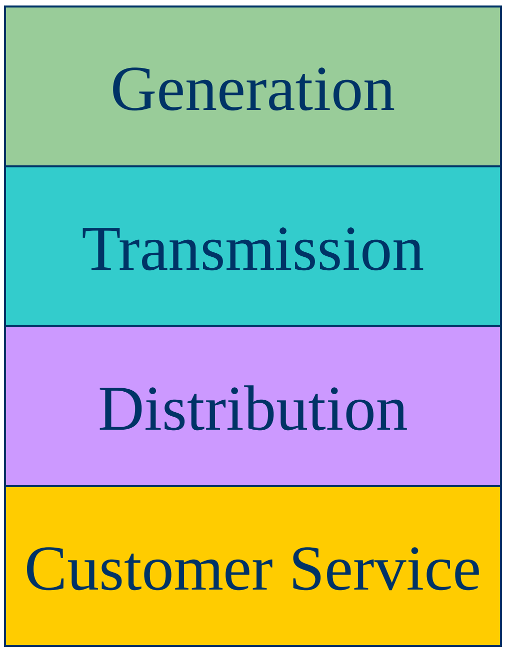
- 1896 – ac lines deliver electricity from hydro generation at Niagara Falls to Buffalo, 20 miles away; also 30kV line in Germany
- Early 1900's – Private utilities supply all customers in area (city); recognized as a natural monopoly; states step in to begin regulation
- By 1920's – Large interstate holding companies control most electricity systems

History, cont'd

- 1935 – Congress passes Public Utility Holding Company Act to establish national regulation, breaking up large interstate utilities (repealed 2005)
  - This gave rise to electric utilities that only operated in one state
- 1935/6 – Rural Electrification Act brought electricity to rural areas
- 1930's – Electric utilities established as vertical monopolies
- Frequency standardized in the 1930's

Vertical Monopolies

- Within a particular geographic market, the electric utility had an exclusive franchise



In return for this exclusive franchise, the utility had the obligation to serve all existing and future customers at rates determined jointly by utility and regulators

It was a "cost plus" business

Vertical Monopolies

- Within its service territory each utility was the only game in town
- Neighboring utilities functioned more as colleagues than competitors
- Utilities gradually interconnected their systems so by 1970 transmission lines crisscrossed North America, with voltages up to 765 kV
- Economies of scale keep resulted in decreasing rates, so most every one was happy

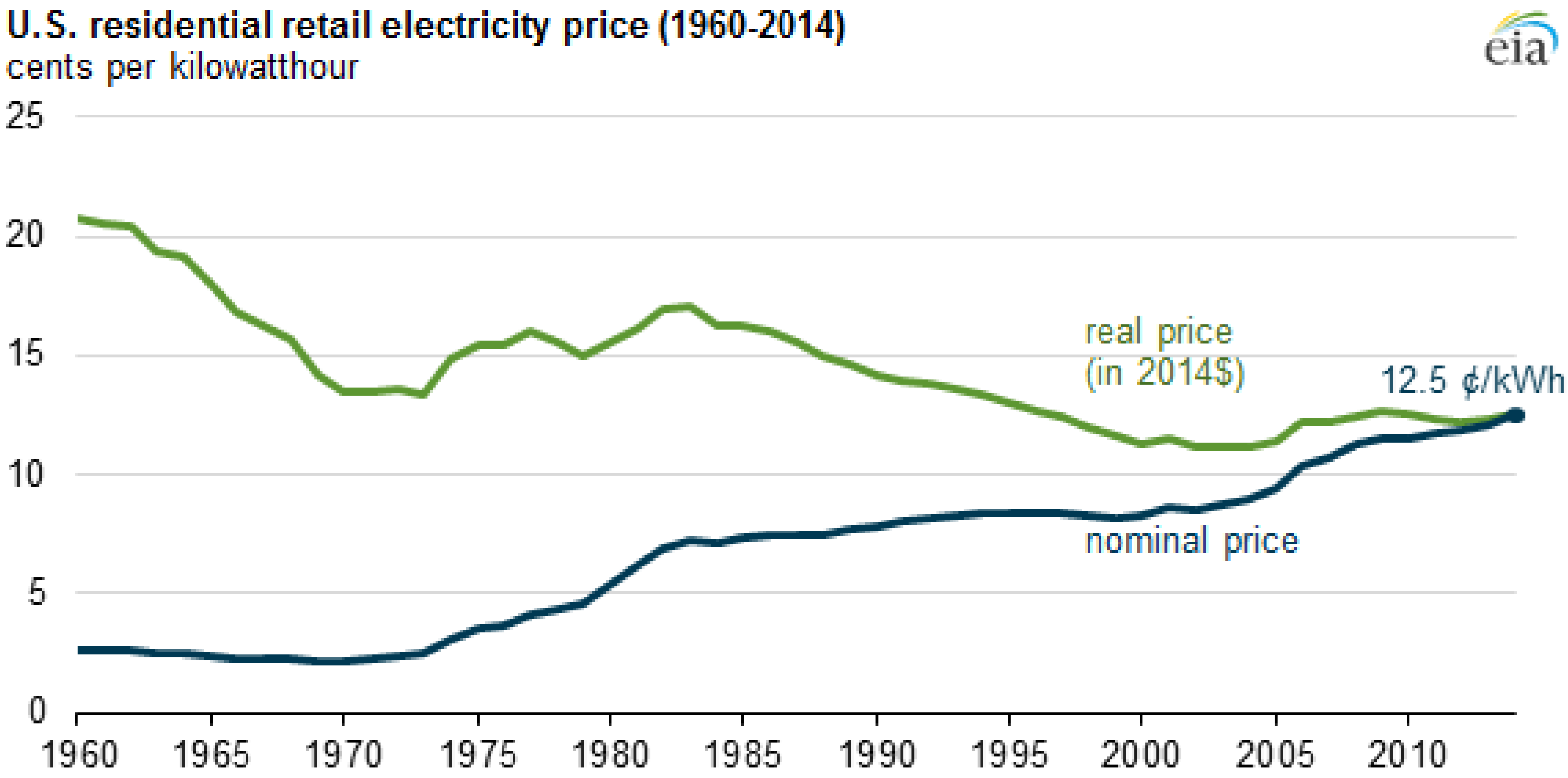
History, cont'd -- 1970's

- 1970's brought inflation, increased fossil-fuel prices, calls for conservation and growing environmental concerns
- Increasing rates replaced decreasing ones
- As a result, U.S. Congress passed Public Utilities Regulator Policies Act (PURPA) in 1978, which mandated utilities must purchase power from independent generators located in their service territory (modified 2005)
- PURPA introduced some competition

History, cont'd – 1990's & 2000's

- Major opening of industry to competition occurred as a result of National Energy Policy Act of 1992
- This act mandated that utilities provide "nondiscriminatory" access to the high voltage transmission
- Goal was to set up true competition in generation
- Result over the last few years has been a dramatic restructuring of electric utility industry (for better or worse!)
- Energy Bill 2005 repealed PUHCA; modified PURPA

Electricity Prices, 1960-2014

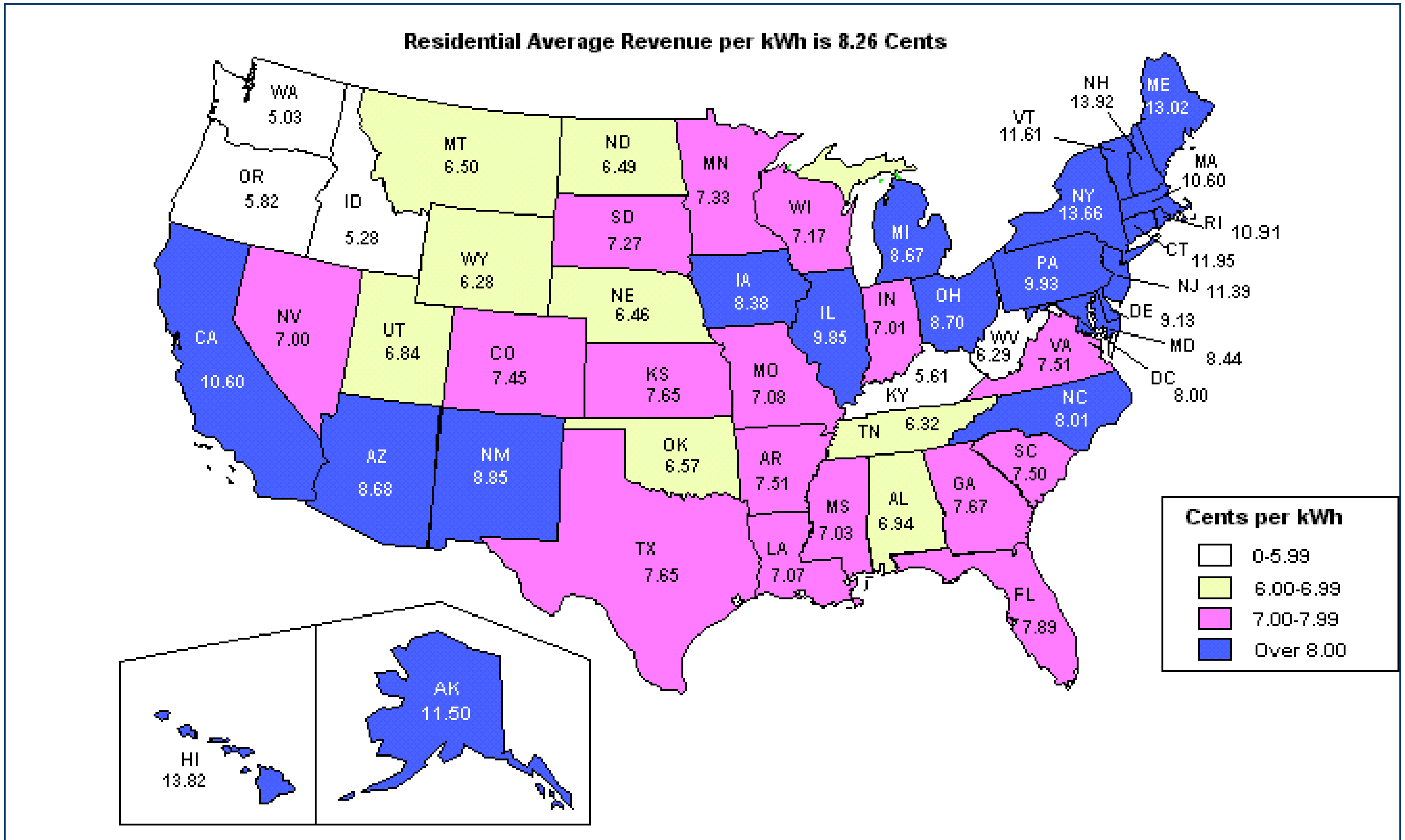


Source: EIA

Utility Restructuring

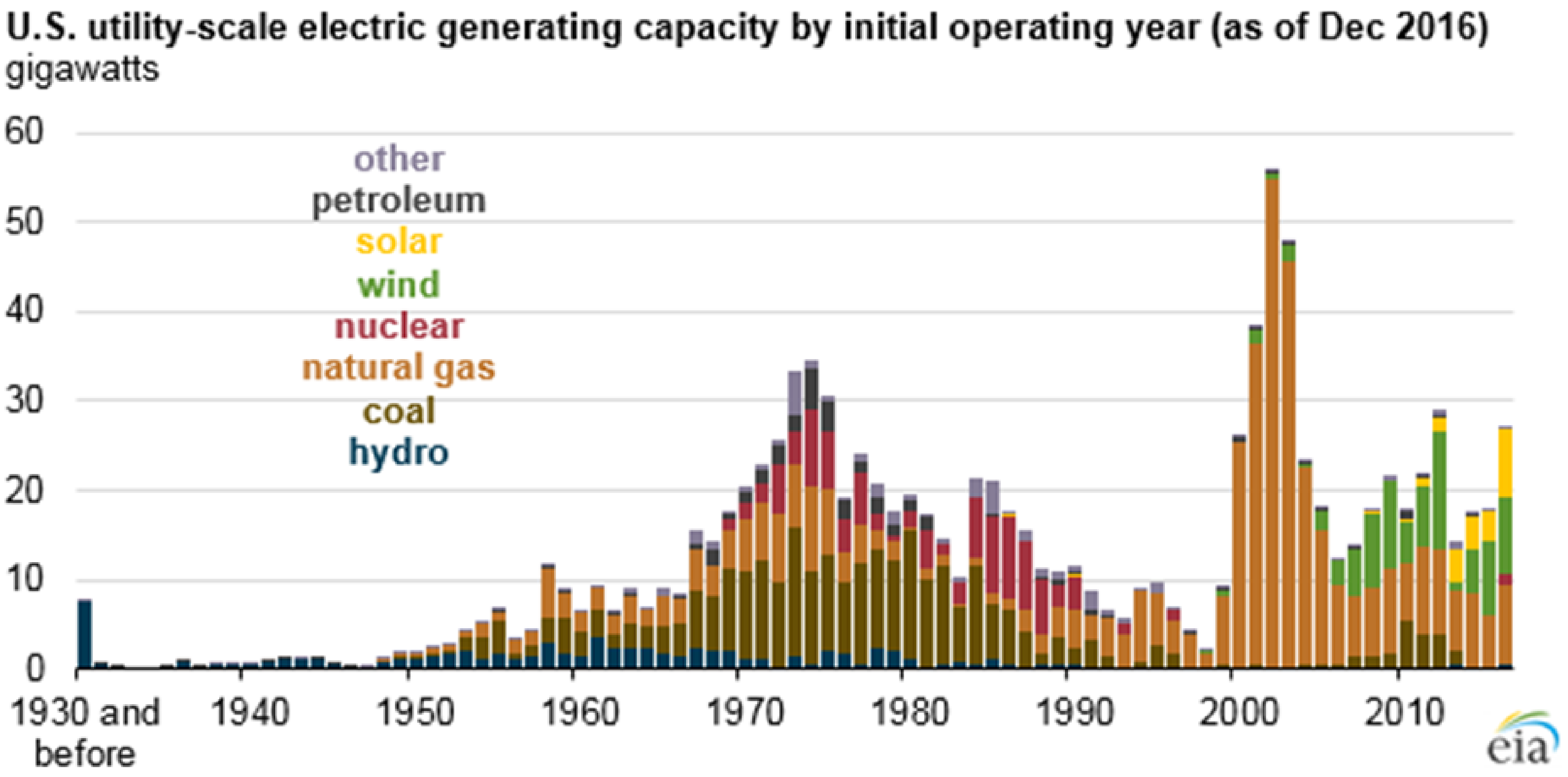
- Driven by significant regional variations in electric rates
- Goal of competition is to reduce rates through the introduction of competition
- Eventual goal is to allow consumers to choose their electricity supplier

State Variation in Electric Rates



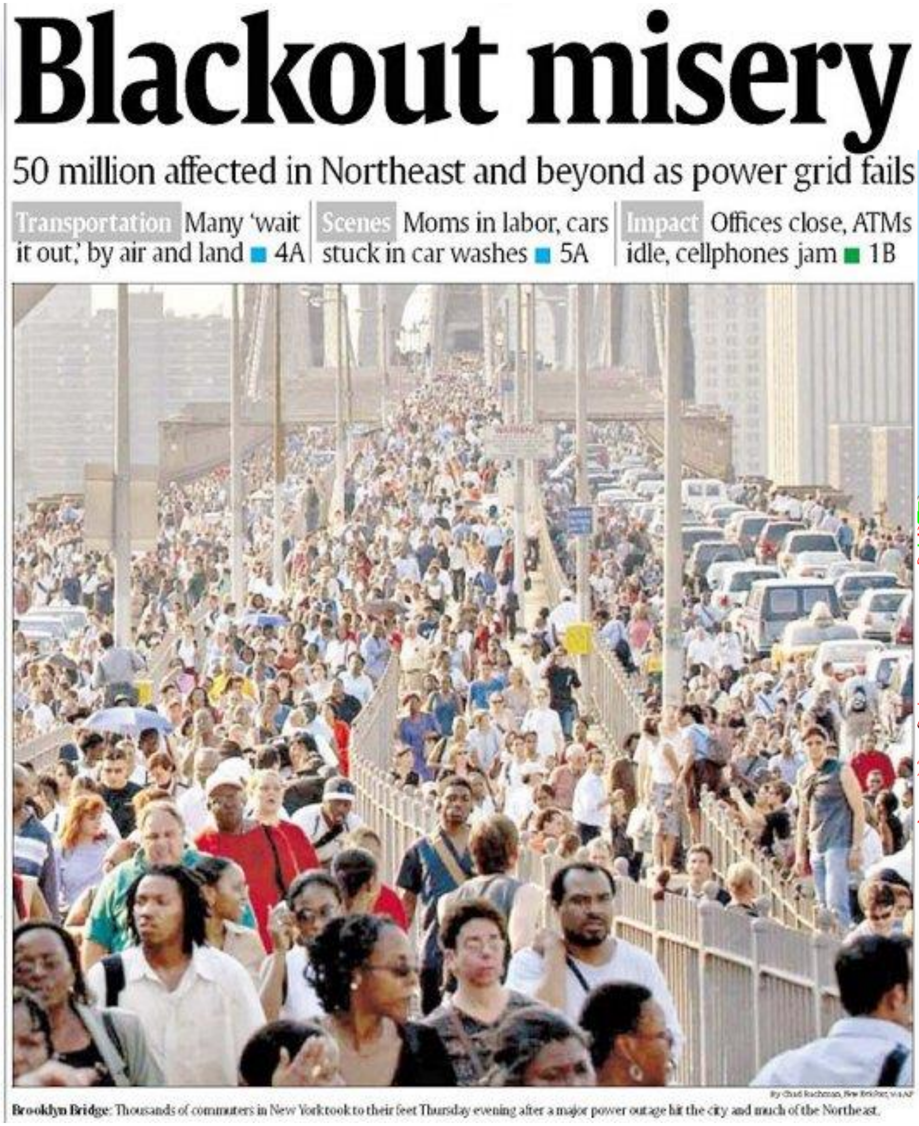
KWh = Kilowatthour.
Note: The average revenue per kilowatthour of electricity sold is calculated by dividing revenue by sales.
Source: Energy information Administration, Form EIA-861, "Annual Electric Utility Report."

The Rise of Natural Gas Generation



Source: US EIA, 2016

August 14th, 2003 Blackout

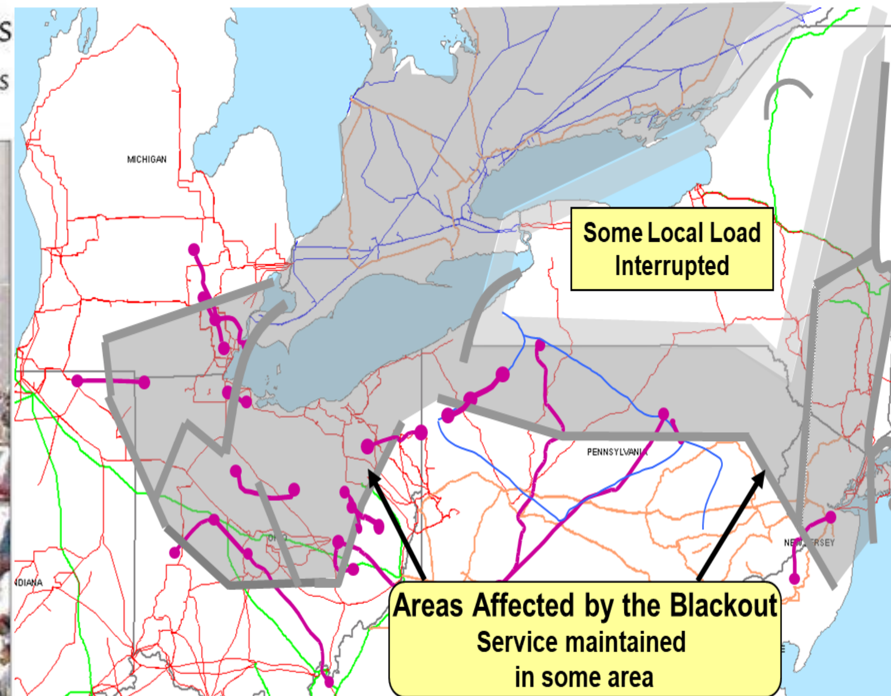

Blackout misery
50 million affected in Northeast and beyond as power grid fails

Transportation Many 'wait it out,' by air and land ■ 4A

Scenes Moms in labor, cars stuck in car washes ■ 5A

Impact Offices close, ATMs idle, cellphones jam ■ 1B

Brooklyn Bridge: Thousands of commuters in New York took to their feet Thursday evening after a major power outage hit the city and much of the Northeast.



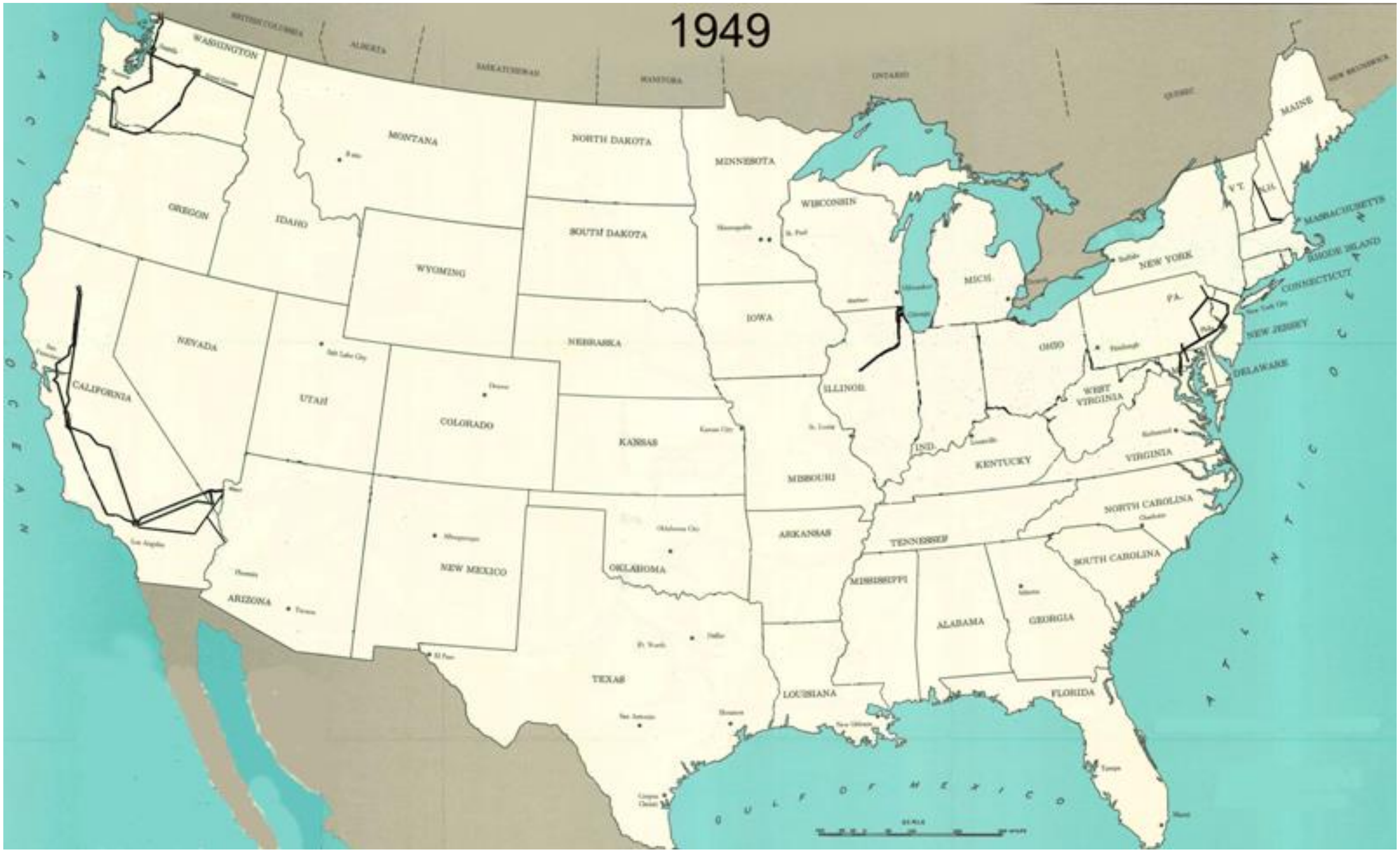
Above image from energy.gov, August 14, 2003 Blackout Final Report

My Favorite 8/14/2003 Blackout Cartoon!

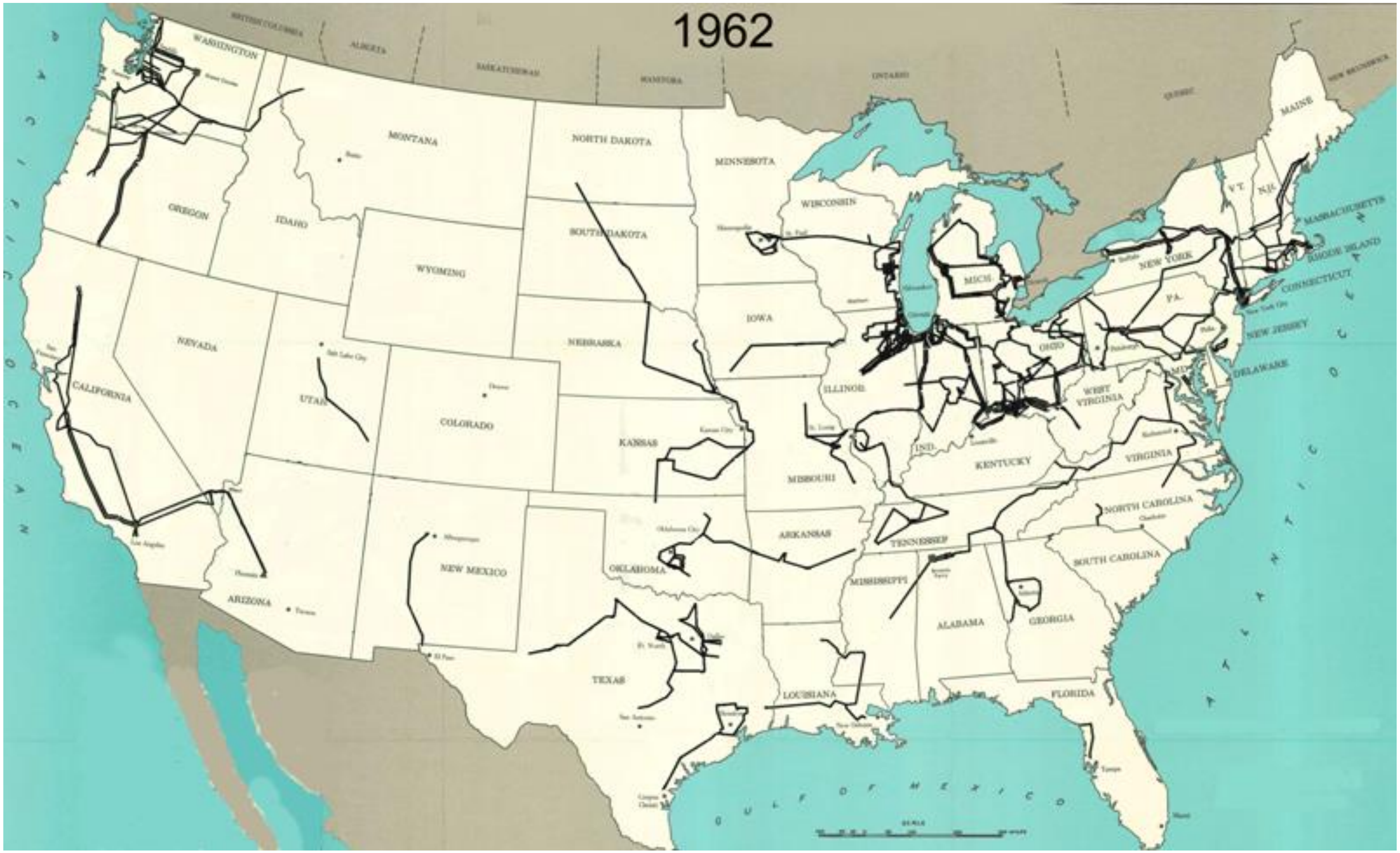
Suddenly, knowing a lot about the U.S. power grid became sexy at cocktail parties.

My Favorite Blackout Hoax Photo

345 kV+ Transmission Growth at a Glance (From Jay Caspary)



345 kV+ Transmission Growth at a Glance (From Jay Caspary)



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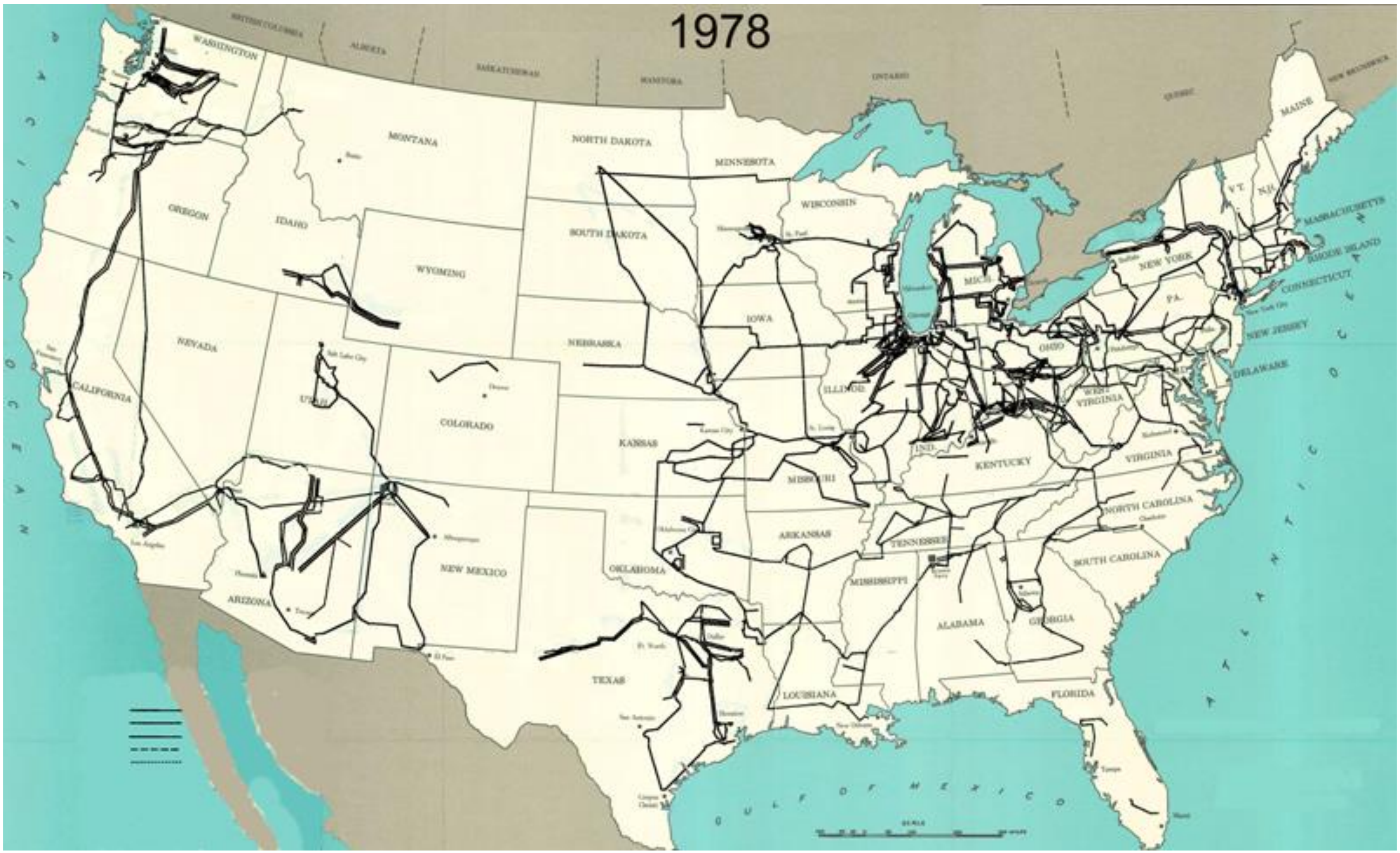

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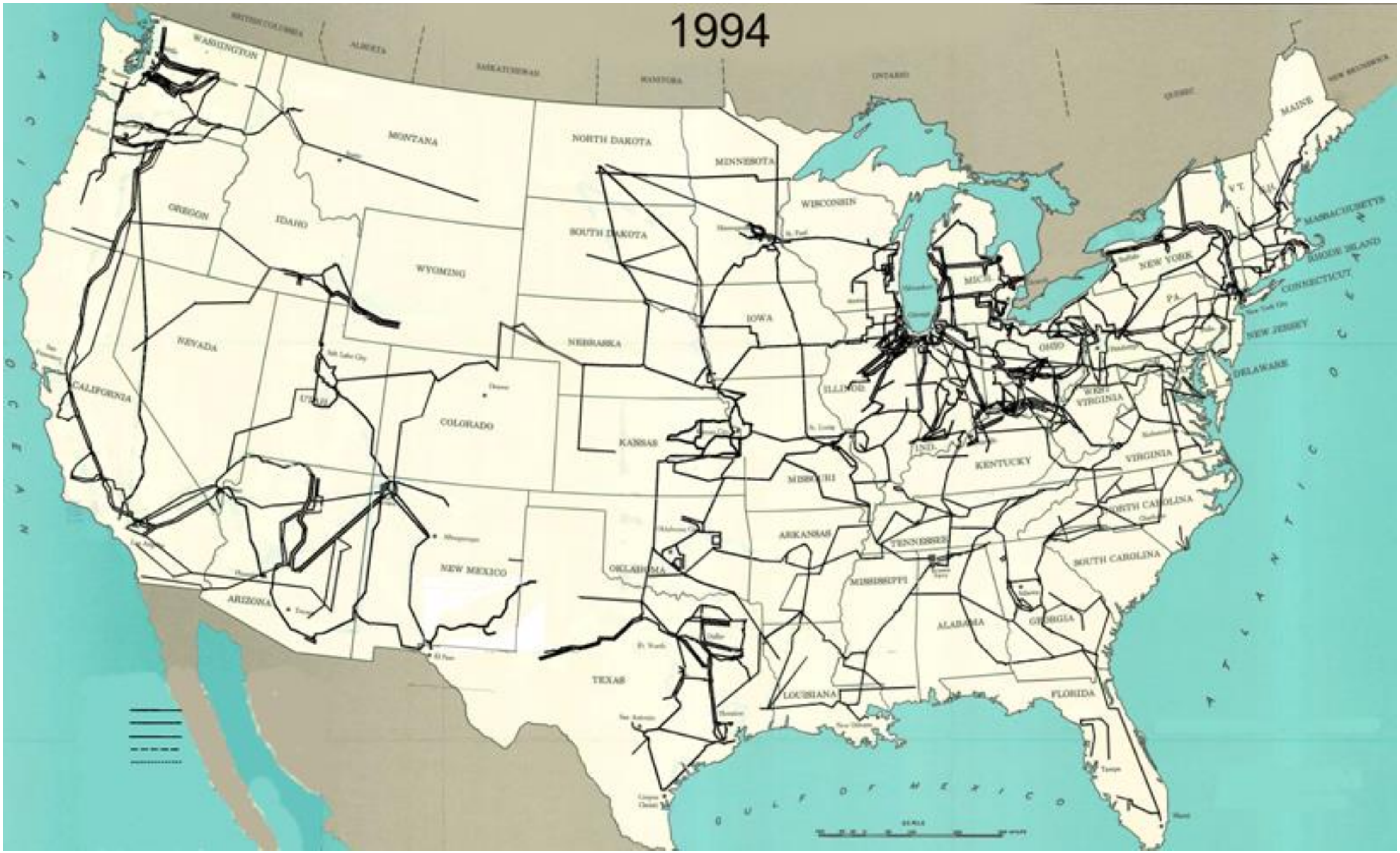
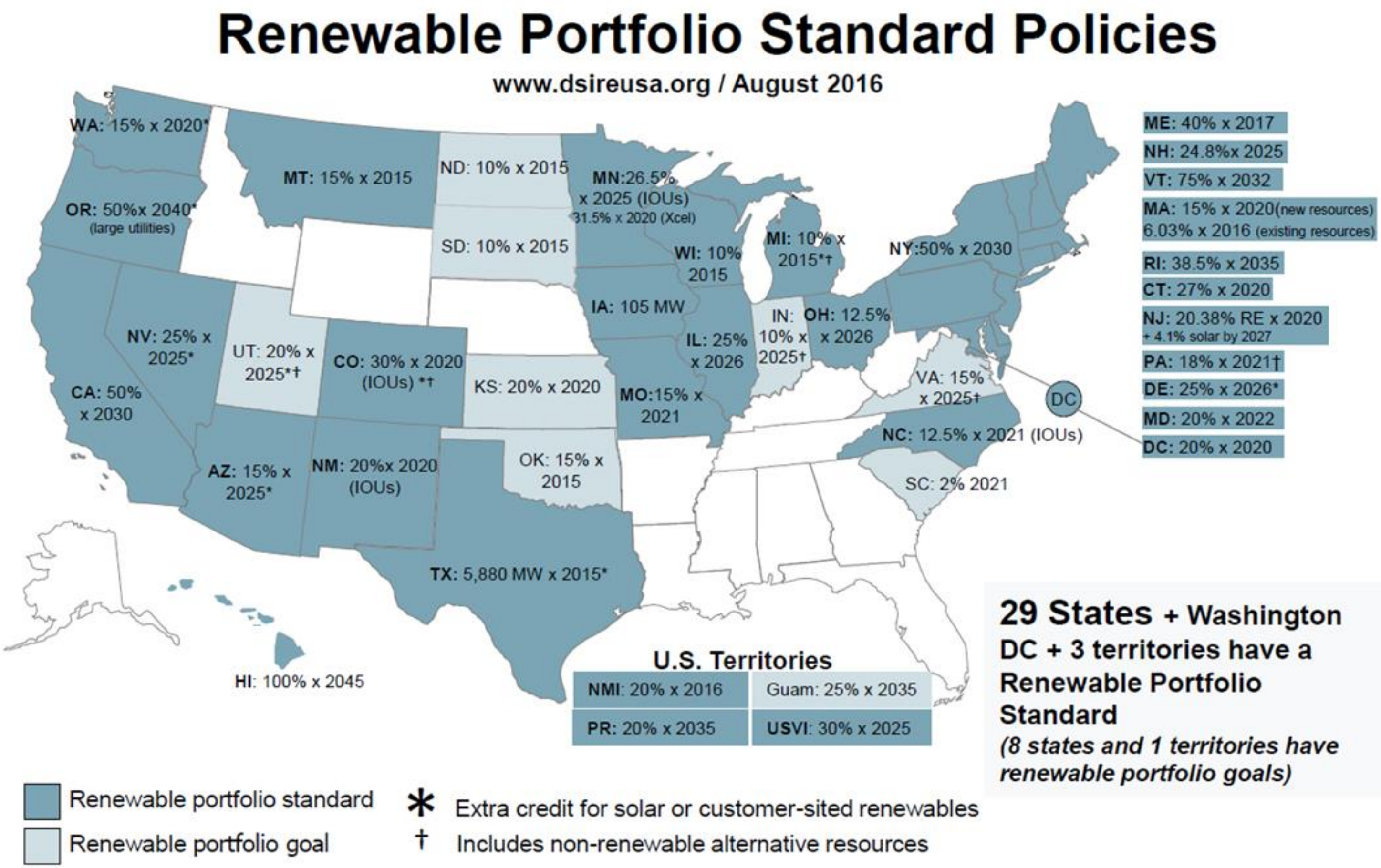


The Smart Grid

- The term “Smart Grid” dates officially to the 2007 “Energy Independence and Security Act”, Title 13 (“Smart Grid”)
  - Use of digital information and control techniques
  - Dynamic grid optimization with cyber-security
  - Deployment of distributed resources including
  - Customer participation and smart appliances
  - Integration of storage including PHEVs
  - Development of interoperability standards

Smart Grid Perceptions (Some of Us Like the Term “Smarter”)

Renewable Portfolio Standards (August 2016)

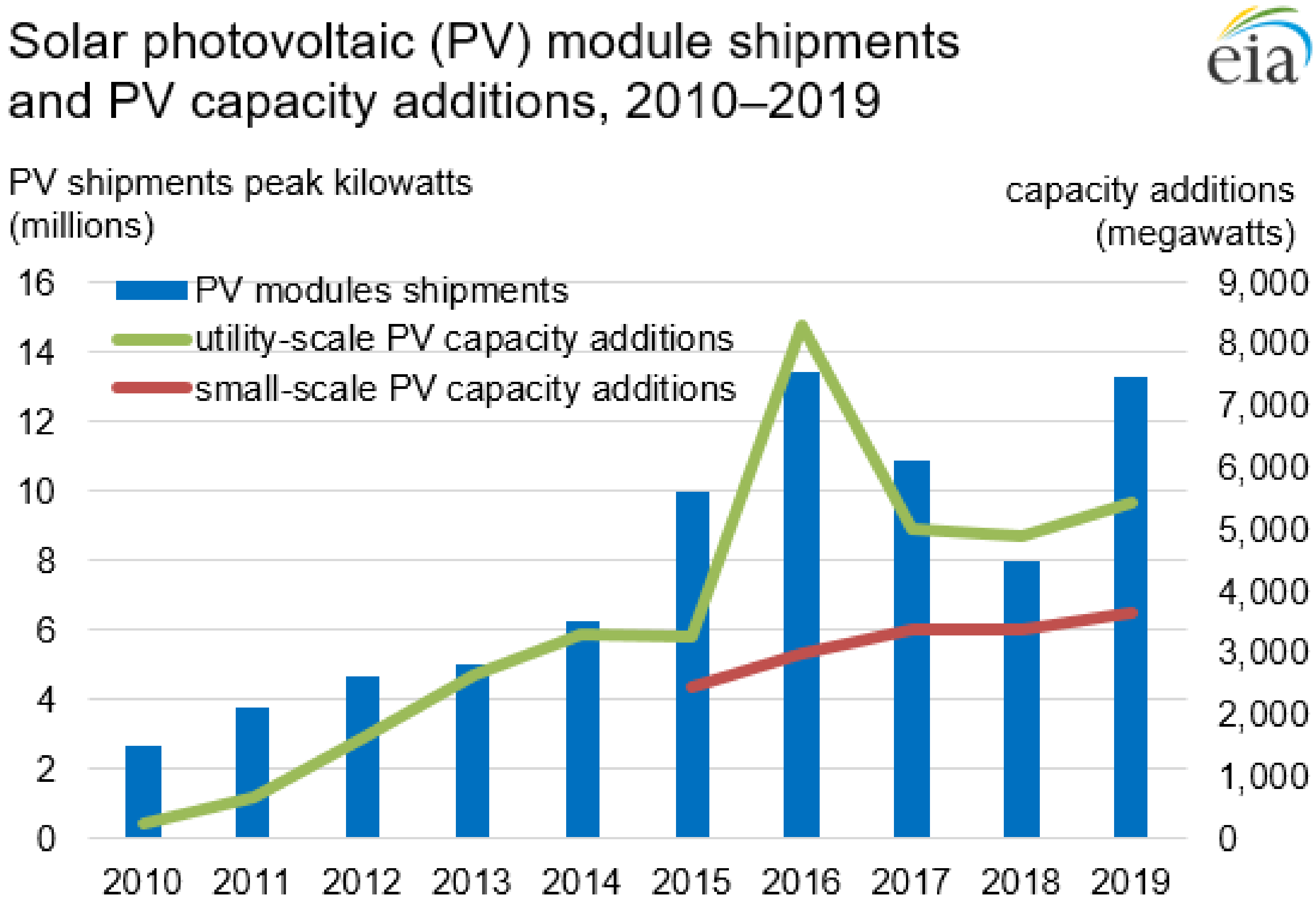


TX is now 10 GW by 2025 which we've met (i.e., 29 GW of wind now); CA is 60% by 2030 and 100% by 2045

Image source: http://www.dsireusa.org/

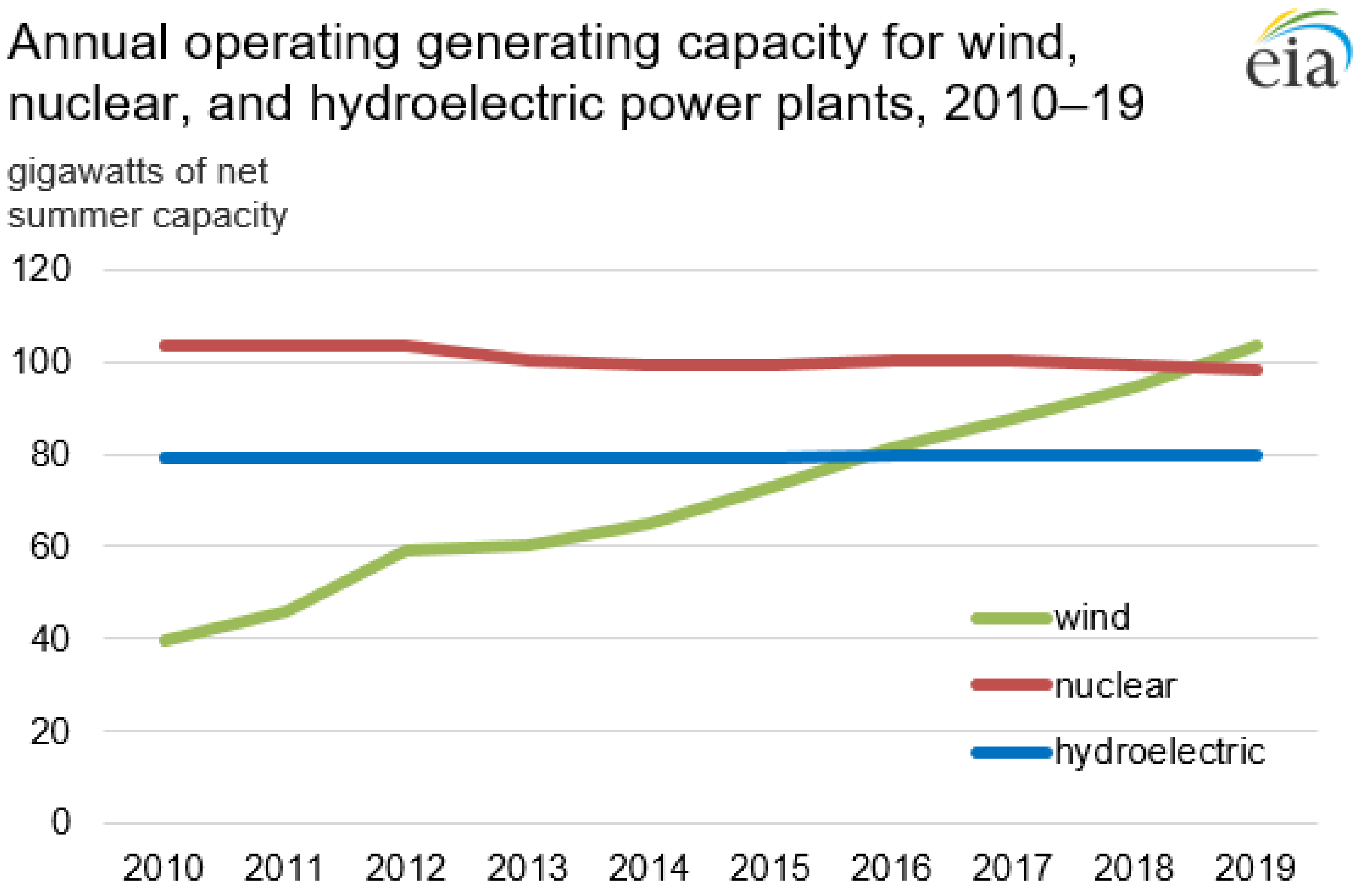
See also www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

Growth in Solar PV and Wind



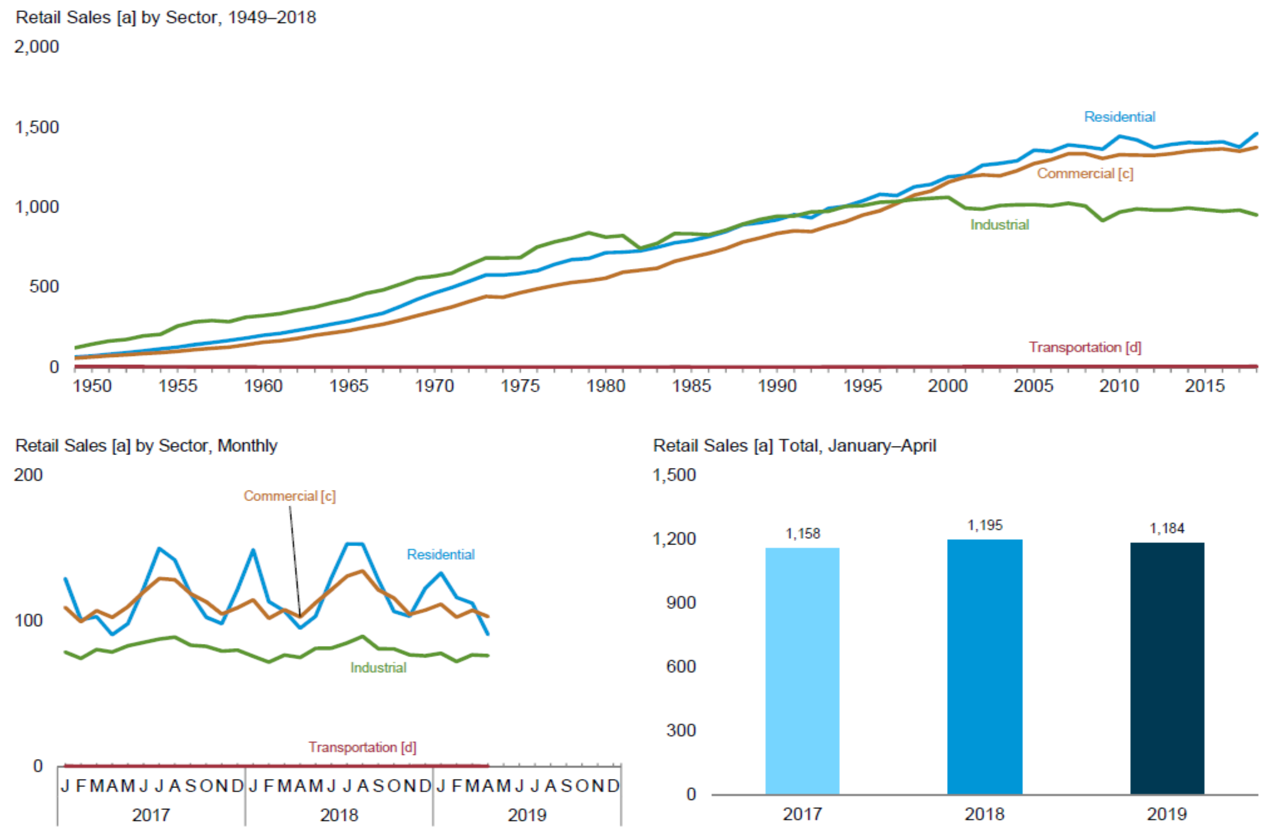
Source: www.eia.gov/electricity/monthly/update/

Wind now surpasses nuclear and hydro



Source: www.eia.gov/electricity/monthly/update/ (April 2020)

Slowing Electric Load Growth



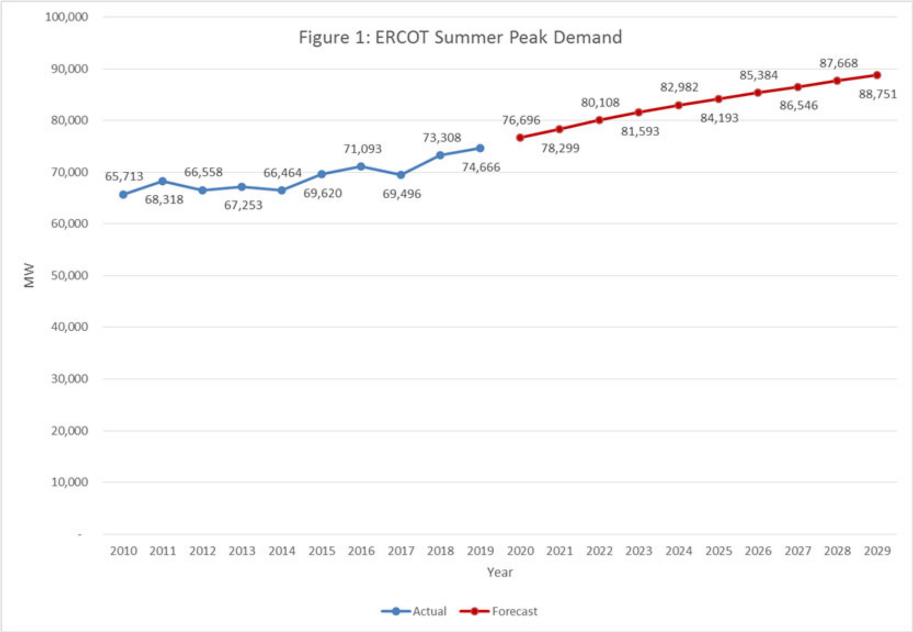
[a] Electricity retail sales to ultimate customers reported by utilities and other energy service providers.
[b] See "Direct Use" in Glossary.
[c] Commercial sector, including public street and highway lighting, interdepartmental sales, and other sales to public authorities.
[d] Transportation sector, including sales to railroads and railways.
Web Page: http://www.eia.gov/totalenergy/data/monthly/#electricity.
Source: Table 7.6.

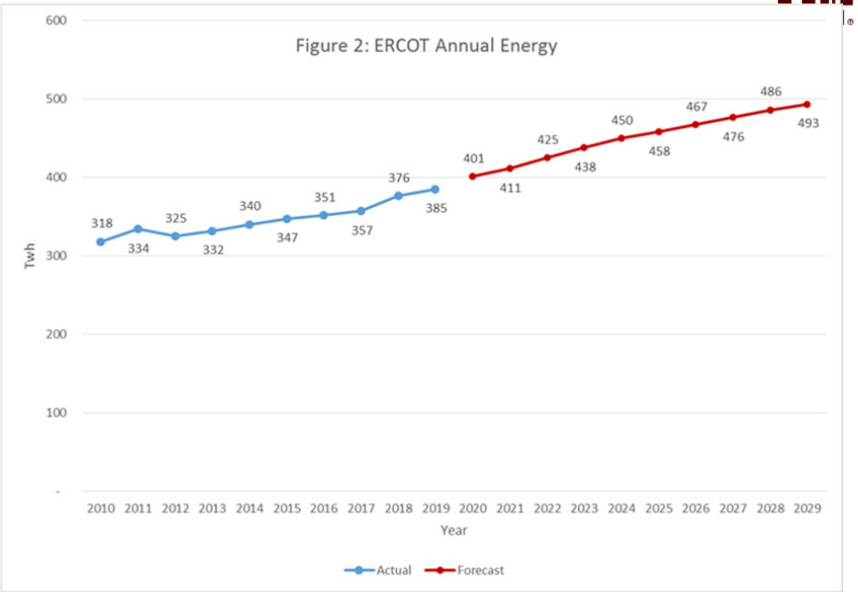
138 U. S. Energy Information Administration / Monthly Energy Review July 2019

Much of the slowing load growth is due to distributed generation, such as solar PV, which sits on the customer side of the meter

Source: EIA Monthly Energy Review, July 2019

Except in Texas!





The left graph is peak demand, the right energy

ERCOT set a new peak electric load of 74.5 GW on 8/12/19, surpassing the 73.3 GW record from 2018; total energy in 2017 was 357 billion kWh

Source: www.ercot.com/gridinfo/load/forecast

Interconnected Power System Basic Characteristics

- Three – phase AC systems:
  - generation and transmission equipment is usually three phase
  - industrial loads are three phase
  - residential and commercial loads are single phase and distributed equally among the phases; consequently, a balanced three – phase system results
- Synchronous machines generate electricity
  - Exceptions: some wind is induction generators; solar PV
- Interconnection transmits power over a wider region with subsystems operating at different voltage levels