ECEN 460
Power System Operation and Control
Spring 2025

Lecture 2: Electric Grid History, Review of Phasors, Complex Power, Three-Phase

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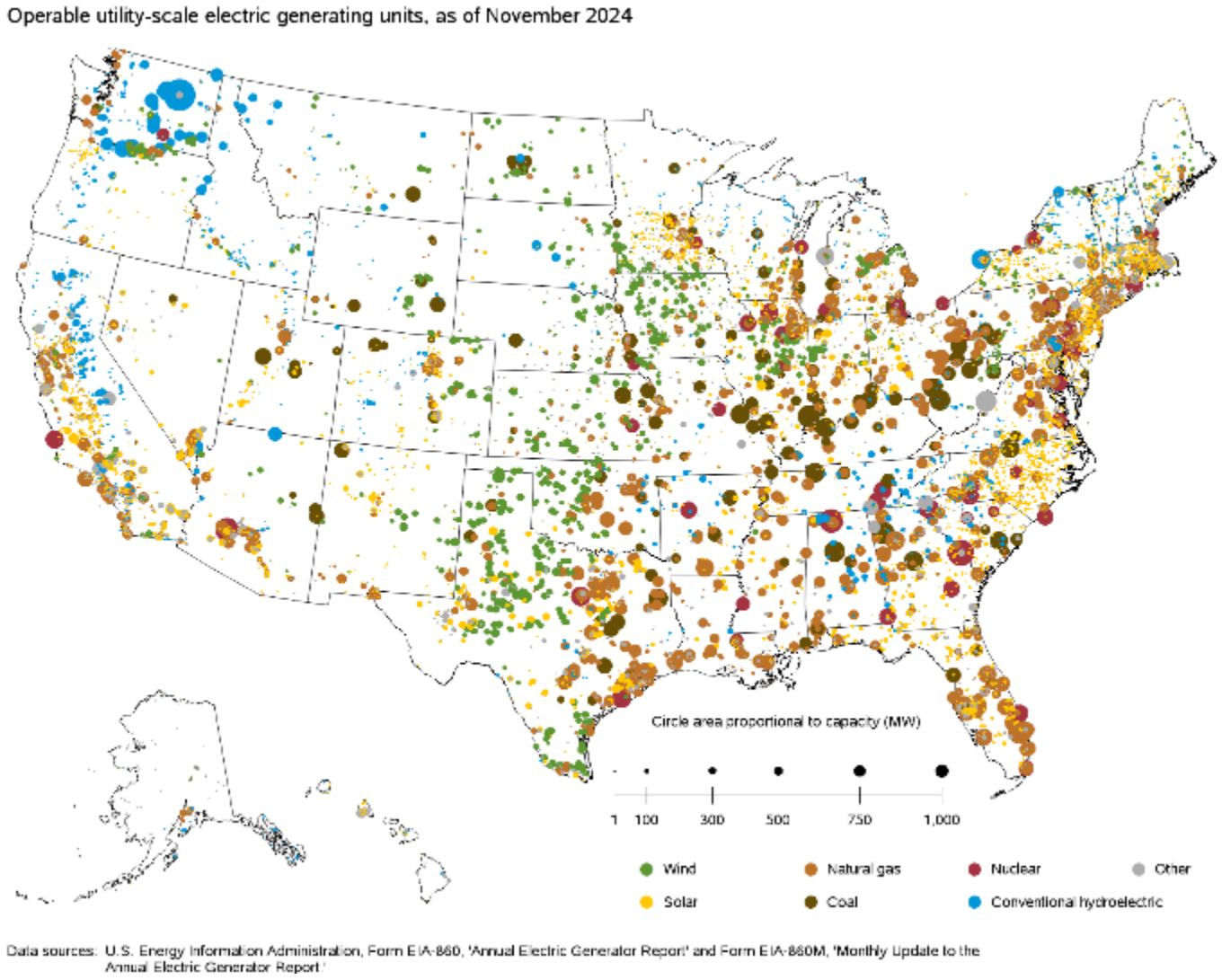
TEXAS A&M UNIVERSITY

US Generation (November 2024) by Fuel Type

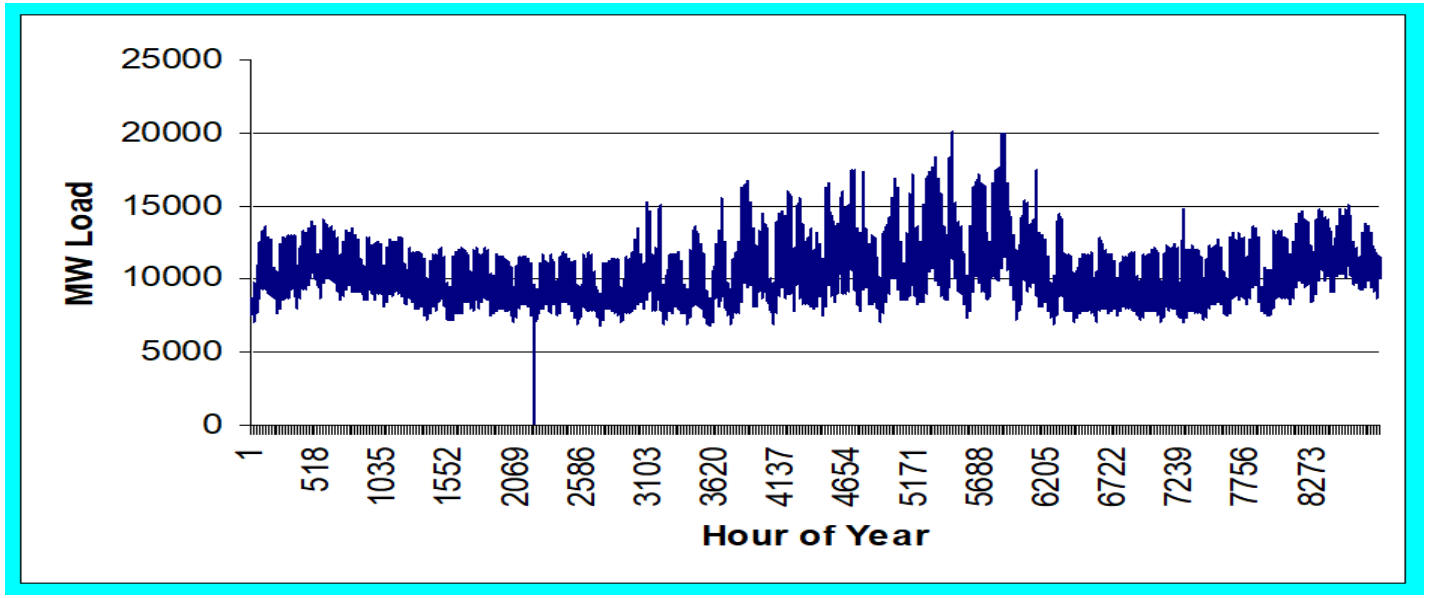


The sources variety substantially by state

Image Source: www.eia.gov/electricity/data/eia860m/

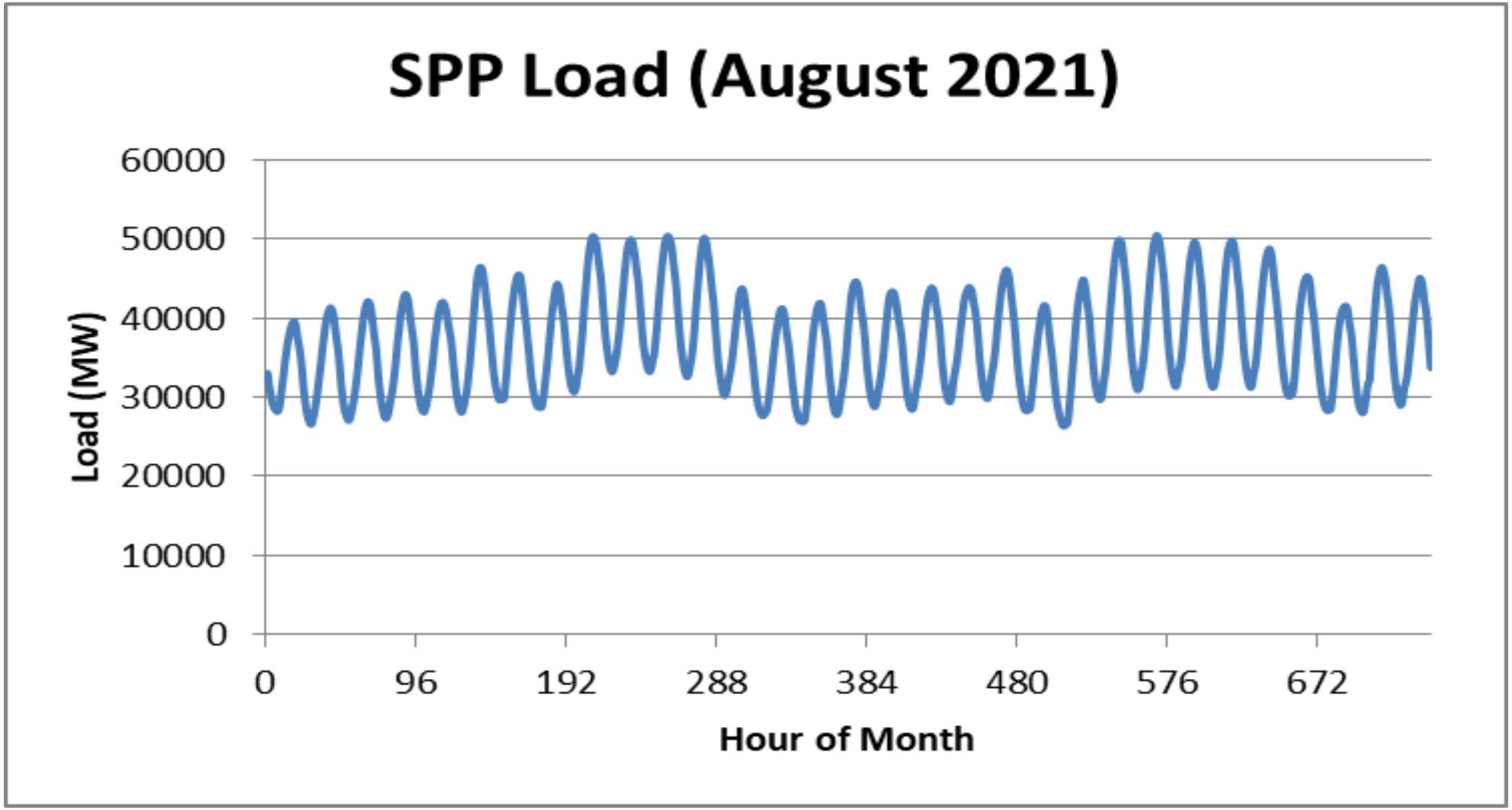
Loads

- 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: Southwest Power Pool Monthly Load

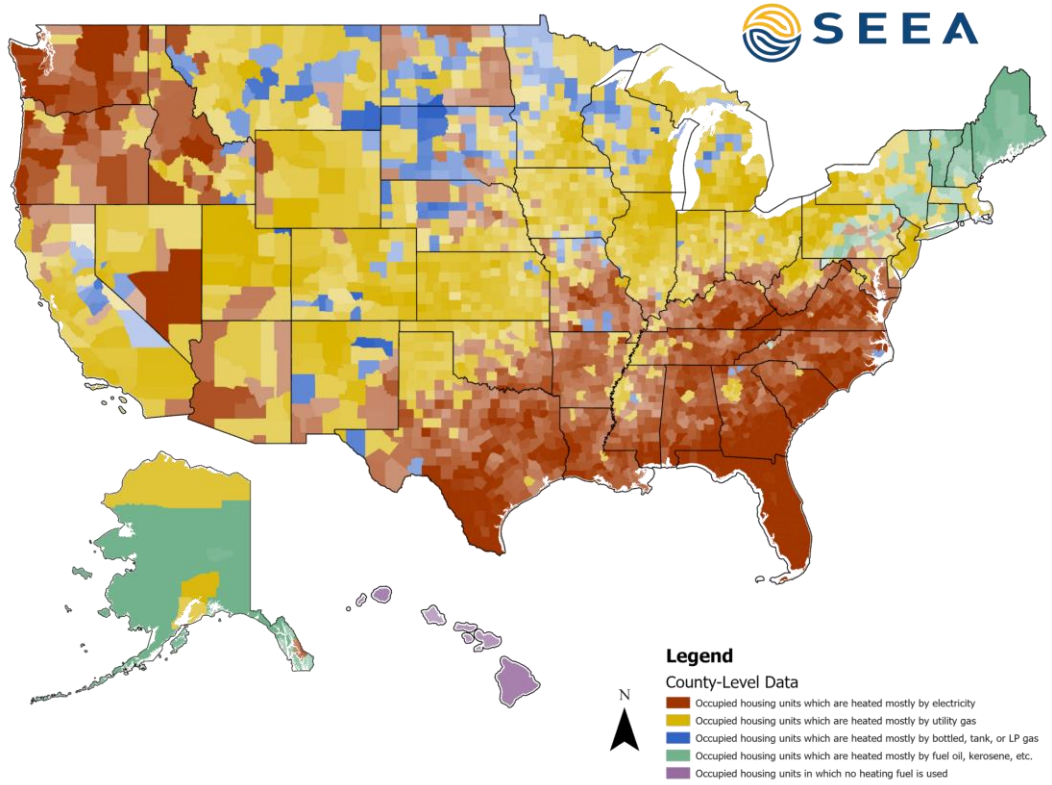


SPP Load Data Source: marketplace.spp.org

ERCOT Loads

- Public information about the ERCOT grid is available at www.ercot.com/gridmktinfo/dashboards
  - This includes the current load and the 6-day forecast for loads
- The ERCOT load tends to be highest in the summer due to air conditioner use; however, it can be high in the winter also when it is cold because of the large amount of electric heating in Texas (and the rest of the south)

Major fuels for heating in the US



https://www.seealliance.org/map-of-the-month-february/

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.

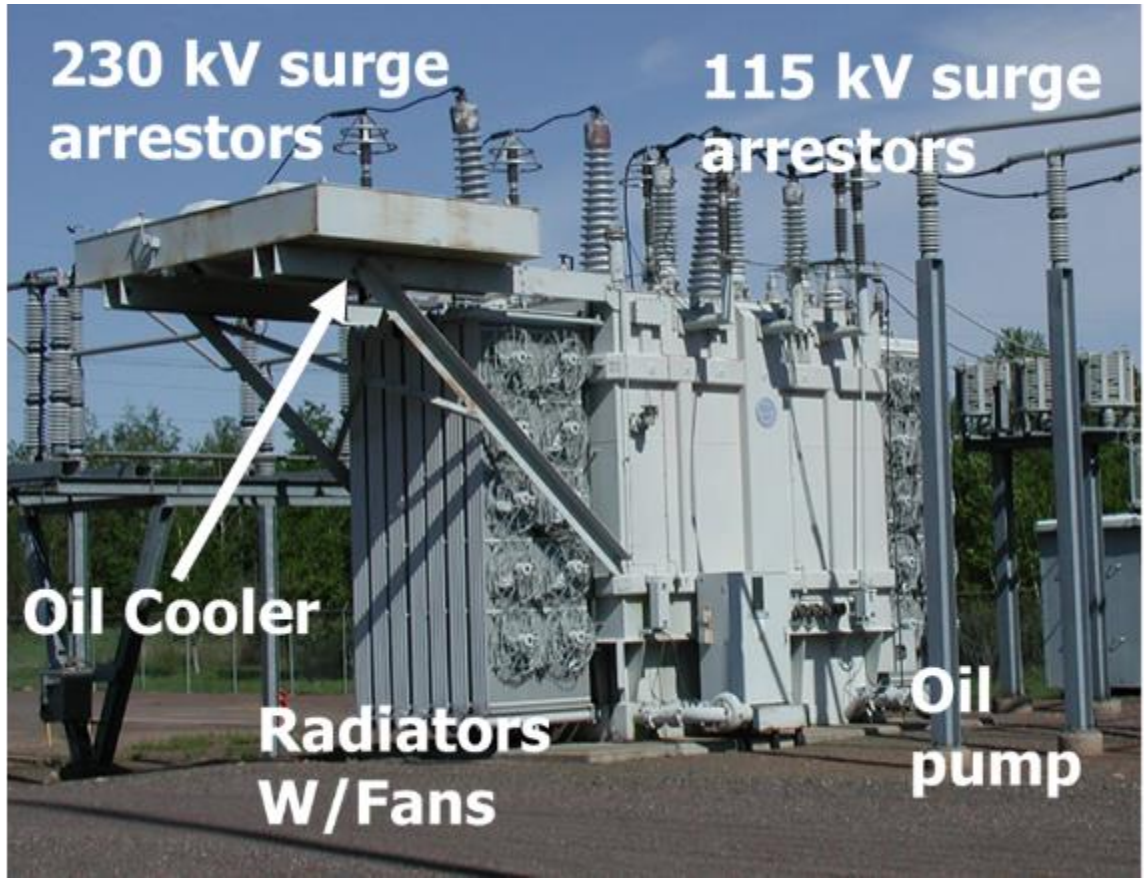
Transmission & Distribution

- 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

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

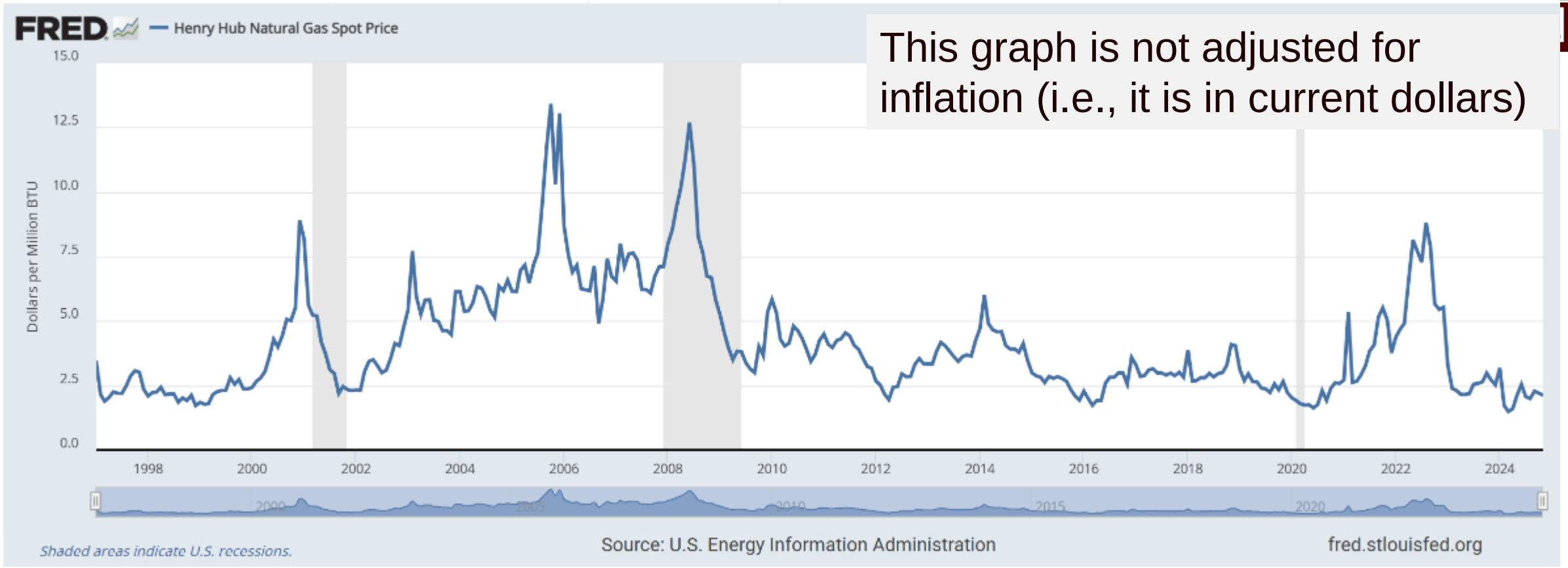


Components Join Together at a Bus

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 the ultimate cost of electricity

Natural Gas Prices 1997 to 2024



This graph is not adjusted for inflation (i.e., it is in current dollars)

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: fred.stlouisfed.org/series/MHHNGSP

US Natural Gas Prices Adjusted for Inflation

Image source: www.macrotrends.net/2478/natural-gas-prices-historical-chart

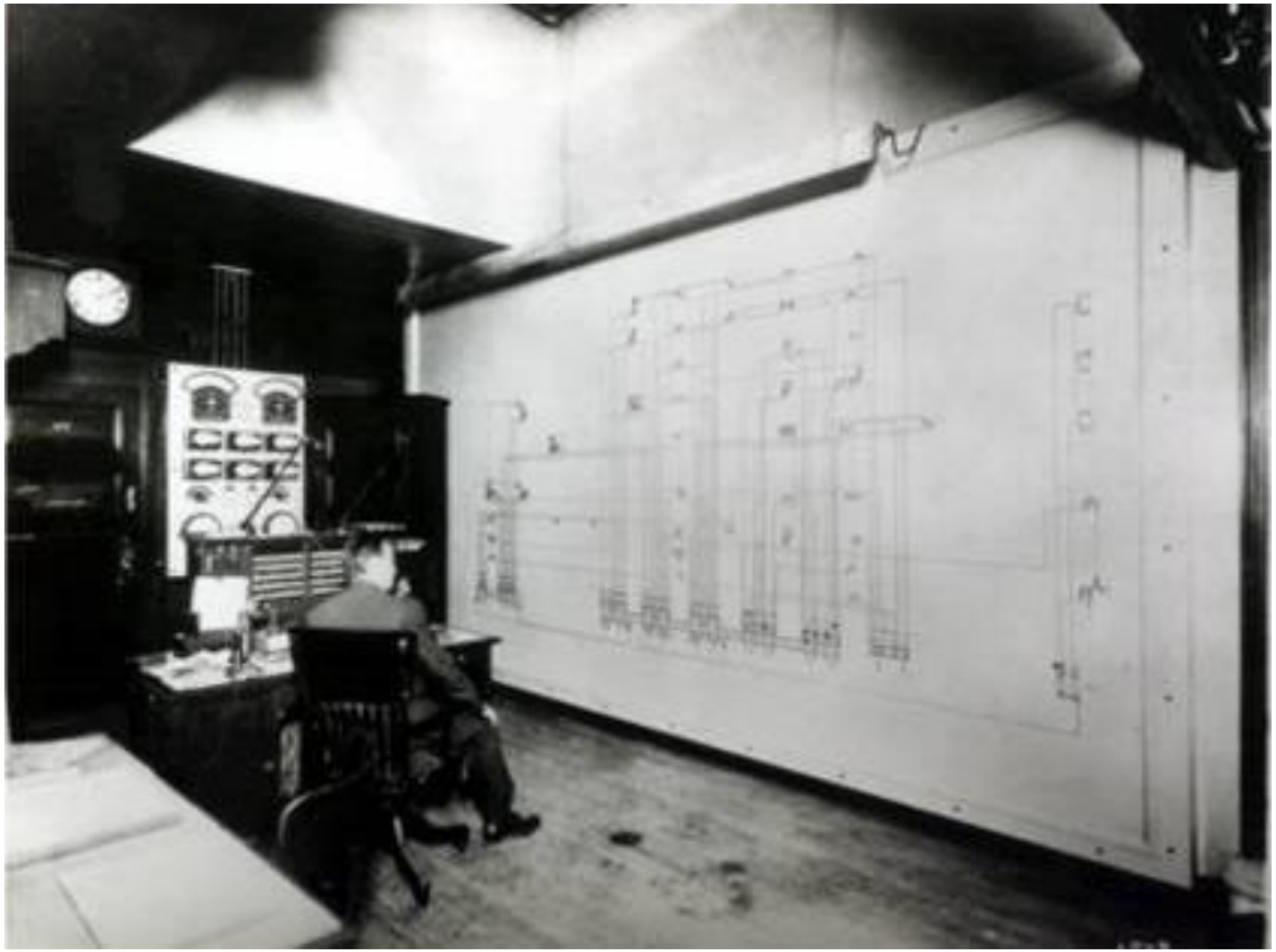
Brief History of Electric Power

- 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

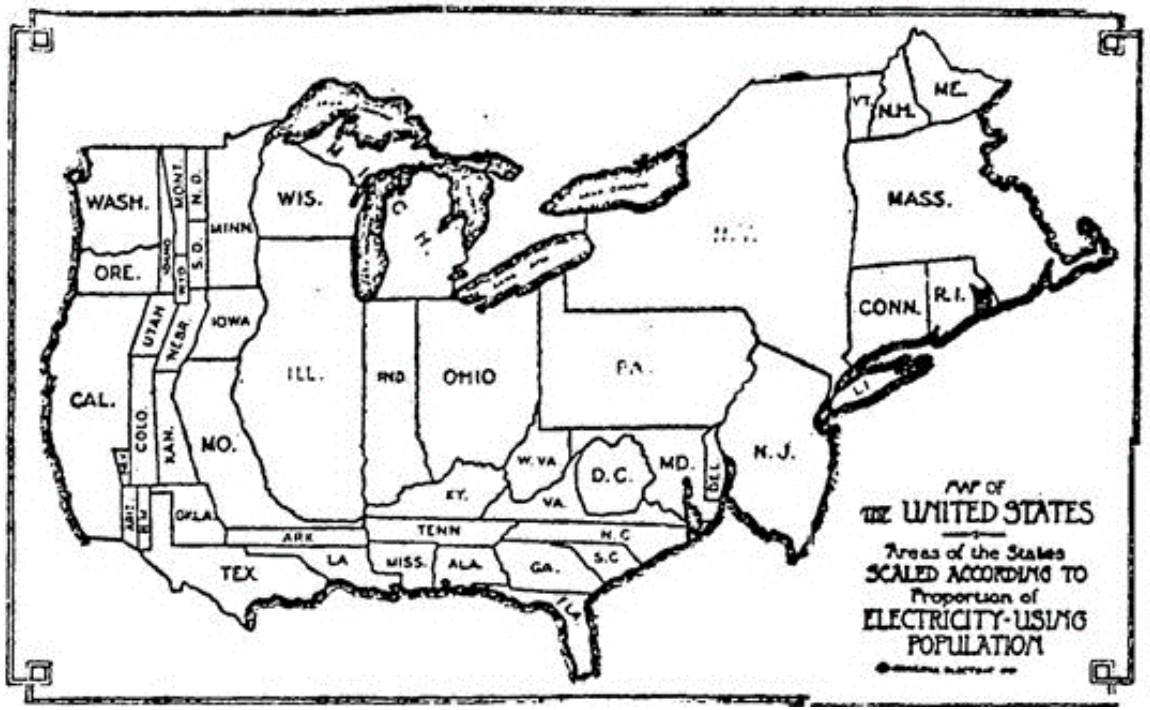
- 1896 – ac lines deliver electricity from hydro generation at Niagara Falls to Buffalo, 20 miles away; also 30kV line in Germany
- Early 1900's – Private utilities supply all customers in area (city); recognized as a natural monopoly; states step in to begin regulation
- 1918: Charles Fortescue, "Method of Symmetrical Coordinates applied to the Solution of Polyphase Networks,"
- By 1920's – Large interstate holding companies control most electricity systems
- 1930's – Electric utilities established as vertical monopolies

ComEd Control Center: Circa 1920



History, cont'd

- Map of which states had the most electric generation in 1921



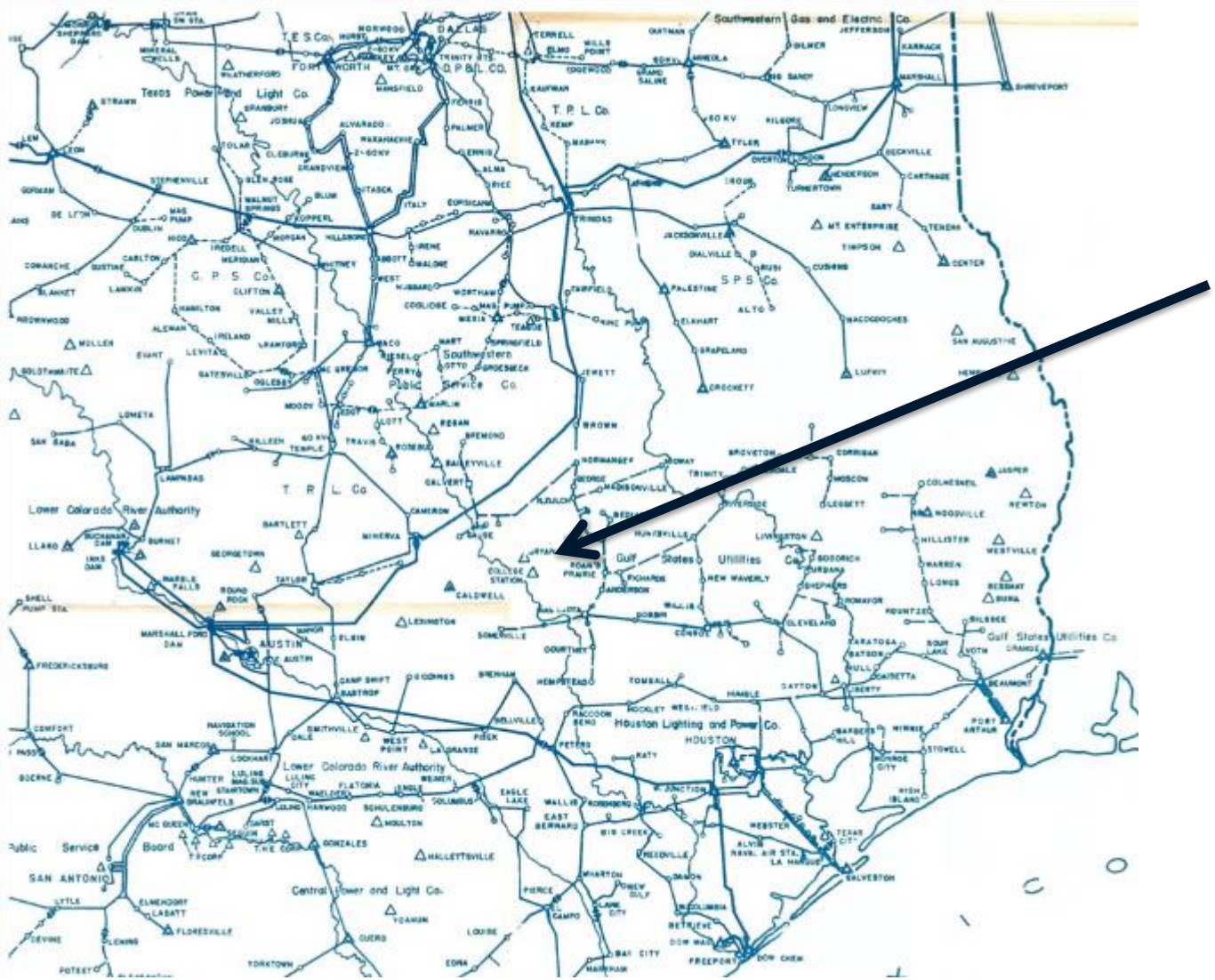
The invention of self-starting synchronous machines in 1916 led to motorized clocks, which led to time error correction

- 1927: PJM formed with three utilities
- 1933: Tennessee Valley Authority

History, cont'd

- Frequency standardized in the 1930's
- Short circuit analysis done using a dc calculating power (since 1920's); power flows determined using network analyzers
  - In mid 1950's there were 50 network analyzer installations in North America
- Transmission voltages up to 345 kV by 1949
- During 1940's to 1960's utilities gradually interconnected their systems so by 1970 transmission lines crisscrossed North America, with voltages up to 765 kV

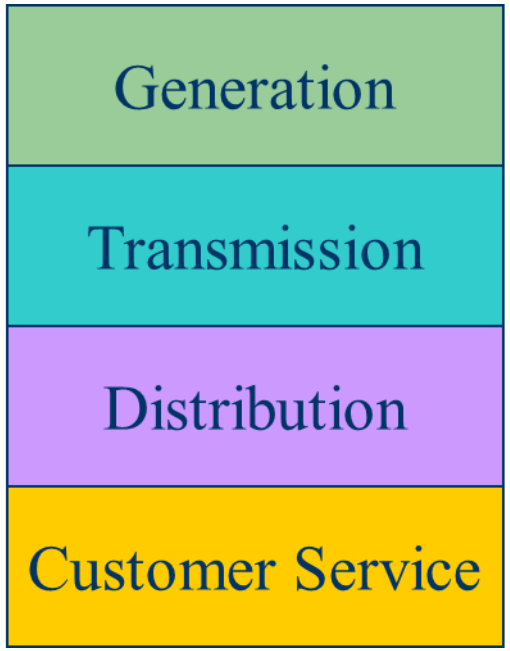
Southeast Texas Grid, 1943



Bryan and College Station evidently had no lines at or above 22 kV!

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

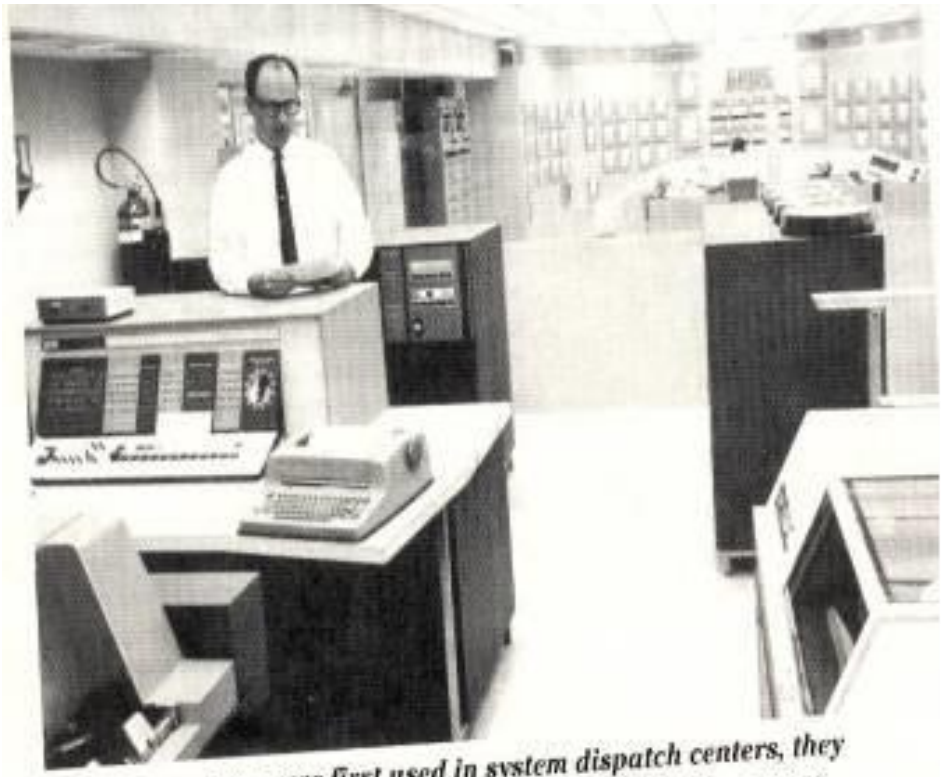


In return for this exclusive franchise, the utility had the obligation to serve all existing and future customers at rates determined jointly by utility and regulators.

History, cont'd

- 1956: James Ward and Harry Hale, "Digital Computer Solution of Power Flow Problems"
  - Power flow and load flow have been used interchangeably since at least the 1950's ; 1960's: Sparsity develops, power flow by Newton's method
- Northeast blackout of 1965 affects over 30 million people
- 1969: First 765 kV transmission in US
- 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)

Utility Control Centers: Early 1960's and 1988



When computers were first used in system dispatch centers, they augmented the traditional analog systems. These systems were referred to as digital-directed analog control computers. As the digital computer became more reliable, it assumed full control.

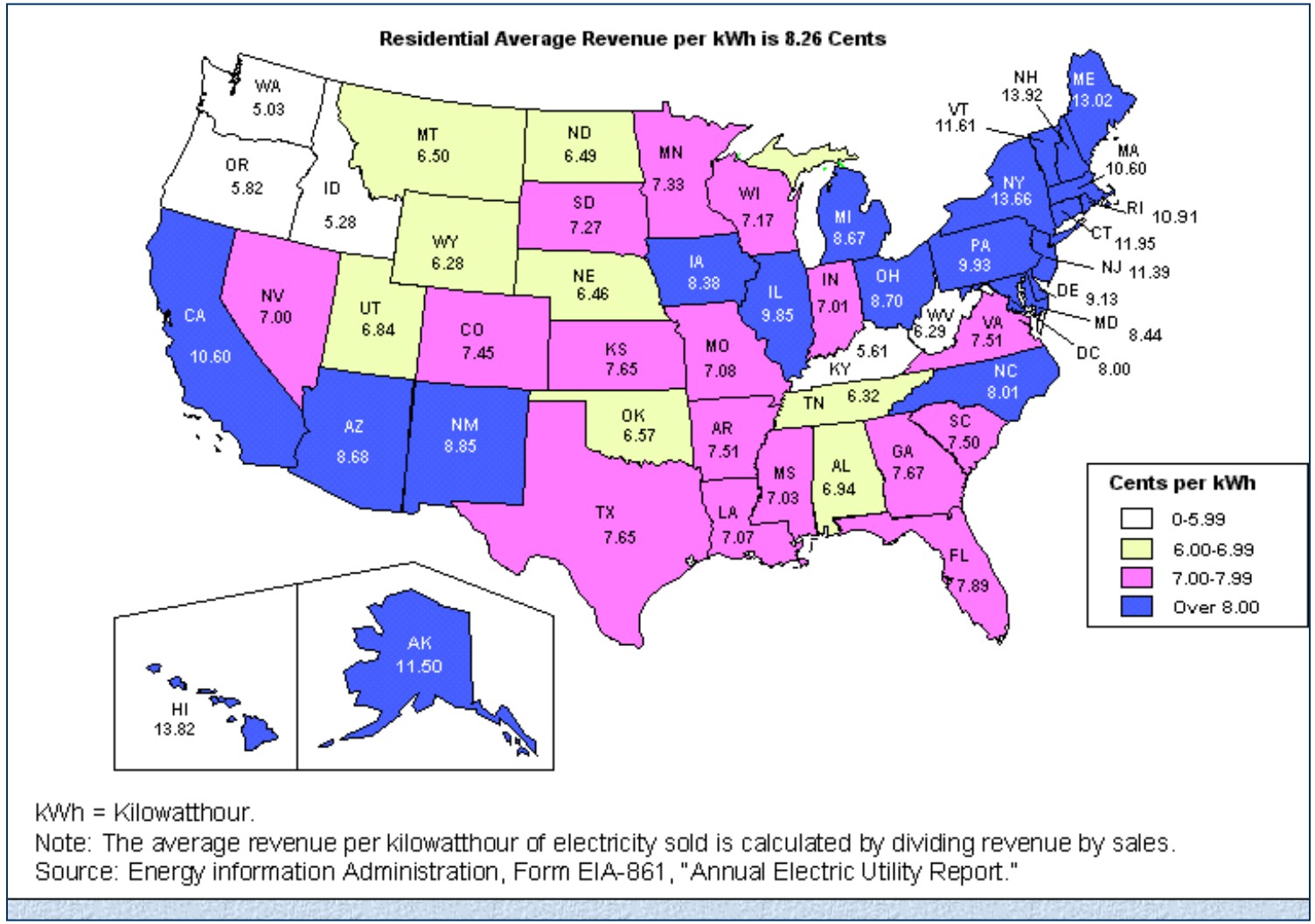
Left Image Source: G.W. Stagg, M. Adibi, M. Laughton, J.E. Van Ness, A.J. Wood, "Thirty Years of Power Industry Computer Applications," *IEEE Computer Applications in Power*, April 1994, pp. 43-49

Right Image Source: J.N. Wrubel, R. Hoffman, "The New Energy Management System at PSE&G," *IEEE Computer Applications in Power*, July 1988, pp. 12-15

History, cont'd

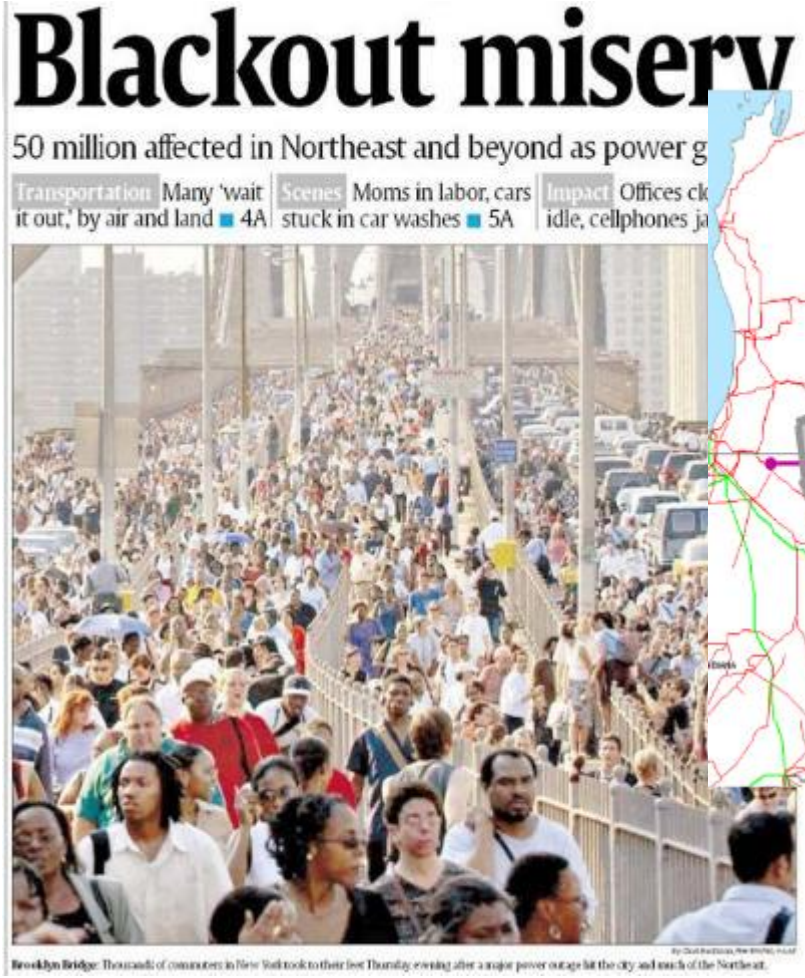
- Major opening of industry to competition occurred as a result of National Energy Policy Act of 1992
- This act mandated that utilities provide "nondiscriminatory" access to the high voltage transmission
- Goal was to set up true competition in generation
- Result over the last few years has been a dramatic restructuring of electric utility industry (for better or worse!)
- Energy Bill 2005 repealed PUHCA; modified PURPA
- Electric grid restructuring took place in the 1990's into the 2000's
  - Goal has been to reduce rates through the introduction of competition and consumer choice

Historical 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."

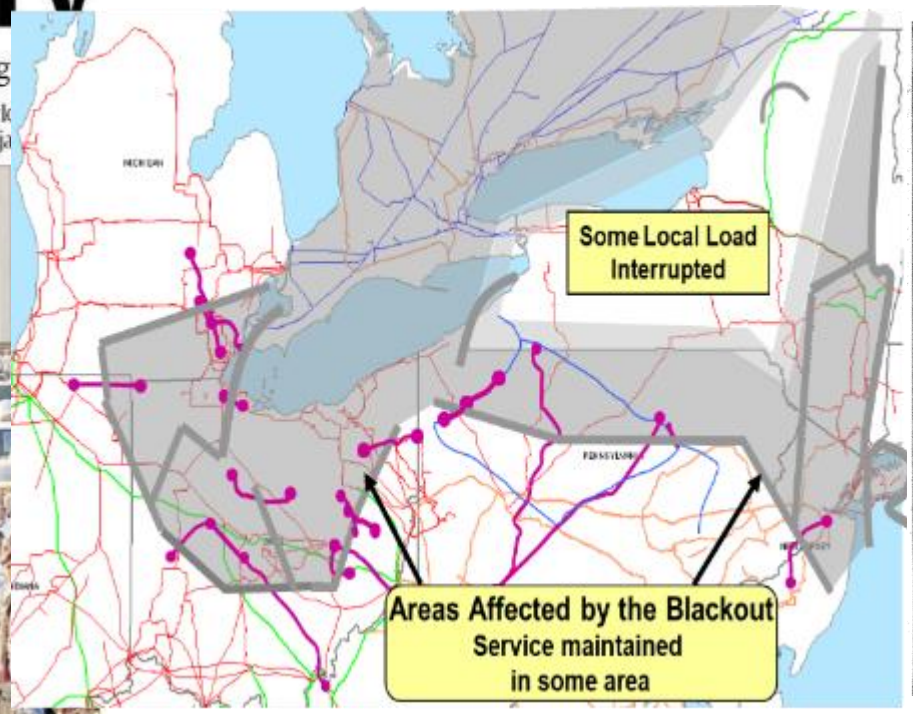
August 14th, 2003 Blackout

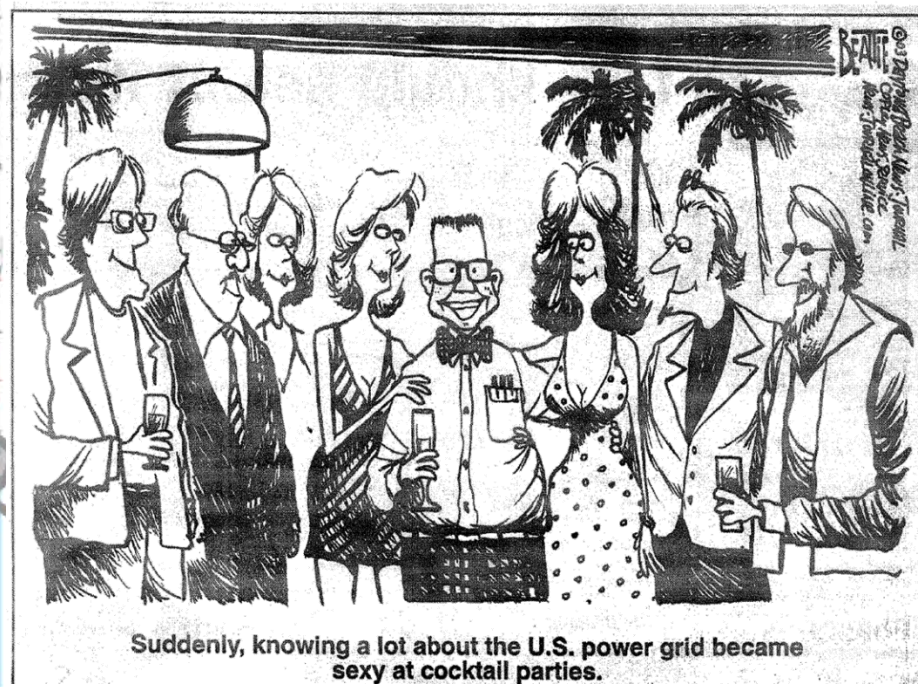

Blackout misery

50 million affected in Northeast and beyond as power g

Transportation Many 'wait it out,' by air and land ■ 4A | Scenes Moms in labor, cars stuck in car washes ■ 5A | Impact Offices cl idle, cellphones ja

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.





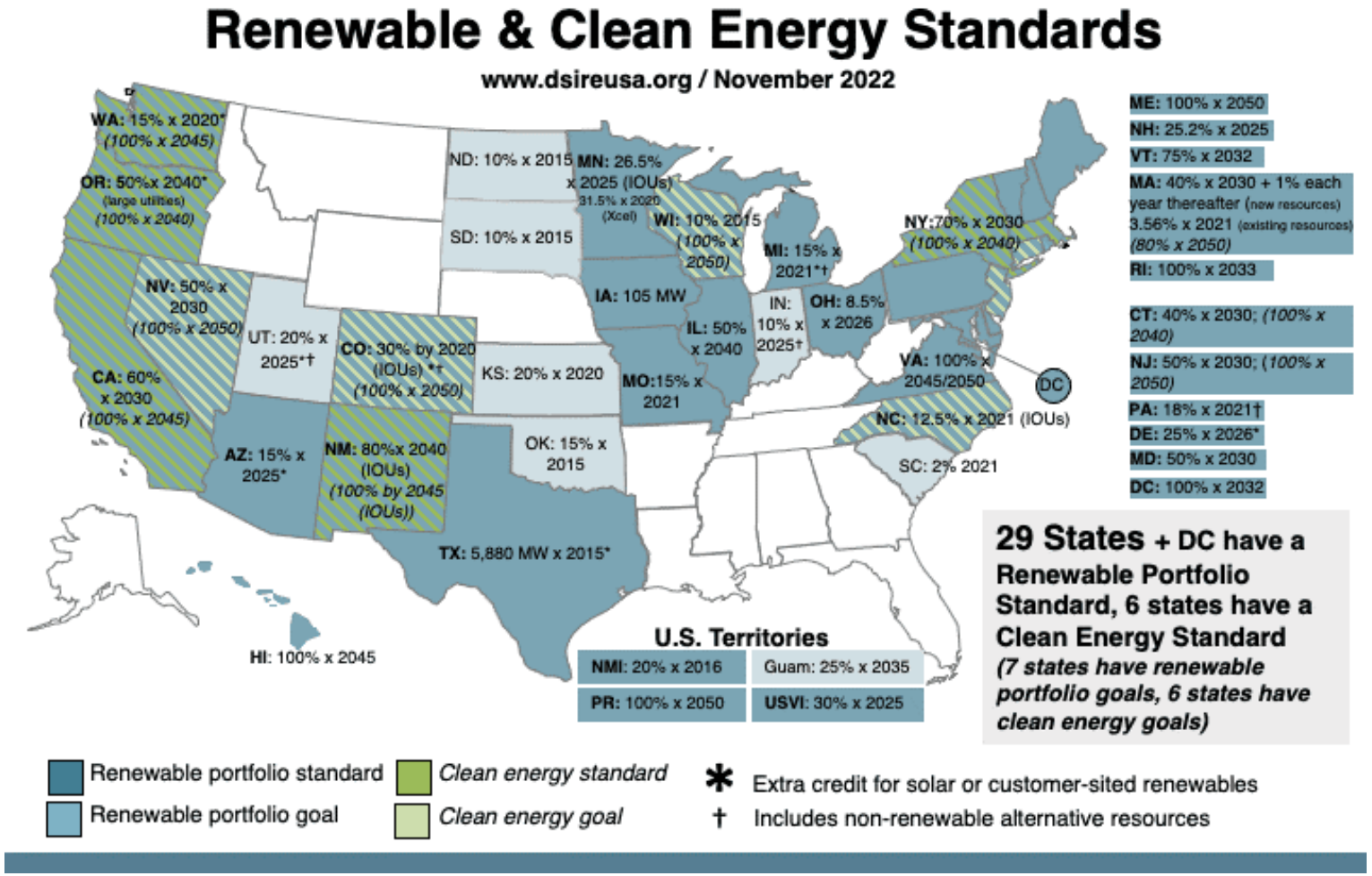
Above image from energy.gov, August 14, 2003 Blackout Final Report

I will talk about this event and the 2021 Texas one later in the course

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

Renewable Portfolio Standards (November 2022)



TX is now 10 GW by 2025 which we've met a number of times over

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

In the News! ERCOT Issues Regional Transmission Plan

- In December 2024 ERCOT issued their regional transmission plan, looking at electric grid needs in Texas from 2026 to 2030
  - It is available at www.ercot.com/mp/data-products/data-product-details?id=pg7-048-m
- ERCOT is experiencing unprecedented growth in its electric load, with projects now showing a potential load in 2030 of 150 GW, up from the maximum load of 85 GW experienced in summer 2023
- This will require the construction of large amounts of new transmission, including the potential to add a new 765 kV backbone to their grid
- Note that on page 4 the software they used to do much of this analysis is the same tool that we'll be using here in 460, including in the labs

A Few ERCOT Plan Figures

For reference, Centerpoint's max electric load is about 20 GW

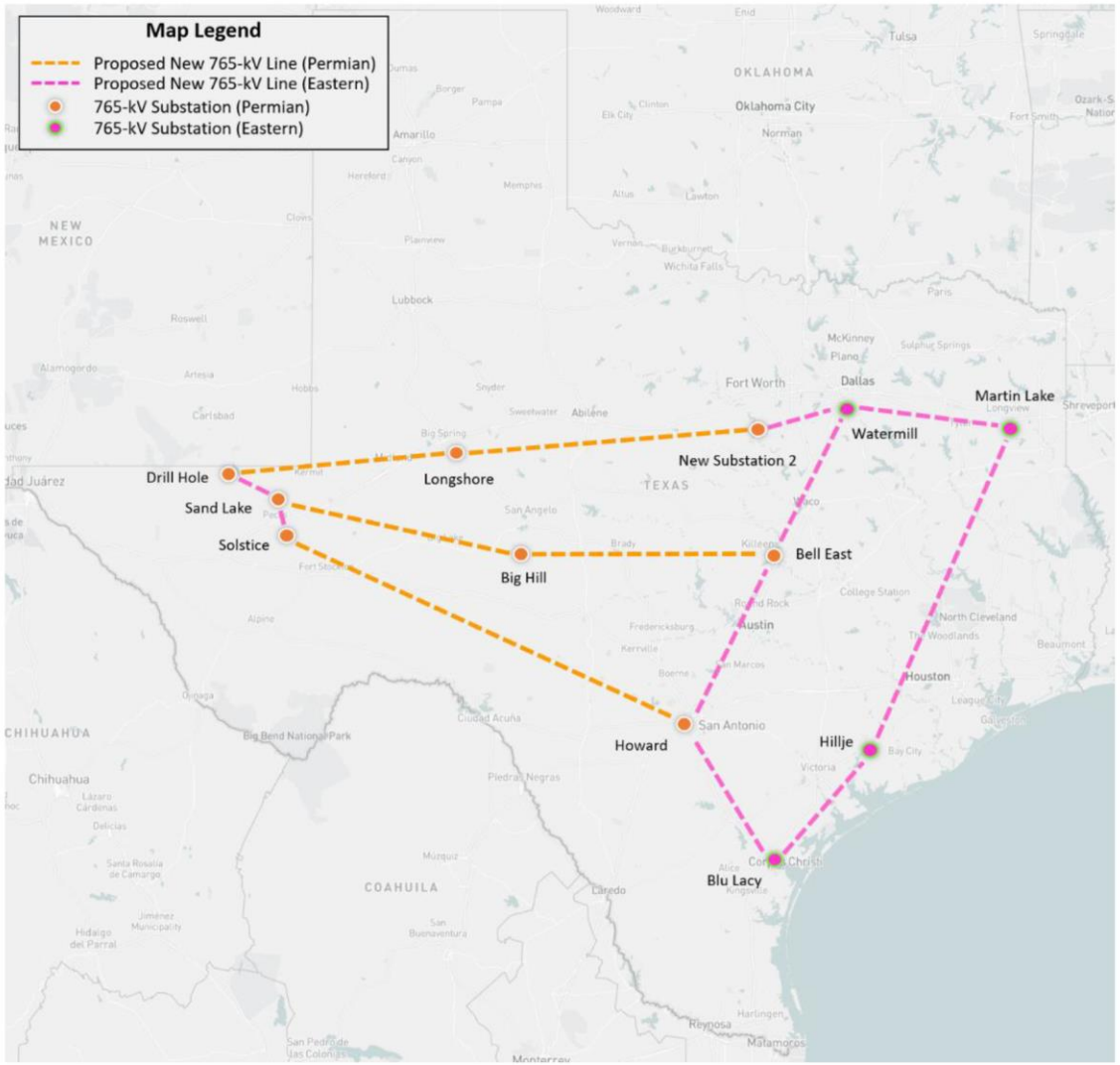


Figure 18: The 765-kV Core Plan needed in 2030

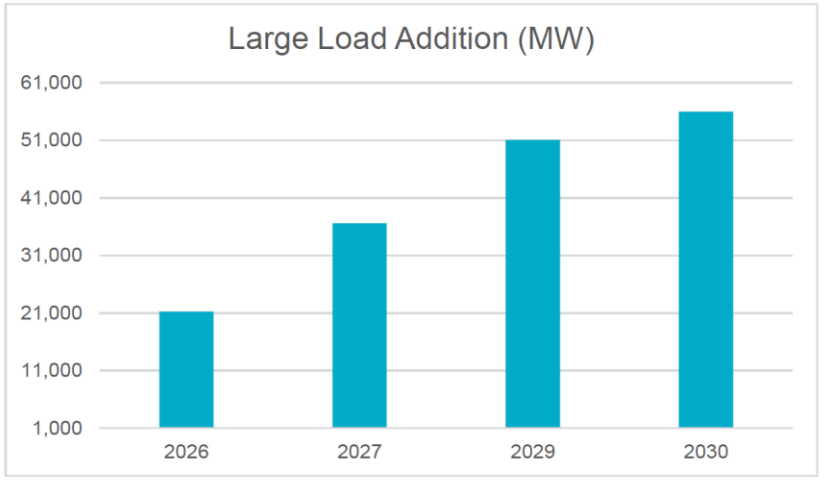


Figure 3: Large Load Addition in 2024 RTP (MW)

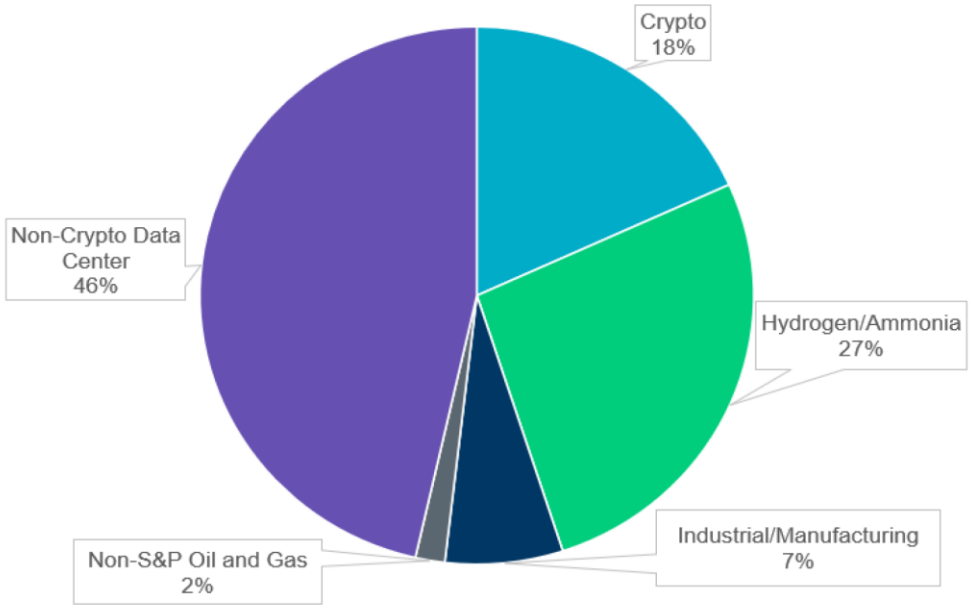


Figure 4: Types of Large Loads in 2024 RTP

Simple Power System and Complications

- Every power system has three major components
  - generation: source of power, ideally with a specified voltage and frequency
  - load: consumes power; ideally with a constant resistive value
  - transmission system: transmits power; ideally as a perfect conductor

Complications

- No ideal voltage sources exist
- Loads are seldom constant
- Transmission system has resistance, inductance, capacitance and flow limitations
- Simple system has no redundancy so power system will not work if any component fails

Notation - Power

- Power: Instantaneous consumption of energy
- Power Units
  - Watts = voltage x current for dc (W)
  - kW – 1×10^3 Watt
  - MW – 1×10^6 Watt
  - GW – 1×10^9 Watt
- Installed U.S. generation capacity is about 1300 GW (about 3 kW per person)

Estimated Maximum Loads for ERCOT Entities

Transmission Operator	Summer Load (% MW)	Estimated Total MW
AEP Texas Central Company	8.22	7028
Brazos Electric Power Cooperative Inc.	5.20	4446
Brownsville Public Utilities Board	0.34	291
Bryan Texas Utilities	0.53	453
CenterPoint Energy Houston Electric LLC	24.78	21187
City of Austin dba Austin Energy	3.50	2993
City of College Station	0.28	239
City of Garland	0.74	633
City of Lubbock, acting through Lubbock Power	0.56	479
CPS Energy	6.59	5634
Denton Municipal Electric	0.47	402
GEUS	0.15	128
Golden Spread Electric Cooperative	0.41	351
Lamar County Electric Cooperative Inc. dba LEC	0.07	60
LCRA Transmission Services Corporation	3.73	3189
Oncor Electric Delivery Company LLC	35.63	30464
Pedernales Electric Cooperative Inc.	2.37	2026
Rayburn Country Cooperative Inc.	1.52	1300
South Texas Electric Cooperative Inc.	2.19	1872
Texas-New Mexico Power Company	2.72	2326

Source: www.ercot.com/gridinfo/load

Notation - Energy

- Energy: Integration of power over time; energy is what people really want from a power system
- Energy Units
  - Joule = 1 Watt-second (J)
  - kWh = Kilowatthour (3.6 x 10^6 J)
  - Btu = 1055 J; 1 MBtu=0.292 MWh
  - One gallon of gas has about 0.125 MBtu (36.5 kWh);
- U.S. electric energy consumption is about 3600 billion kWh (about 13,333 kWh per person, which means on average we each use 1.5 kW of power continuously)

Review of Phasors

$$v(t) = V_{max}\cos(\omega t + \theta_v)$$
$$i(t) = I_{max}\cos(\omega t + \theta_I)$$

Root Mean Square (RMS) voltage of sinusoid

$$\sqrt{\frac{1}{T}\int_0^T v(t)^2 dt} = \frac{V_{max}}{\sqrt{2}}$$

Euler's Identity: $e^{j\theta} = \cos\theta + j\sin\theta$

Phasor notation is developed by rewriting using Euler's identity

$$v(t) = \sqrt{2}\,|V|\cos(\omega t + \theta_V)$$
$$v(t) = \sqrt{2}\,|V|\,\mathrm{Re}\left[e^{j(\omega t + \theta_V)}\right]$$

(Note: $|V|$ is the RMS voltage)

Phasor Representation, cont'd

The RMS, cosine-referenced voltage phasor is:

$$
\begin{aligned}
V &= |V|e^{j\theta_V} = |V|\angle\theta_V \\
v(t) &= \mathrm{Re}\sqrt{2}\,Ve^{j\omega t}e^{j\theta_V} \\
V &= |V|\cos\theta_V + j|V|\sin\theta_V \\
I &= |I|\cos\theta_I + j|I|\sin\theta_I
\end{aligned}
$$

(Note: Some texts use "boldface" type for complex numbers, or "bars on the top")

Advantages of Phasor Analysis

Device	Time Analysis	Phasor
Resistor	$v(t) = Ri(t)$	$V = RI$
Inductor	$v(t) = L\frac{di(t)}{dt}$	$V = j\omega LI$
Capacitor	$\frac{1}{C}\int_0^t i(t)dt + v(0)$	$V = \frac{1}{j\omega C} I$

Z = Impedance $= R + jX = |Z|\angle\phi$

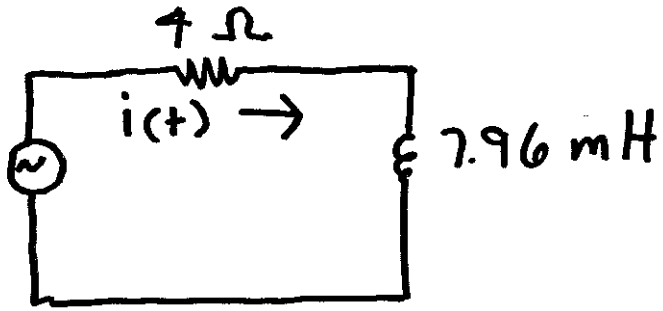
R = Resistance

X = Reactance

$|Z| = \sqrt{R^2 + X^2}$ $\quad \phi = \arctan(\frac{X}{R})$

(Note: Z is a complex number but not a phasor)

RL Circuit Example



$$V(t) = \sqrt{2}\,100\cos(\omega t + 30°)$$

$$f = 60\text{Hz}$$

$$\text{R} = 4\Omega \qquad X = \omega L = 3$$

$$|Z| = \sqrt{4^2 + 3^2} = 5 \quad \phi = 36.9°$$

$$I = \frac{V}{Z} = \frac{100\angle 30°}{5\angle 36.9°}$$

$$= 20\angle -6.9° \text{ Amps}$$

$$\text{i(t)} = 20\sqrt{2}\cos(\omega t - 6.9°)$$

Complex Power

Power

$$p(t) = v(t)\, i(t)$$

$$\mathrm{v(t)} = V_{\max}\cos(\omega t + \theta_V)$$

$$i(\mathrm{t}) = I_{\max}\cos(\omega t + \theta_I)$$

$$\cos\alpha\cos\beta = \frac{1}{2}[\cos(\alpha-\beta)+\cos(\alpha+\beta)]$$

$$p(t) = \frac{1}{2}V_{\max}I_{\max}[\cos(\theta_V-\theta_I)+ \cos(2\omega t+\theta_V+\theta_I)]$$

Complex Power, cont'd

Average Power

$$p(t) = \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)]$$

$$P_{avg} = \frac{1}{T} \int_0^T p(t) dt$$

$$= \frac{1}{2} V_{\max} I_{\max} \cos(\theta_V - \theta_I)$$

$$= |V||I| \cos(\theta_V - \theta_I)$$

Power Factor Angle = $\phi = \theta_V - \theta_I$

Complex Power

$$S = |V||I|[\cos(\theta_V - \theta_I) + j\sin(\theta_V - \theta_I)]$$

$$= P + jQ$$

$$= V\ I^*$$

(Note: S is a complex number but not a phasor)

P = Real Power (W, kW, MW)

Q = Reactive Power (var, kvar, Mvar)

S = Complex power (VA, kVA, MVA)

Power Factor (pf) = $\cos\phi$

If current leads voltage then pf is leading

If current lags voltage then pf is lagging

Complex Power, cont'd

Relationships between real, reactive and complex power

$$P = |S|\cos\phi$$

$$Q = |S|\sin\phi = \pm|S|\sqrt{1-pf^2}$$

Example: A load draws 100 kW with a leading pf of 0.85.
What are ϕ (power factor angle), Q and $|S|$?

$$\phi = -\cos^{-1}0.85 = -31.8°$$

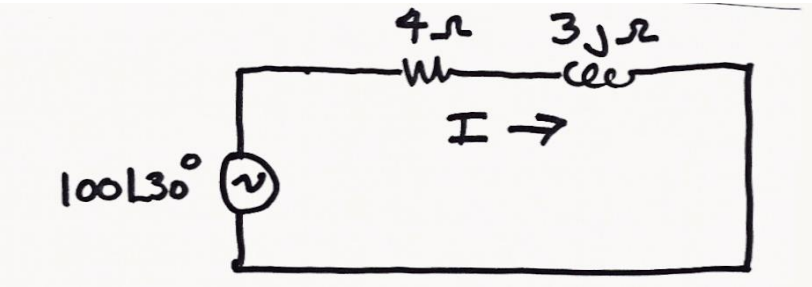
$$|S| = \frac{100kW}{0.85} = 117.6 \text{ kVA}$$

$$Q = 117.6\sin(-31.8°) = -62.0 \text{ kVar}$$

Conservation of Power

- At every node (bus) in the system
  - Sum of real power into node must equal zero
  - Sum of reactive power into node must equal zero
- This is a direct consequence of Kirchhoff's current law, which states that the total current into each node must equal zero.
  - Conservation of power follows since S = VI*

Conversation of Power Example



Earlier we found $I = 20\angle -6.9°$ amps

$$S = V\,I^{*} = 100\angle 30° \times 20\angle 6.9° = 2000\angle 36.9° \ \text{VA}$$

$$\phi = 36.9° \quad \text{pf} = 0.8 \text{ lagging}$$

$$\text{S}_\text{R} = V_R\,I^{*} = 4 \times 20\angle -6.9° \times 20\angle 6.9°$$

$$\text{P}_\text{R} = 1600W = |I|^2 R \quad (\text{Q}_\text{R} = 0)$$

$$\text{S}_\text{L} = V_L\,I^{*} = 3j \times 20\angle -6.9° \times 20\angle 6.9°$$

$$\text{Q}_\text{L} = 1200\,\text{var} = |I|^2 X \quad (\text{P}_\text{L} = 0)$$

Power Consumption in Devices

Resistors only consume real power

$$P_{Resistor} = |I_{Resistor}|^2 R$$

Inductors only consume reactive power

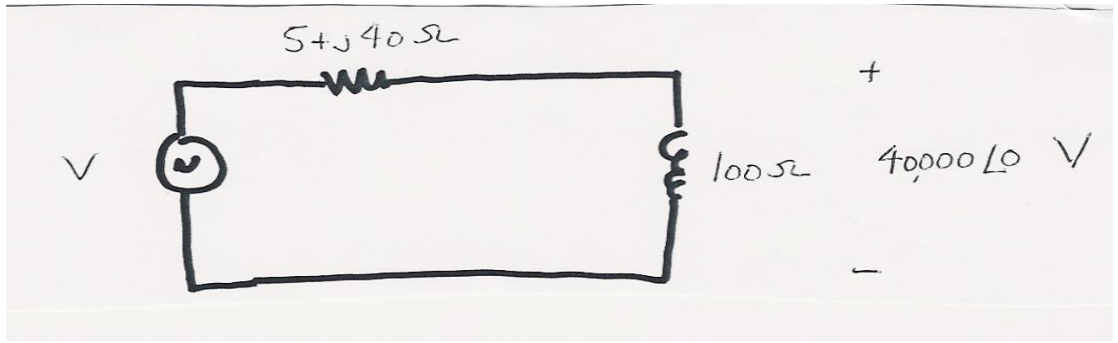
$$Q_{Inductor} = |I_{Inductor}|^2 X_L$$

Capacitors only generate reactive power

$$Q_{Capacitor} = -|I_{Capacitor}|^2 X_C \qquad X_C = \frac{1}{\omega C}$$

$$Q_{Capacitor} = -\frac{|V_{Capacitor}|^2}{X_C}$$ (Note-some define X_C negative)

Example



First solve the basic circuit

$$I = \frac{40000\angle 0^\circ\, V}{100\angle 0^\circ\, \Omega} = 400\angle 0^\circ \text{ Amps}$$

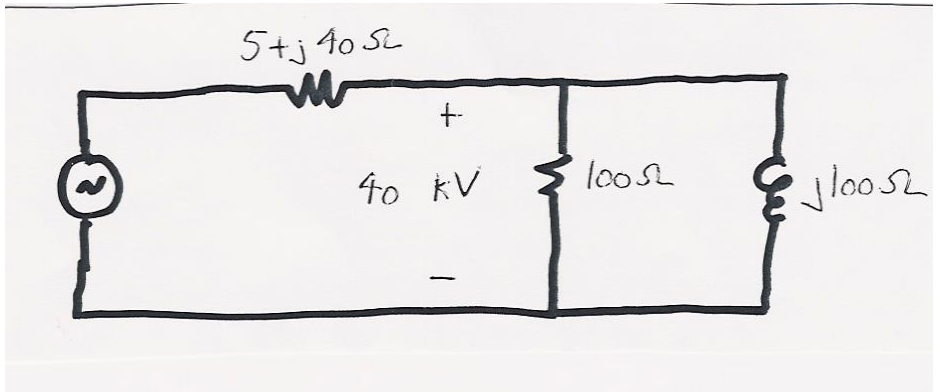
$$V = 40000\angle 0^\circ + (5 + j40)\, 400\angle 0^\circ$$

$$= 42000 + j16000 = 44.9\angle 20.8^\circ \text{ kV}$$

$$\text{S} = VI^* = 44.9\text{k}\angle 20.8^\circ \times 400\angle 0^\circ$$

$$= 17.98\angle 20.8^\circ \text{ MVA} \quad = 16.8 + j6.4 \text{ MVA}$$

Example, cont'd



Now add additional reactive power load and resolve

$$Z_{Load} = 70.7\angle 45° \quad pf = 0.7 \text{ lagging}$$

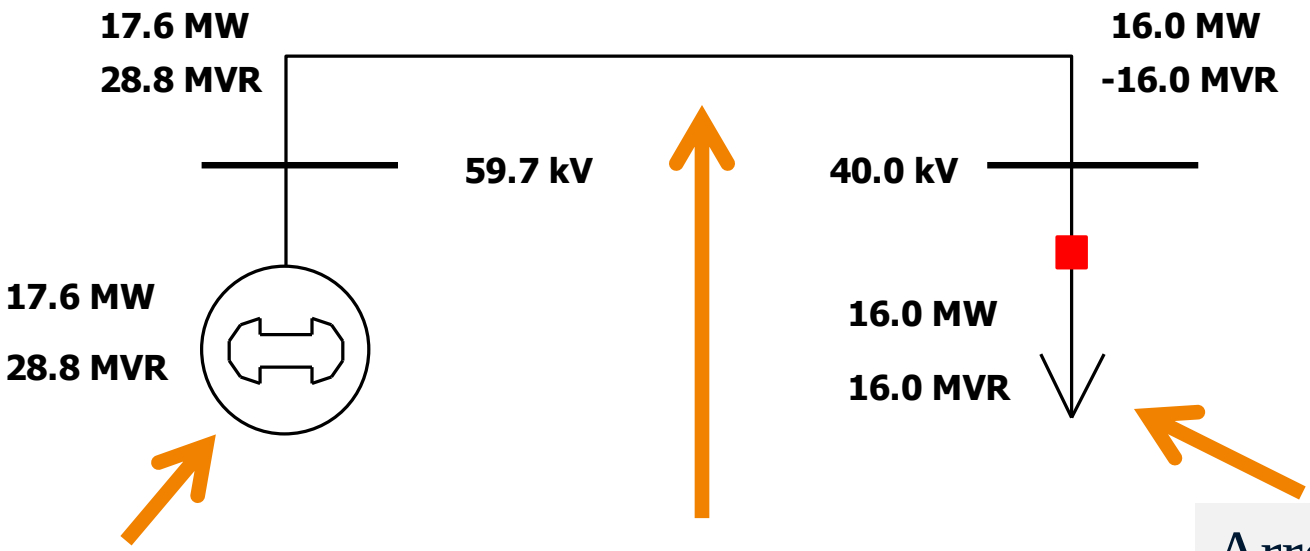
$$I = 564\angle -45° \text{ Amps}$$

$$V = 59.7\angle 13.6° \text{ kV}$$

$$S = 33.7\angle 58.6° \text{ MVA} = 17.6 + j28.8 \text{ MVA}$$

Power System Notation

- Power system components are usually shown as oneline diagrams
  Previous circuit redrawn



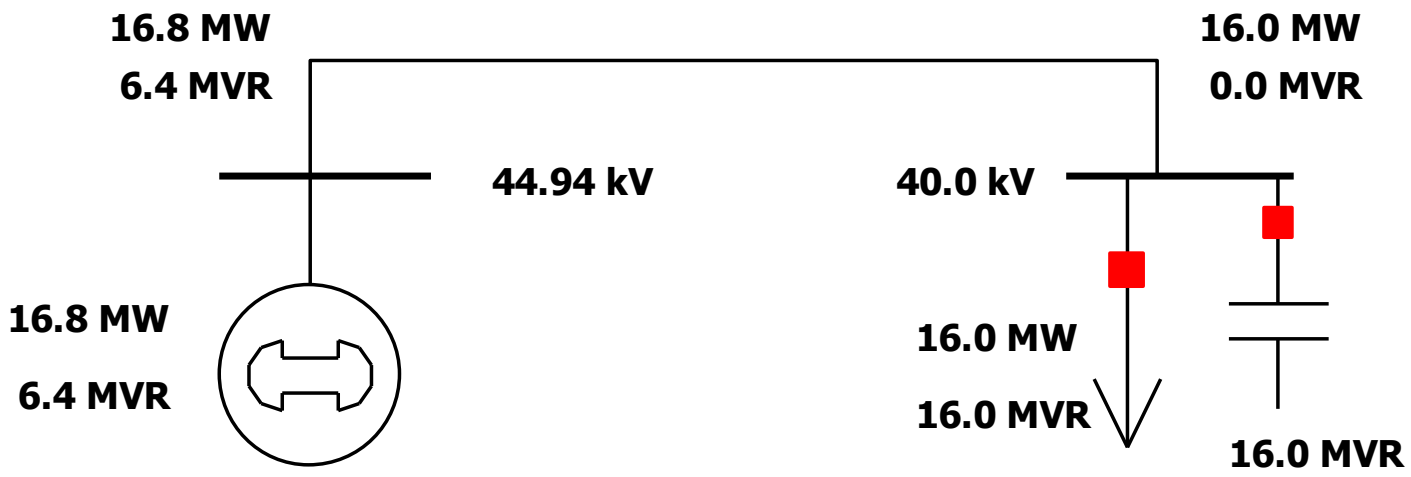
Generators are shown as circles

Transmission lines are shown as a single line

Arrows are used to show loads

Reactive Compensation

- Key idea of reactive compensation is to supply reactive power locally. In the previous example this can be done by adding a 16 Mvar capacitor at the load



Power engineers think of capacitors in terms of how much reactive power they can supply at a specified (rated) voltage; not in terms of Farads

Compensated circuit is identical to first example with just real power load

Reactive Compensation, cont'd

- Reactive compensation decreased the line flow from 564 Amps to 400 Amps. This has advantages
  - Lines losses, which are equal to $I^2 R$ decrease
  - Lower current allows utility to use small wires, or alternatively, supply more load over the same wires
  - Voltage drop on the line is less
- Reactive compensation is used extensively by utilities
- Capacitors can be used to "correct" a load's power factor to an arbitrary value.

Power Factor Correction Example

Assume we have 100 kVA load with pf=0.8 lagging,

and would like to correct the pf to 0.95 lagging

$$S = 80 + j60 \text{ kVA} \qquad \phi = \cos^{-1} 0.8 = 36.9°$$

$$\text{PF of 0.95 requires } \phi_{\text{desired}} = \cos^{-1} 0.95 = 18.2°$$

$$S_{new} = 80 + j(60 - Q_{cap})$$

$$\frac{60 - Q_{cap}}{80} = \tan 18.2° \quad \Rightarrow \quad 60 - Q_{cap} = 26.3 \text{ kvar}$$

$$Q_{cap} = 33.7 \text{ kvar}$$

Distribution System Capacitors