Grid

Outline

- **Grid: Transmission and Distribution**
- **ERCOT**

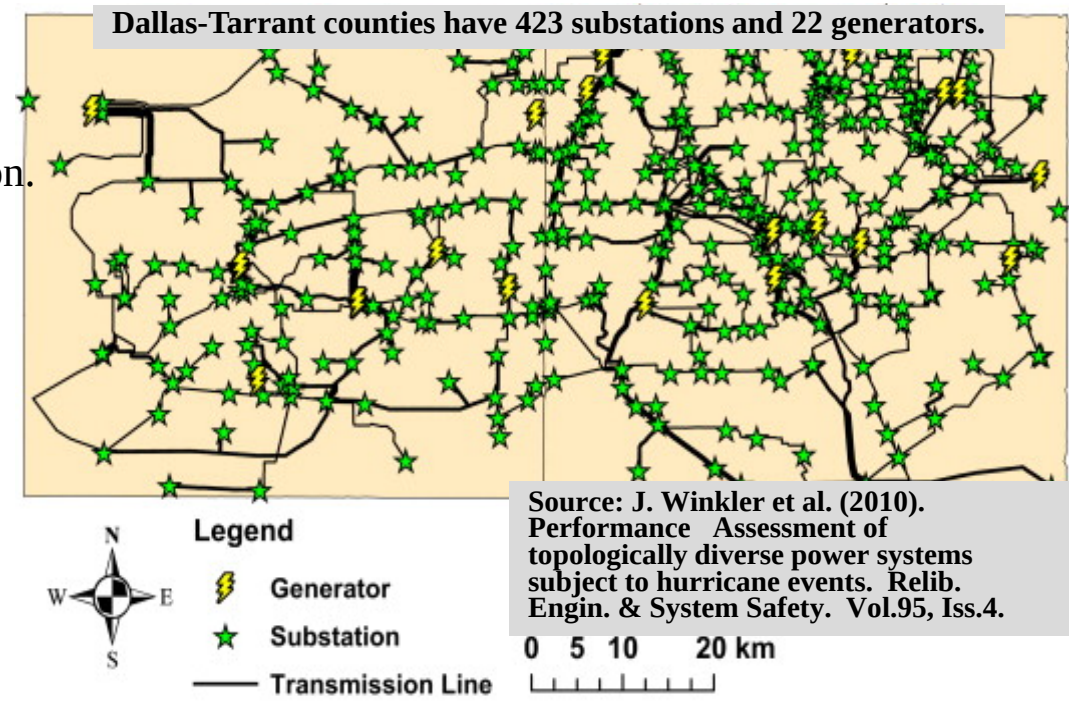
Based on

- **Electricity. Chapter 2.2 of *Energy Trading and Investing*. D. Edwards, 2010.**
- ***Fundamentals of Power System Economics*. D. Kirschen and G. Strbac, 2010.**
- **Reevaluation of Vertical Integration and Unbundling in Restructured Electricity Markets. Chapter 1 in *Competitive Electricity Markets*, ed., F.P. Sioshansi, 2008.**

Transmission and Distribution Lines

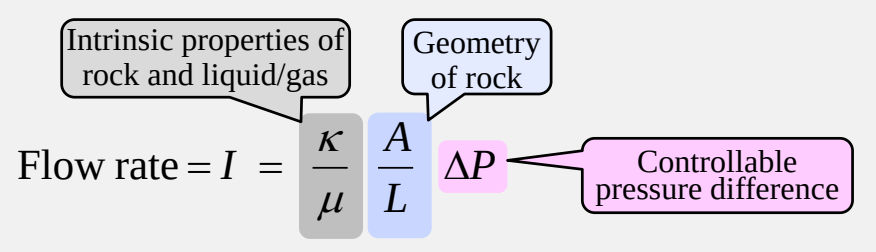
- Once electricity is generated, it has to be brought to the consumers.
- While the current (electron) is flowing in a transmission line, it is subject to resistance (friction). Friction creates power losses during transmission. Losses are proportional to the square of the current. To reduce losses:
  - Lower current (the number of electrons passing through a cross section of the wire per time).
  - Thicker transmission lines.
- To transmit a constant amount of power at a less loss, reduce the current and increase the voltage. Transmission lines carry high voltage electricity; see next page.

- Transmission lines: power plant → substation.
  - Transmission ≥ 100,000 Volts.
- Distribution lines: substation → consumers.
  - Distribution ~ 2,000-30,000 Volts.
- Substations to reduce voltage from transmission to distribution lines.



Source: J. Winkler et al. (2010). Performance Assessment of topologically diverse power systems subject to hurricane events. Relib. Engin. & System Safety. Vol.95, Iss.4.

Darcy's Law → Ohm's Law



- Darcy's Law:

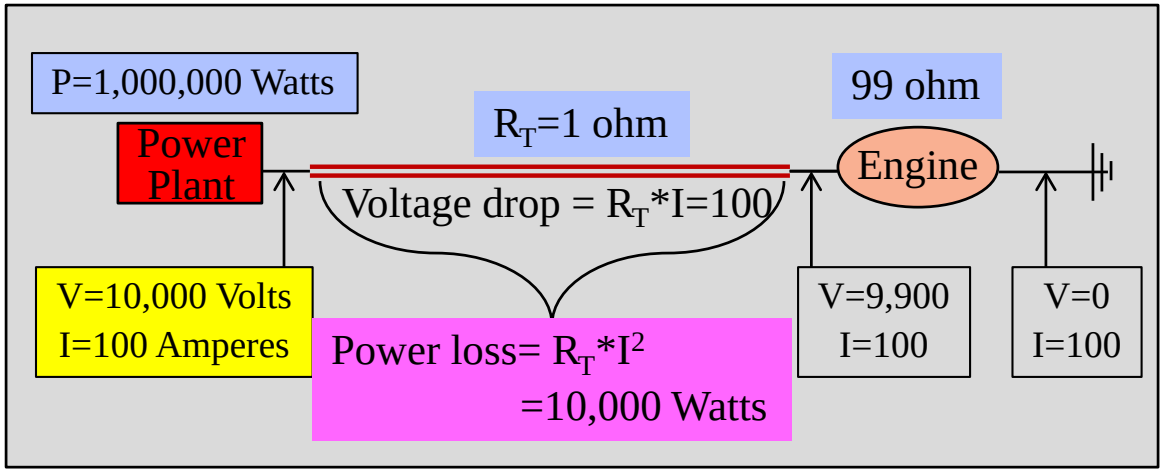
$$\text{Flow rate of liquids} = \frac{\text{Pressure difference}}{\text{Properties of rock}}$$

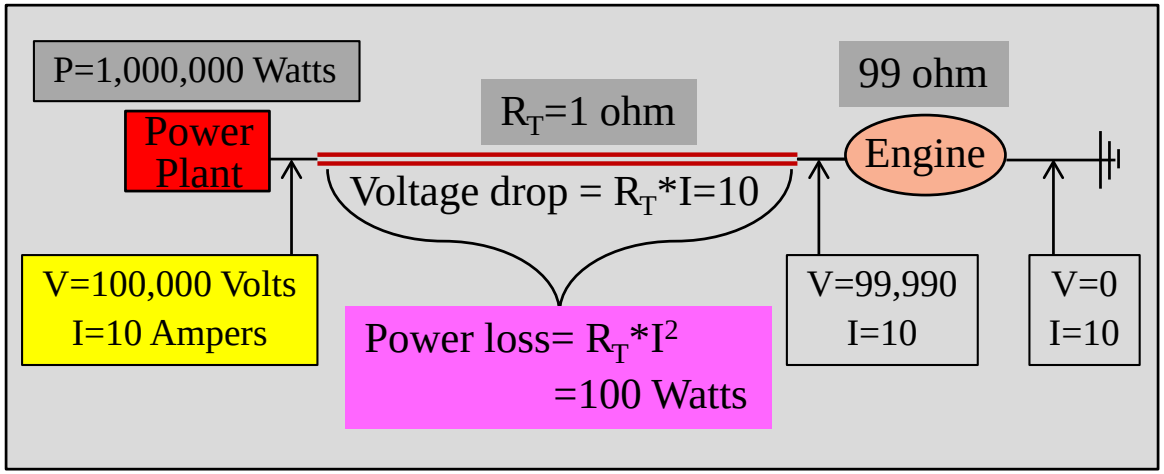
- Analogous quantities
  - Flow rate of liquid: Flow rate of electrons
  - Properties of rock: Properties of wire
  - Pressure difference: Voltage difference
- Ohm's Law

$$\text{Flow rate of electrons} = \frac{\text{Voltage difference}}{\text{Properties of wire}}$$

Why High Voltage?

- To transmit a constant amount of power at a less loss, reduce the current and increase the voltage.
- Consider a 1 MW generator feeding into 1 ohm transmission lines to operate a 99 ohm engine.
  - Georg Ohm's law: I = Current = Voltage / Resistance = V/R.
  - Electric Power law: P = Power = Resistance * Current^2 = R I^2 = V*I.





Power is preserved

1,000,000=10,000 + 990,000, or

= 100 + 999,900

But loss is less with high voltage.

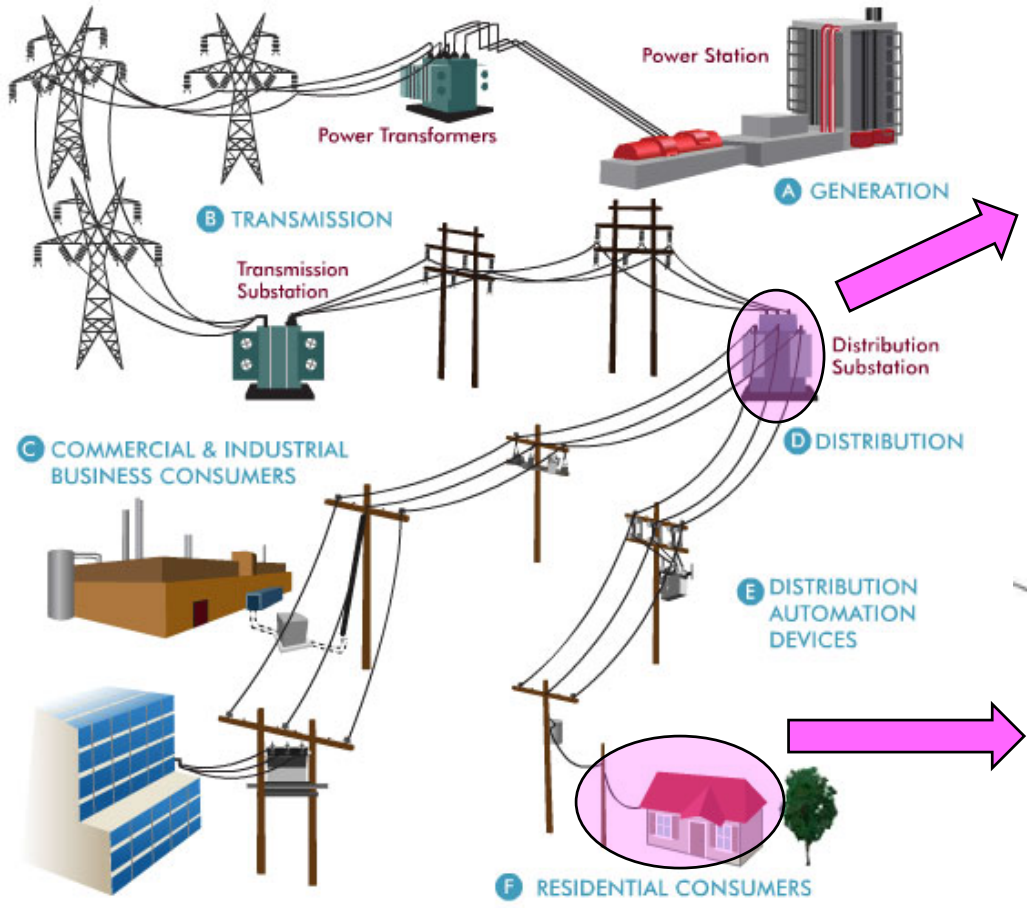
Power loss percentage:

$$\frac{\text{Loss in Transmission}}{\text{Power from Generator}} = \frac{R_T I^2}{P = VI}$$

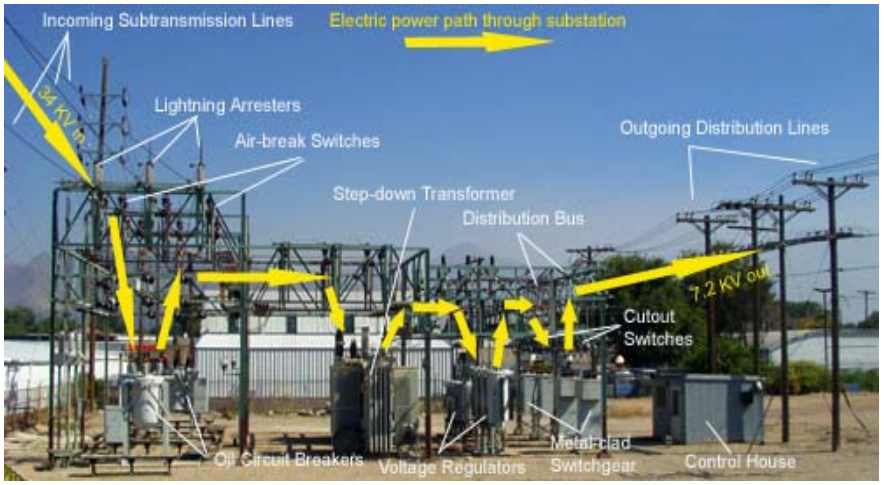
$$= \frac{R_T}{P}\left(\frac{P}{V}\right)^2 = R_T P\left(\frac{1}{V}\right)^2$$

Increasing voltage by a factor of 10 decreases transmission loss by a factor of 100.

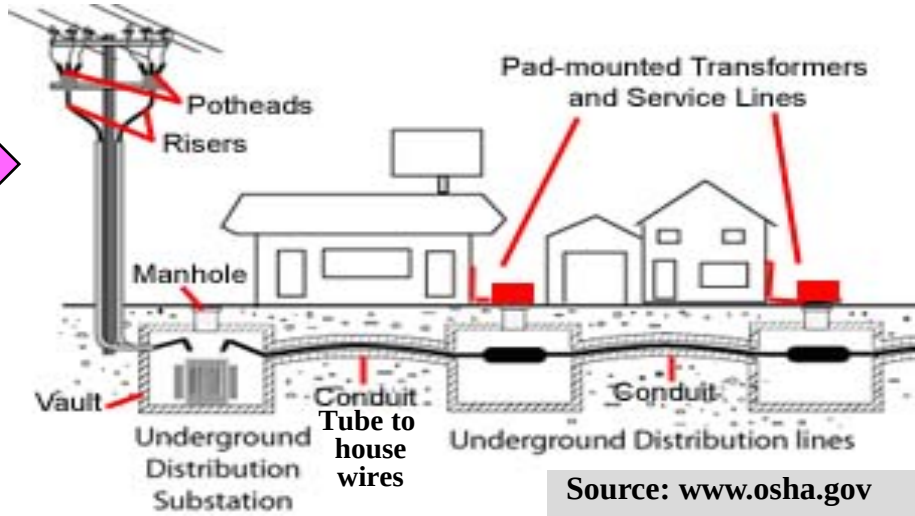
Grid Overview



Source: www.oncor.com



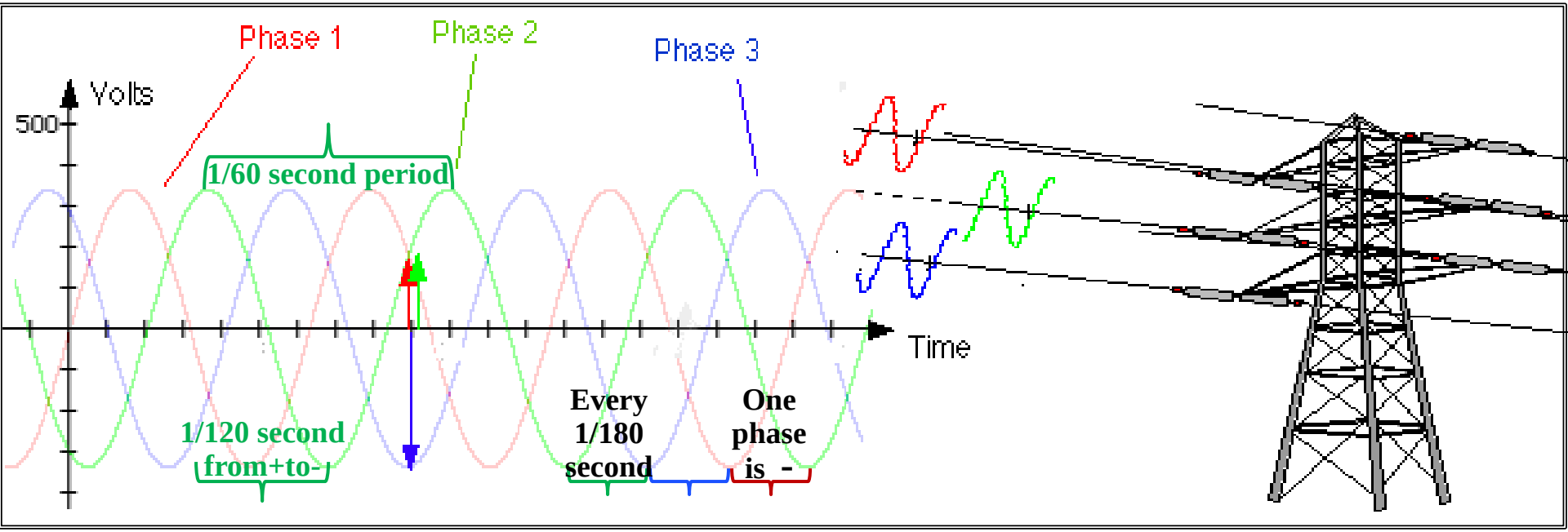
Substation security is a concern:
DOE says disabling 2 substations in TX causes a black out. Which 2?



Source: www.osha.gov

Current on Transmission Lines

- Transmission lines carry alternative current not direct current. Nikola Tesla's win over Thomas Edison.
- Alternative current changes direction many times in a second.
  - 60 times in the USA. So the frequency is 60 Hertz. 50 Hertz in in Europe. How many Hertz in Japan, see next page?
  - Positive end becomes negative in 1/120 seconds and positive again in 1/60 seconds.
  - Over [0,1/60] seconds interval, voltage has a sinusoidal wave pattern.
- 3 transmission lines, each carrying a different phase
  - Phases are 1/(3*60) of second apart; Every 1/180 second one of them reach max voltage; or every 1/180 second one reach min voltage.

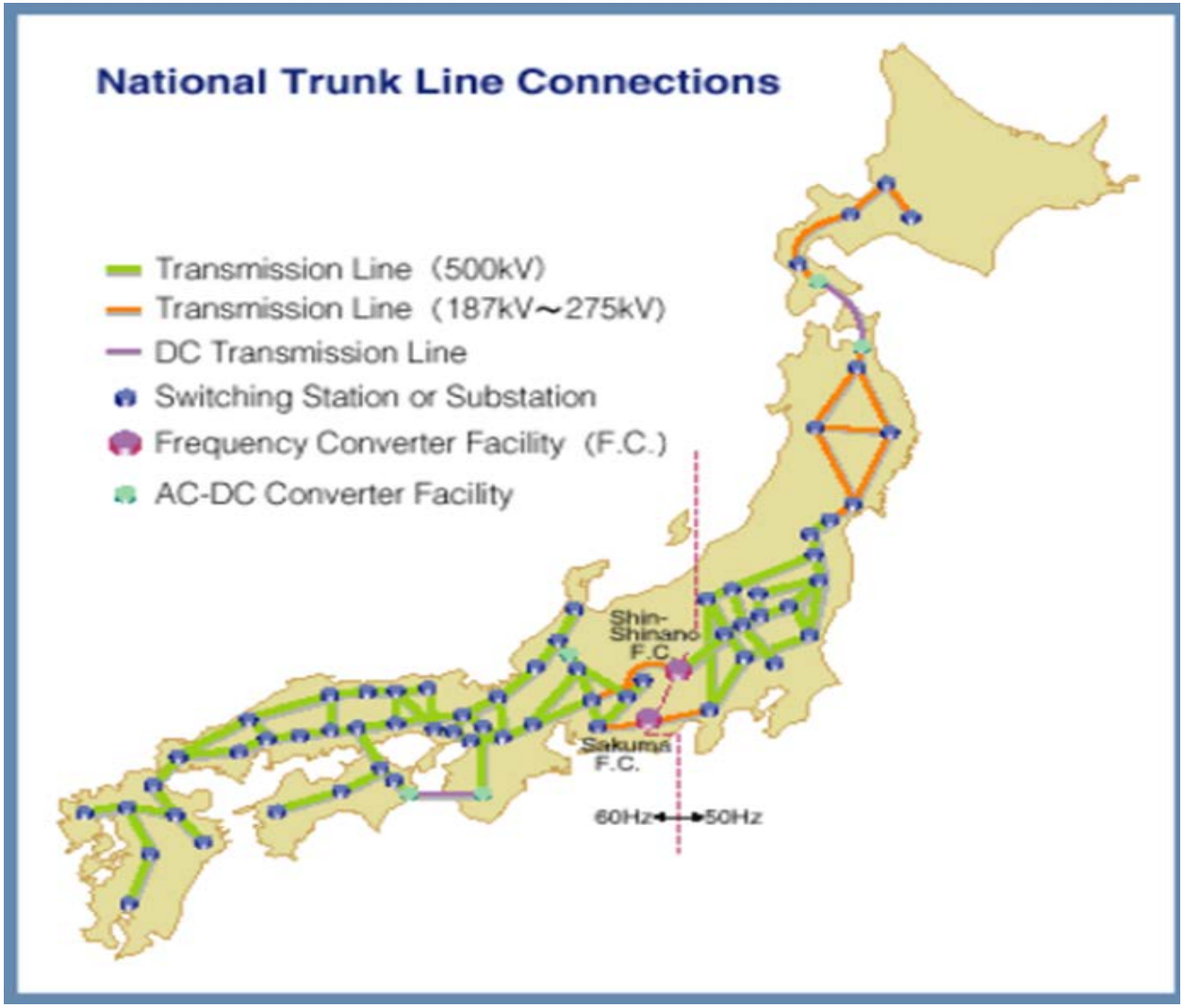


- For transmission loss in an alternating current, keep the time-dependent current $I(t)$ low.

$$\text{Transmission loss over } [0,T] = \frac{R_T}{T}\int_0^T I^2(t)dt$$

Japanese Grid has Two Different Frequencies

- West has 60 Hertz as in USA; East has 50 Hertz as in Europe.

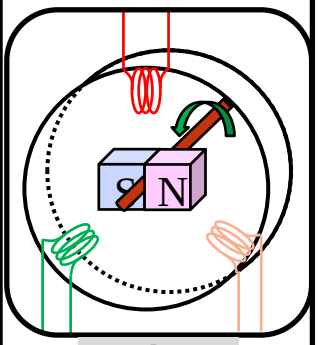


Why Alternating Circuit and Why Three Phases?

- Alternating circuit: No need to complete the circuit
  - Electrons do not circulate the entire grid: from home to power plant.
  - Electrons move back and forth locally.
- Three-phases generate magnetic fields that amplify each other in the same direction.
  - A three phase induction motor has a simple design, inherently high starting torque, and high efficiency. Such motors are applied in industry for pumps, fans, blowers, compressors, conveyor drives, and many other kinds of motor-driven equipment.

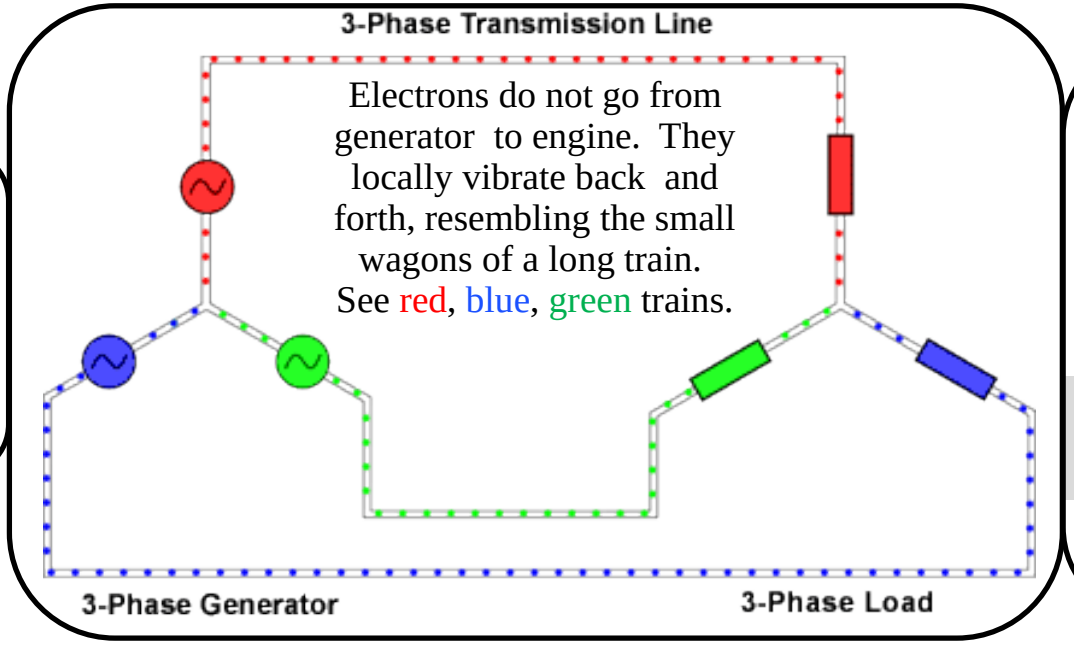
3-Phase Electricity Supply Chain

Generation

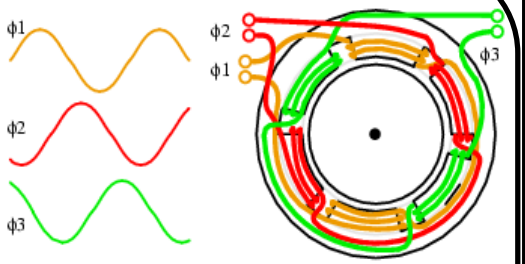


3 phase generator

Distribution & Transmission



Consumption



3 phase pool load (motor); See AC connections.

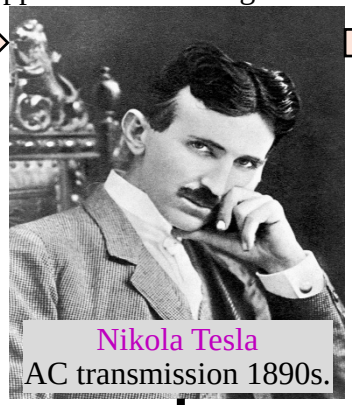
Challenge: Power generators and other synchronous connected grids must be at the same frequency.

Power Wars: Direct vs. Alternating Current

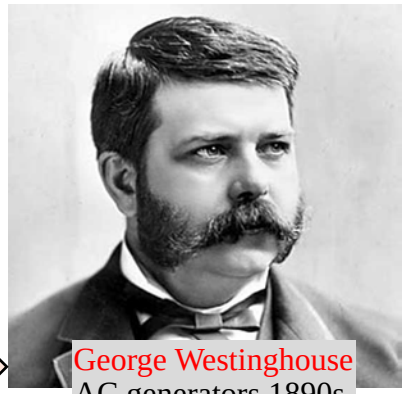
Thomas Edison, long-lasting incandescent bulb ~1880.

Edison developed bulbs and wanted to use his direct electricity generators (e.g., car alternator charging batteries) & transmission system

- But DC transmission losses were great
- To overcome losses needed a solution and hired Nikola Tesla who
  - At 28 yeas of age arrived in America in 1884
  - Redesigned Edison's generators but suggested AC for transmission
  - Left Edison in 1885 and established own company
  - Got financial support from Westinghouse



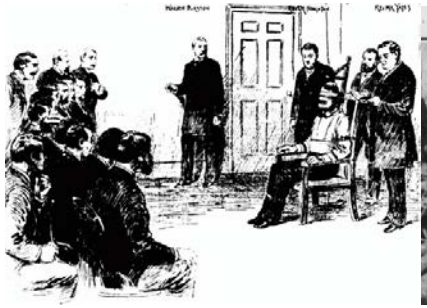
Nikola Tesla
AC transmission 1890s.



George Westinghouse
AC generators 1890s.

Edison threatened by Westinghouse success

- Sought ways to illustrate the dangers of AC
  - Execution of William Kemmler on an electric chair by NY state in 1890
  - Execution of Elephant Topsy in Coney Island in 1903



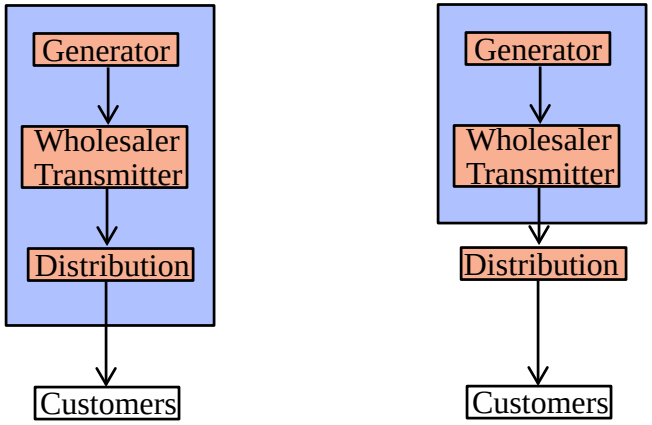
Edison General Electric Company merged with Thomson-Houston Electric Company to establish General Electric (GE) in 1892.

Westinghouse with Tesla patents in 1887

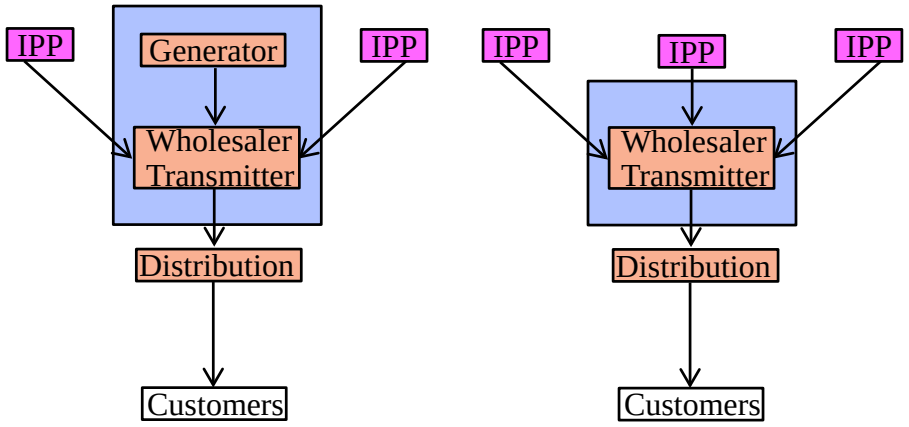
- Installed AC generators in rural and less populated areas that were not covered by Edison's DC system
- Sold generators about 1/2 of Edison
- Won the contract to illuminate Chicago Fair in 1893

- G. Westinghouse lost control of Westinghouse co. in 1907
- Westinghouse co. built its first nuclear reactor in 1957
- It was sold to British Nuclear Fuels Ltd. in 1999
- It was put up for sale again in 2006, Toshiba won over GE
- Toshiba Westinghouse failing over nuclear reactor construction in Georgia and South Carolina filed for Chapter 11 bankruptcy protection on March 29, 2017.

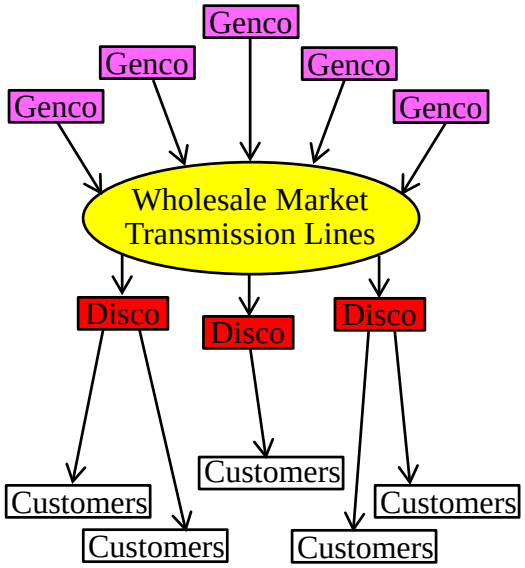
Electricity Markets: A Preview



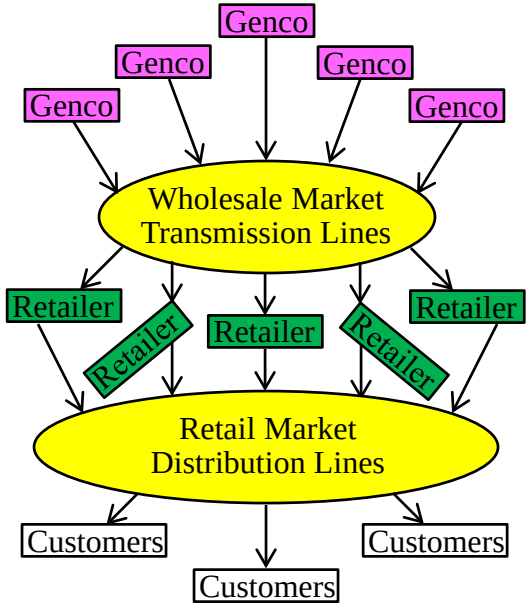
Monopoly may spin off Distribution.



Generation capacity partially or entirely owned by Independent Power Producers (IPP).



Competitive wholesale market is connected to Distribution Companies (Discos) who own the transmission lines in their territory. Each Disco serves its own territory.



Competitive retail market, where customers can buy from any one of the retailers.

Participants in Electricity Markets

- Market Operator (MO): Clears the wholesale or retail markets, or both, by matching bids to buy and offers to sale electricity. It handles the transactions: It receives payments from buyers and forwards them to sellers.
- Independent System Operator (ISO): Maintains the security and reliability of the grid. ISO does not own infrastructure to generate/transmit power; its role is more of policing the grid. One of the challenges is supply and demand mismatches in real time:
  - Supply >> demand: Black out possible as a result of melting transmission wires.
  - Supply << demand: Brown out in certain districts to reduce demand.

  ISO is also the operator of the last-minute market to match demand and supply in real time.
- Transmission companies: Own transmission infrastructure (lines, substations, transformers). Operate the lines according to the ISO instructions. If transmission lines are owned by an independent company that acts as an ISO, organization is called an independent transmission company (ITC).
- Regulator: Governmental body responsible for ensuring fair and efficient operation of electricity sector. It sets market rules and investigates violators.

- Texas Examples:
  - QSE: Qualified Scheduling Entity, many in Texas. They submit offers to sell and bids to buy electricity.
  - PUCT (Public Utility Commission of Texas) is the regulator and monitor.
  - ERCOT (Electric Reliability Council of Texas) is the ISO and monitor.
- A market manipulation concern is addressed by Ercot's working group, Ercot itself or PUCT in that order
  - Suspicious manipulation cases
    - » Several producers turn their generators off for maintenance at the same time.
    - » A producer's capacity that is unavailable in a day-ahead market becomes available in the spot market after manipulating the market to increase the prices.

Easements of Farmlands by Transmission Companies

- Renewable resources, especially wind, are away from urban centers. New transmission lines necessary over rural areas.
- Residents of rural areas do not want transmission lines:
  - Lines look ugly, interfere with farming, reduce land value, apathy to lines on my farm land to serve "city snobs"
- In general, transmission line (and pipeline) companies seek an easement in the courts.
- Easement: a right, privilege or advantage in real property, existing distinct from the ownership of the land. Easements consist of an interest (or estate) in real property that does not constitute full ownership. Most commonly, an easement entails the right of a person (or the public) to use the land of another in a certain manner. When the government or a company with the support of a government goes for the easement on a land, the land owner is often forced to allow the use of the land but can ask for more compensation. Easements in Texas http://recenter.tamu.edu/pdf/422.pdf

- Edward Clack, a Burkburnett area landowner, North of Wichita Falls, sued Oncor claiming his land lost value when an easement was taken for a high-voltage transmission line.
  - He won a $445,365 judgment ($393,165 loses + interest and court costs) against Oncor after a 3 day trial in Wichita County Court of Judge Gary Butler. Case is *Oncor Electric Delivery Company, LLC v. Edward Clack*, No. C-330. Oncor may appeal.
  - The dispute began in 2011 when Oncor sued Clack to gain 33.6 acres of easement on his property for a 345,000-volt power line. Oncor initially offered him < $55,000 before raising the offer to ~ $140,000.
  - "This judgment sends a clear message. Texas landowners … have a constitutional right to collect fair damages when power lines lower the value of their land. Landowners only get one opportunity to recover, but the easements remain forever," said eminent domain attorney Luke Ellis in a news release.

    Source: Times Record News of Wichita Falls, TX, Feb 17, 2015.
- "Grain Belt Express" line is to carry electricity generated by wind. Kansas → Missuuri → Illinois. Opposed by Missouri farmers. The line is proposed by Clean Line Energy Partners
  - Grain Belt Express is voted down in Missouri Public Service Commission
  - Clean Line Energy Partners is filing a new application to the commission
  - Clean Line has permission from DoE for an Oklahoma → Tennessee line

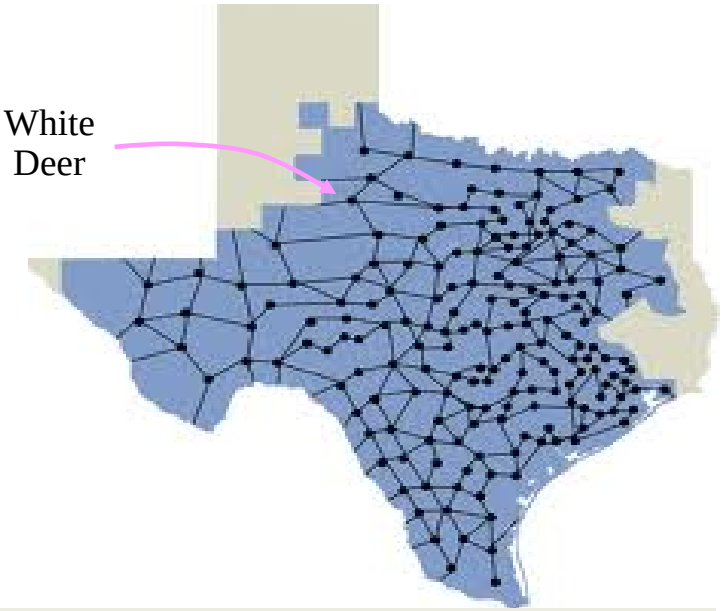
  Source: *Making Way for Wind Power* by the Editorial Board of NYT on Apr 5, 2016.

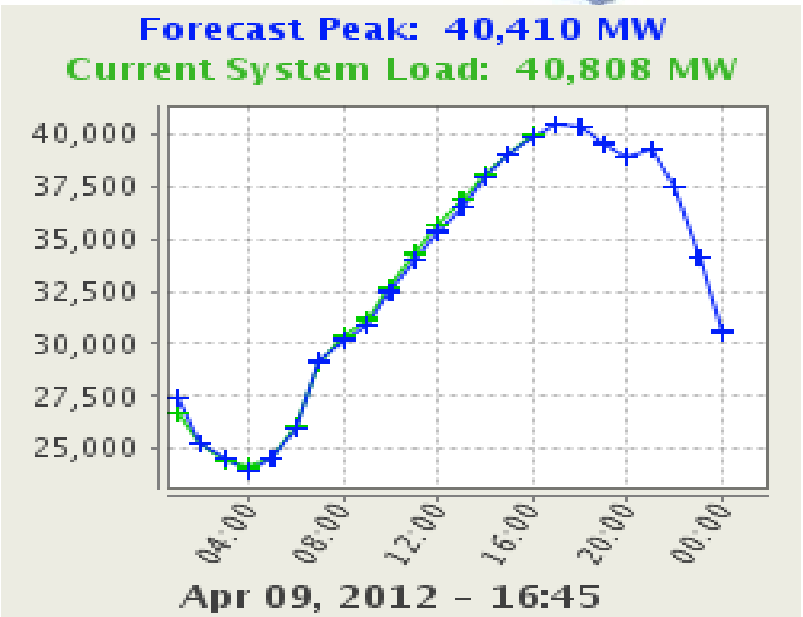
Russ Pisciotta, adoring clear skies over his Missouri farm, opposes Grain Belt Express

ERCOT: Lone Star's ISO

- Nonprofit organization managing electric flow to
  - 500+ power plants;
  - 40,000+ miles of transmission lines;
    - » 9,249 miles of 345,000 Volts,
    - » 19,565 miles of 138,000 Volts,
    - » 11,715 miles of 69,000 Volts.
  - 23 million customers;
  - 85% of state's electric load;
  - 75% of state's land;
  - $32 billion market.
- Real time system conditions:
  - Apr 9, 2012, 16:45 and Apr 9, 2014 18:00
    - » Frequency 60.015 and 60.021 Hertz.
    - » Demand: 40,808 and 36,081 MW

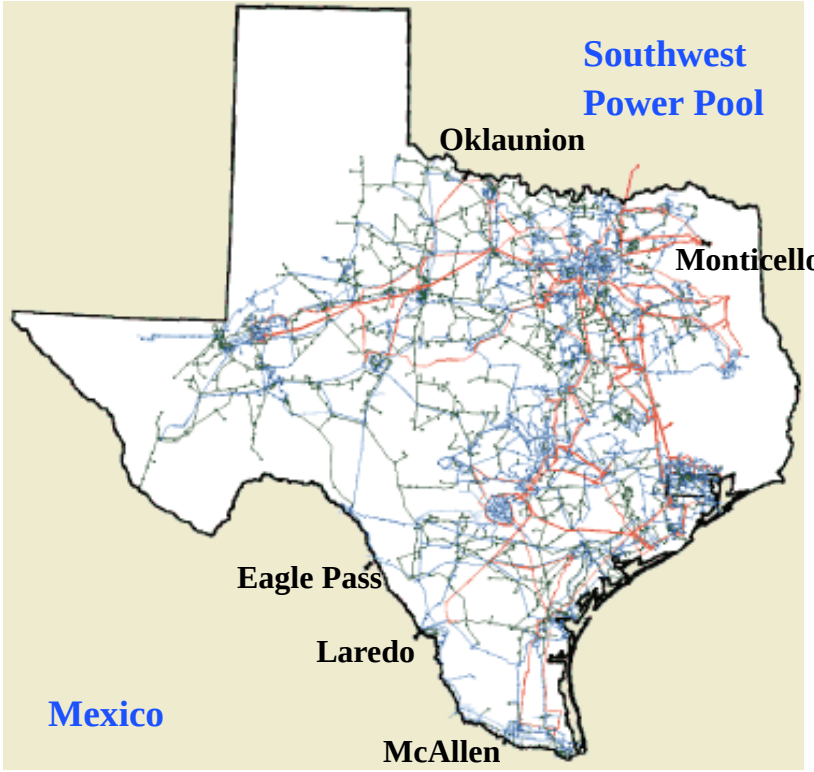
    In 2012, it turned out to be > forecast peak of 40,410 MW.
    - » Capacity: 45714 MW.
    - » Hourly average wind output 2843 MW.
- In addition to Oncor of Dallas, transmission firms
  - Austin Energy
  - CenterPoint Energy
  - Brazos Electric Cooperative
  - Lower Colorado River Authority
  - CPS Energy
  - AEP Texas Central and North
  - South Texas Electric Cooperative
  - Texas-New Mexico Power Company





ERCOT's Interaction with Others and FERC

- Connections, going clockwise starting from north,
  - To Southwest Power Pool
    - » at Oklaunion (DC_N) for 220 MW
    - » at Monticello (DC_E) for 600 MW
  - To Mexico
    - » at McAllen (DC_R for railroad) for 150 MW
    - » at Laredo (DC_L) for 100 MW
    - » at Eagle Pass (DC_S) for 36 MW
- All connections are Direct Current lines, so there is no issue of equalizing frequency of phases.
- Without Alternating Current (AC) connections to neighbors, ERCOT is limited to Texas and hence it is exempt from federal jurisdiction.
  - Lone star has a lone ISO
- For Energy Federal Policy Act of 2005 and related issues ERCOT is accountable to FERC. When the issue is reliability related Texas Reliability Entity (TRE) also steps in.
- FERC is the Federal Energy Regulatory Commission, i.e., federal version of ERCOT.



ERCOT Monitors Capacity in Advance

- ERCOT targets for 13.75% Reserve Margin (safety stock in supply chain terminology)

  Capacity – Peak Demand / Peak Demand = 13.75%

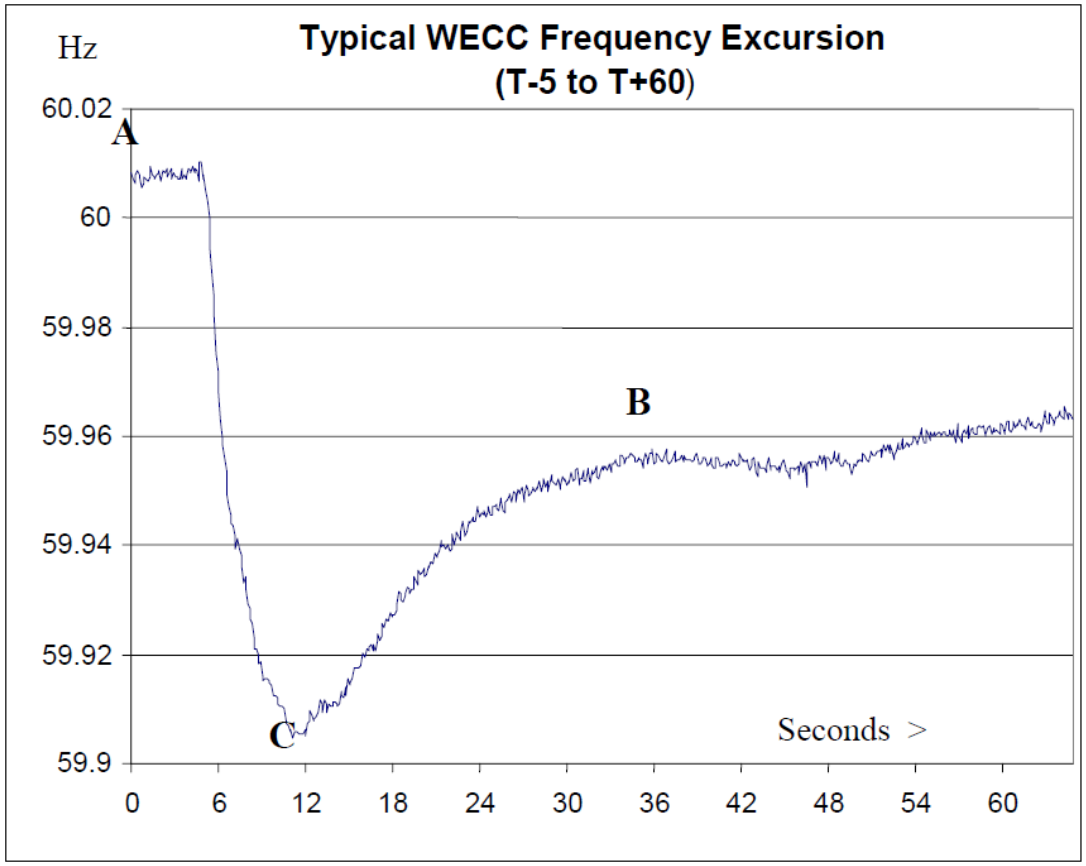
  Capacity = 113.75% of Peak Demand

- Peak demands in Texas are during summer months and in late afternoons. This is when ACs need to work hard.
- According to Dec 2011 ERCOT Report on the Capacity, Demand and Reserves, Reserve Margin is **negative** in 2022.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Load Forecast:											
Summer Peak Demand (Normal weather basis), MW	66,195	67,168	70,087	73,552	76,001	77,596	78,919	79,411	81,382	82,765	84,013
less Energy Efficiency Programs (per SB1125)	119	240	366	498	635	775	917	1,060	1,206	1,355	1,506
less LAARs Serving as Responsive Reserve, MW	1,038	1,038	1,038	1,038	1,038	1,038	1,038	1,038	1,038	1,038	1,038
less Emergency Interruptible Load Service	420	462	509	559	615	677	745	819	901	991	1,000
Firm Load Forecast, MW	64,618	65,428	68,174	71,457	73,713	75,106	76,219	76,494	78,237	79,381	80,469
Resources:											
Installed Capacity, MW	63,025	63,025	63,025	63,025	63,025	63,025	63,025	63,025	63,025	63,025	63,025
Capacity from Private Networks, MW	4,390	4,390	4,390	4,390	4,390	4,390	4,390	4,390	4,390	4,390	4,390
ELCC* of Wind Generation, MW	836	836	836	836	836	836	836	836	836	836	836
RMR Units to be under Contract, MW	-	-	-	-	-	-	-	-	-	-	-
Operational Generation, MW	68,251	68,251	68,251	68,251	68,251	68,251	68,251	68,251	68,251	68,251	68,251
Non-Synchronous Ties, MW	553	553	553	553	553	553	553	553	553	553	553
Switchable Units, MW	2,962	2,962	2,962	2,962	2,962	2,962	2,962	2,962	2,962	2,962	2,962
Available Mothballed Generation , MW	826	651	690	509	570	592	592	592	592	592	592
Planned Units (not wind) with IA and Air Permit, MW	130	1,115	1,115	1,895	4,675	5,955	5,955	5,955	5,955	5,955	5,955
ELCC* of Planned Wind Units with Signed IA, MW	39	112	129	140	140	140	140	140	140	140	140
Total Resources, MW	72,761	73,644	73,700	74,309	77,150	78,453	78,453	78,453	78,453	78,453	78,453
less Switchable Units Unavailable to ERCOT, MW	317	317	317	317	317	317	317	317	317	-	-
less future Unit Retirements, MW	-	-	-	-	-	-	-	-	-	-	-
Resources, MW	72,444	73,327	73,383	73,992	76,833	78,136	78,136	78,136	78,136	78,453	78,453
Reserve Margin (Resources - Firm Load Forecast)/Firm Load Forecast	12.11%	12.07%	7.64%	3.55%	4.23%	4.03%	2.51%	2.15%	-0.13%	-1.17%	-2.51%

ERCOT Monitors Frequency in Real Time

- A: Pre-disturbance point
- B: Settling frequency after disturbance
- C: Maximum excursion away from standard frequency.



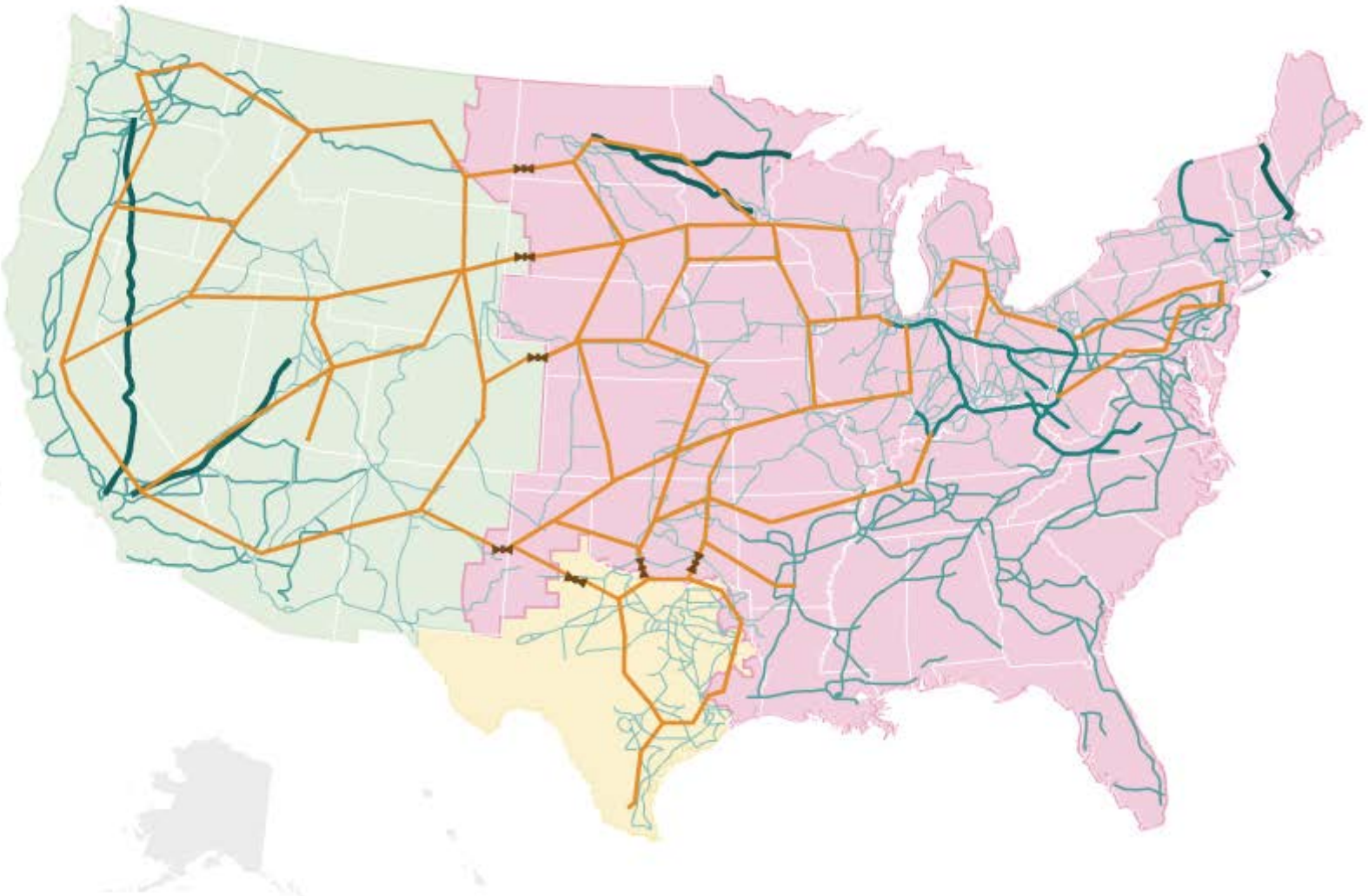
Western Interconnection's (WECC) Frequency

National View: ERCOT and the Others

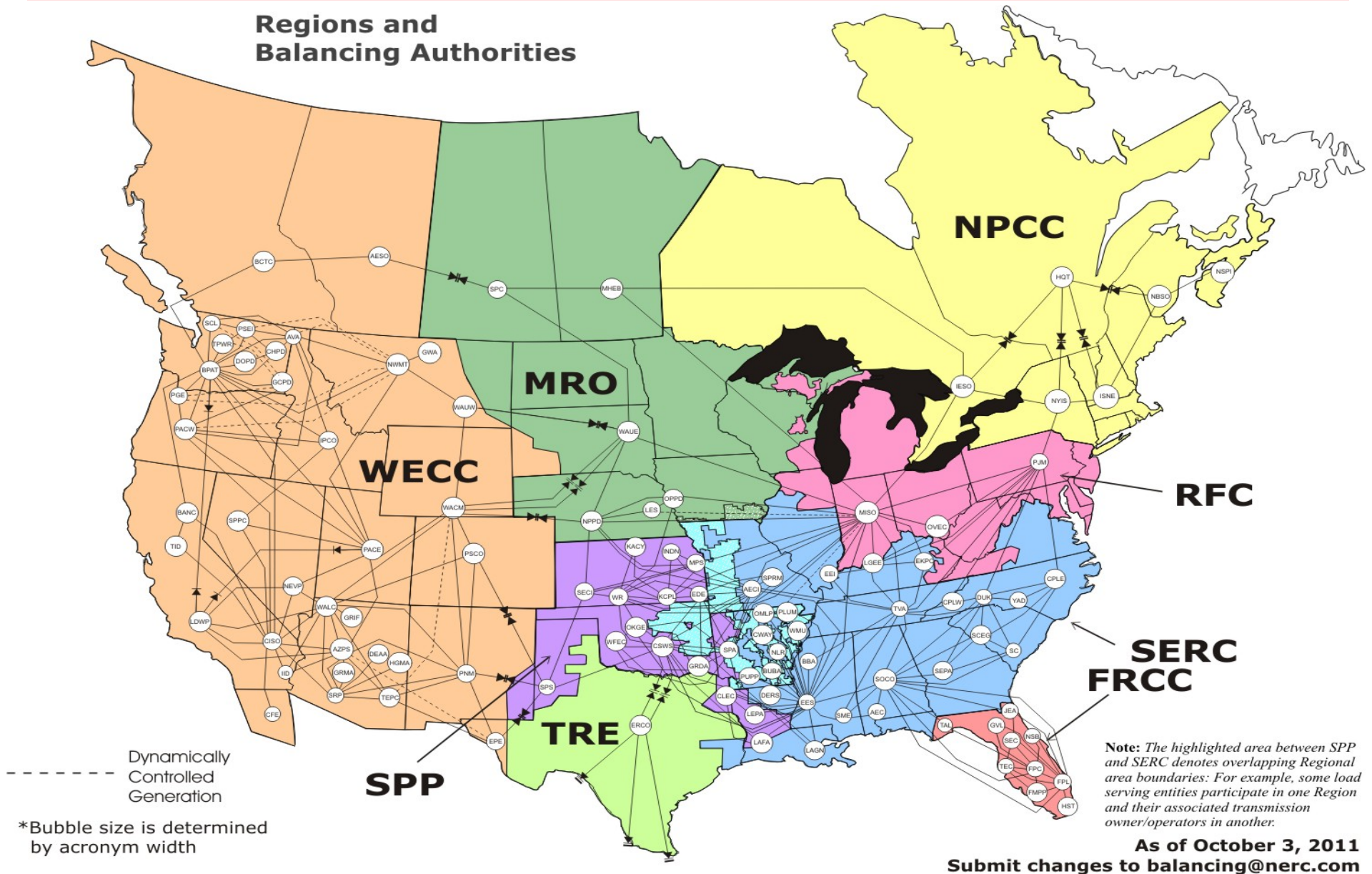
The U.S. electric grid is a complex network of independently owned and operated power plants and transmission lines. Aging infrastructure, combined with a rise in domestic electricity consumption, has forced experts to critically examine the status and health of the nation's electrical systems.

THE GRID | SOURCES OF POWER | POWER PLANTS | SOLAR POWER | WIND POWER

This map is from npr.org for story titled "Visualizing the US Electric Grid".



North American System Operators and Load Balancing Authorities



ERCOT's Actions on Feb 2, 2011
Blackout of Aug 14, 2003; Outage of Apr 7, 2015

- First week of Feb in 2011 was exceptionally cold in Texas.
  - Cold caused
    - » Drops in gas pressure in the pipelines feeding gas-powered generators and failures in some generators.
    - » Rises in the electricity demand for heating
      - ERCOT's electricity demand broke a winter record of 56,334 MW ~ 7 pm on Feb 2, 2011.
  - Rotating outages were ordered to avoid an uncontrolled blackout in North Texas.
  - When necessary for the reliability of the grid, ERCOT has the responsibility and authority to order outages. When portions of grid or high-power consuming facilities are shut down, the capacity can meet the remaining demand. This stabilizes the grid and lets the grid equipment work within reasonable voltage and current ranges.

- If there is a local problem in the grid and it cannot be contained, it becomes a global problem.
  - On Aug 14, 2003, a power plant goes offline in Ohio.
  - This strains high-voltage lines, which later went out of service.
  - FirstEnergy Co. active there did not assess the voltage volatility and did not operate the system within appropriate voltage regions.
  - Some capacitors in Cleveland-Akron corridor were removed during the peak time for inspections. These capacitors could have provided temporary voltage support.
  - Equipment failures started in Ohio and continued like falling dominos; they went into Canada and came back to New York, Michigan, New Jersey.
  - Eventually, 55 million people in the Northeast are left without power for 7 to 20 hours on a hot August day.

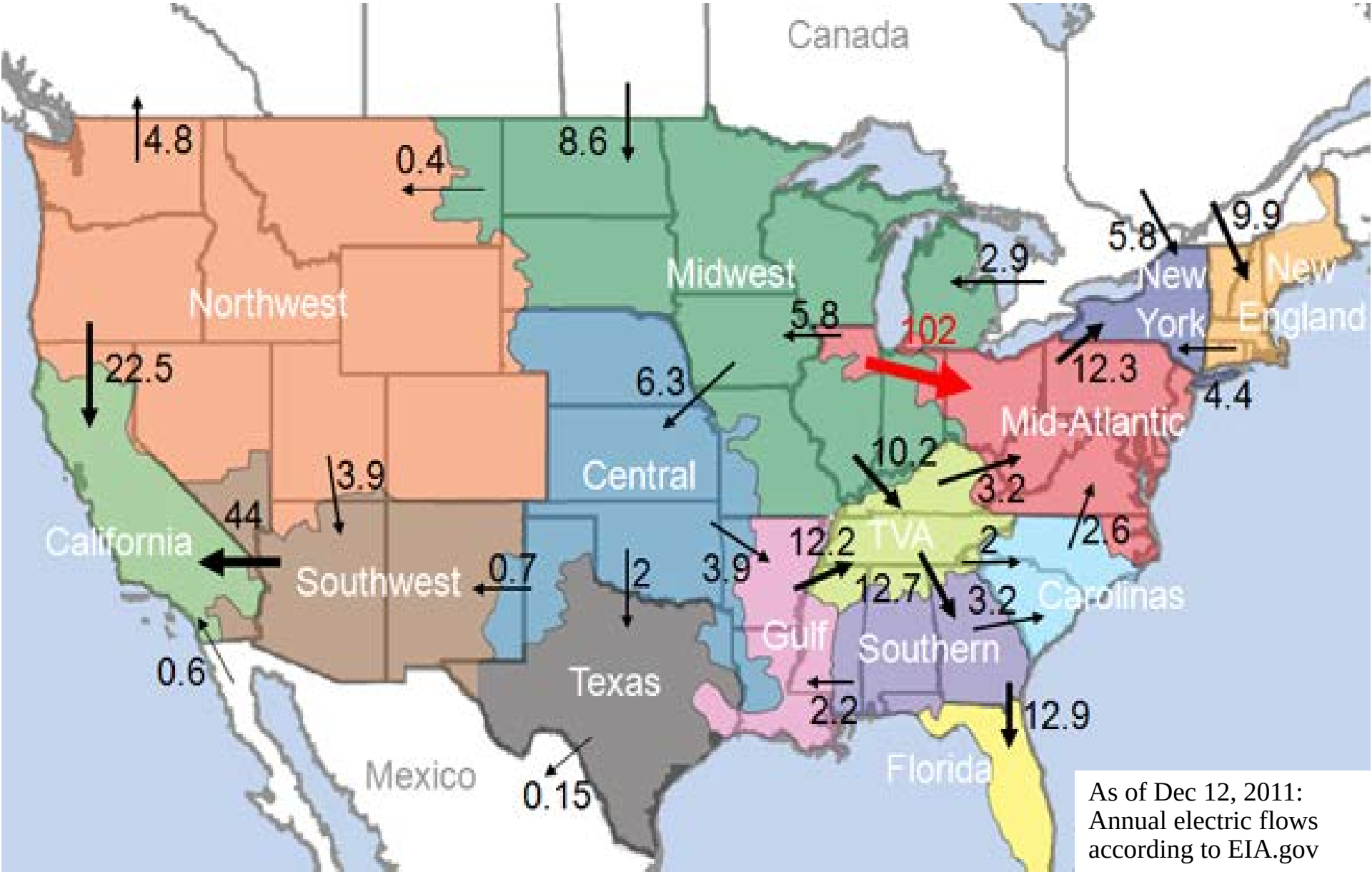
April 7, 2015 Washington Outage.

Marie Harf, spokeswoman for the US Department of State, at the Daily Briefing. She used her cellphone light to refer to her notes in the dark.

Summary

- **Grid: Transmission and Distribution**
- **ERCOT**

Annual Electric Flows
Often from North to South



As of Dec 12, 2011:
Annual electric flows
according to EIA.gov

Cost of Power Outages

- Read and incorporate
  - LaCommare, Kristina Hamachi, and Joseph H. Eto. “Cost of Power Interruptions to Electricity Consumers in the United States.” Energy, Vol. 31. Elsevier: April 7, 2005.
  - http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf