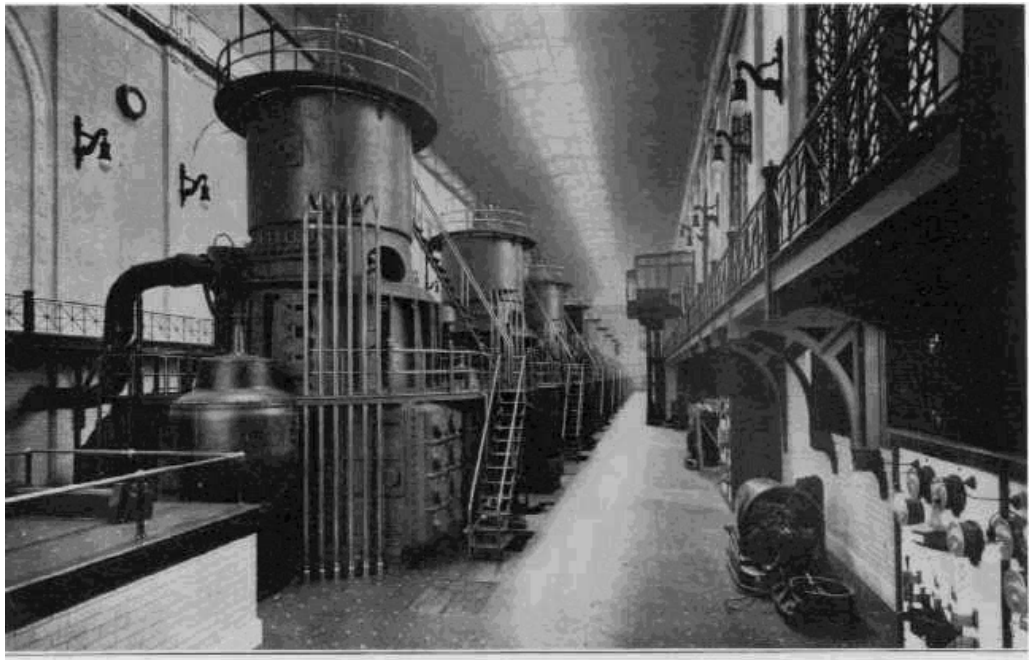
GEOS 24705 / ENST 24705 / ENSC 21100

2018

# Lecture 13

# Electricity IV

# **Electric sector history** – from individual private companies



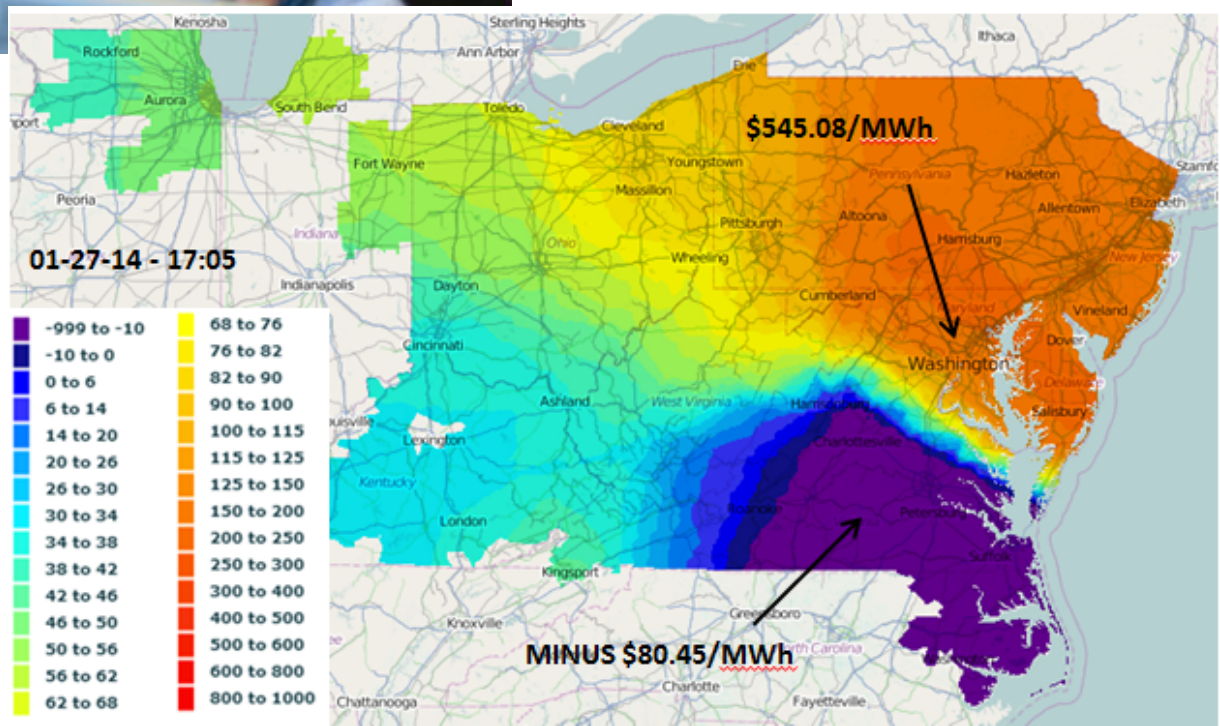
STEAM TURBINE GENERATING PLANT, FISK STREET STATION, COMMONWEALTH EDISON COMPANY, CHICAGO

Fisk Street power station, Chicago, 1903
Commonwealth Edison Chicago
first turbine-driven electricity in U.S.
(vertical turbines, AC power)


Edison Illuminating Co., Detroit, ~1900
*(Detroit Historical Society)*

# **Electric sector history -** ... to organized, regulated markets


PJM control room, 2016




Locational marginal price, PJM, 5 PM Jan 27, 2014

# Topics

- Transmitting electricity: the grid
- Faraday's law in
  - generators, DC motors, transformers
- Generating electricity
- ~~Powering electricity production~~
- Marketing and managing electricity

# **The electrical grid:** link between generation and consumption

*carries 1/3 of U.S. power usage*

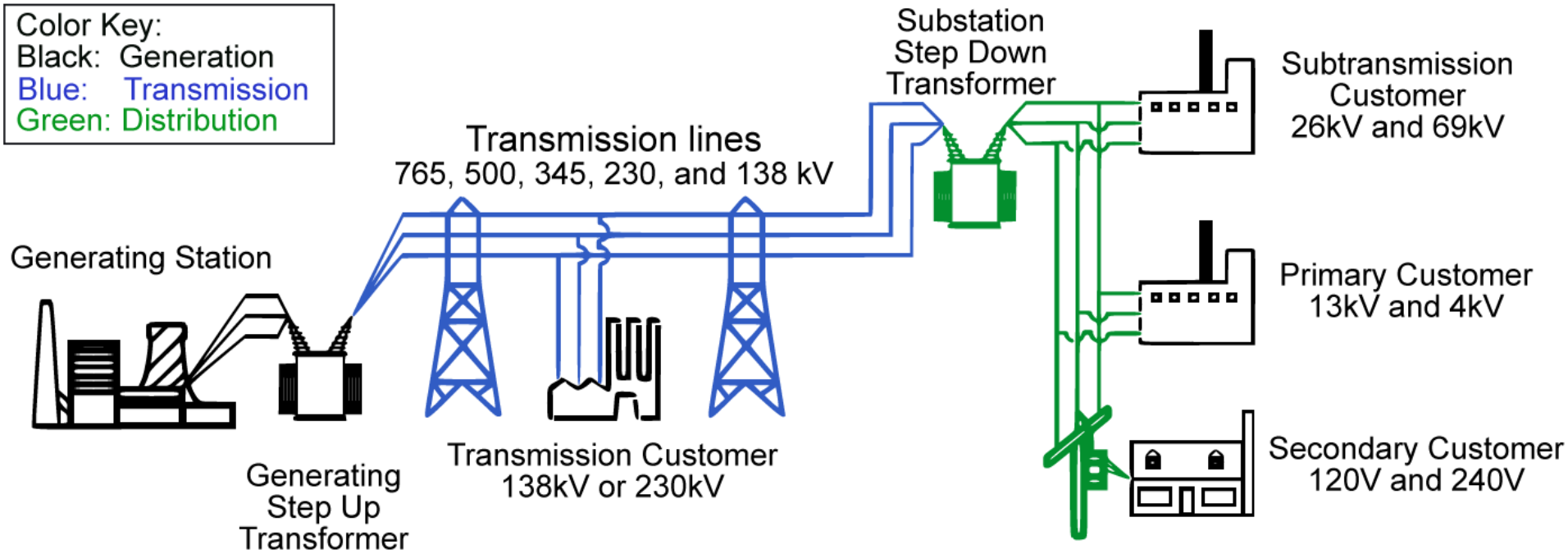



*Image: Wikipedia*

# Edison put safe, low-voltage lines underground

Chicago, 1887

Chicago Edison digs up Jackson and LaSalle streets to lay DC wires

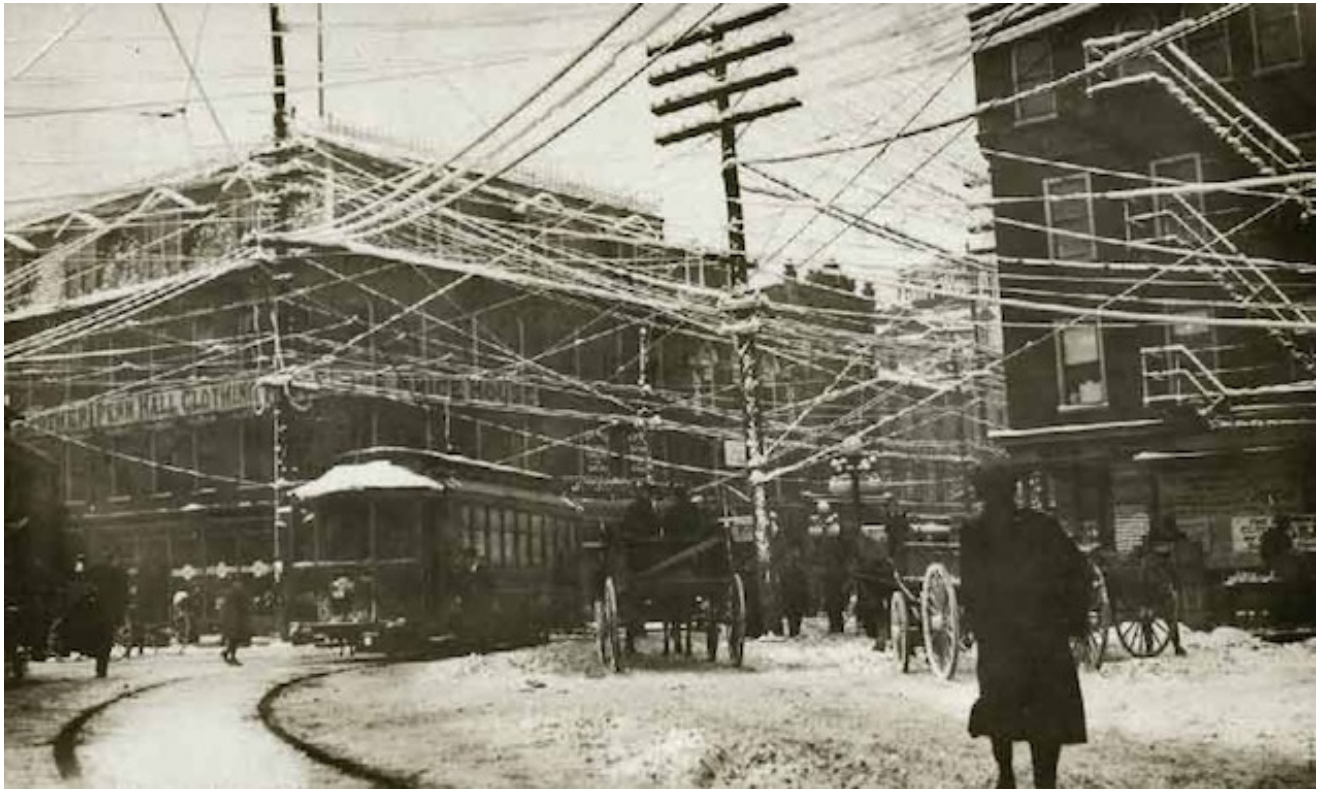
great latitude given to private companies to affect public space

# Electrification soon became a kind of “Wild West”

New York, 1887

wires for electricity, telephone, telegraph, all from private companies

AC lines were fatal if touched



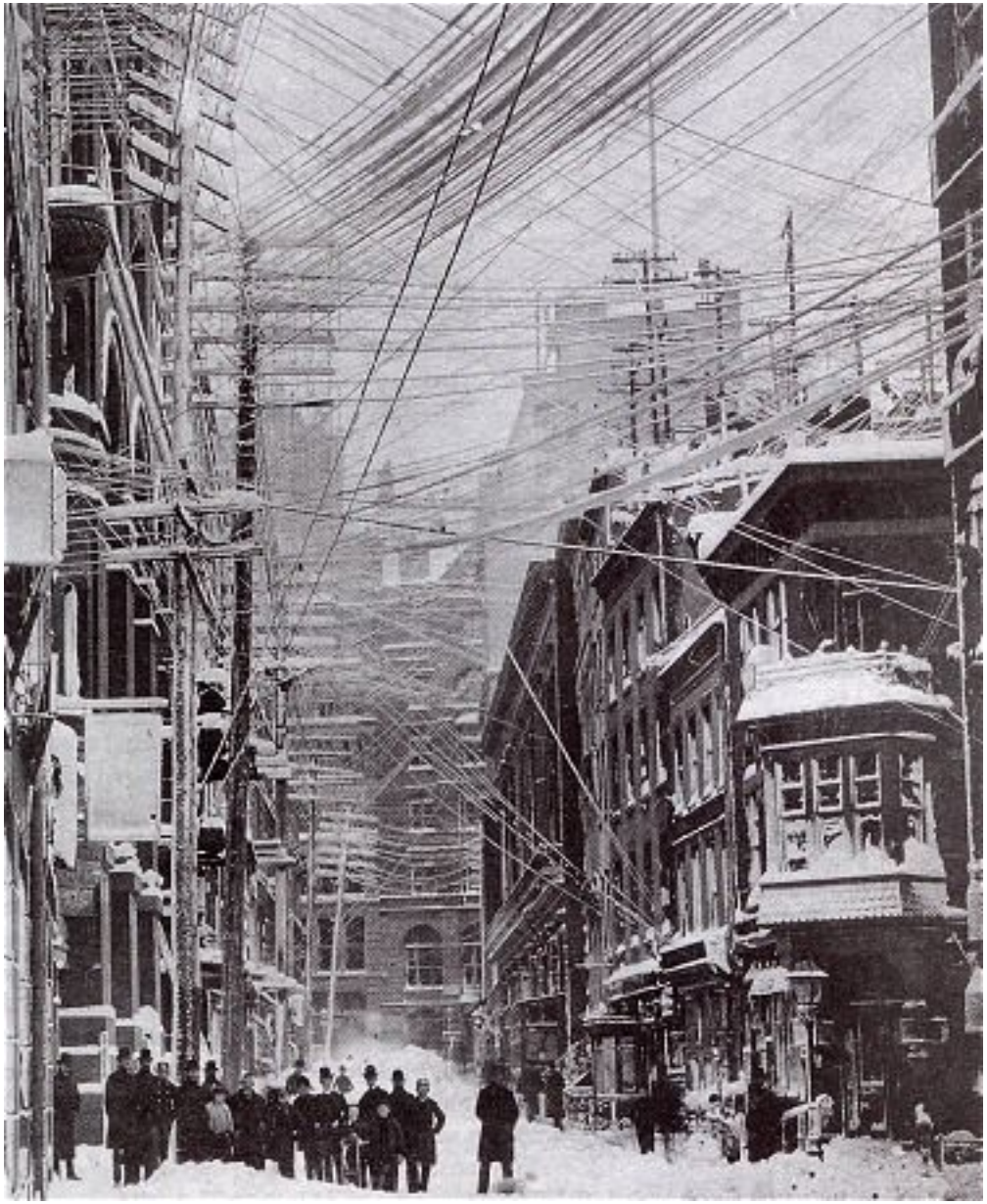
# Electrification soon became a kind of “Wild West”

New York, 1888

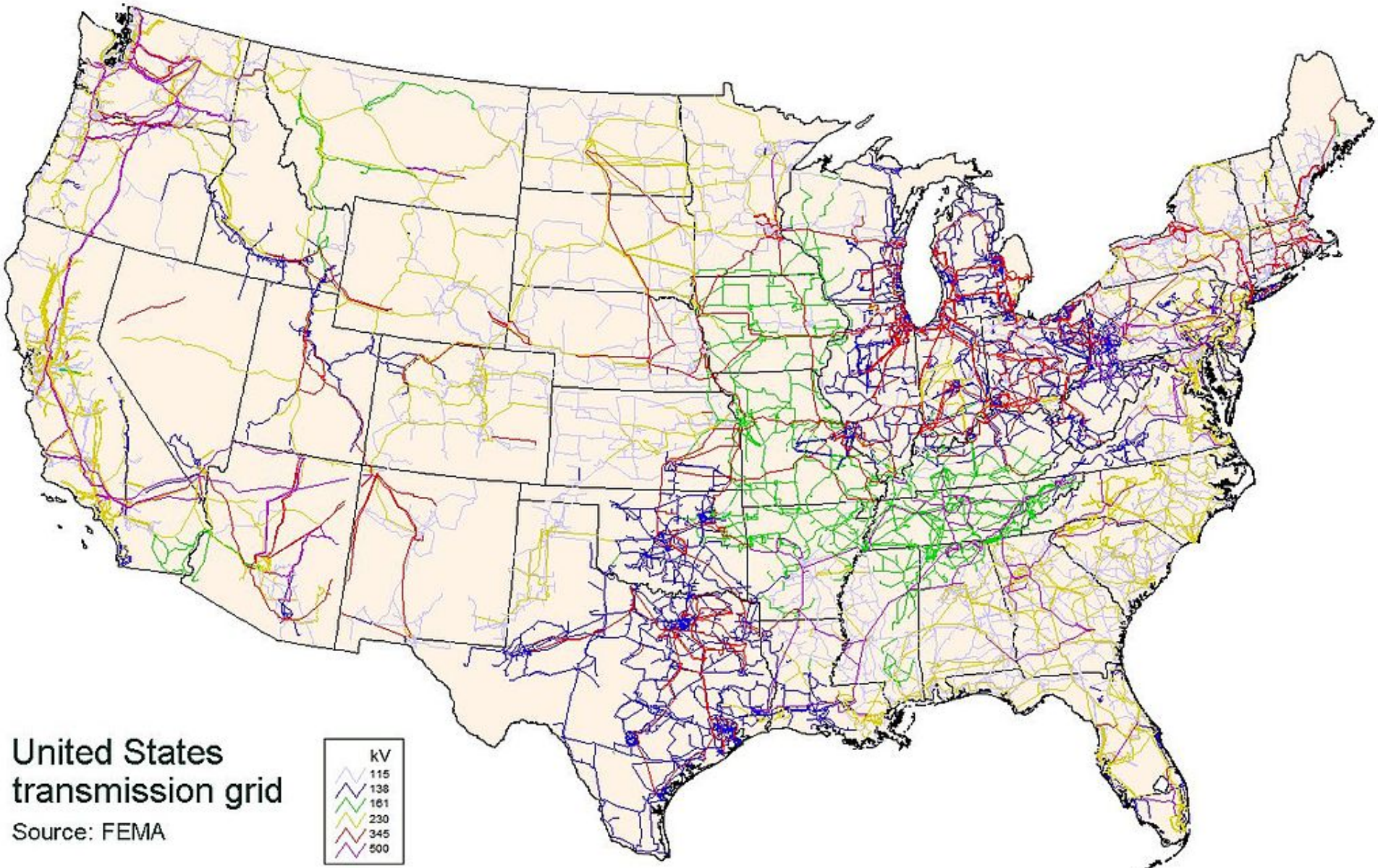
after the blizzard

by 1890 the city was demanding shutdowns of power companies to address safety issues

***gradual push to coordinate, regulate***



# Why so many different voltages?



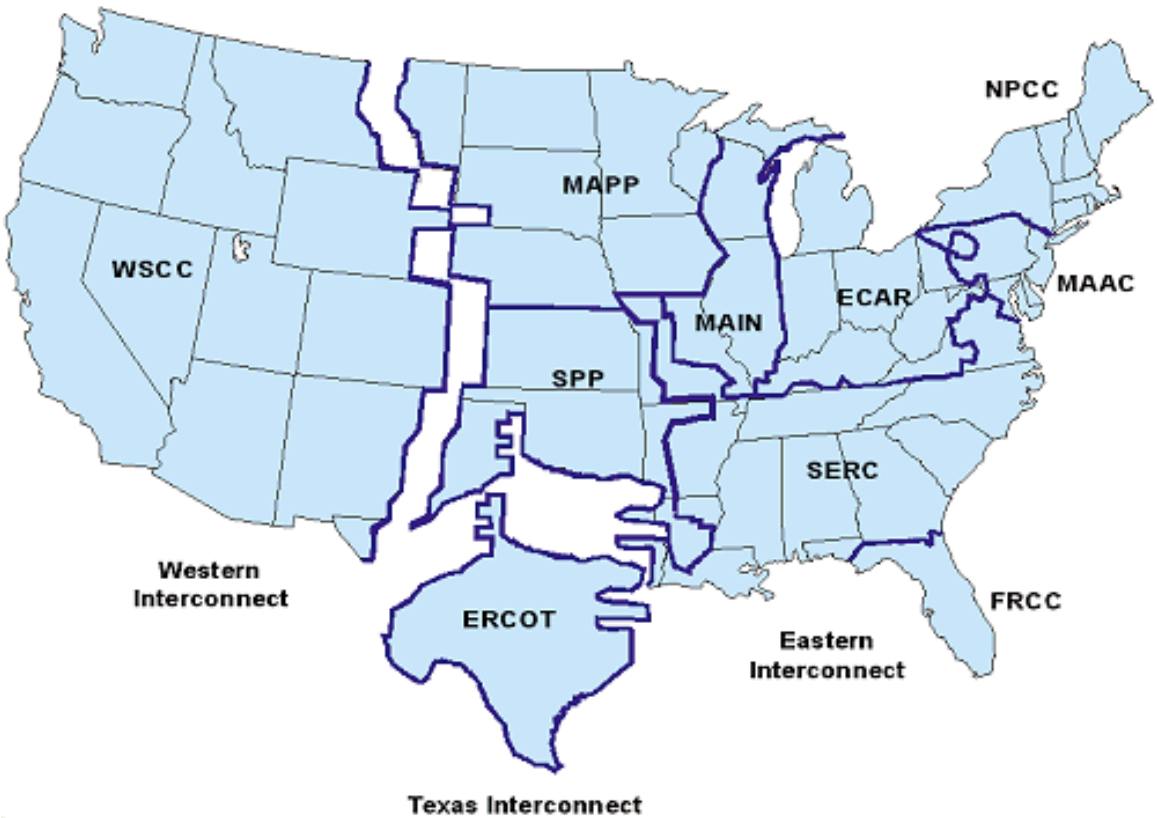
# Why so many different voltages?

To some extent is logical – use higher voltage, more expensive lines for transmitting power long distances

Diversity is due to historical circumstance – grid arose from many independent companies and regions, all of which picked their own voltage standards.

# Linked grid: limited control on how much & where power flows

**No control except the balance of generation and demand.** The entire interconnected grid is a single complex circuit. Imagine a plumbing system with interconnected pipes but no "valves" that control the flow of current. You can't control what power flows where except by tinkering with inputs and outputs




*From the Energy Information Agency, U.S. Dept. of Energy.*

*The U.S. grid is broken into 3 weakly connected regions, and not much power flows in between. But the regions are connected to Canada (strongly) & Mexico (weakly).*

*Texas is its own grid! And its own regulatory entity.*

# High-voltage transmission lines are multiples of 3

Image: PennLive.com

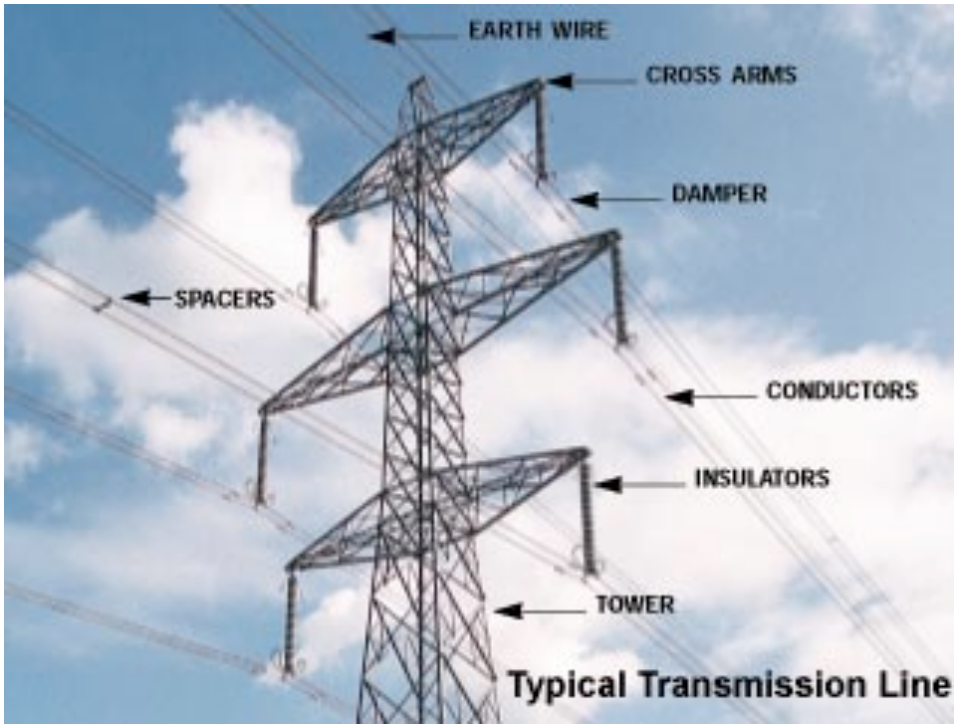
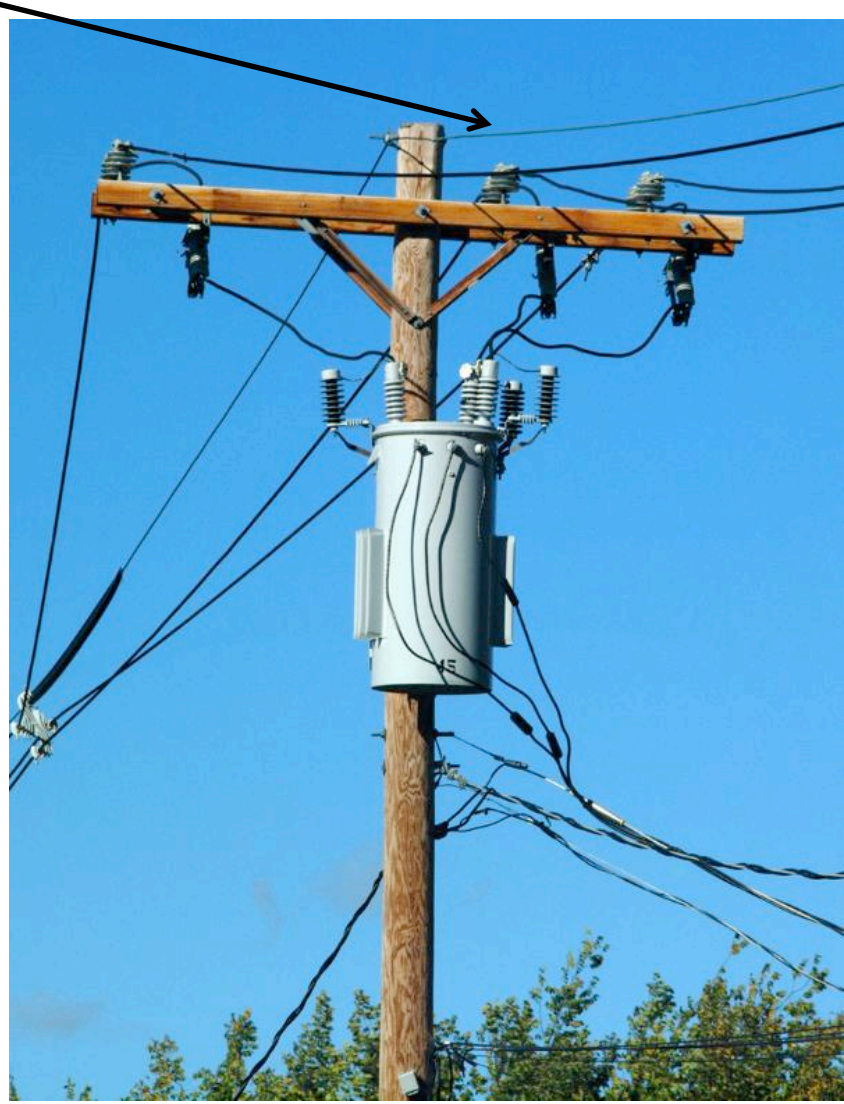



Image: NationalGrid

# **Distribution:** why 4 wires now?



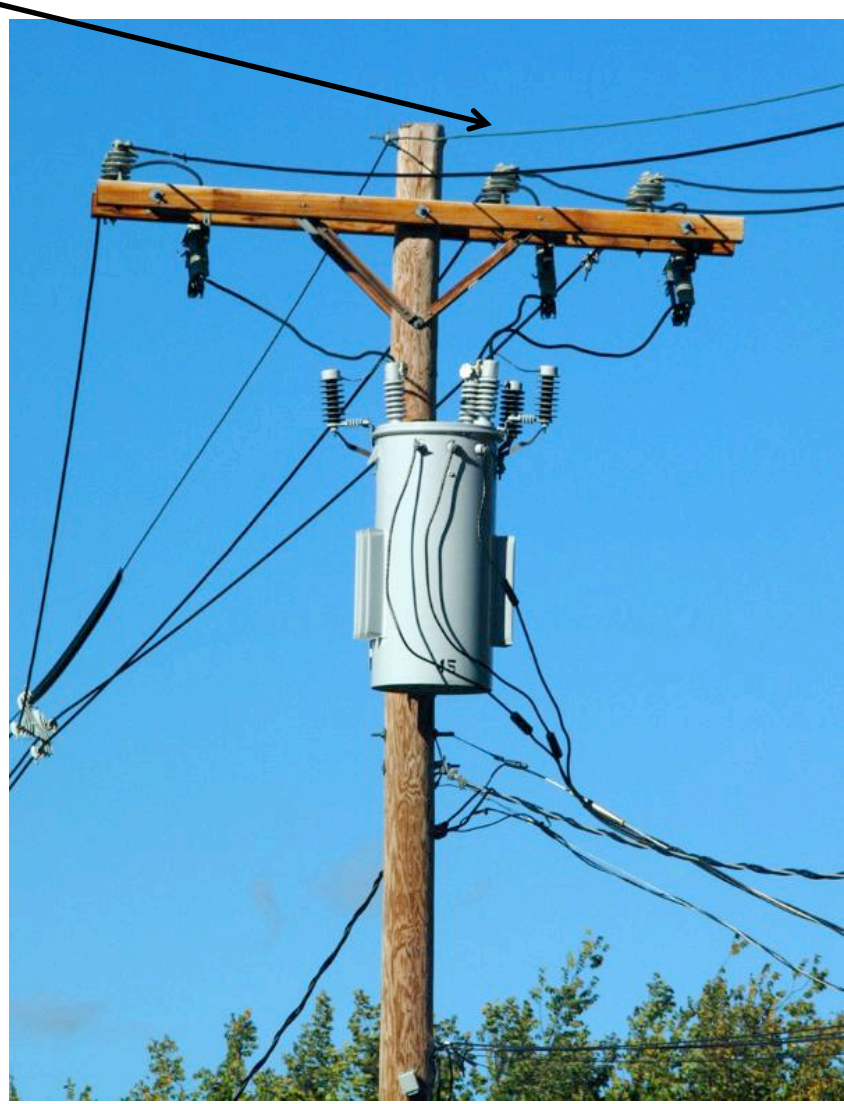
# **Distribution:** neutral wire is added

For long-distance high-voltage transmission, there is no need for return wires: we assume the same power draw on each line.

But, at the household level demand can become unbalanced. Each household circuit uses only ONE of the three AC phases, so lines could see different loads.

If demand is unbalanced, then a net flow of current would occur.

Therefore add a neutral (return) wire is therefore added at some point. The return loop just goes back to the substation, or sometimes even just to the local transformer.



# Electricity transmission: what's unusual about this picture?

Long-distance transmission line, Western U.S.

# DC lines carry 4% of U.S. electricity

http://en.wikipedia.org/wiki/Pacific_DC_Intertie

**Pacific DC intertie** (WA to S. California): 1362 km, ±500 kV, carries 3.1GW (3100 A)

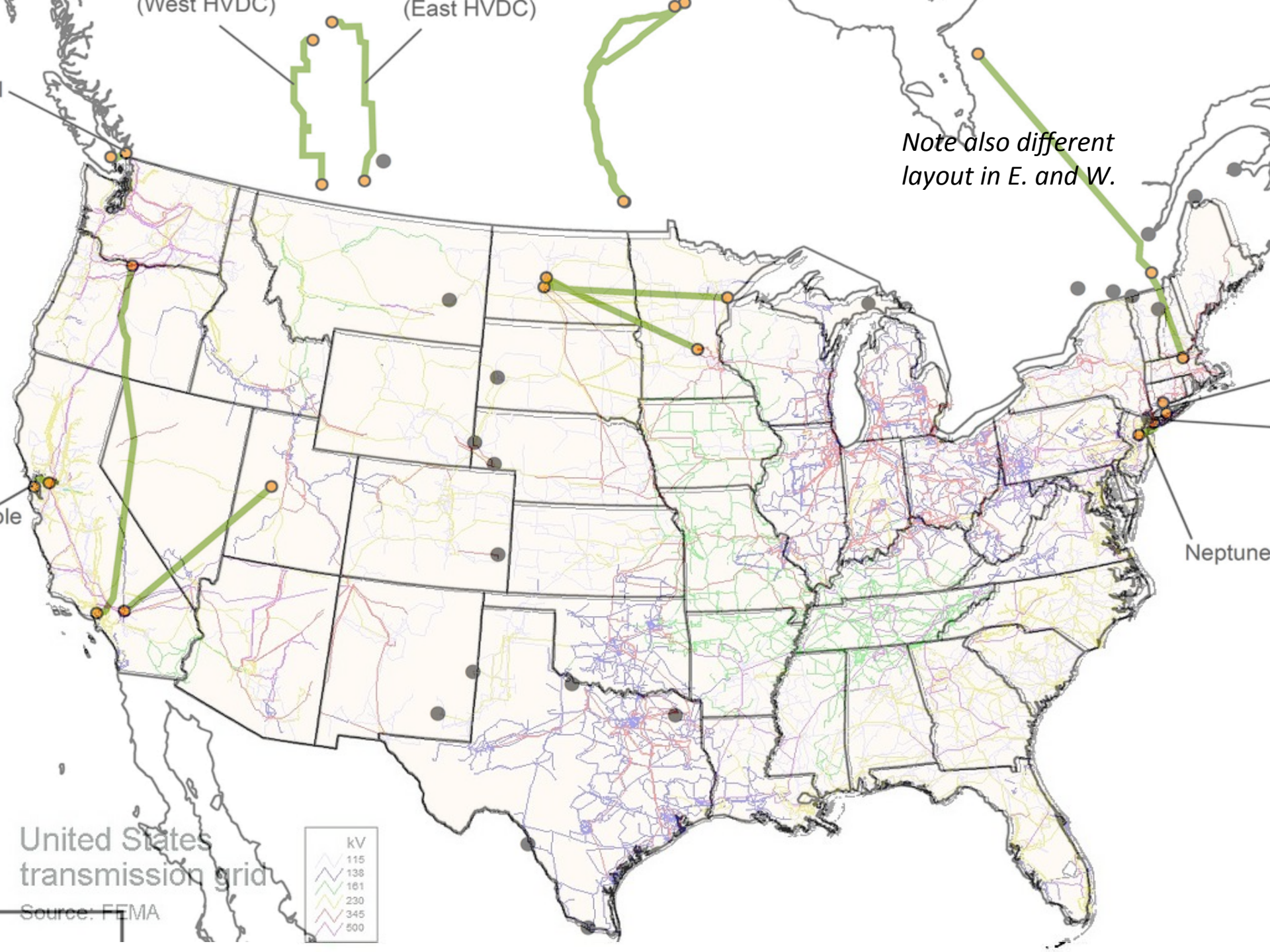
*This is longer and higher-power than is normal in the U.S. The average U.S. AC line is ~400 km at 400 kV, 1600 A --> 650 MW)*

Each wire is uninsulated, 3.9-cm (1.5”) diameter, mostly copper with steel core

Losses on this line = 8% *(~ U.S. average even though line is longer)* Losses w/ DC are lower than those w/ AC since no inductive reactance – only direct $I^2R$ Joule heating.

Most DC is very long, very high-voltage lines. Why? Because rectifying/inverting is expensive and inefficient. DC only offers net benefit for long-distance transmission.

Longest HVDC in world is the Rio Madeira in Brazil (2385 km). *Used to be (1982): DRC, Inga Dam to Shaba copper mine (1700 km)*


(West HVDC)
(East HVDC)
Note also different layout in E. and W.
Neptune
United States transmission grid
Source: FEMA
kV
115
138
161
230
345
500

# China is leading in DC transmission now

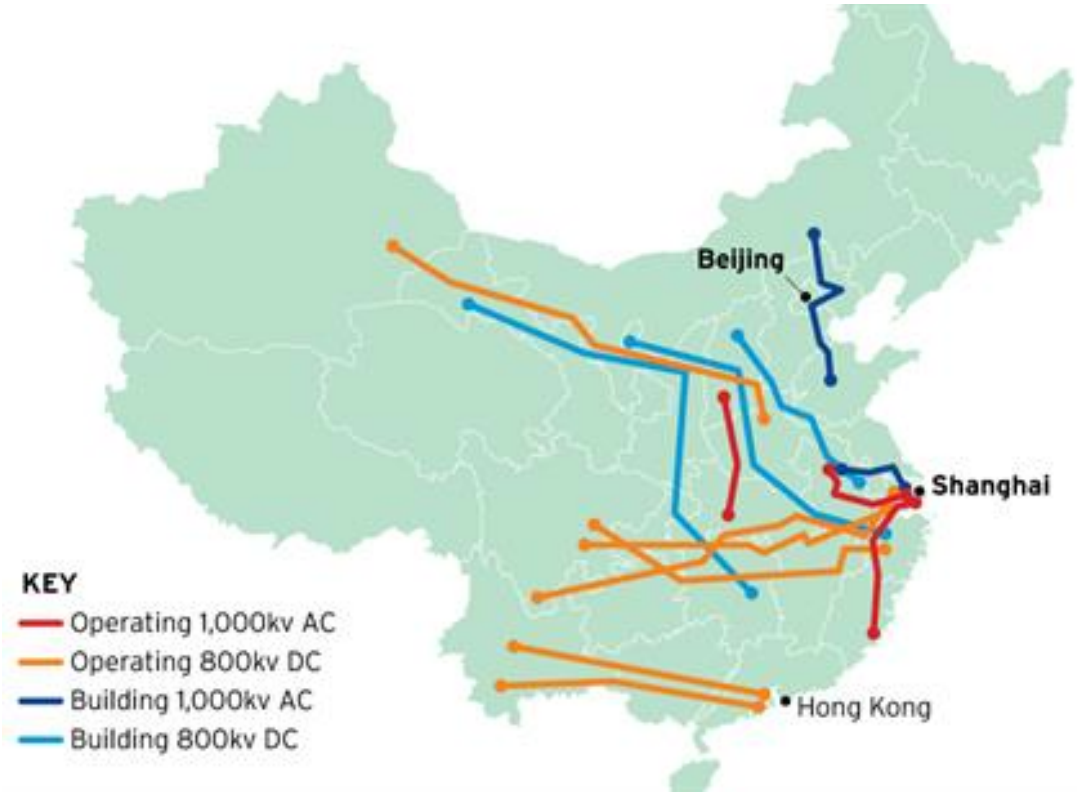
China has completed thousands of miles of HVDC transmission lines in the last decade

The last long distance HVDC transmission line in the United States was completed in 1989

**Online Date**

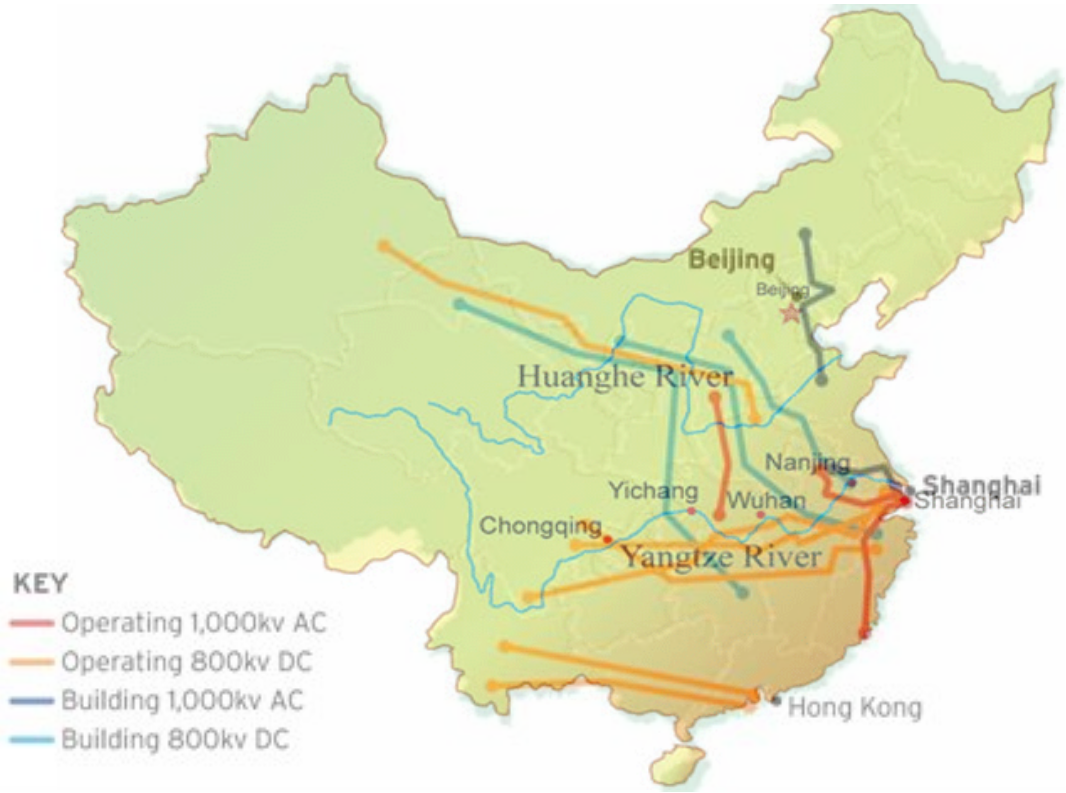
- 1970s
- 1980s
- 1990s
- 2000s

# China is leading in DC transmission now




Where are DC lines connecting to?

# China is leading in DC transmission now




Where are DC lines connecting to?

*...many are for hydro*

# Faraday’s law in transformers, generators, motors

# Motors and generators are converses

**Ampere's law:**

current flowing in a wire generates a magnetic field

*If I flow current through a wire loop in a magnetic field it will rotate*

→ *motors*

**Faraday's law:**

changing magnetic flux in a wire loop induces current to flow

*If I rotate a wire loop in a magnetic field it will produce a current*

→ *generators*

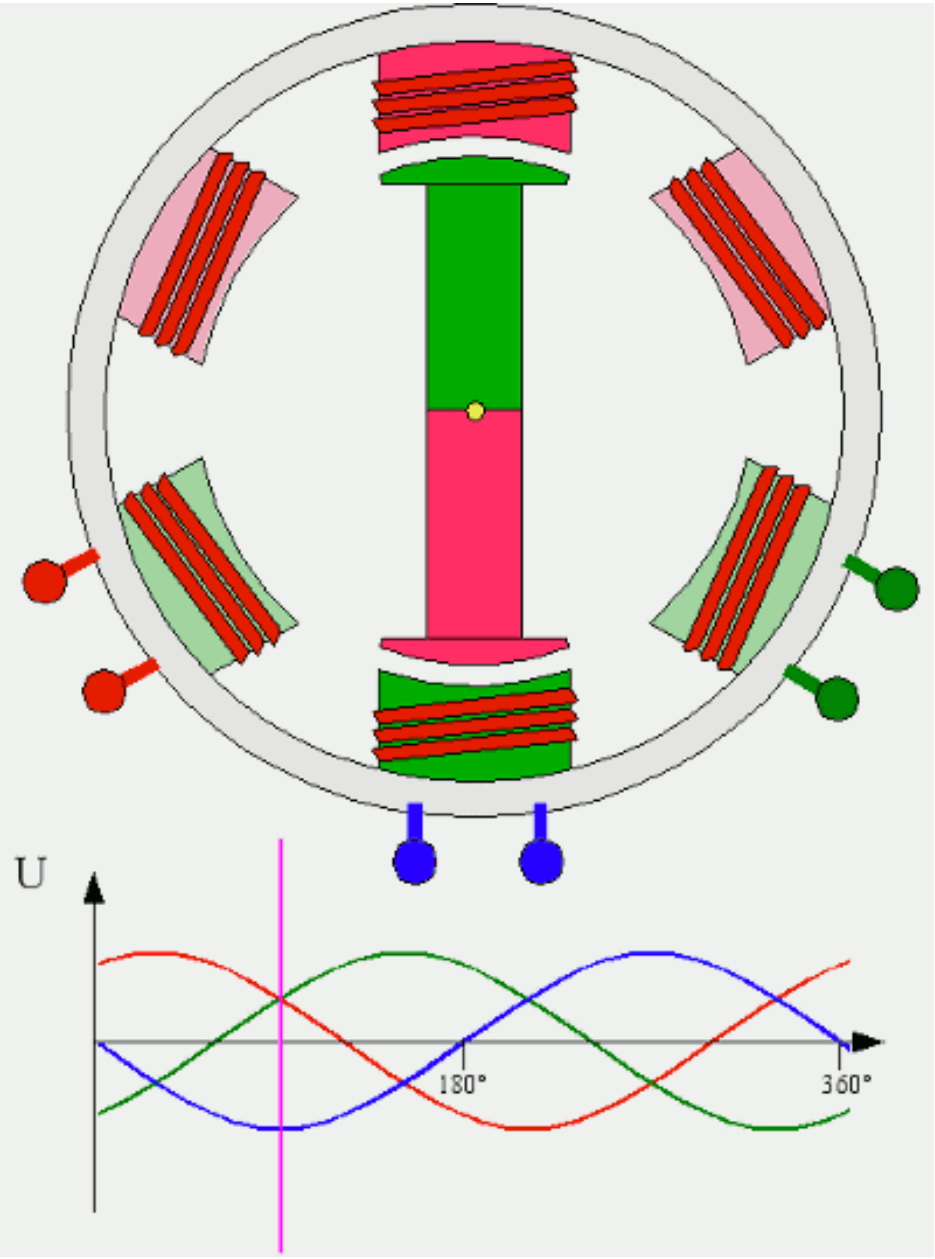
$\varepsilon = -N\, d\phi/dt$ where $\varepsilon$ = electromotive force (voltage), &

$\phi$ = magnetic flux, field lines captured by loop

Lenz's law: the induced $\varepsilon$ opposes the change producing it

# Rotation rate of turbine directly sets AC frequency

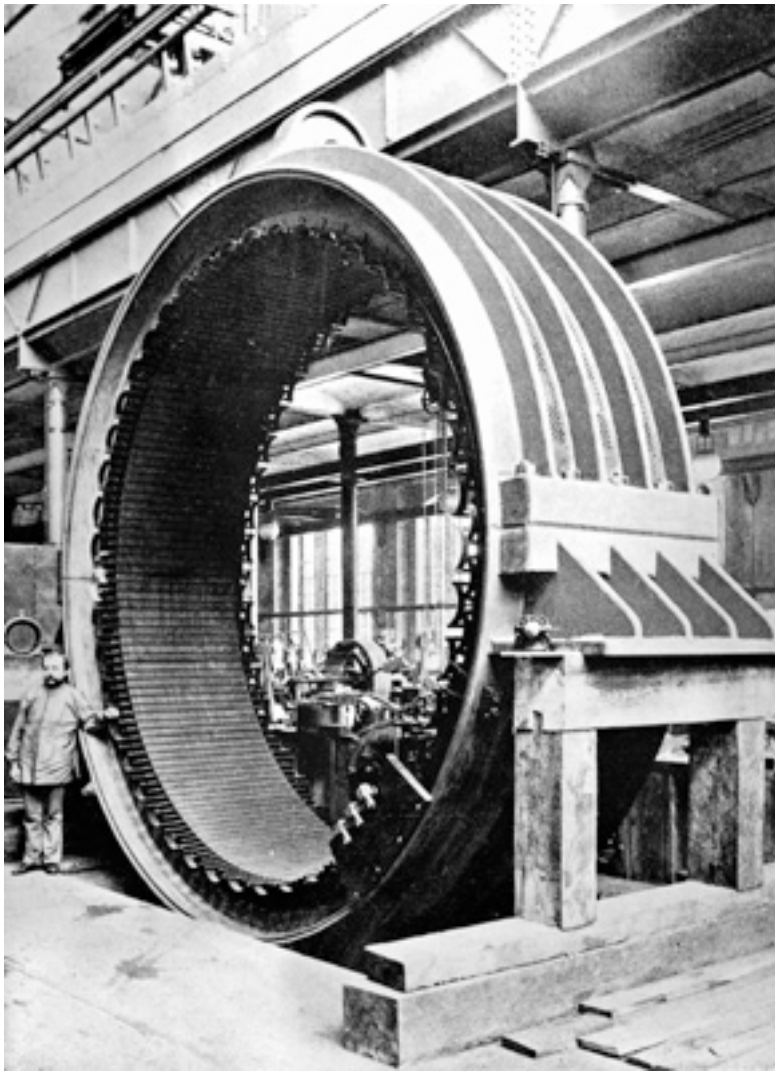
By Faraday's law, also sets electrical power produced



# Generating electricity

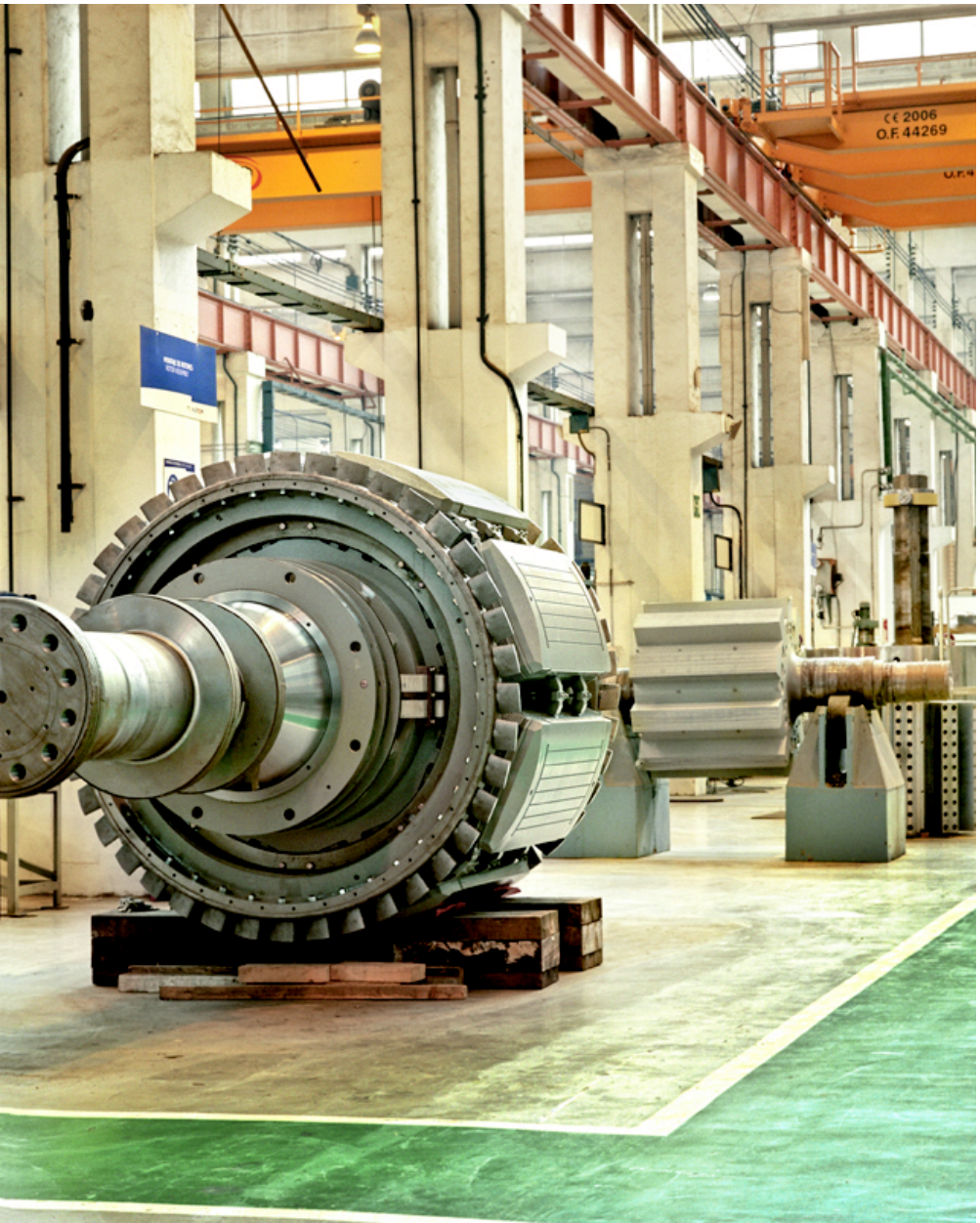
# Generator design virtually unchanged in 100 yrs

Stator, 3-phase generator, Wellluck Co., China, 12.5 MW, 2010



Stator, 3-phase generator, Brakpan, South Africa, 1897. *Photo: Siemens*

# Rotor carries electromagnet




*Old mill rotor (source unknown)*

*Small Hydro Generator rotor - Rotor Assembly Area - Alstom Hydro Manufacturing site in Galindo (Spain) copyright © 2010 M. Monteaux for Alstom*

# Marketing and managing electricity

*Key issue:* electricity storage is cost-prohibitive

→ supply and demand must match at all times

→ if they don't match, electricity goes out of spec

# Who owns and manages what?

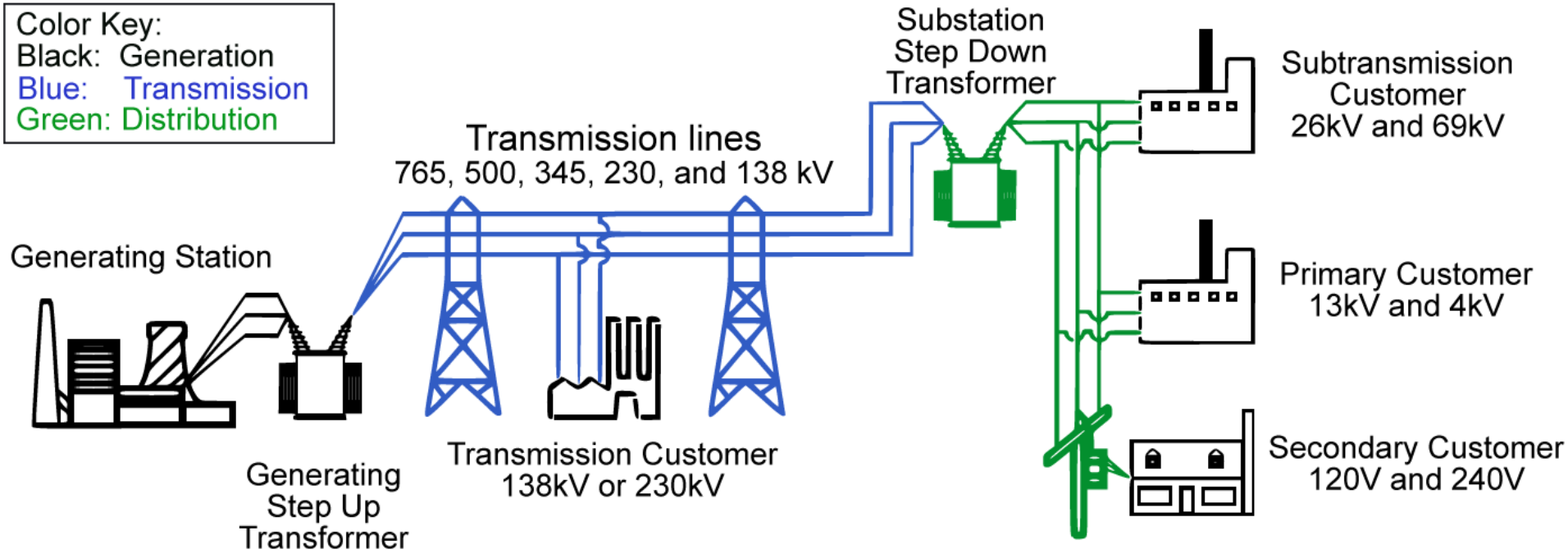



*Image: Wikipedia*

For most of 20th century, one entity owned all components in chain

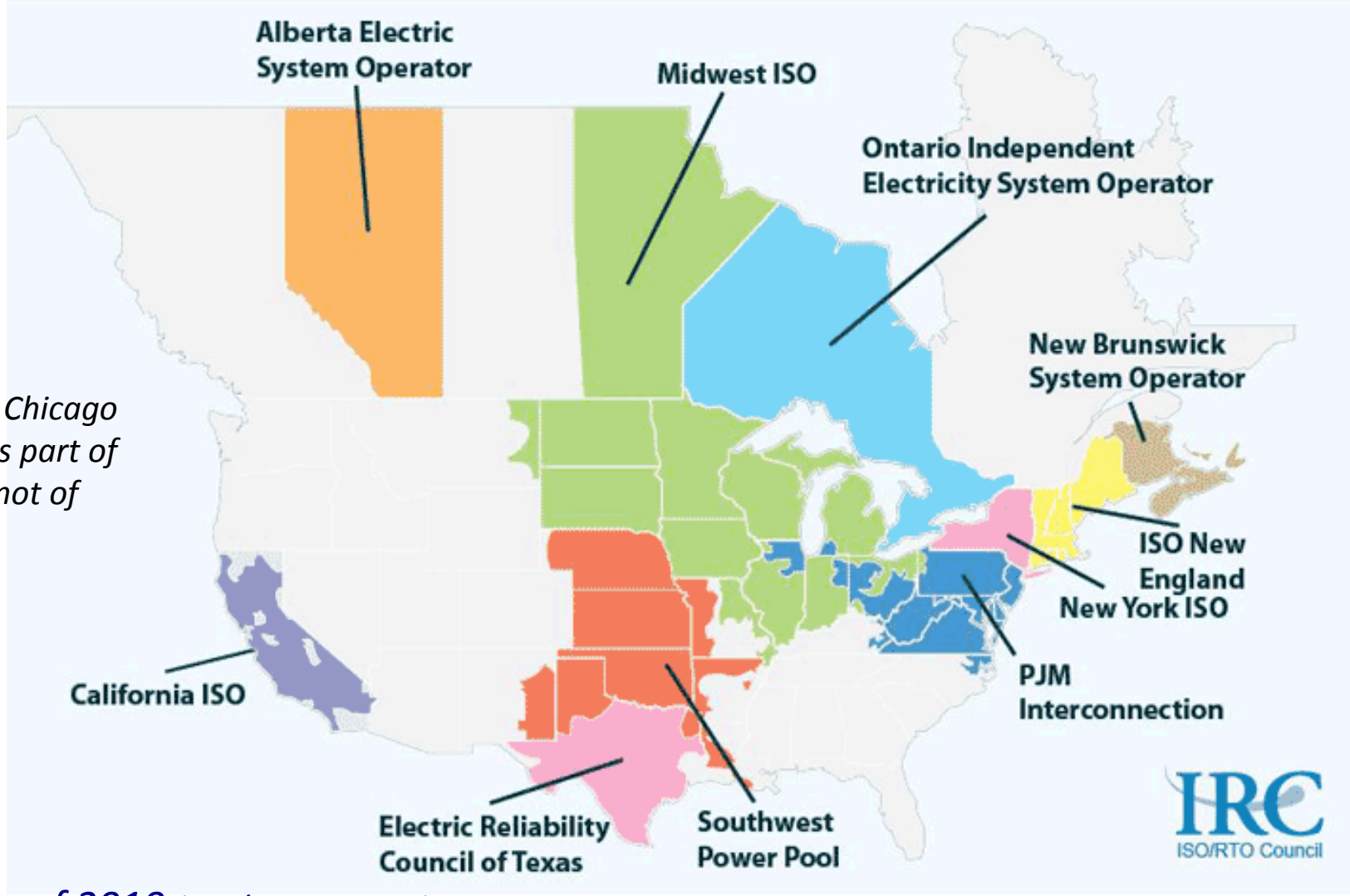
Now typically owned by 2 or 3 diff. entities, managed by another, and market can be managed by outside broker – up to 5 players in game

- Generator
- Transmitter (long-dist. wires)
- Grid operator (wires operator)
- Utility for distribution (local wires)
- Load-serving entity (seller to consumer)

# 60% of U.S. electrical power supply is managed by RTOs and ISOs

*developed in 1990s to encourage competitive generation, access to transmission*

*Note: Chicago area is part of PJM, not of MISO*




*RTOs as of 2010 (ISO/RTO Council)*

# Introducing competition to lower prices increases complexity

### *In the old days*

The utilities owned everything, and would charge customers enough to recover their costs. The state utilities commission would approve the rates.

### *Nowadays*

**Generator price set by the day-ahead market:** Sets the hour by hour price that generators receive for power or for capacity. (Real-time market updates prices to manage supply, congestion)

**Wholesale price set by market and by FERC:** Sets the markup that the RTO can charge over market. Sets the transmission rates.

**Retail price set by state utilities commissions:** Determines the rates that the utilities can charge their customers. Flat rates – no hourly changes.

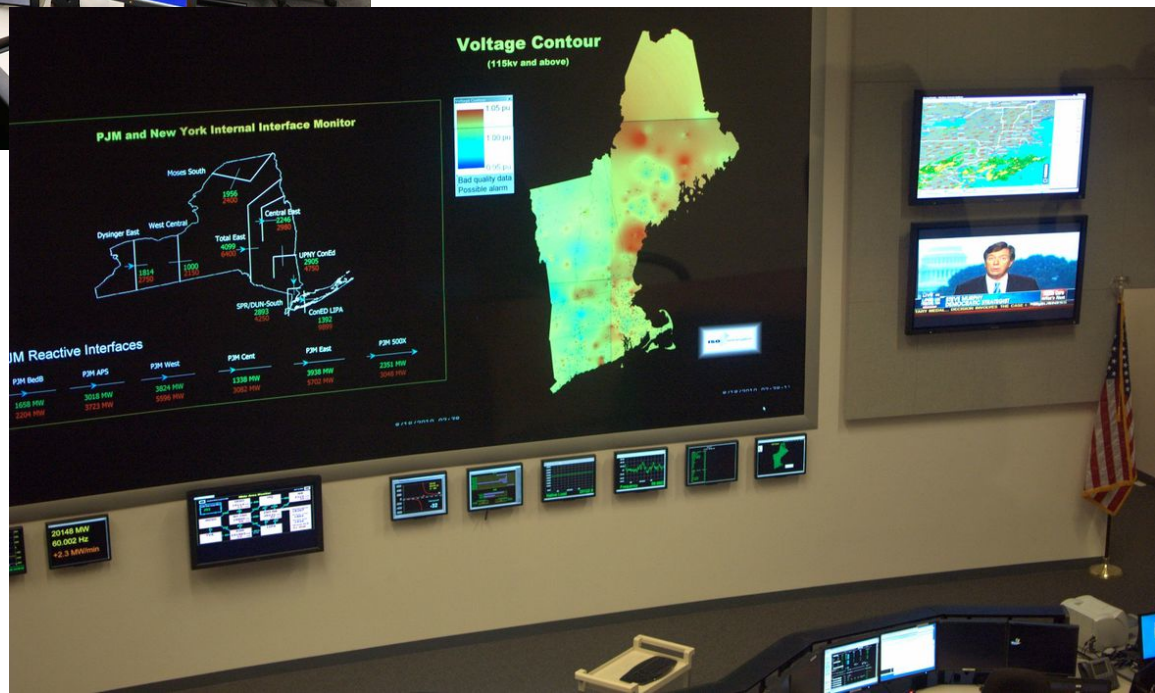
# **Dispatch:** control rooms of ISOs and RTOs

*("independent service operators" and "regional transmission organizations")*


PJM control room
(dual replicates, one in MN)
60 M customers in 13 states

*(photos: top - PJM Interconnection*

# **Dispatch:** control rooms of ISOs and RTOs

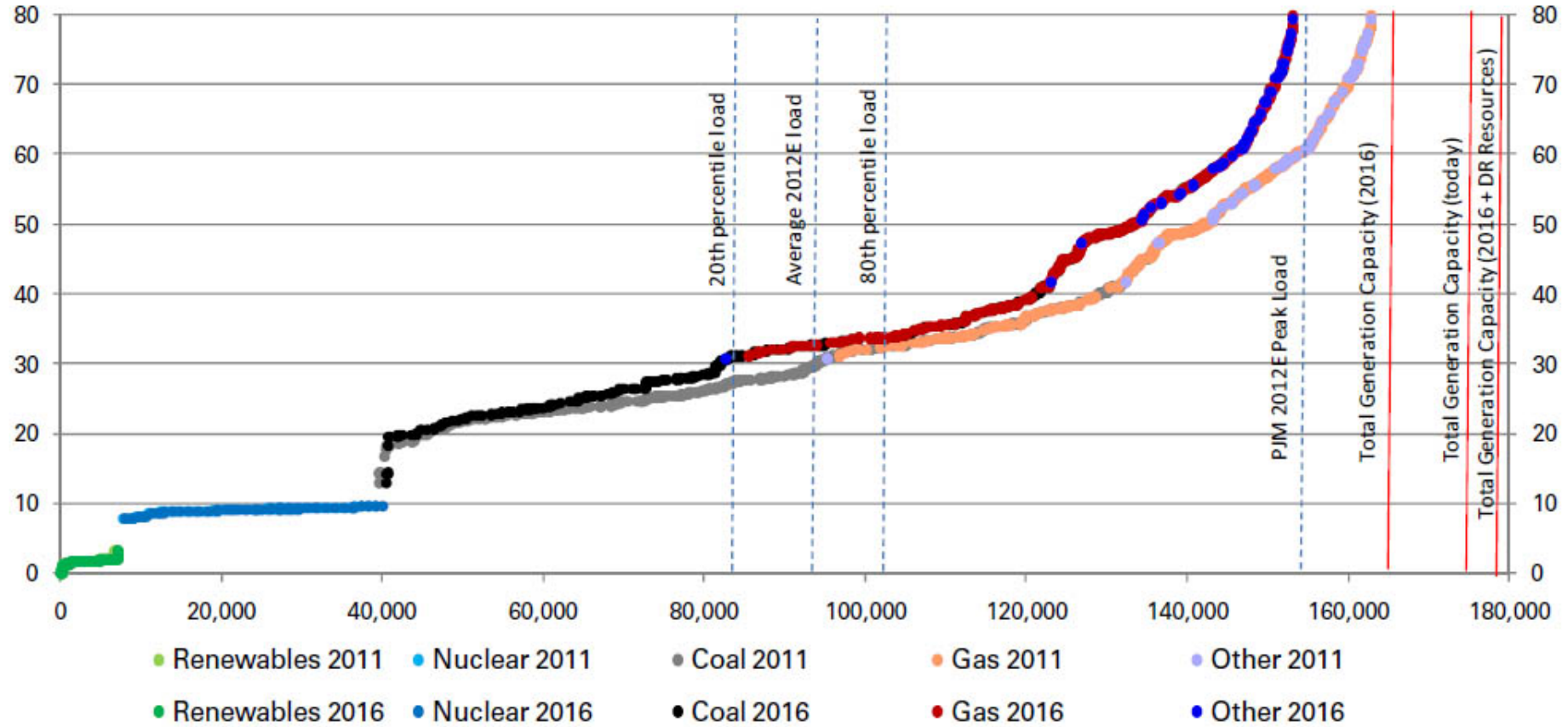




ISO-New England control room
Hoyoke, MA

*(photos: ISO New England)*

# Day-ahead prices set by intersection of demand, supply stack

Figure 19: PJM Supply Curve – 2011 vs. DB 2016E ($/MWh and MWs of Capacity)




*Source: Deutsche Bank; Energy Velocity; PJM. *2012 load estimates are from Energy Velocity.*

**Electricity market used to work, just by coincidence:**

*key feature: peakers were always more expensive than baseload*

In all previous history, the expensive marginal cost generation is fast to turn on and off, so can be used as peakers when demand is high

| Generation Type | Response time |
|---|---|
| Pumped Storage | 10 seconds |
| Gas Turbines | 2 minutes |
| Combined Cycle Gas Turbine | 6 hours |
| Oil Fired | 8 hours |
| Small Coal | 12 hours |
| Large Coal | 24 hours |
| Nuclear | 48 hours |

**Table 4: Typical Response Times of various forms of Power Generation (National Grid Company, 2007).**

***Issue:*** now the marginal generation is often coal, which is slow to dispatch