ECE 333

Green Electric Energy

Lecture 2

Power Grid History

Professor Andrew Stillwell

Department of Electrical and Computer Engineering

Slides Credit Prof. Tim O'Connell and George Gross

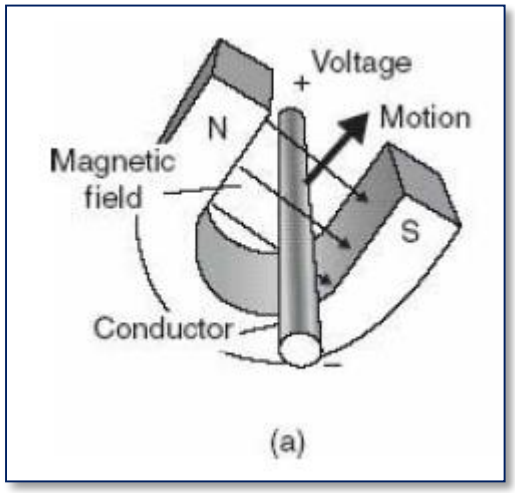
Announcements

- HW 1 will be posted after class
  - Problems are due in-class next Thursday, Jan. 30th
  - Supplemental reading will be discussed next Thursday, Jan. 30th
- TA Office Hours: Wednesdays from 12:00-2:00 pm, Location ECEB 4070
- Today:
  - Sections 1.1 – 1.3 in Masters
    - Electromagnetism
    - AC vs. DC
    - Traditional Electric Utilities
    - De-regulation

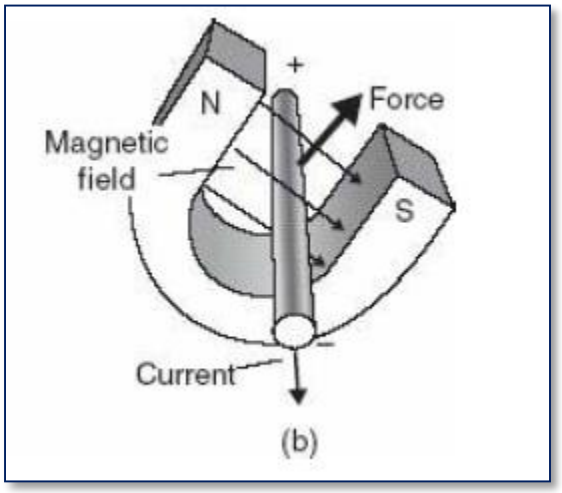
Electromagnetism

- Oersted (1820)
- Faraday (1831)
- Maxwell (1864-1873)

- Tesla (1888); first induction motor and polyphase system

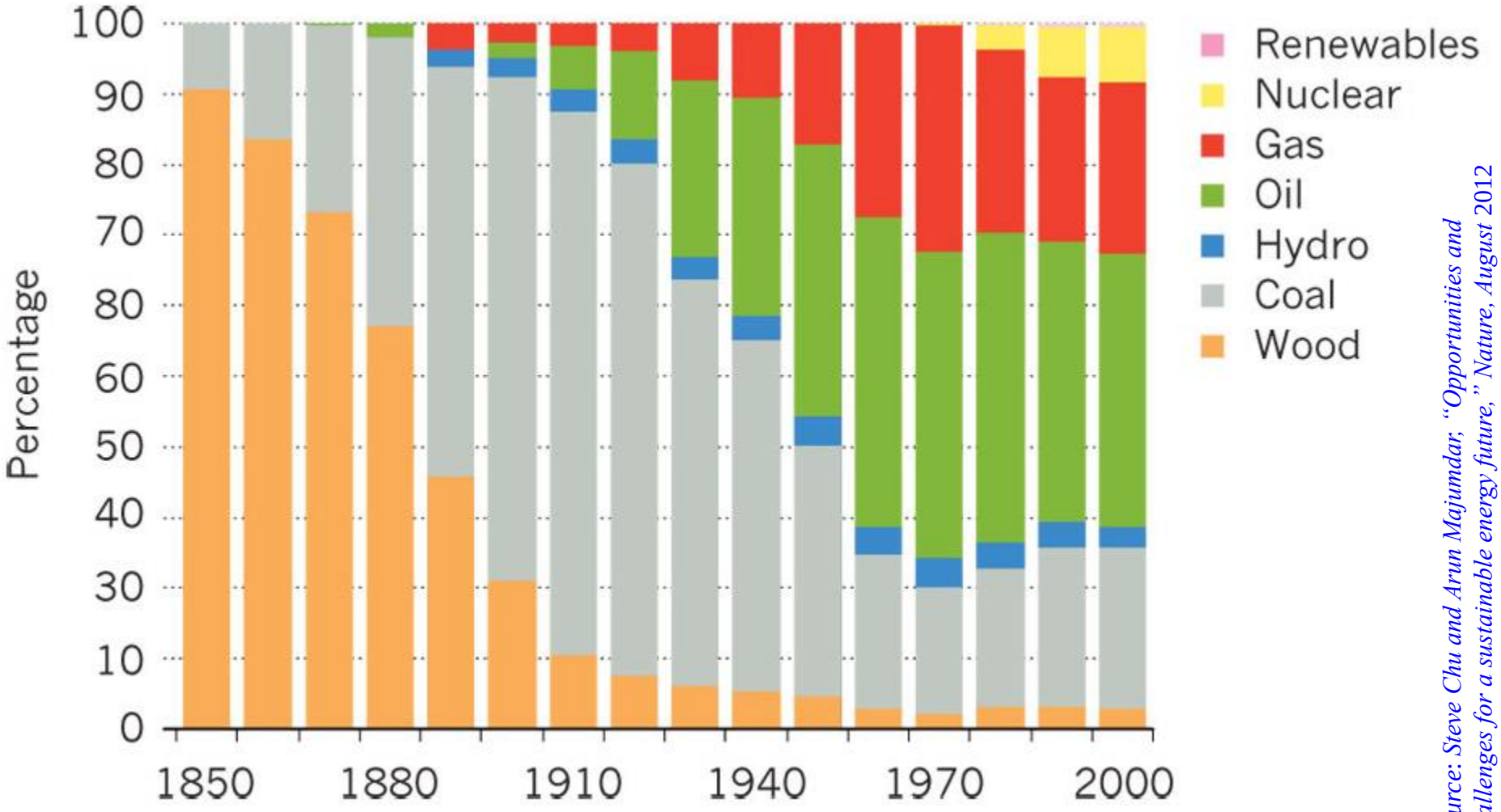


Generator action:
Mechanical to electrical energy conversion



Motor action:
Electrical to mechanical energy conversion

Evolution of the Main Sources of *US* Energy Consumption



Source: Steve Chu and Arun Majumdar, "Opportunities and challenges for a sustainable energy future," Nature, August 2012

US Electric Grid: The Beginnings

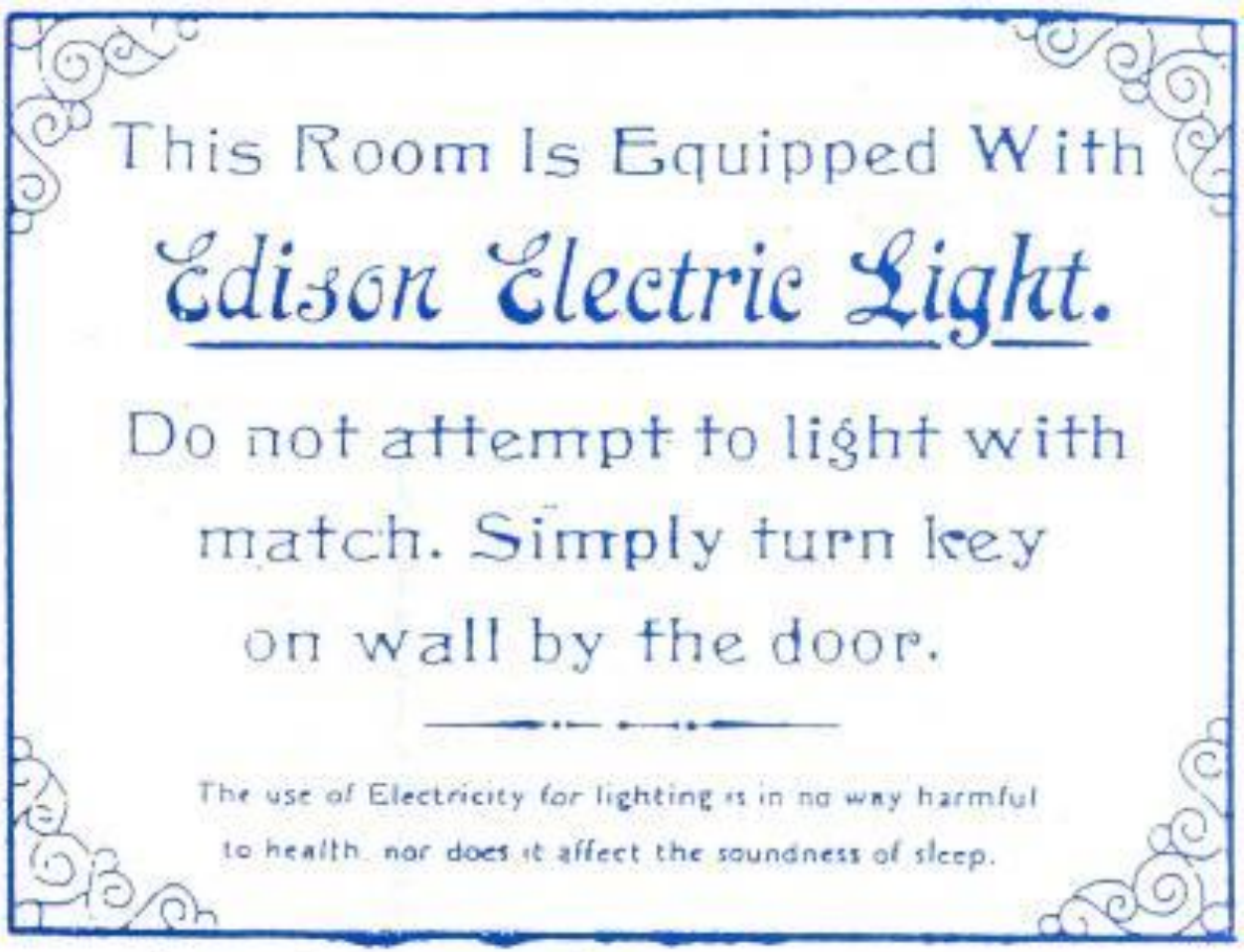
- Commercial use of electricity began in the late 1870's with the development of arc lamps for street lighting and lighthouse illumination
- The first complete electric power system, comprising a generator, cable, fuse, meter and loads, is considered to be *Edison's Pearl Street Station* in New York in 1882
  - DC system with a DC generator supply
  - 59 customers within a 1 – mile radius area

The “Great White Way”

Broadway in 1910, with electrified tracks running through Times Square

Bettmann/CORBIS/Bettmann Archive

1882 Edison Poster on Electric Lighting



Issued during the introduction of electricity supply to New York in 1882.

Check out Courier Café in Urbana!!!

The Beginnings*

- Actually, George Roe had founded in 1879 an electric company in San Francisco, which later became part of *PG&E*
  - this was the **first entity in the nation to offer central station electric service to the public**
  - two brush arc–light dynamos supplied 21 lights to serve from sundown to midnight – Sundays and holidays excluded – for ***$* 10 per lamp per week**

*Prof. Gross started his career at PG&E

Edison vs. Westinghouse (Not MCU Phase 4)

General Zod Dr. Strange Beast

Spider-Man!!!

Major Developments

- Frank Sprague developed ***electrical motors*** in 1884; within a short time, he incorporated them into the electricity system
- The major limitations of DC systems became apparent by 1886:
  - inability to deliver power over longer distances
  - need for high voltages for longer distance transmission so as to reduce the associated losses but, considerably lower voltages for generation and consumption

Major Developments

- Gaulard and Gibbs developed the *transformer* and **AC transmission**, the forerunners of the AC transmission systems in use today
- George Westinghouse immediately bought ***US* rights** to the Gaulard and Gibbs technology
- In 1889, the ***first AC transmission line in North America*** – a single phase $4\ kV$, $21\ km$ line – was put into operation to link Willamette Falls to Portland

Major Developments

- A key and important development was **Tesla's invention of induction motors and polyphase systems**
  - Westinghouse purchased the rights to Tesla's inventions on AC motors, generators, transformers and transmission systems
  - Westinghouse was the key driver of the construction of the basis of today's AC grid

Major Developments

- AC won out over DC because
  - the ease of transformation of voltage levels thereby providing the **flexibility** to use different voltage levels for generation/transmission and consumption
  - the increased **simplicity** of AC over DC generators
  - the increased simplicity and **lower costs** of AC over DC motors
- AC replaced DC over a very brief time period

Major Developments

- In 1893, the **first three–phase transmission line** in North America went into service; it was a $2.3\ kV$, $12\ km$ line in Southern California
- Niagara Falls was connected to Buffalo – a $30\ km$ distance – using AC since DC was *not practical*

Technological Developments

- The push to transmit larger amounts of power over larger distances led to higher voltages
  - early systems: 12, 44 and $66\ kV$ (RMS line–to– line)
  - 1922: $165\ kV$
  - 1923: $220\ kV$
  - 1935: $287\ kV$
  - 1953: $330\ kV$
  - 1965: $500\ kV$
  - 1966: $735\ kV$ (*Hydro Quebec*)
  - 1969: $765\ kV$ (*American Electric Power*)

Technological Developments

- Standardization of voltage levels led to voltage classifications
  - 115, 138, 161 and 230 *kV* are *high voltage* (*HV*)
  - 345, 500 and 765 *kV* are *extra high voltage* (*EHV*)
- The development of mercury arc valves in the early 1950's made *HVDC* economical in specific cases for the transmission of larger blocks of power over longer distances

Image credit T&D World, "https://www.tdworld.com/digital-innovations/hvdc/article/20969945/a-short-history-of-the-mercuryarc-valve"

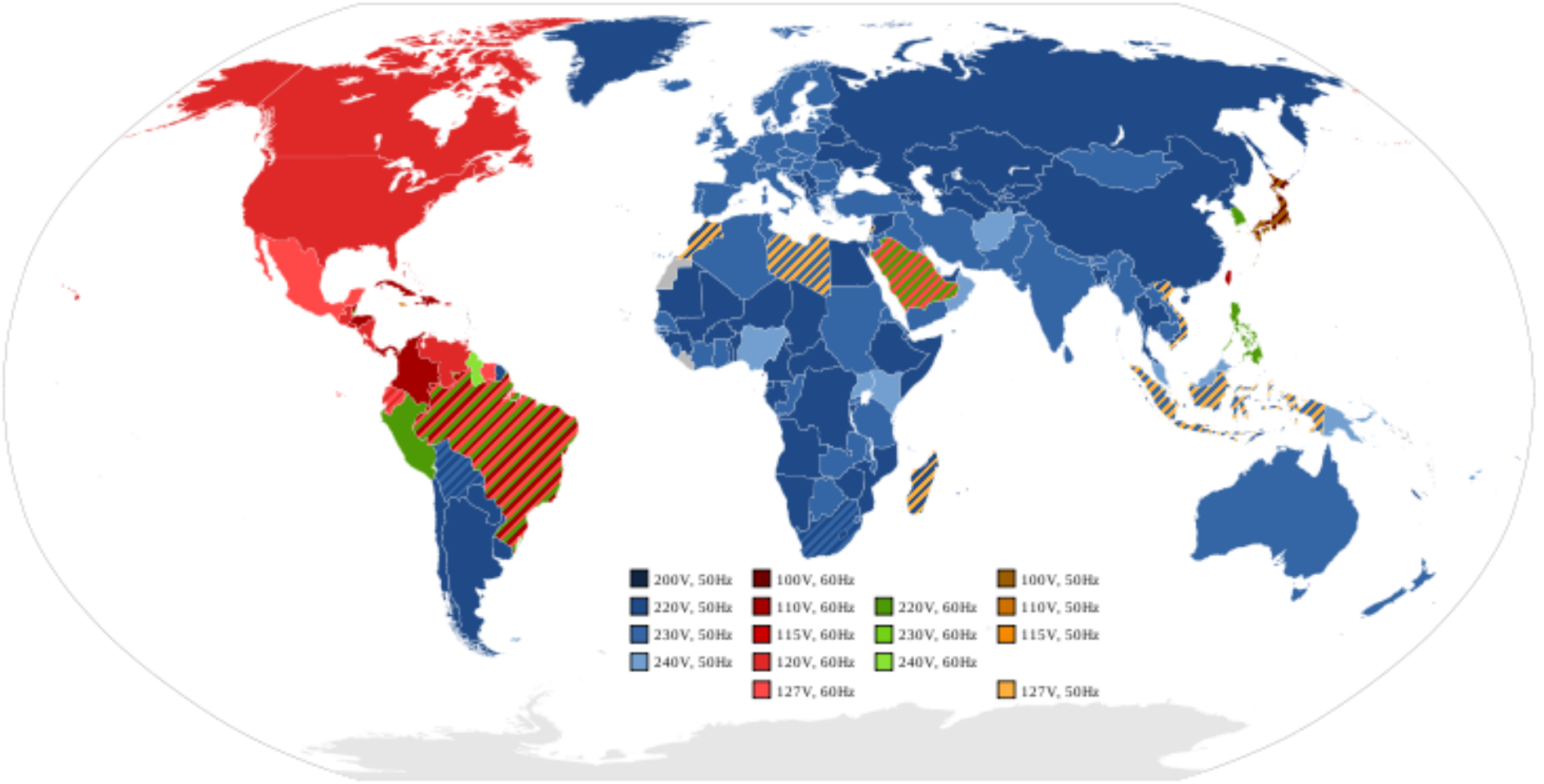
Technological Developments

- Eventually, the various frequencies in use – $25, 50, 60, 125$ and $133\ Hz$ – became standardized to $60\ Hz$ in North America; there are many parts of the world where the frequency is $50\ Hz$ today
- DC became economic over AC for distances that exceed
  - $500\ km$ for overhead lines
  - $50\ km$ for underground/submarine cables

110 or 120 Volts? 220, 230, 240-Volts?

- The standard household voltage used in North America is 120V ±5%, with 240 V ±5% also available.
  - Edison originally used a 100 to 110 V dc system while Westinghouse used a 100 V ac system. The over the years the “standard” has gradually increased to 120 V.
  - It is still quite common to hear the term “110 or 220 V” used, even by power engineers who should know otherwise.
- The European Union has recently standardized on a 230 V system, with some countries changing from 240 V and others from 220 V.

Worldwide Voltages and Frequencies



Source: http://en.wikipedia.org/wiki/File:Weltkarte_der_Netzspannungen_und_Netzfrequenzen.svg

Regulation and Large Utilities

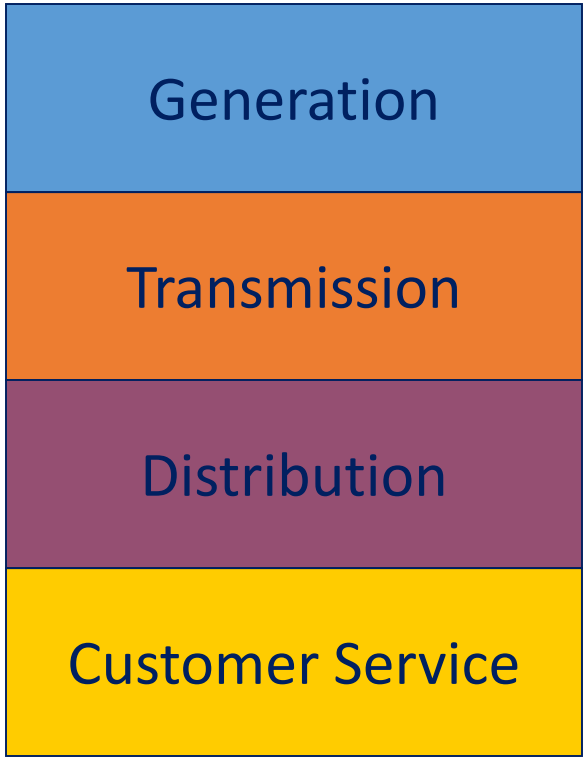
- Electric usage spread rapidly, particularly in urban areas. Samuel Insull (originally Edison's secretary, but later from Chicago) played a major role in the development of large electric utilities and their holding companies
  - Insull was also instrumental in start of state regulation in 1890's
- Public Utilities Holding Company Act (PUHCA) of 1935 essentially broke up inter-state holding companies
  - Coincided with the start of the Securities and Exchange Commission (SEC) (Securities Exchange Act, 1934)

PUHCA (Wheeler-Rayburn Act)

- Enacted in 1935, to facilitate the regulation of electric utilities
  - Limit utility operations to a single state to better regulate them
  - Force divestitures so that each became a single integrated system serving a limited geographic area
- Part of several “trust-busting” activities by congress in response to Wall Street Crash of 1929
- Gave rise to electric utilities that only operated in one state (regulated vertical monopolies)
- Repealed with the Energy Policy Act (EPAct) of 2005

Vertical Monopolies

- For most of the last century electric utilities operated as regulated 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

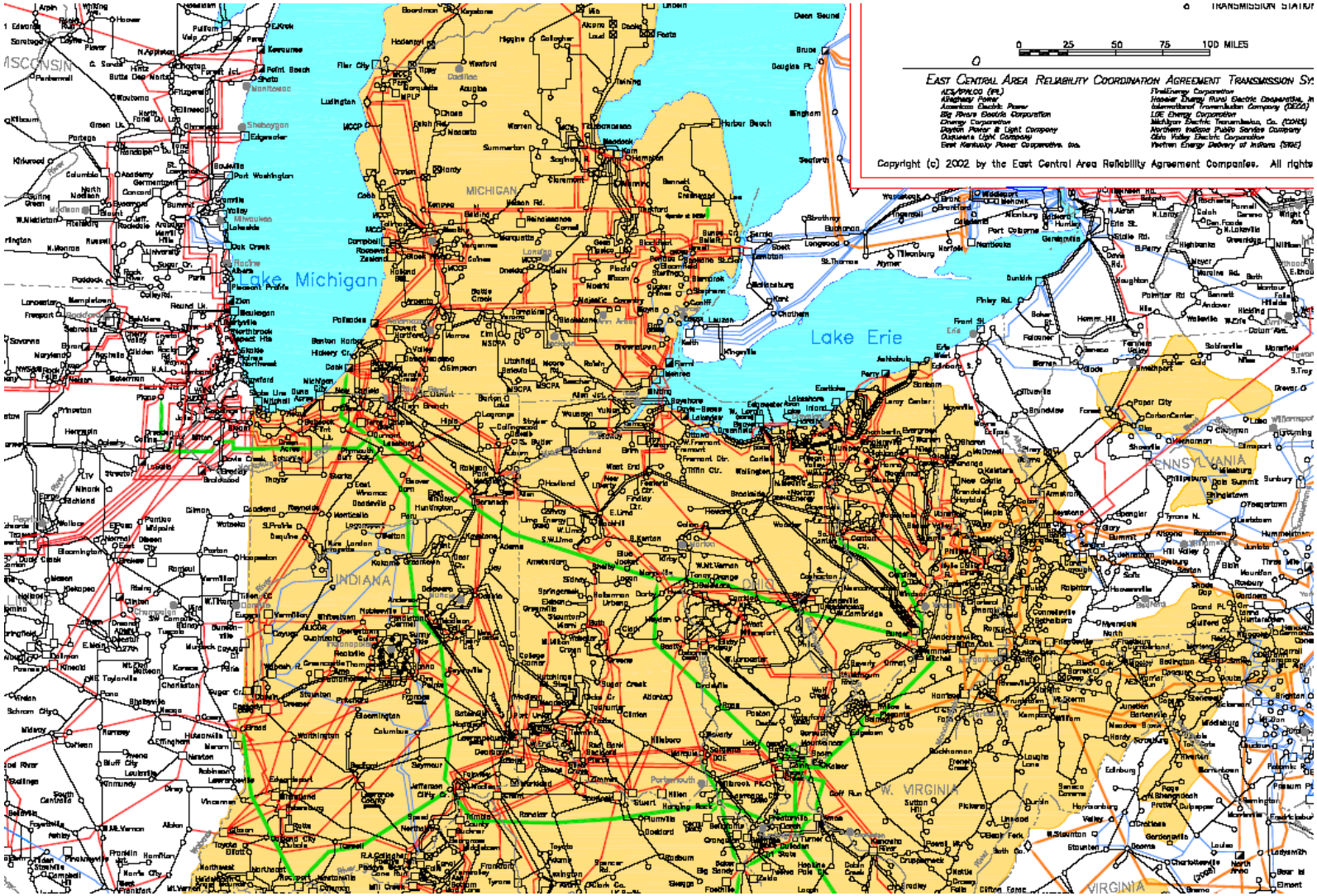
It was a "*cost plus*" business:

- Customer pays the actual production cost plus a fixed fee for profits.
- Little incentive for utility to minimize costs

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 resulted in decreasing rates, so most everyone was happy

Interconnected Electric Grid



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 Utility Regulatory Policies Act (PURPA) in 1978, which mandated utilities must purchase power from independent generators located in their service territory (modified 2005)

PURPA and Renewables

- PURPA was meant to promote greater use of domestic renewable energy
- Forced utilities to buy power from other more efficient producers, if that cost was less than the utility's own "avoided cost" rate to the consumer;
  - *Avoided cost rate*: the additional costs that the electric utility would incur if it generated the required power itself, or if available, could purchase its demand requirements from another source
  - At the time this was typically the cost to build/operate new fossil fuel thermal plants
- It was regulated by states, not federally

Qualifying Facilities (QF's)

- A new class of generating facilities receiving special rate and regulatory treatment via PURPA
- *Small Power Production Facility*
  - 80 MW or less generation
  - Primary energy source is renewable (hydro, wind or solar), biomass, waste, or geothermal resources
- *Cogeneration Facility*
  - Facility that sequentially produces electricity and another form of useful thermal energy (such as heat or steam) in a way that is more efficient than the separate production of both forms of energy.
  - No size limitation

PURPA and Renewables

- Through favorable contracts with QF's, PURPA caused the growth of a large amount of renewable energy in the 1980's (about 12,000 MW of wind, geothermal, small scale hydro, biomass, and solar thermal)
  - California added about 6000 MW of QF capacity during the 1980's, including 1600 MW of wind, 2700 MW of geothermal, and 1200 MW of biomass
  - Inevitably, avoided costs went down over time. By the 1990's the ten-year QFs contracts written at rates of $60/MWh in 1980's had expired, and they were no longer profitable at the $30/MWh 1990 values.
  - Many QF sites (wind farms, mainly) were retired or abandoned

Abandoned Wind Farm: South Point in Hawaii

Source: Prof. Sanders

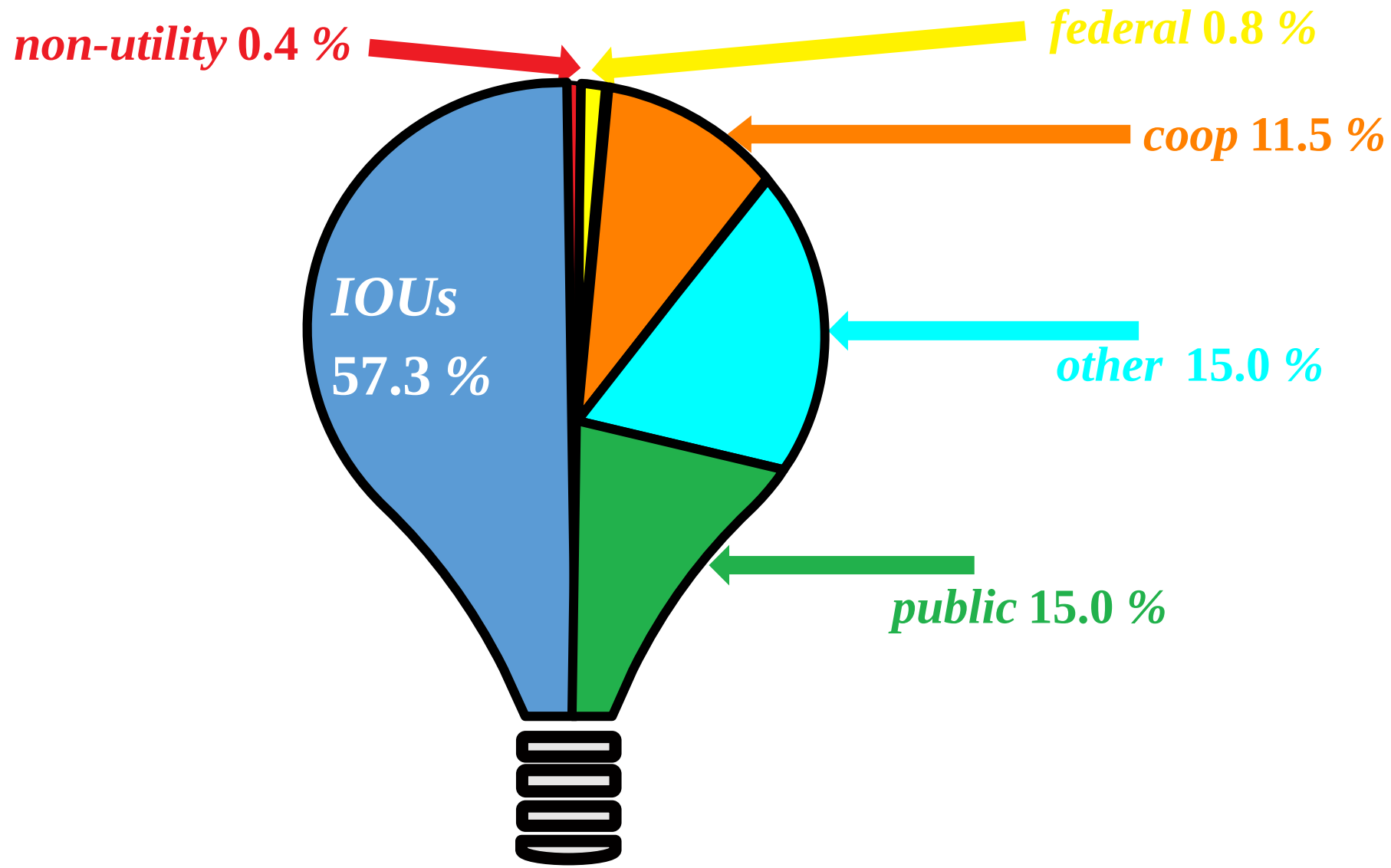
Four Categories of Utilities

- Investor-Owned Utilities (IOUs)
  - Privately owned with publicly traded stock (e.g., Ameren in Illinois; PG&E in California)
- Federally-Owned Utilities
  - Run by the federal government on a non-profit basis (e.g., Tennessee Valley Authority (TVA), U.S. Army Corps of Engineers)
- Publicly-Owned Utilities
  - Local distribution utilities (more on that definition next lecture)
  - Typically exempt from taxes and non-profit
- Rural co-operatives (co-ops)

Independent Power Producers (IPPs) and Merchant Power Plants

- IPPs and Merchant Power Plants are not utilities, in the traditional sense. They are non-utility generators (NUGs) that sell their power into the grid.
  - IPPs sell at pre-negotiated price (Power Purchase Agreement)
  - Merchant Plants sell at wholesale spot market price
  - NUGs were granted access to the grid with the National Energy Policy Act of 1992 (more on this below)
- The introduction of NUGs to the grid required independent system operators (ISOs) to enforce rules and try to make a fair system.

Percent of Customers Served by Electricity Providers

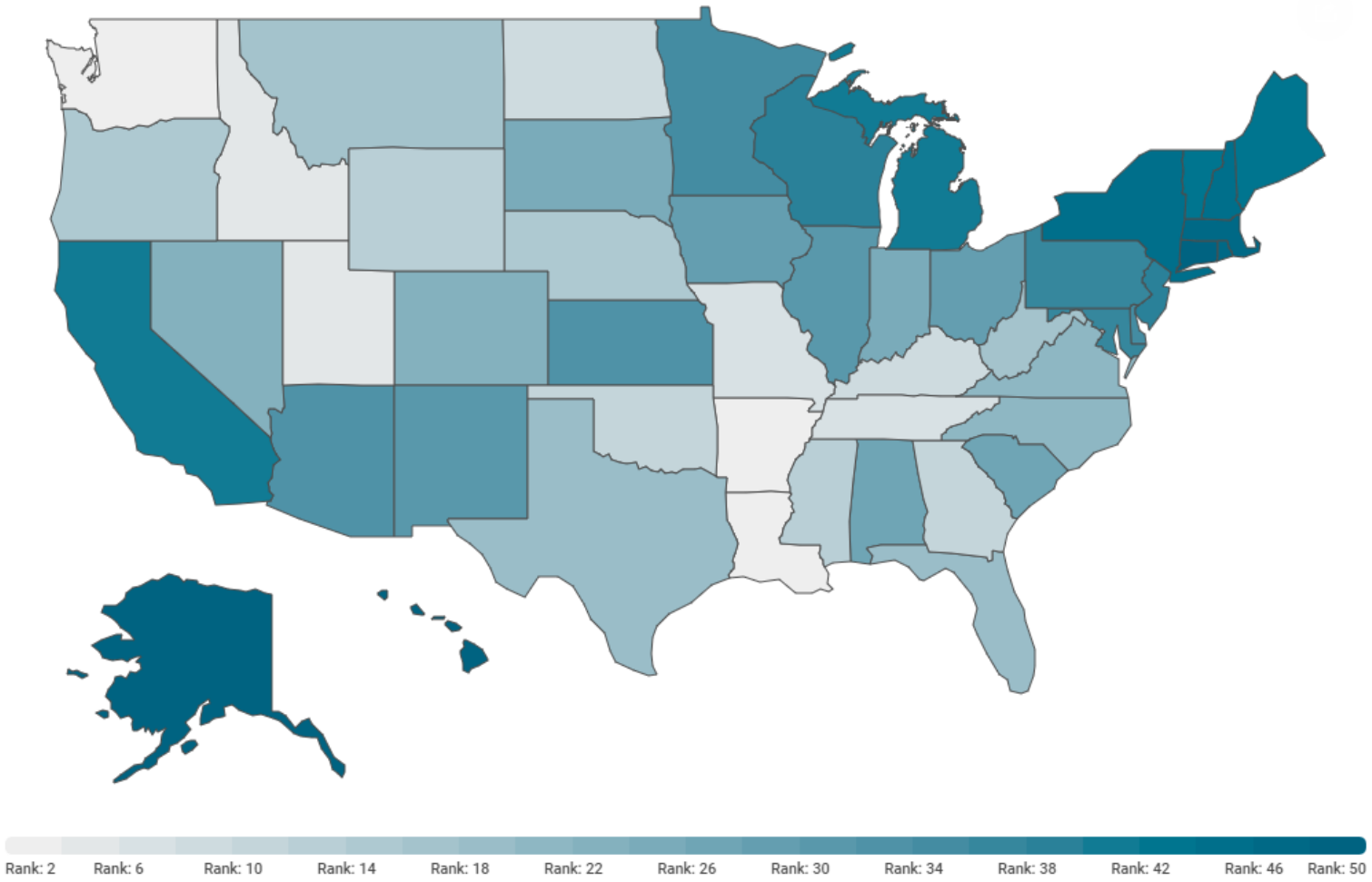


Source: Table 9 at http://www.eia.gov/electricity/state/unitedstates/

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 "non-discriminatory" 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 Policy Act (EPAct) of 2005 repealed PUHCA; modified PURPA

State Variation in Electric Rates



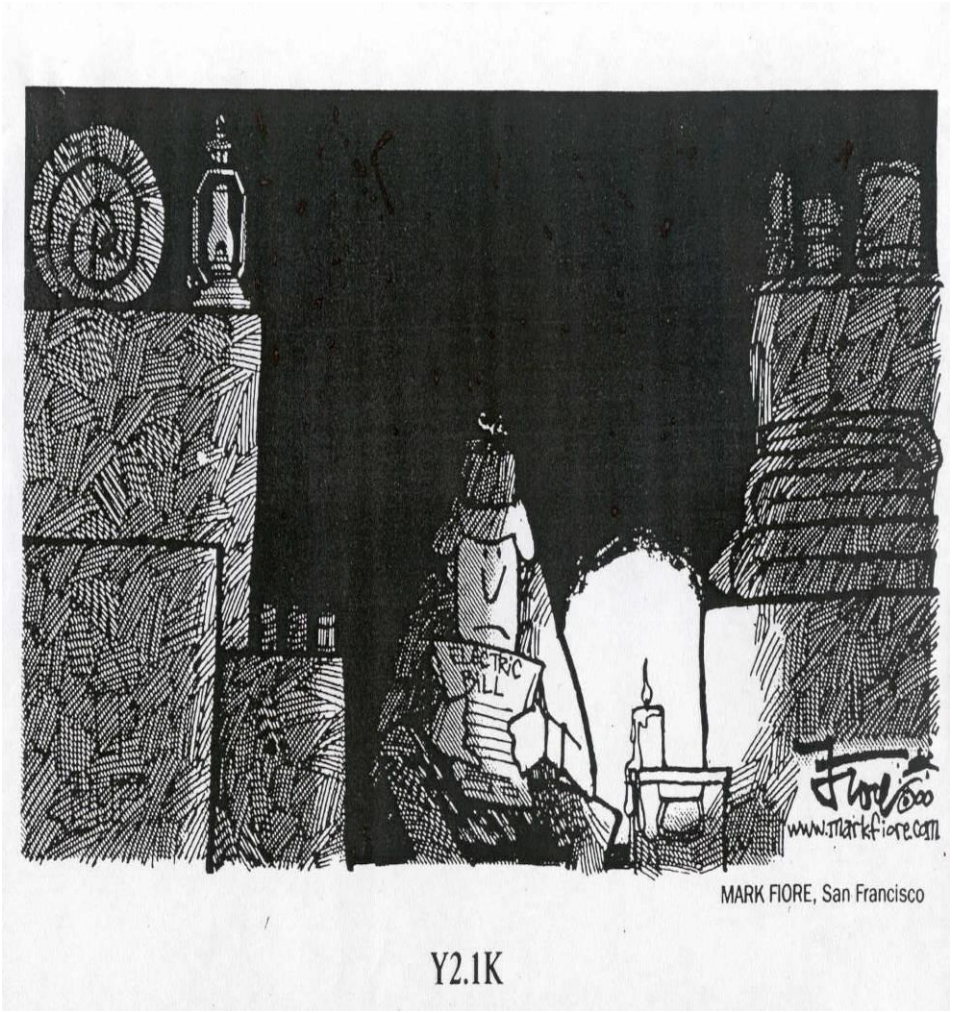
Rate: Average Electric Rate (in ¢/kWh)
Rank: 1=Lowest rate
Change: % Change (from previous month)

Deregulation's Goal: Customer Choice

De-Regulation in California in the 1990's

- California's rates were really high
- Assembly Bill 1890
  - Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) forced to sell of their generation assets to NUGs
    - NUGS would compete to sell power, lowering prices
  - Customers get choice of electricity supplier
  - Utilities would buy power from the competitive market cheaply, and would sell it at guaranteed (high) rates for years (1996-2000)
  - Energy auctions were set up to find the lowest price

The Result for California in 2000/1



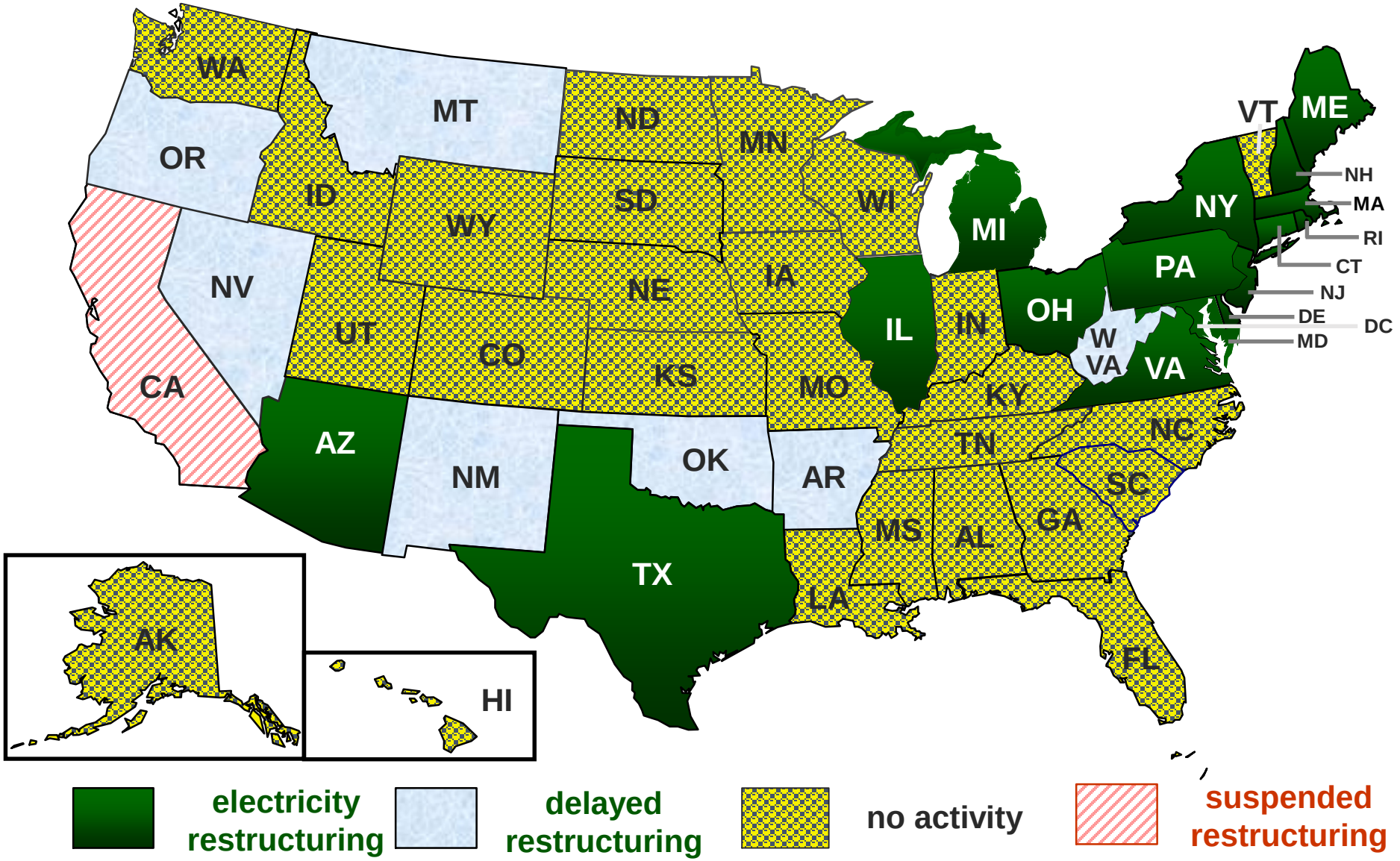
Enron and the California energy crisis

- "Burn baby burn"
  - Forest fire shut down a major transmission line into California, cutting power supplies and raising prices; Enron energy traders celebrated
- "Stick it to Grandma Millie"
  - Enron (and other company) traders manipulated the California market by turning off generators to raise rates
  - Rates rose to $1.50/kWh in some cases (in Illinois they are roughly $0.12/kWh)

The Enron disaster

- Enron: The Smartest Guys in the Room
  - 2003 book, 2005 documentary movie about the Enron Scandal
  - Examines the 2001 collapse of Enron (Houston-based energy, services and commodities company), which resulted in criminal trials for several of the company's top executives
  - Shows the involvement of the Enron traders in the California energy crisis
  - Enron went bankrupt in 2001, largely due to bad business moves hidden by accounting fraud
  - Enron traders partially to blame for California energy crisis by gaming the power grid to raise rates and make more money

The California-Enron Effect



Source : *http://www.eia.doe.gov/cneaf/electricity/chg_str/regmap.html*

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.

Electricity Market De-Regulation

- De-Regulation: The electricity market is open to competition rather than being controlled by utilities with monopolies
  - Goal is to introduce competition into the market, which should reduce prices and give consumers more choice
  - However, only applies to the supplier; the utility is still in charge of maintenance and delivery (the infrastructure)
- CA, CT, DC, DE, **IL**, MA, MD, ME, MI, MT, NH, NJ, NY, OH, PA, RI, and TX are all de-regulated
  - None are in the top 10 states with the cheapest energy rates, but several are in the top 10 most expensive
  - Expensive states tend to de-regulate

From: https://www.electricchoice.com/blog/ultimate-guide-illinois-electricity/
https://www.publicpower.org/

De-Regulation in Illinois

- 1997: The Illinois Electric Service Customer Choice and The Rate Relief Law
  - Enacted to combat Illinois' extremely high electricity rates
  - Rates were dramatically lowered by 20% and locked in for 10 years
  - Too low for competitors to emerge, though, so it backfired a little bit.
- 1999: Lawmakers began to remove supply-related services from the major utilities
- 2002: Commercial entities could select their energy provider

2007 Illinois Electricity Crisis

- The two main electric utilities in Illinois are ComEd and Ameren
- A restructuring law from 1997 had frozen electricity prices for ten years, with rate decreases for many.
- Prices rose on January 1, 2007 as price freeze ended; price increases were especially high for electric heating customers who had previously enjoyed rates as low as 2.5 cents/kWh
- Illinois General Assembly had to intervene with the Illinois Power Agency Act
  - One billion dollars in rate relief to residential and commercial customers over 4 years

Average Residential Electricity Rates (October 2018)

- Cheapest:
  - Louisiana, 9.11 cents/kWh
- Most Expensive:
  - Hawaii, 32.46 cents/kWh
  - Alaska, 22.51 cents/kWh
- Close to home:
  - Illinois, 13.23 cents/kWh (31st cheapest)
  - Indiana, 12.39 cents/kWh (25th cheapest)
  - Missouri, 10.71 cents/kWh (7th cheapest)

Wrap-up

- AC vs DC
- Public Utilities Holding Company Act (PUHCA) 1935
- Public Utility Regulatory Policies Act (PURPA) 1978

Next week:

- The Grid and Generation Technologies