The Electrical Grid

The greatest, most complex machine ever built

Agenda

- High-end energy: electricity uses
- Growth predictions

- U.S. Power Plants, geographical distribution
- Power transmission lines, network
- Voltage transformation, reactive power
- Balancing supply & demand

- E-Grid failures/vulnerabilities
- Grid organization/management
- Internet of Things

- **Tutorial:** electricity, electronics
  Electric generators (dynamos) and motors, transformers
  AC-DC circuits, 3-phase currents
  complex calculus

High-End Energy Now: Electricity

Manufacturing Industry

Home Entertainment

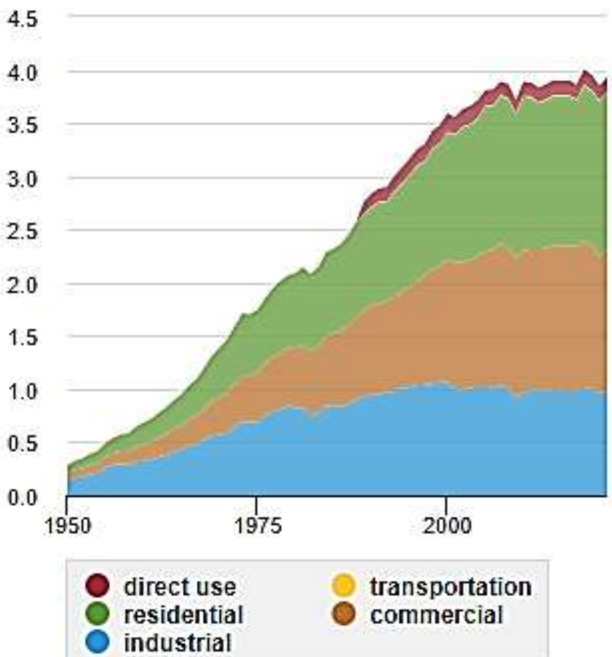
Household Appliances

The Future of Transportation (?)

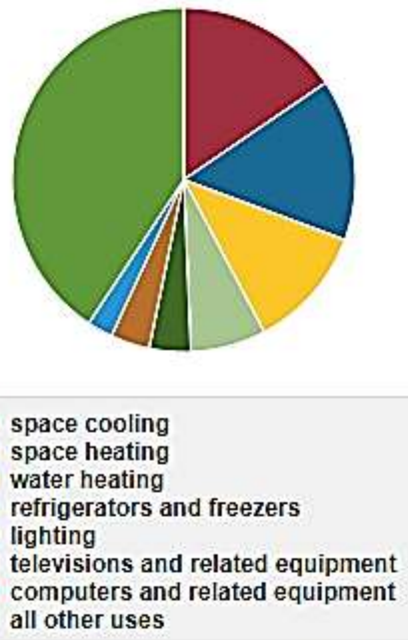
U.S. Electricity Consumption

electricity direct use by all sectors, 1950-2021

trillion kilowatthours =PWh



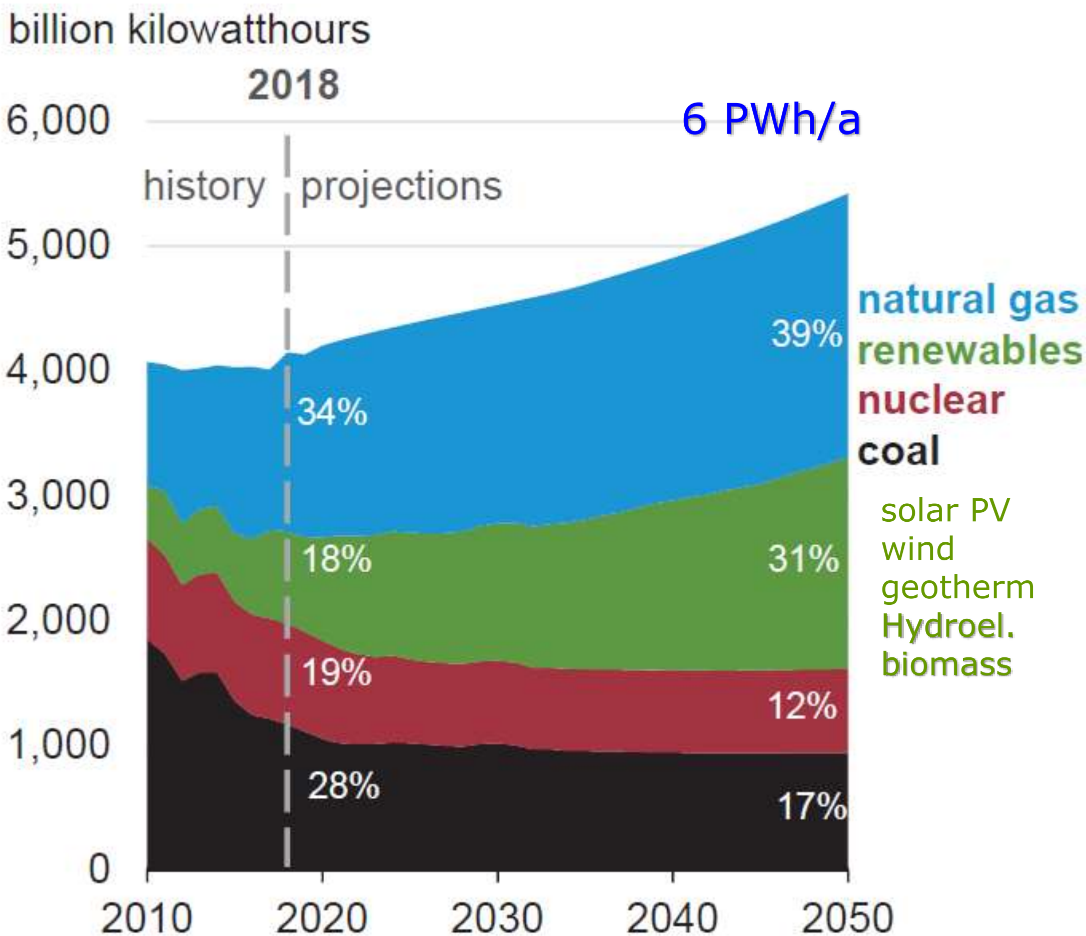
2021 Residential Use



Electricity consumption in the United States in 2020, by sector (in terawatt hours)

Characteristic	Consumption in terawatt hours
Residential	1,464.6
Commercial	1,287.4
Industrial	959.1
Transportation	6.5

U.S. Electricity Generation: Planning The Future



Projections for U.S. future energy sector:

Even with increased efficiencies, significant > 20% increase in electricity demand.

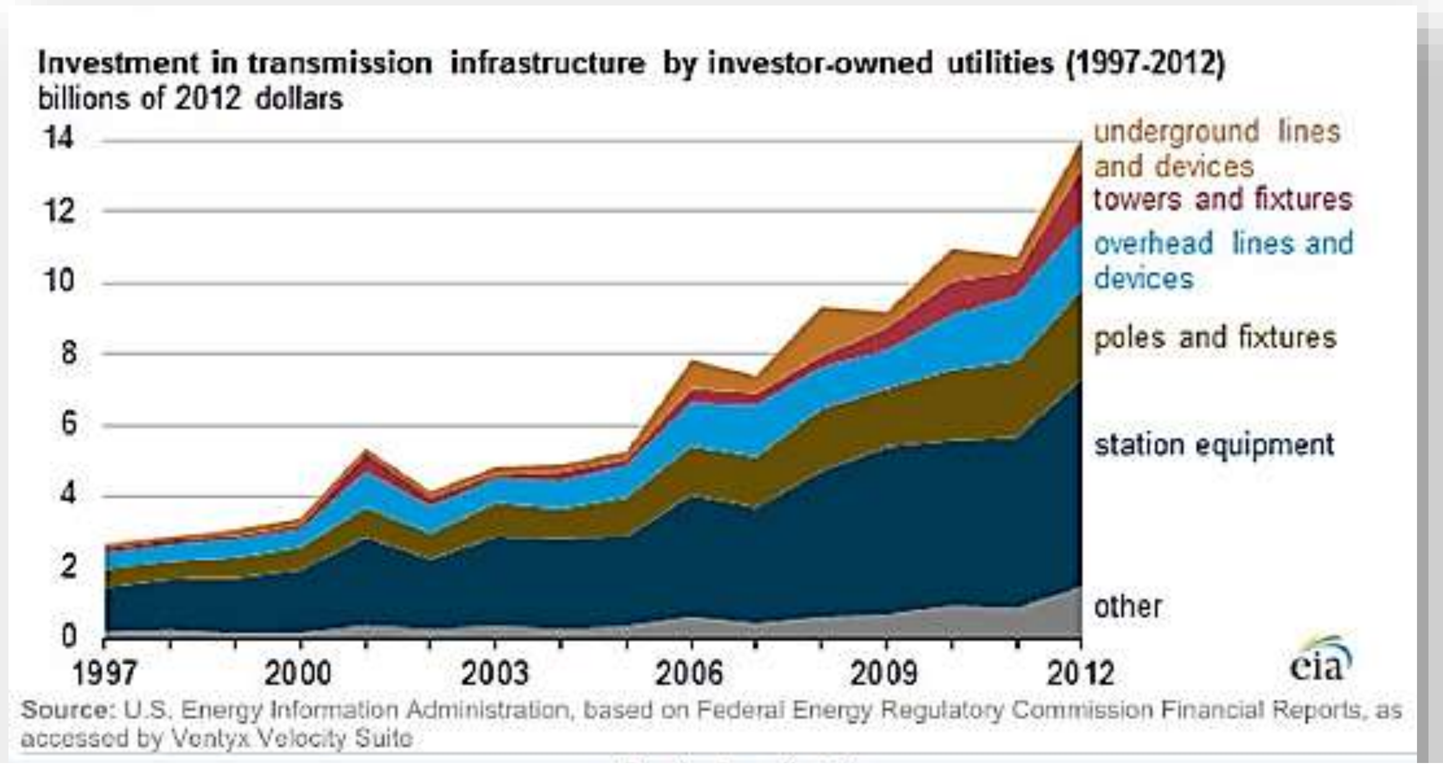
←(2018 >10% Hydro)

Generation: BAU + new policies
Tax credits, C tax ?

State-level policies, federal renew. en. requirements + cost reductions for wind (- 13%), solar PV (-22%) favor renewable (+ hydro) technologies 18%→31%.

Predict increased electricity demand, planning supported by investments into existing electrical grid.

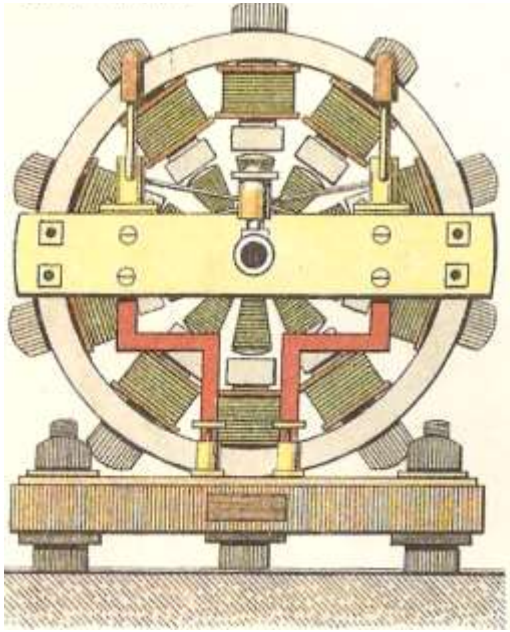
Transmission Grid Investments/Costs



The Federal Energy Regulatory Commission (FERC)—agency responsible for overseeing the transmission grid—recently issued a rule (Order 1000): Transmission expansion plans have to incorporate “socialized” investments.

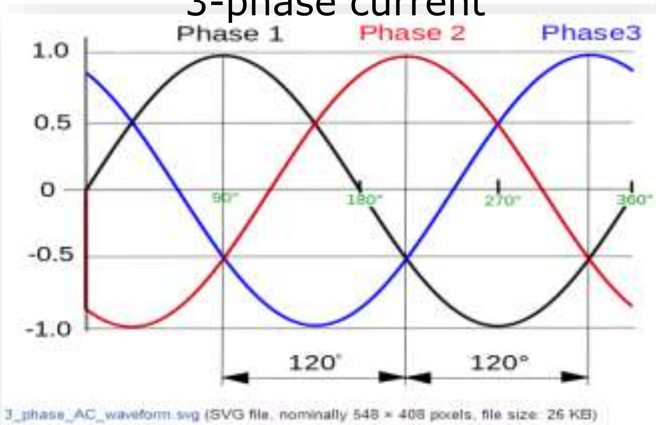
This, plus other policy changes (Energy Policy Act 2005) increases investment in the transmission grid. Requirements to accommodate renewables. Disputes about grid charges for feed-in wind+PV electricity.

Electro-Generators



Modern alternator (dynamo) at a power station (Iolotan hydroelectric power station on Murghab River).

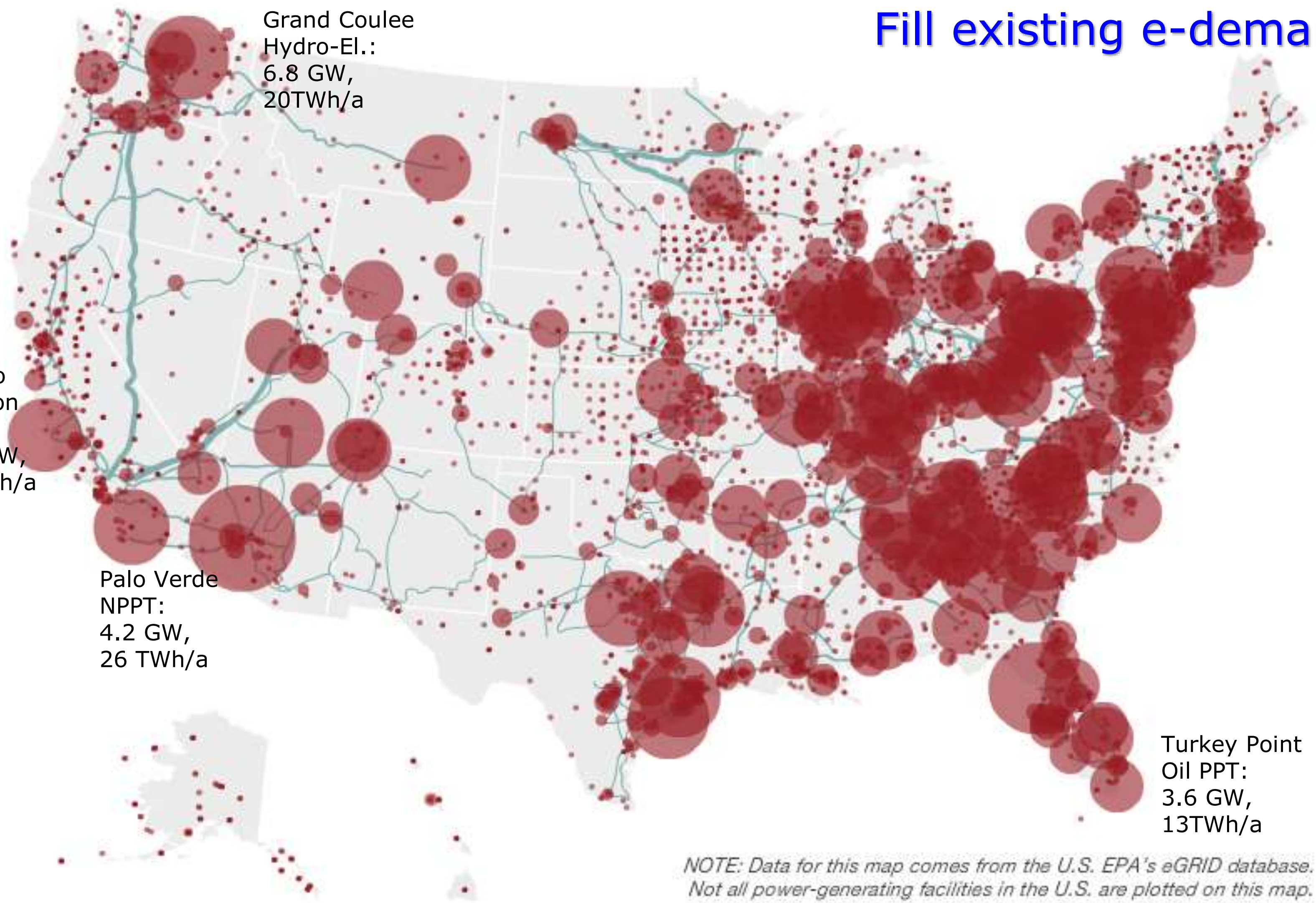
3-phase current



U.S. Electrical Power Plants (2009, All)

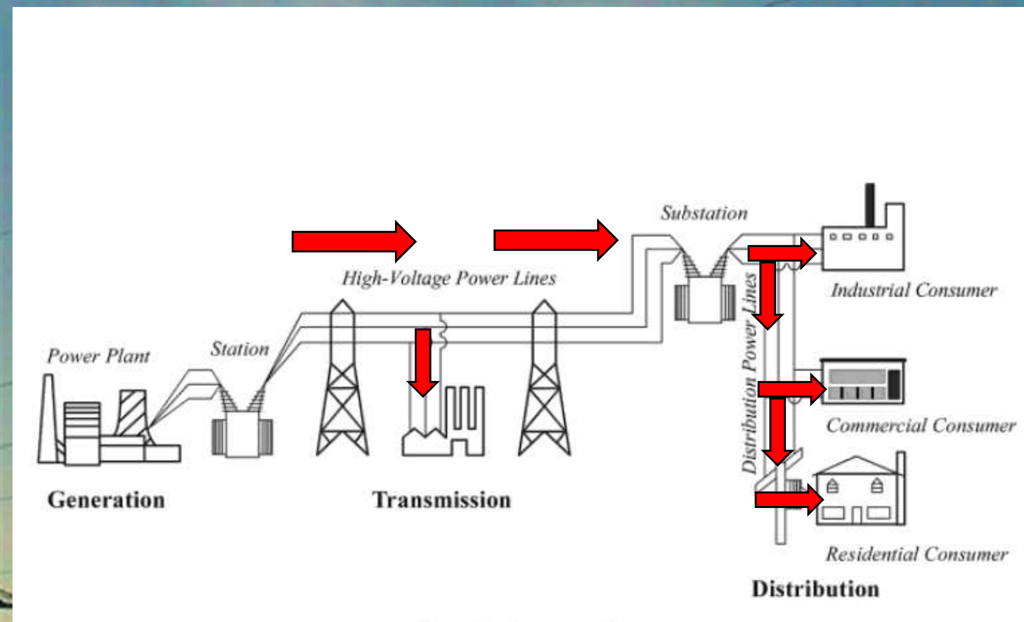
Interactive Map (NPR): http://www.npr.org/2009/04/24/110997398/visualizing-the-u-s-electric-grid

Fill existing e-demand



The Current U.S. Electrical Grid

USA, 2014: 170,000 miles of HV (>200kV) AC transmission lines.
6 million miles lines of lower voltage,
3,000 miles of 500 kV dc lines.
$(1-3)M/mi



Tasks: Balanced Electrical Power Distribution

Control and provide (in real time, ~20 sec lag):

Reliable instantaneous power $\boxed{\text{supply} \overset{!}{=} \text{demand}}$

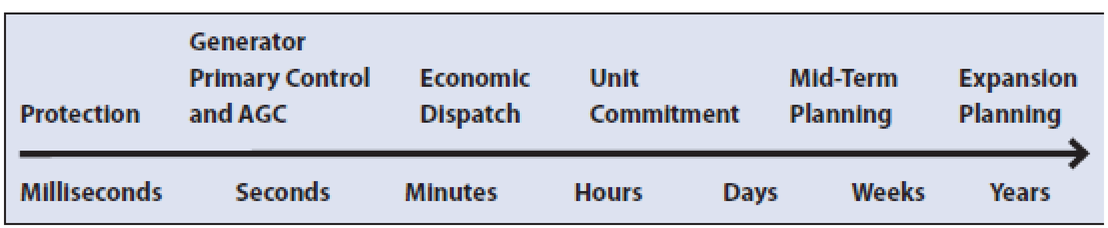
Stability: Regulated voltage ($\lesssim 1\%$)
Regulated frequency (~ 0.1 Hz)

Flexibility in response to diurnal, annual variations

Develop and keep reserves: active/standby (idling)
"Peak shaving" (add generation/reduce demand)

Minimize transfer losses (distance, method)

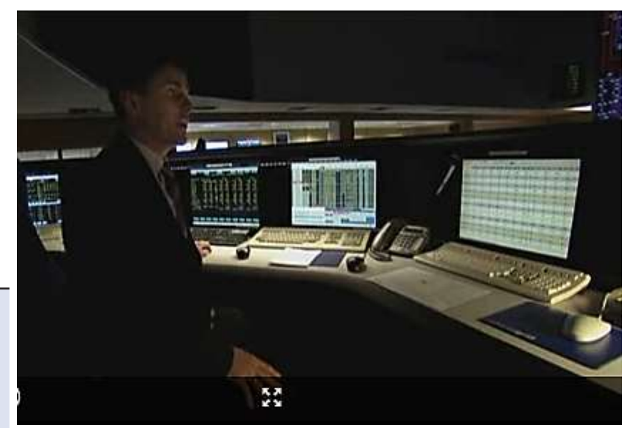
Optimize economy (price)



The Wires

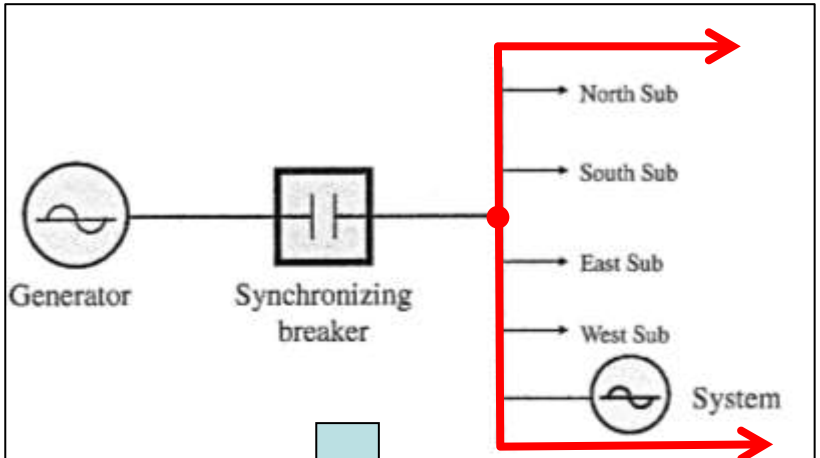
video

The Brain (Computer Assisted)



video

Generator Grid Matching

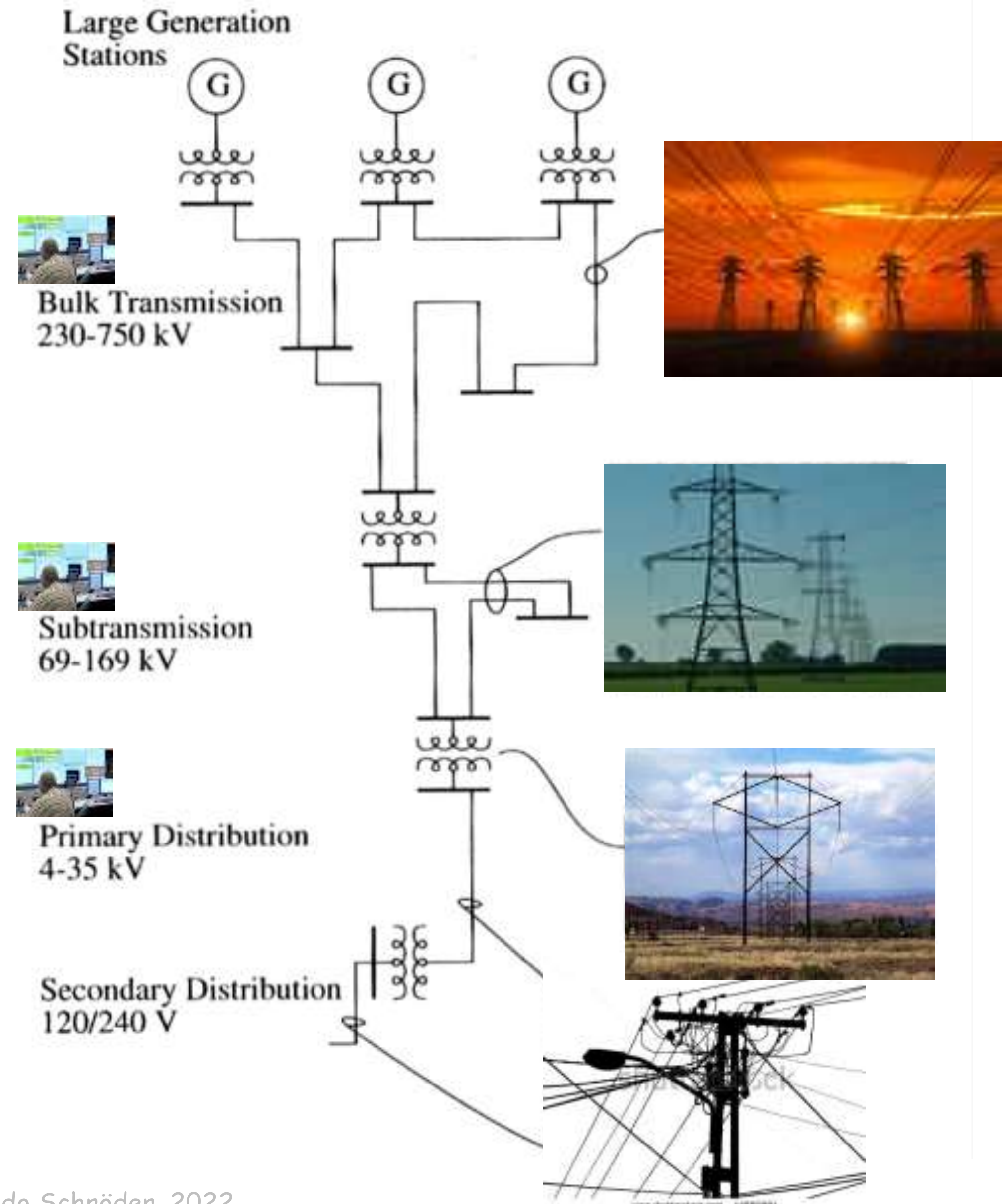


Reliable instantaneous power
supply = demand

Synchronize before connection:

- Frequency (60Hz, $\Delta\nu<0.1$Hz)
- Voltage (≈voltage of grid side)
- Phase angle ($\Delta\phi<15^0$)
- Rotation (matching 3-phases)

Basic U.S. Power Transmission



Dominantly 3-phase AC systems @ constant voltage, use synchronous generators (60 Hz)

Easy conversion, switching, control, reliability, maintenance.
AC motors and generators are simpler and cheaper than DC.

Good performance: Grid power losses 16%(1926)→ 5-7%(2014)

Standard voltage levels

High Voltage (HV):

115, 138, 161, 230 kV

Extra High Voltage (EHV):

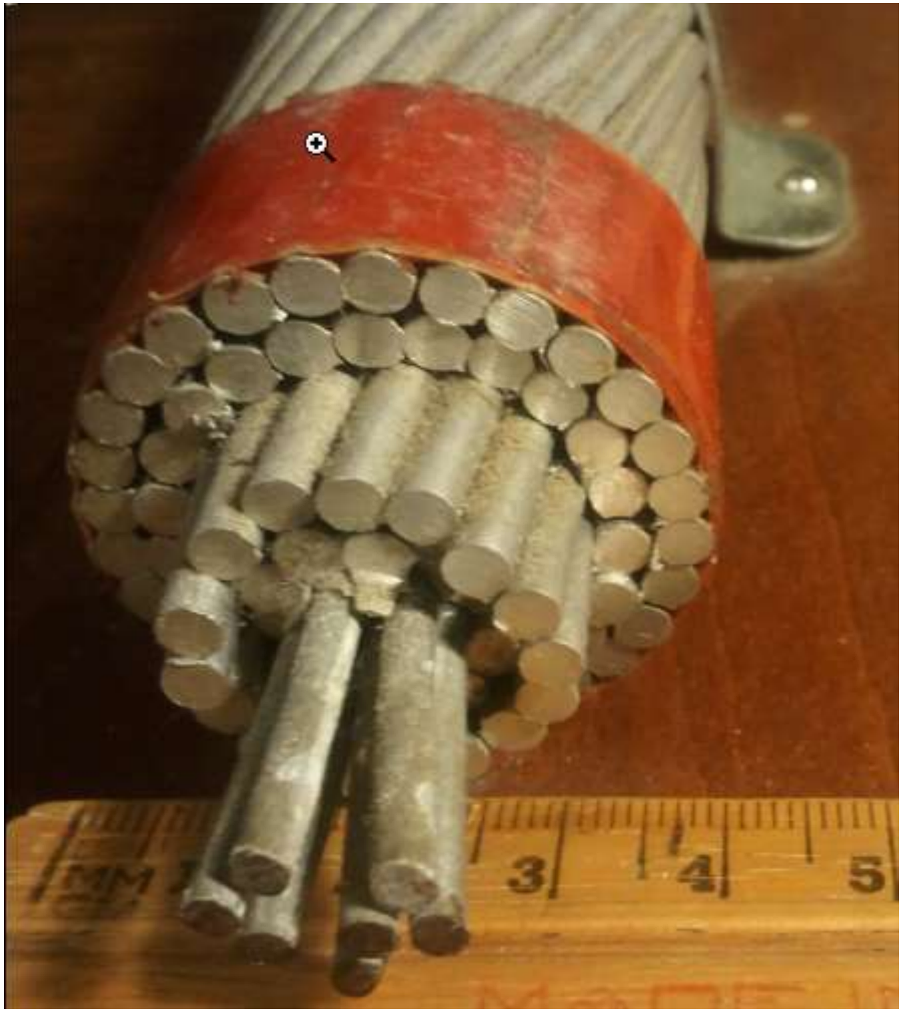
345, 500, 765 kV

DC systems are cost effective only over long distances (>500 km)

High Voltage DC (HVDC):

(0.5 – 1)MV →Few locations (US, Europe, China)

Transmission Conductors (Aluminum Conductor Steel-Reinforced)



Steel strands form core bundle, for stability. HV overhead conductors, not insulated. Different standard gauges (AWG)

Main conductors:

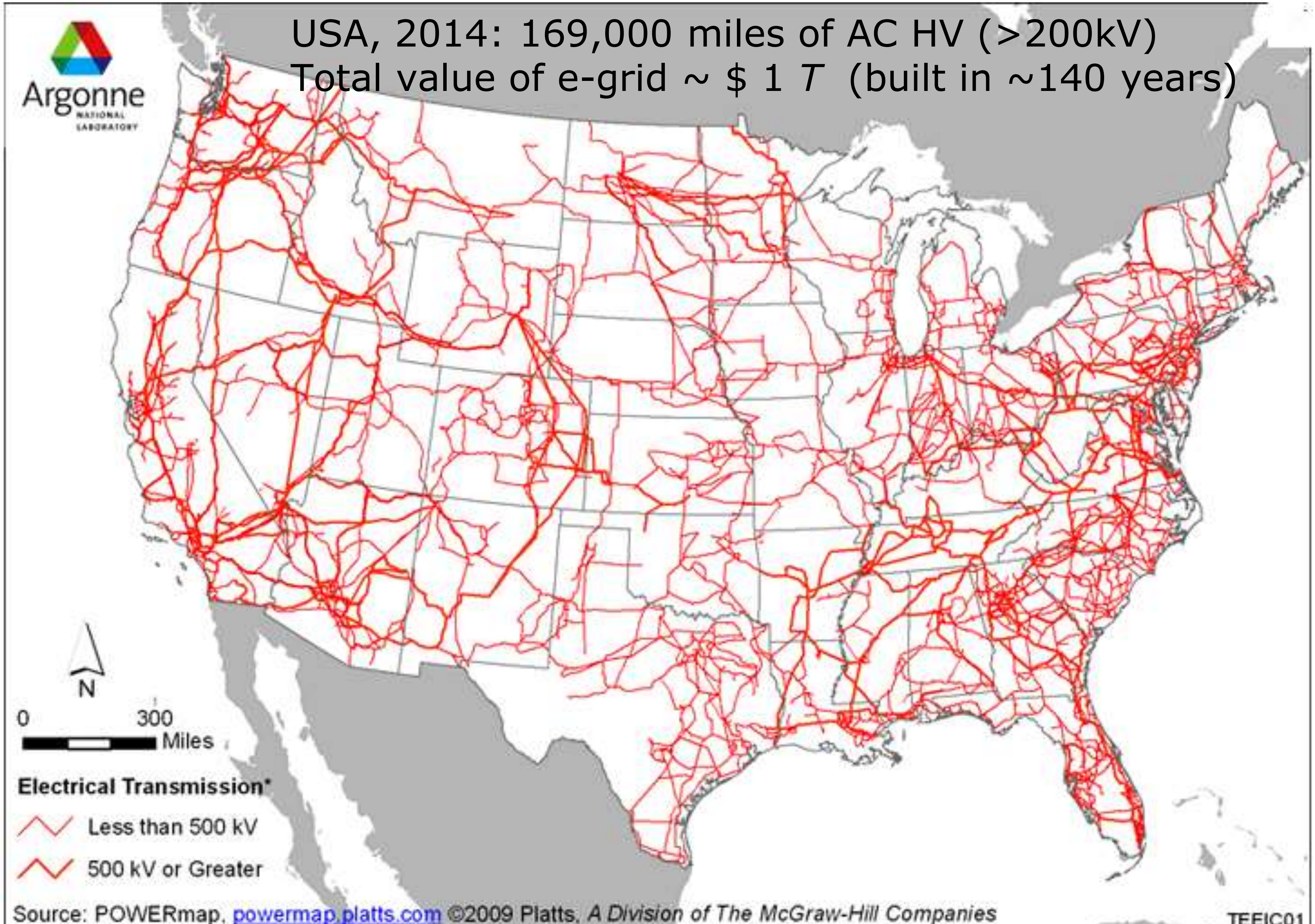
4 twisted strands of aluminum.

Better conductors Cu, Ag, Au not economical

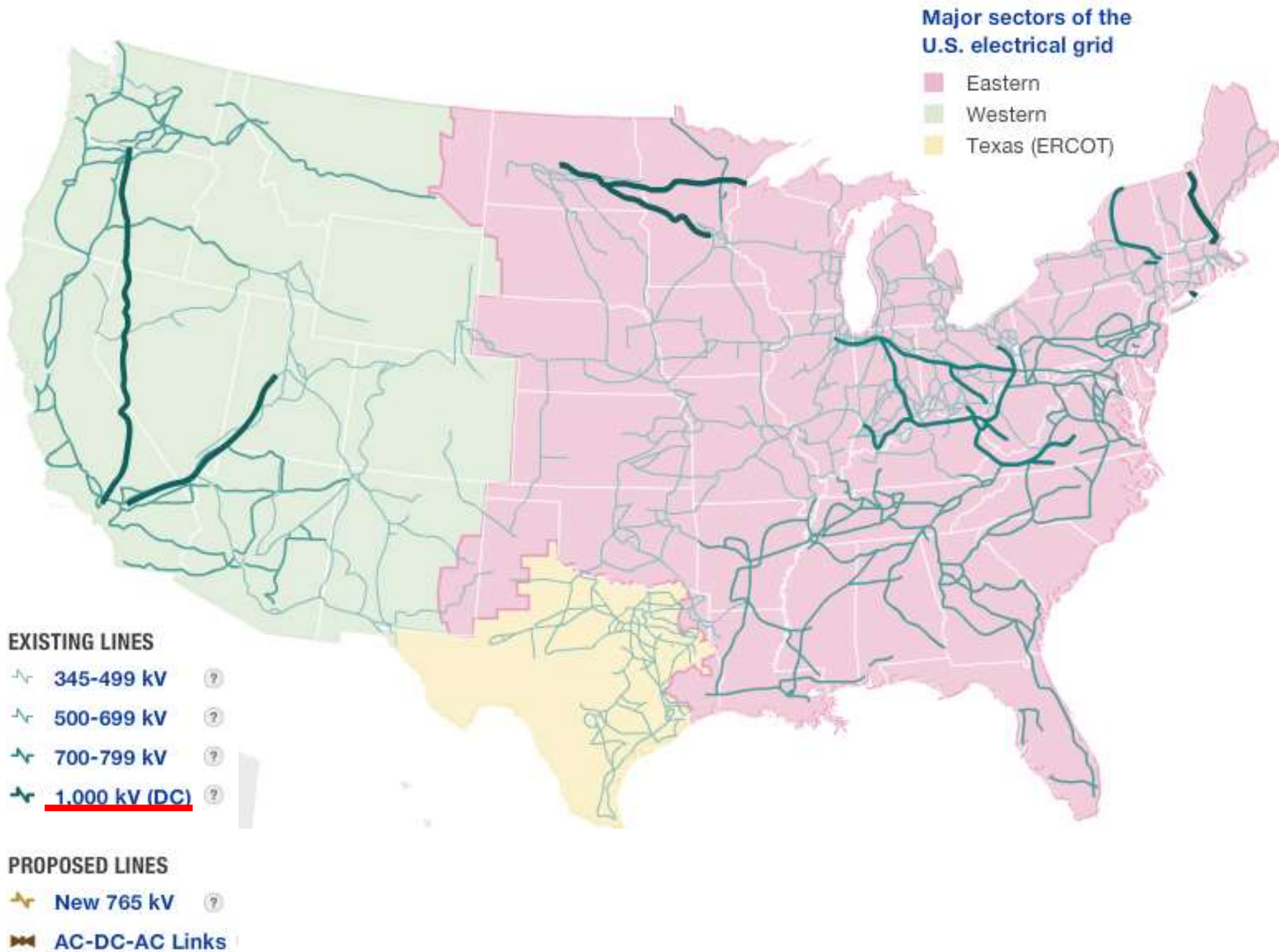
Underground conductors are insulated → cooling problem

U.S. Electrical Transmission Lines

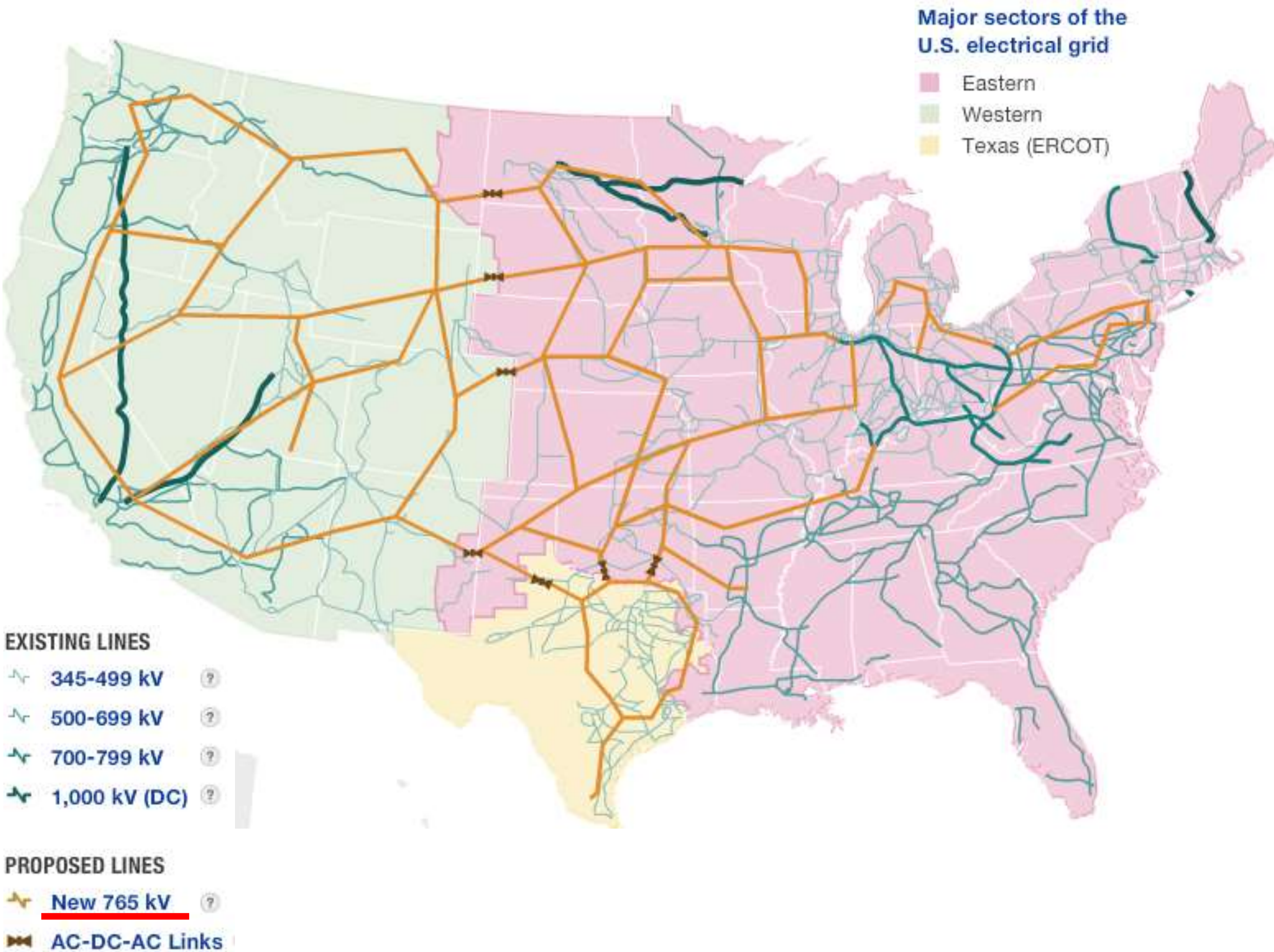
USA, 2014: 169,000 miles of AC HV (>200kV)
Total value of e-grid ~ $ 1 *T* (built in ~140 years)



U.S. Major Electrical Transmission Lines



U.S. Major Electrical Transmission Lines

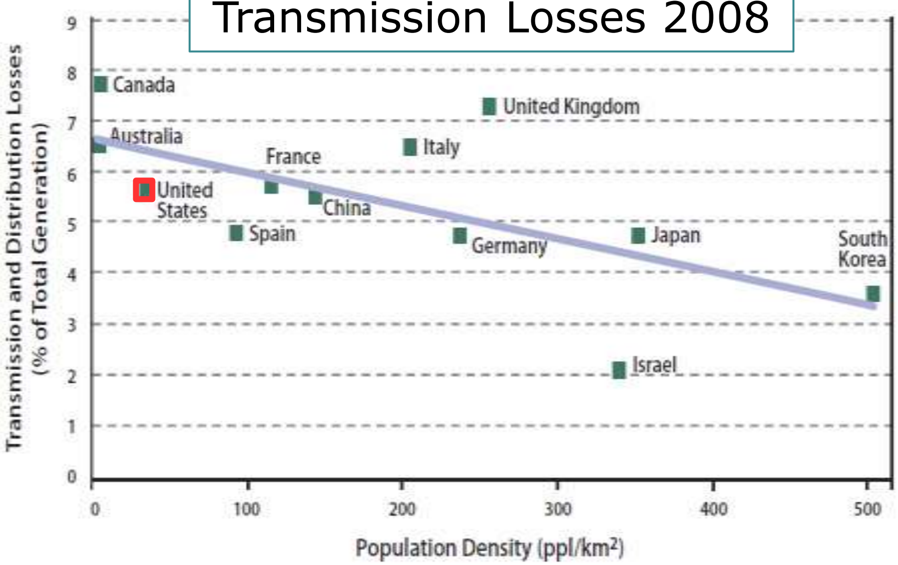


Transmission Performance

Line Type	Voltage (kV)	Miles
Alternating Current (ac)	200–299	84,000
	300–399	54,000
	400–599	26,000
	≥ 600	2,400
	Total ac	161,000
Direct Current (dc)	200–299	700
	300–399	0
	400–599	1,800
	≥ 600	0
	Total dc	2,500
	Total	**169,000**

Source: North American Electric Reliability Corporation (NERC) Electricity Supply & Demand Database, http://www.nerc.com/page.php?cid=4|38.

Transmission Losses 2008



Source: World Bank Development Indicators, http://data.worldbank.org/indicator.

2010: Almost 5,000 generating units with > 50 MW of expected on-peak summer capacity (North American Electric Reliability Corporation).

169,000 mi HV (> 200kV) lines
6,000,000 mi HV (< 200kV) lines

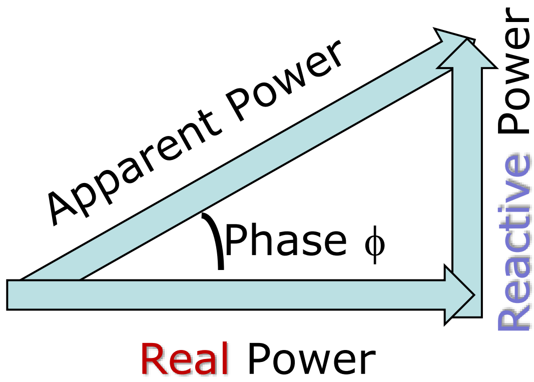
Grid serves about 125 million (37%) residential, 17.6 million (36%) commercial, 775,000 industrial (27% use) customers.

Retail price ≈ $100/MWh.

Grid performance: low losses (heat),
Reliability (few outages): US customers have 1.5 - 2 power interruptions per year,
2 - 8 hours without power.

Real and Reactive Power

$$Power\ P(t) = V(t) \cdot I(t)\ or,\ in\ complex\ notation\ P = V \cdot I^*\ (* = complex\ conjugate)$$



$$Purely\ resistive\ loads: P_R = V_R \cdot I = V^2/R = I^2 \cdot R$$

$$Power\ P_R(t) = V_R(t) \cdot I(t)$$

$$Apparent\ power: P_A(t) = \sqrt{P_R^2(t) + P_{LC}^2(t)}$$

$$Real\ power\ P_R(t) = P_A(t) \cdot \cos\phi$$

$$\boxed{Power\ Factor = P_R / P_A}$$

Real and reactive power are "out of phase"

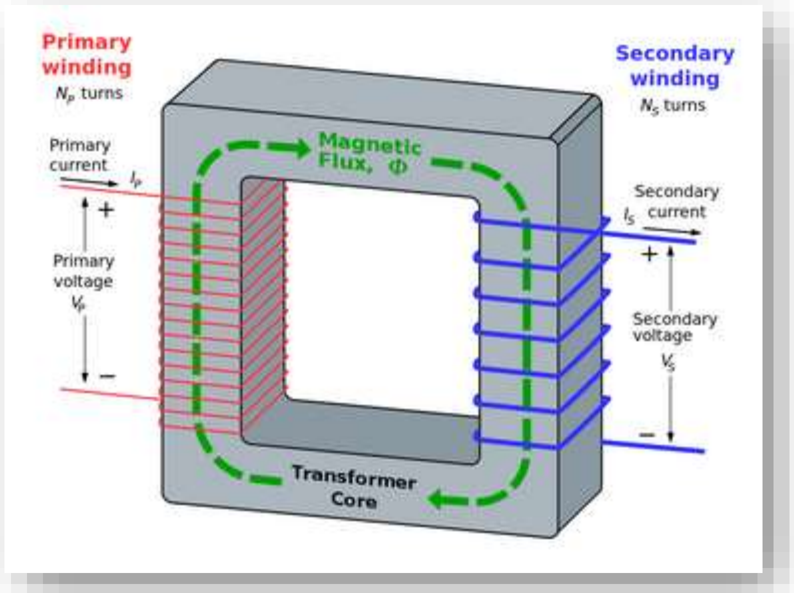
$$Apparent\ power: P_A^2(t) = P_R^2(t) + \left[P_C^2(t) + P_L^2(t)\right]$$

$$Reserve: Oscillating\ reactive\ power\ P_C(t) \rightleftarrows P_L(t)$$

$$Reactive\ power\ P_{LC}(t) = P_A(t) \cdot \sin\phi \quad \text{"var"}\ voltage-ampere-reactive$$

Actual loads on the power supply (e-grid) like an e-motor are always complex (Ohm + capacitive + inductive) → have feedback effect on supply → Affect power factor (available power) and frequency.
→ General effect on stability of electrical grid.

AC Transformers/Shunt Reactors



$$V_{primary} = -N_{primary}\, d\Phi/dt$$
$$V_{secondary} = -N_{secondary}\, d\Phi/dt$$
$$V_{secondary}/V_{primary} = N_{secondary}/N_{primary}$$

Changes load impedance $Z_{primary}$

Laminated or toroidal transformer cores.

Iron/steel laminations prevent eddy currents. Insulated with a nonconducting material, such as varnish or epoxy.

Toroidal: coils wrapped around cylindrical core.

Shunt Reactor, compensates capacitance

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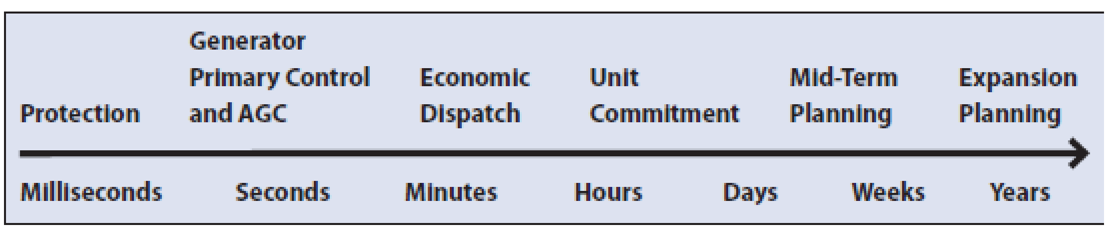

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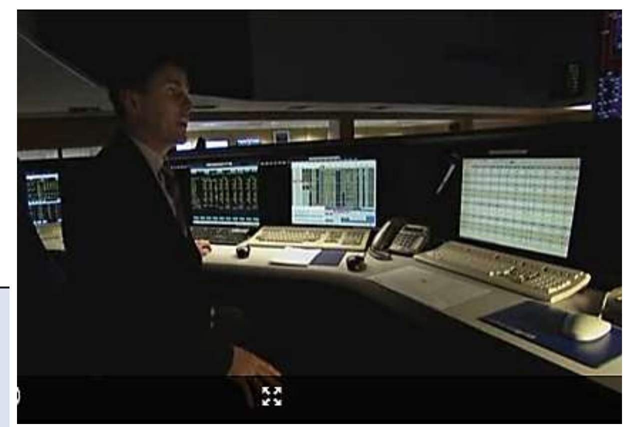
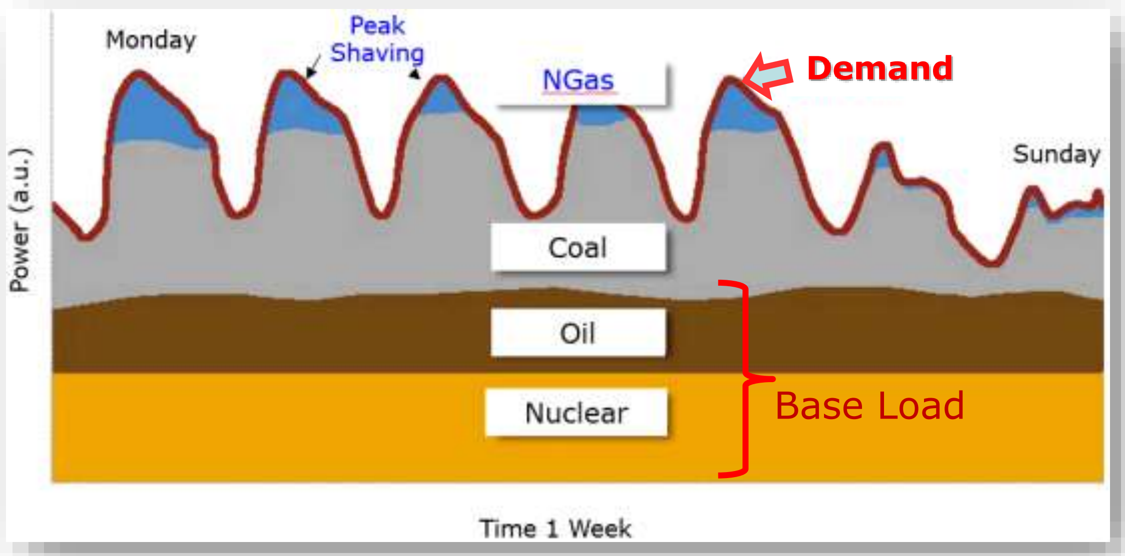


video

Tasks of the Balancing Agencies

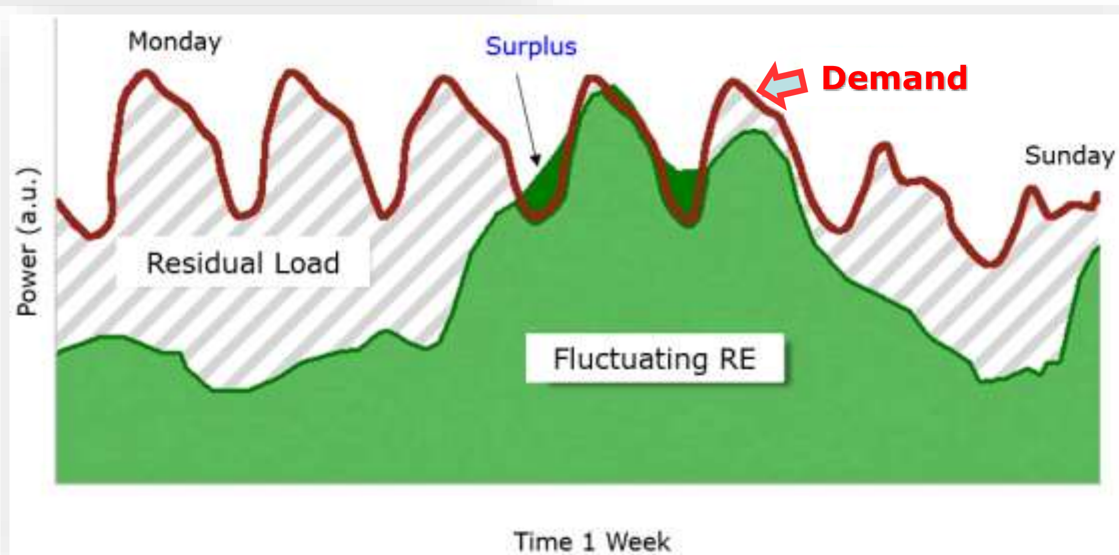


Conventional base load: Thermal stations (nuclear, oil, coal, gas).

Peak power demands needs quick-responding generators (natural gas, LNG) for "peak shaving."

Take into account spot prices for power. Uncertainty discourages investment !

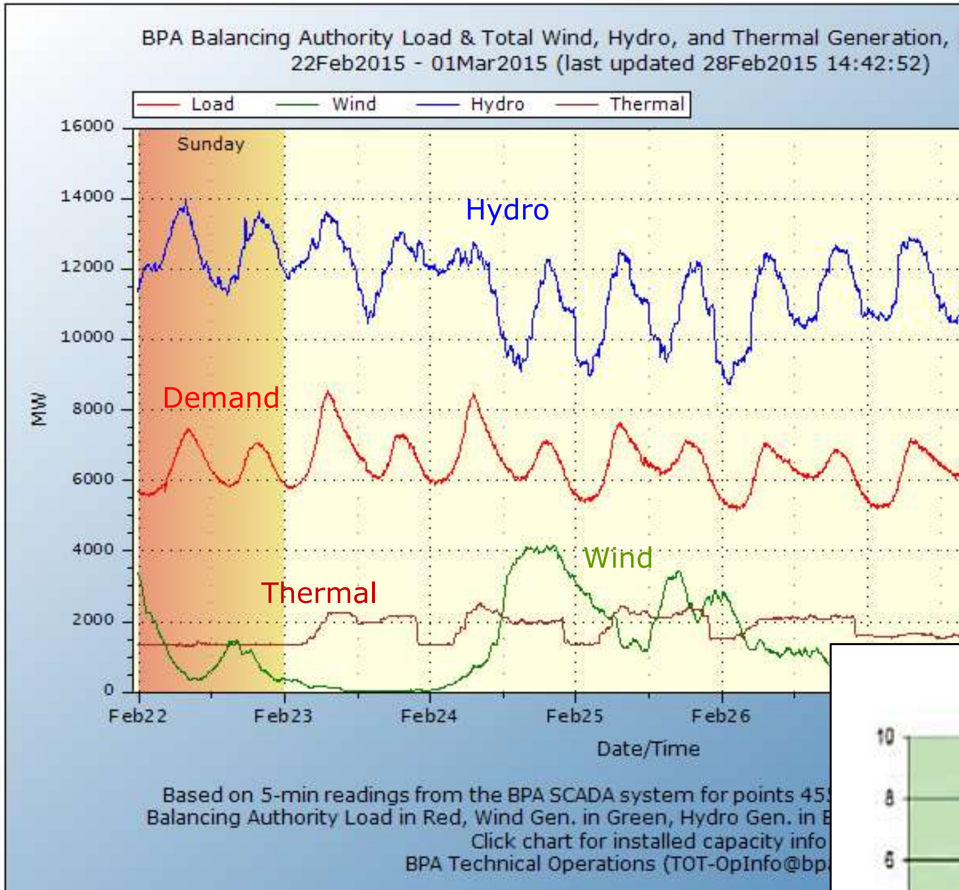
Accepting large fractions of variable renewable sources (wind/solar) with few traditional base load generators → great potential "residual loads."

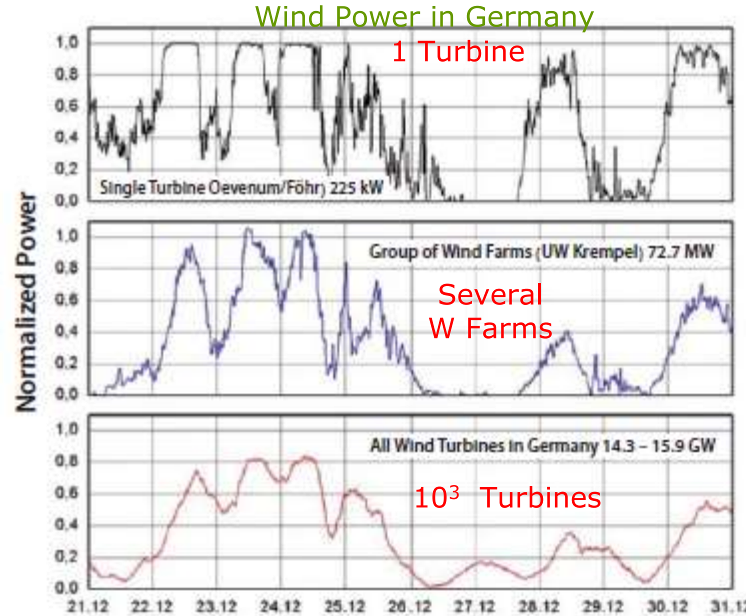


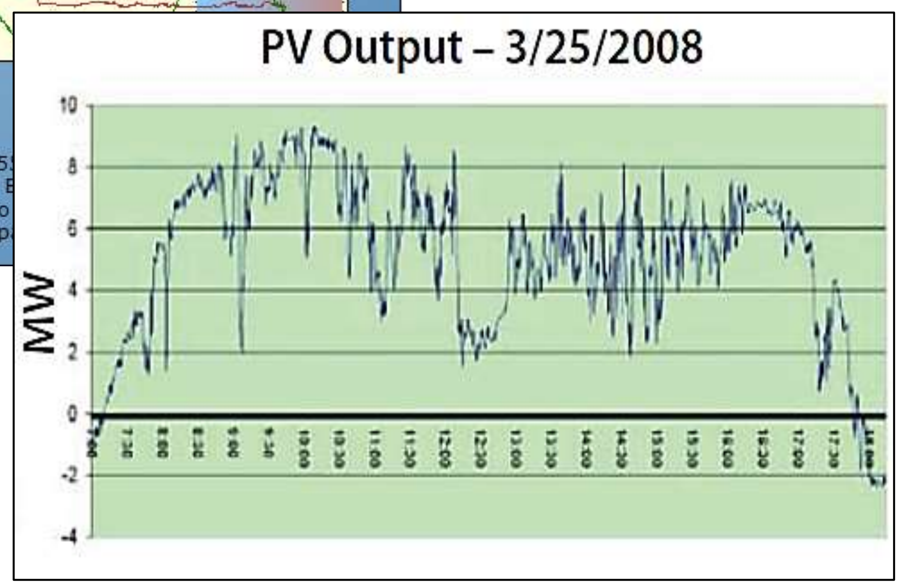
Base load →
Storage or idling fossil fuel, hydro or nuclear generators.

Good planning requires good RenEnergy/weather forecasts.

Actual BA Records

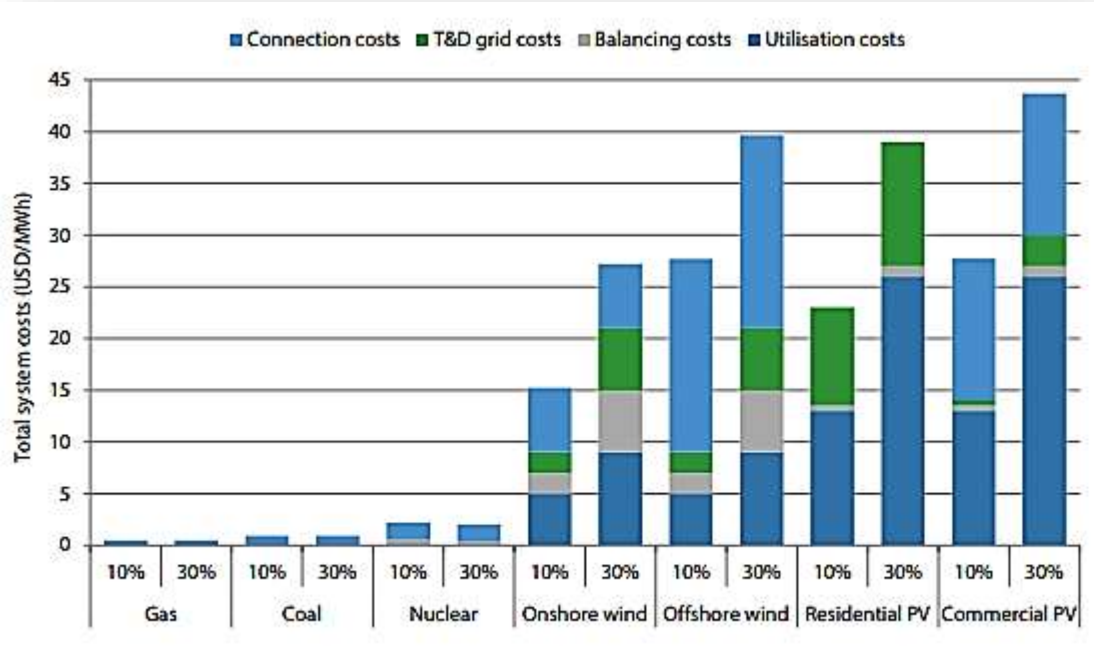






http://transmission.bpa.gov/business/
operations/wind/baltwg.aspx

Grid System Costs of Generation Technologies



OECD 2018/NEA Report: Full Cost of Electricity Provision

For 10% and 30% shares by VRE (intermittent wind and solar) technologies

Profile costs: variability of VRE output → needs baseline response to sudden demand changes the residual load on short notice.

Balancing costs: unpredictability of VRE power production → ramping/cycling of conventional power plants, inefficiencies in plant scheduling.

Grid and connection costs: extra transmission and distribution grid infrastructure to service the locational constraint of VRE generation plants.

→ Higher VRE penetration → higher specific auxiliary costs

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- E-Grid failures/vulnerabilities
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- **Tutorial:** electricity, electronics

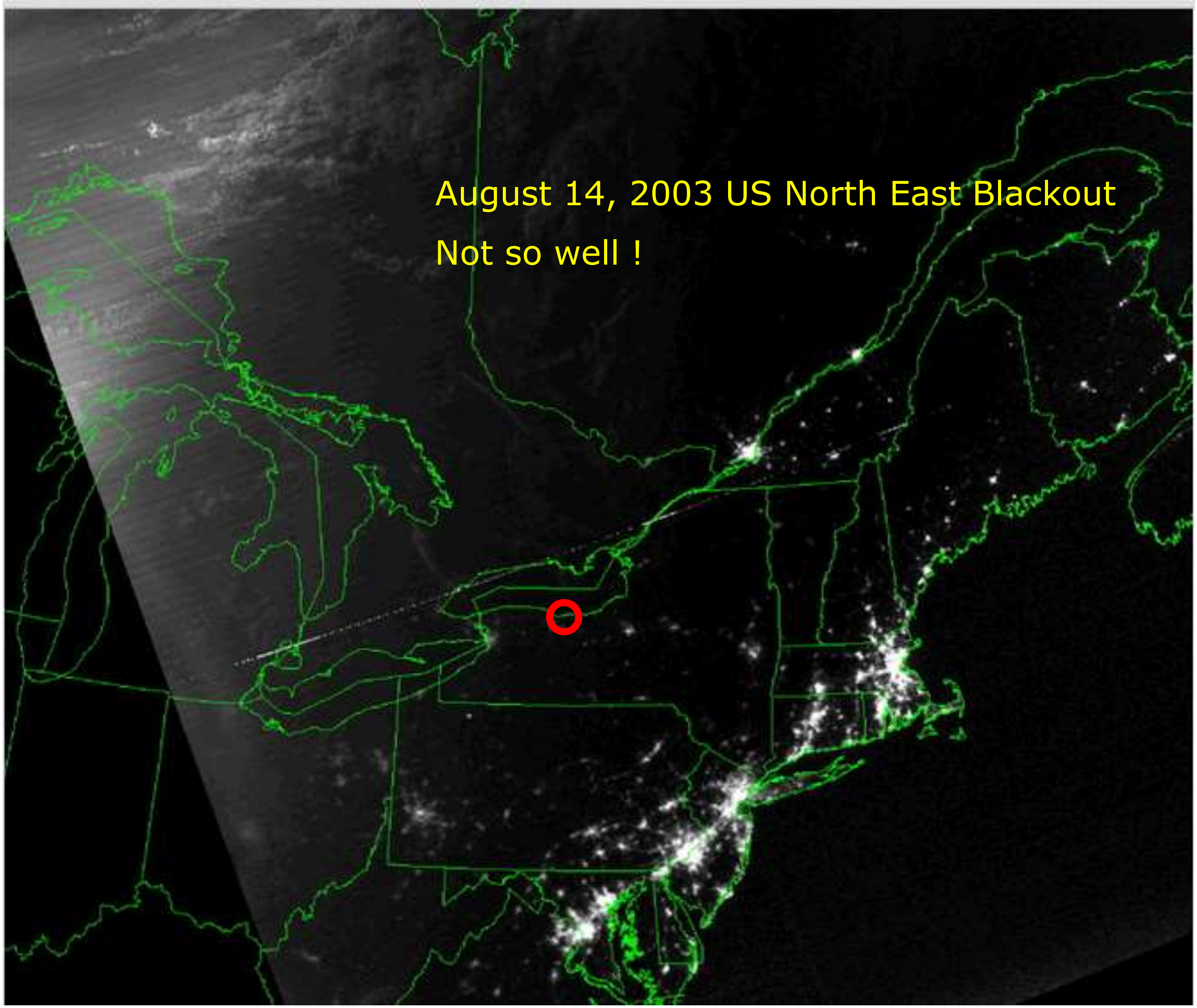
  Electric generators (dynamos) and motors, transformers

  AC-DC circuits, 3-phase currents

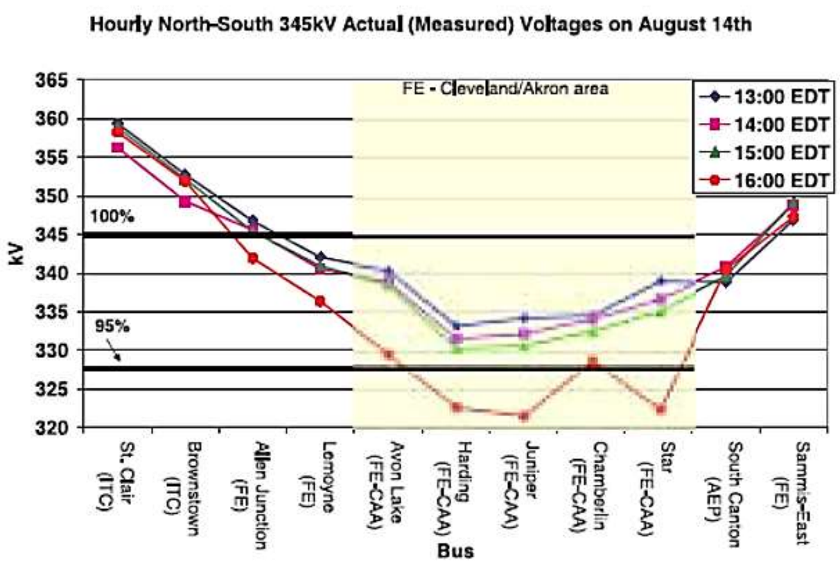
  complex calculus

Electricity Transmission Grid (On a good day)

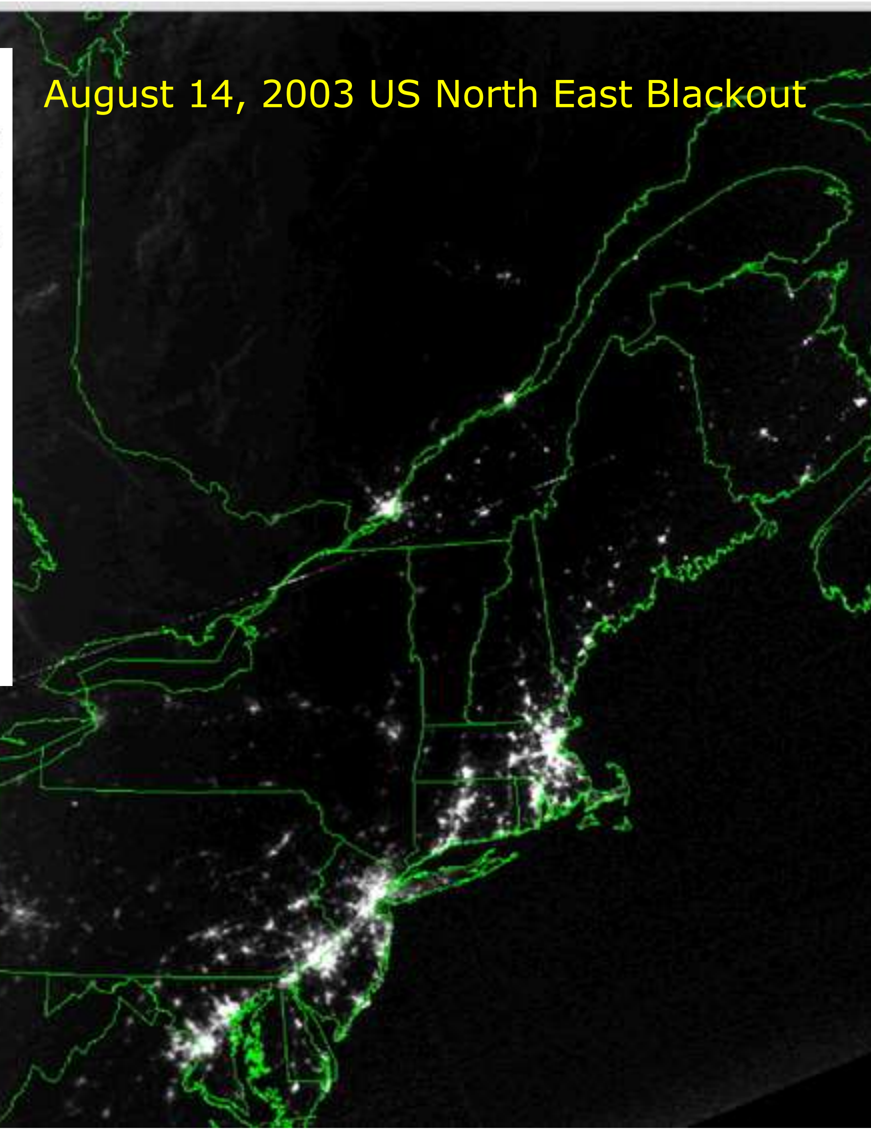
Electricity Transmission Grid (On a bad day)



Vulnerable National e-Grid



Voltage profile in northern Ohio prior to blackout.



Present e-grid has fundamental technical & capacity limitations. Future ("smart") e-grid (?): additional cyber-vulnerabilities.

Tasks for network R&D !

Other Grid Blackouts: 600 Million People Affected

July 30, 2012: Blackout in India (cascading)
- 32 GW, several days

Half of India Crippled by Second Day of Power Failures

Rajesh Kumar Singh/Associated Press

Vehicles clogged streets in New Delhi after a power failure disrupted traffic lights and the city's rail services.

Further blackouts in Northern Europe

Risk Assessment In Complex Interacting Infrastructure Systems

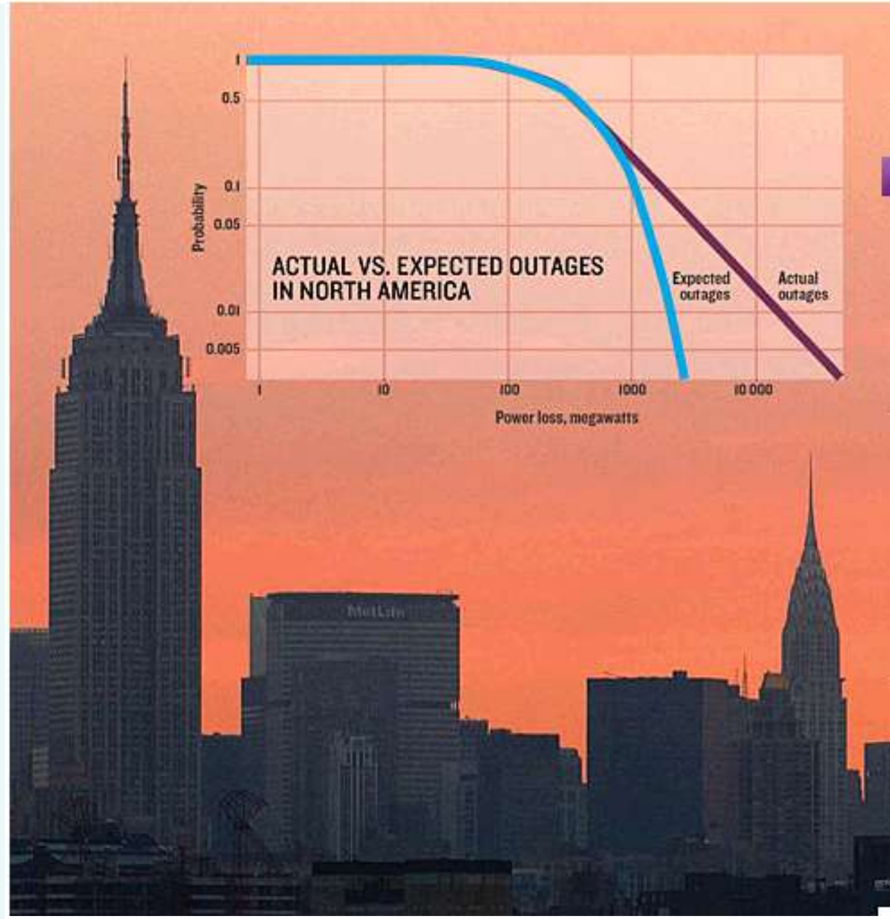
Conference, Paper Abstract:

On August 14th 2003, a cascading outage of transmission and generation facilities in the North American Eastern Interconnection resulted in a blackout of most of New York state as well as parts of Pennsylvania, Ohio, Michigan and Ontario Canada.

On September 23rd 2003, nearly four million customers lost power in eastern Denmark and southern Sweden following a cascading outage that struck Scandinavia. Days later, a cascading outage between Italy and the rest of central Europe left most of Italy in darkness on September 28th.

These major blackouts are among the worst transmission system failures in the last few decades. The Power System Stability and Power System Stability Controls Subcommittees of the IEEE PES Power System Dynamic Performance Committee sponsored an all day panel session with experts from around the world. The experts described their recent work on the investigation of grid blackouts.

Conferences were held offering forums for discussion of possible root causes and necessary steps to reduce the risk of blackouts.



Can grid/network crashes be prevented at all ?
Various reasons for fundamental instabilities → Complexity→ Chaotic Tendency

Chaos In Highly Non-Linear Networks

CHAOS VOLUME 14, NUMBER 3 SEPTEMBER 2004

Complex dynamics of blackouts in power transmission systems

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(Received 27 August 2003; accepted 21 June 2004; published online 1 September 200

In order to study the complex global dynamics of a series of blackouts in power t
systems a dynamical model of such a system has been developed. This model includ
representation of the dynamical evolution by incorporating the growth of power d
engineering response to system failures, and the upgrade of generator capacity. Tw
ynamical properties. One type
ng their load limits but no line c
e outages. The dominance of
s and the proximity of the syste
tics such as a probability dis
in real blackout data from Nor
/1.1781391]

Chaos, Vol. 14, No. 3, 2004

FIG. 1. Diagram of the IEEE 118 bus network. Generators are gray squares; loads are the black squares.

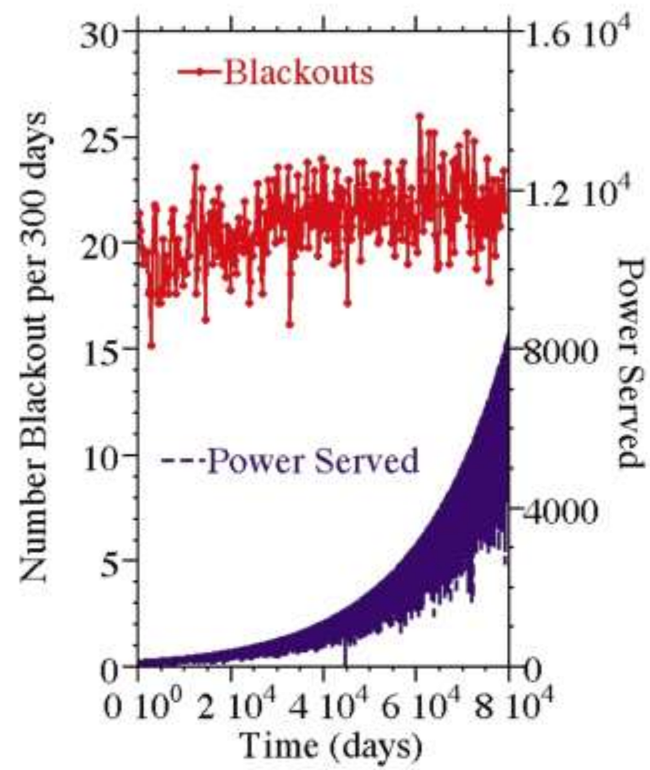


FIG. 2. (Color) Time evolution of the power served and number of blackouts per year from the model.

Cyber Vulnerabilities Of e-Grid

1^{st} known cyber attack: Ukraine, Dec. 23, 2015
e–Grid partial blackout.
225,000 customers 1-6 hrs w/o power.

Reconstruction:
→ deep reconnaissance over a 6-mos period
→ well-coordinated attack @ several points.

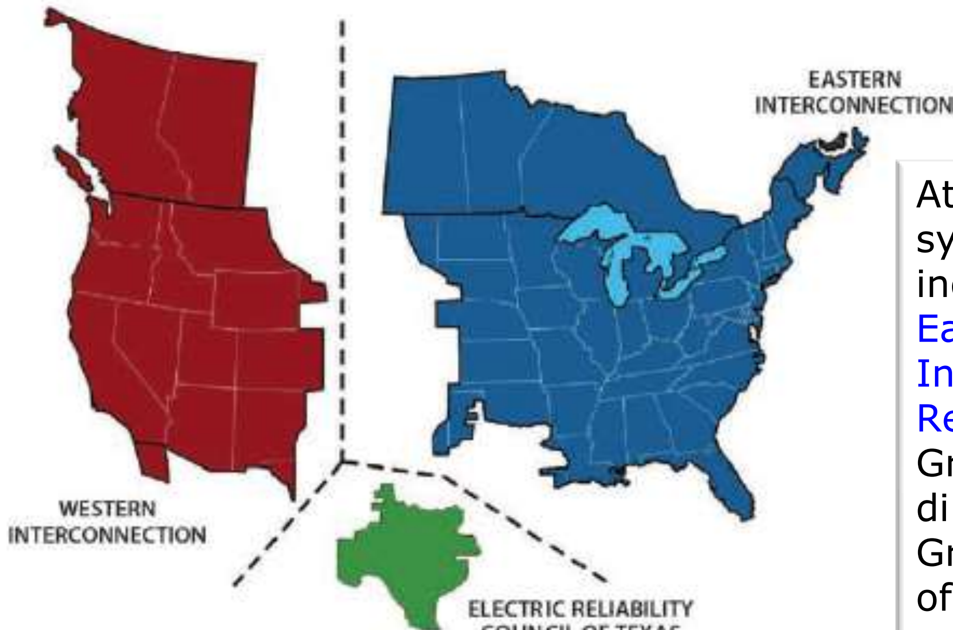
→ 2009: US NSA's "Stuxnet" malware destroyed few hundred Iranian nuclear centrifuges.

Nation states develop cyber strategies
→ spear-phishing emails compromise corporate networks
→ seizing Supervised Control And Data Acquisition, switch off substations;
→ disable/destroy IT infrastructure (uninterruptible power supplies, modems, RTUs, commutators);
→ destruction of server files;
→ denial-of-service attack on info call-centers

Daily criminal "Denial of Service" attacks on internet sites

US e-Grid Super Structure

Interconnections of the North American Electric Grid



Department of Energy, http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/NERC_Interconnection_

At the highest level, the electric power systemcontinental U.S. consists of 3 independently synchronized grids: the Eastern Interconnection, the Western Interconnection, and the Electric Reliability Council of Texas (ERCOT).
Grids are linked by a few low-capacity direct current (DC) lines.
Grids account for 73%, 19%, and 8% of U.S. electricity sales, resp.
MIT Rep.: The future of the electrical grid, 2015.

Economic organization:
Past organizational structure was vertical, utility companies owned generators, substations, energy, lines from generation to consumers.
Now fractionated corps. Capital flow and investment strategies have changed. Discourage large capital investment, future planning. At the distribution level, now about 3,200 organizations provide electricity to retail customers

Organized Electricity Markets

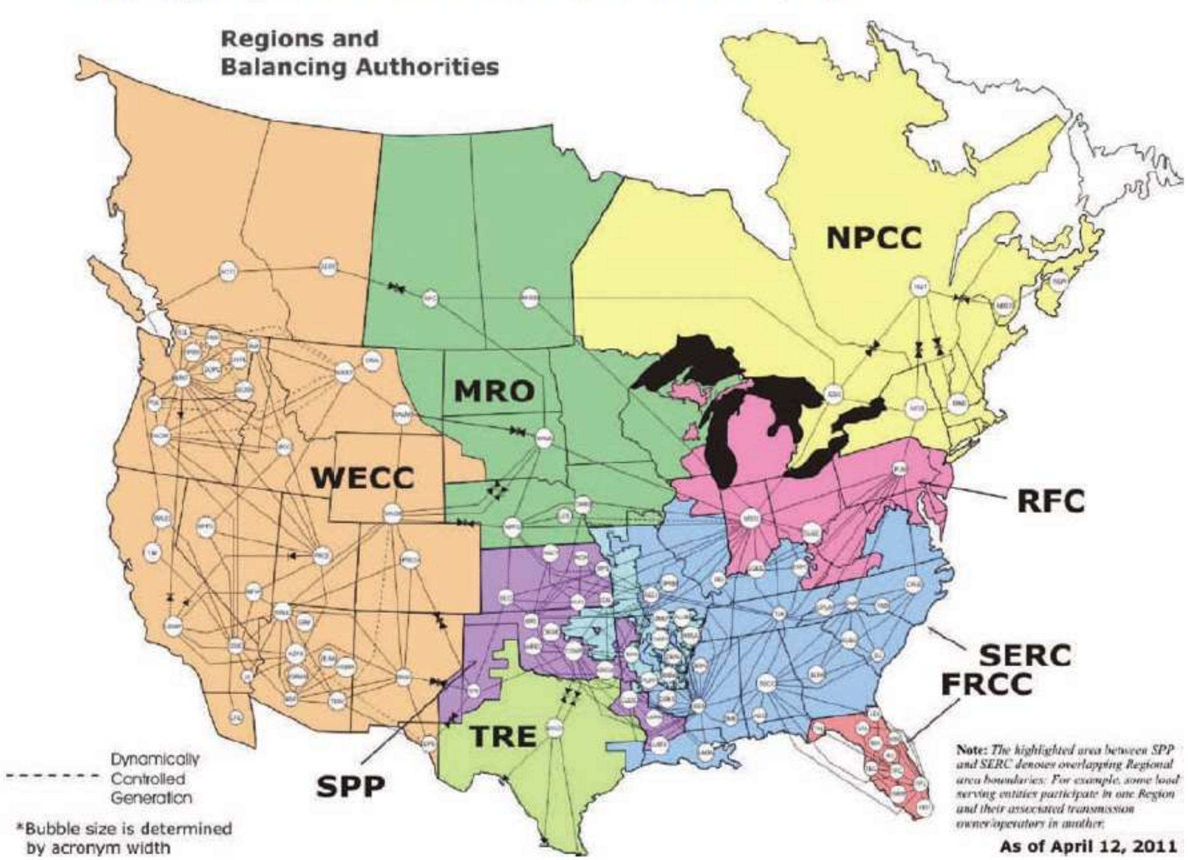
Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) do not own generators or serve retail customers. These markets now cover two-thirds of the U.S. population/demand.
MIT: The future of the electrical grid, 2015.

Selling wholesale electric energy: bidding process whereby generators offer energy (MWh) for sale during specific periods of the next day at a specific price ($/MWh). These offers are arranged by the ISO/RTO in ascending order called the "bid stack" and the generators are dispatched (told to generate) in this order until generation matches load.
Offers at negative price (nuclear, VRE) guarantee remaining online, dispatch. Renewables (VRE) make still profit because of subsidies.
Large swings in daily electricity prices \$(0-1,000)/MWh, mean= \$100/MWh.

Grid Power Flow Monitoring

Overseeing the transmission grid:
Federal Energy Regulatory Commission (FERC)

Balancing Authorities in the North American Electric Grid, 2011



Source: North American Electric Reliability Corporation, http://www.nerc.com/docs/oc/rs/BubbleMap_2011-04-12.jpg

Note: FRCC = Florida Reliability Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RFC = ReliabilityFirst Corporation; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Regional Entity; WECC = Western Electricity Coordinating Council.

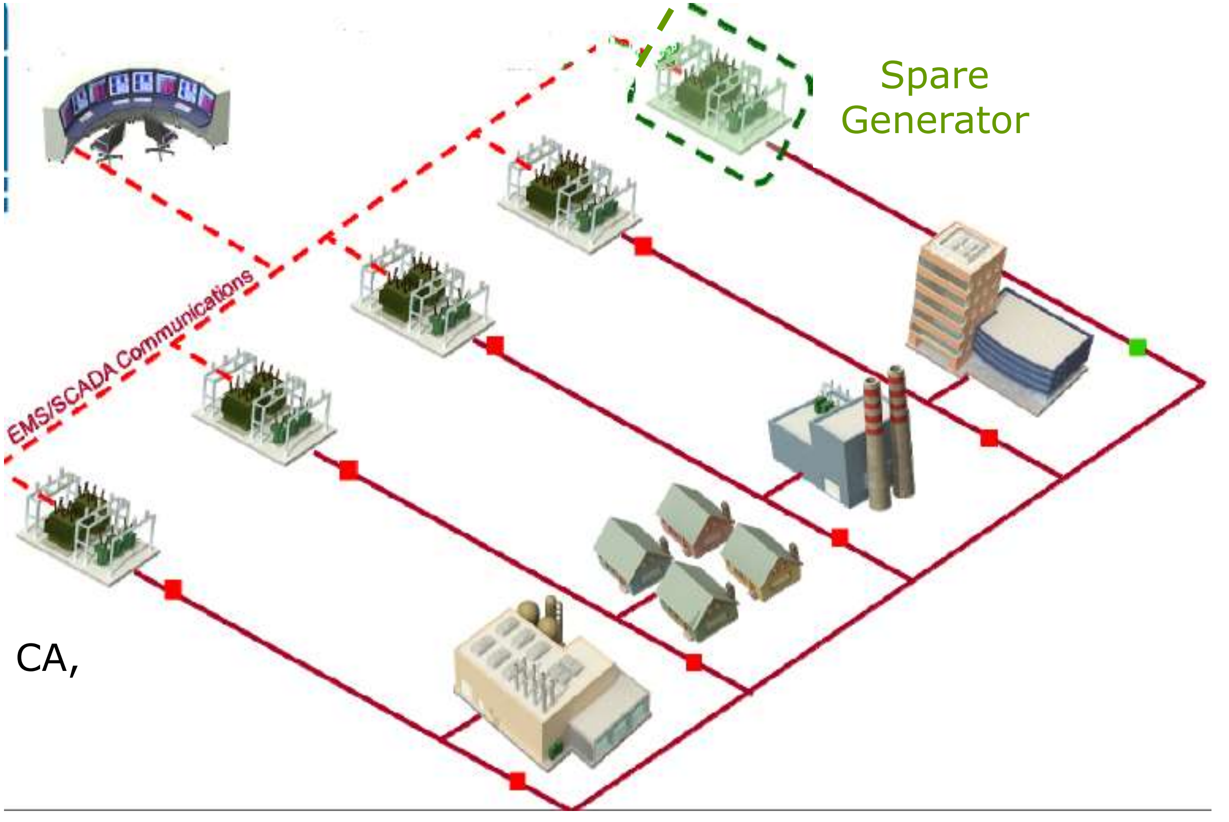
The grid is actively monitored 24/7 by grid operators, "balancing authorities."
No current technology for cost-effective, large-scale electricity store.

BAs have to rely on generators' (PPTs) fast (<15 min notice) response to demand changes.

107 Balancing Authorities are responsible for balancing in real time the supply and demand for power in specified areas.

Different degrees of integration of electricity markets (NY,.., TX highly integrated).

Balancing Power Flow



Example: Brownouts in CA, flexible charges

Task of Balancing Authority:
1. Continuously balance the Control Area’s net scheduled interchange with its actual interchange by dispatching generation units as needed for regulation.

2. Direct/dispatch power flows.

3. Helps the Interconnection to regulate and stabilize the alternating current frequency.

The Future “Internet Of Things”

Planning for a great expansion (→“smart grid”) of existing grid. However,....

Fin Current Grid