# Distribution Grids

# Agenda

## Distribution Grids for primary fuels and electricity

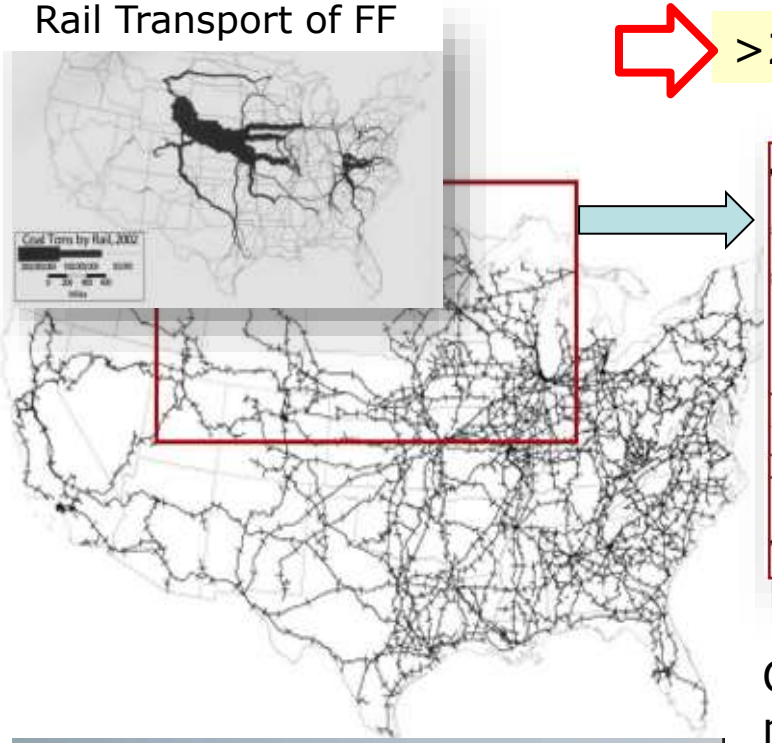
- Domestic coal transport
- Primary FF carrier flows
- U.S. crude oil trunklines
- U.S. Natural gas pipeline grid
- U.S. Power Plants (all), geographical distribution

- Electricity generation, outlook
- U.S. electrical grid, schematics
  Network of transmission lines
  Electrical specifications, cables, transformation

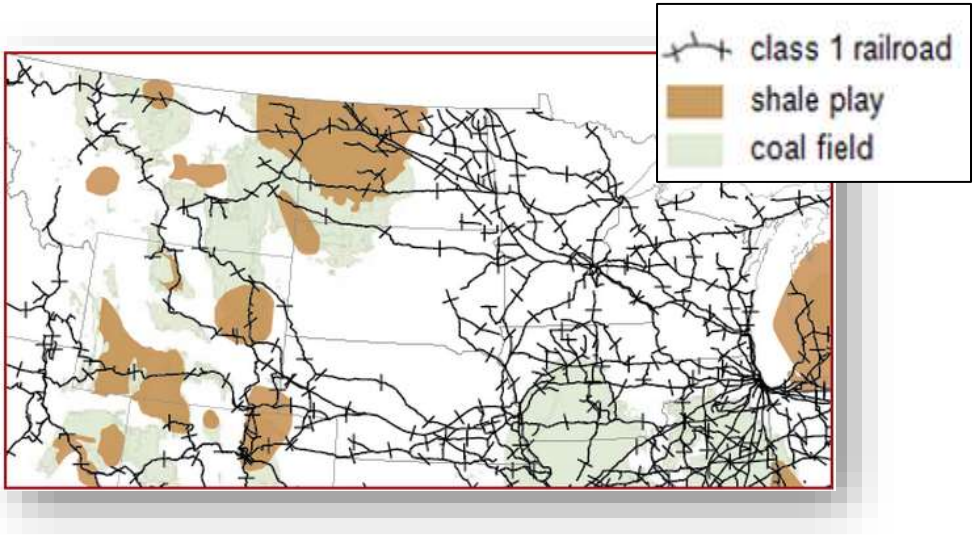
- Balancing task: supply = demand
- E-Grid failures/vulnerabilities
- Grid organization/management

# Coal Transport by Rail/Barge

Rail Transport of FF



>2014: U.S. rail system Capacity exceeded




Coal: largest volume moved by rail, 4.9 million carloads @ $(12-17)/t. 2023: 425.9M st

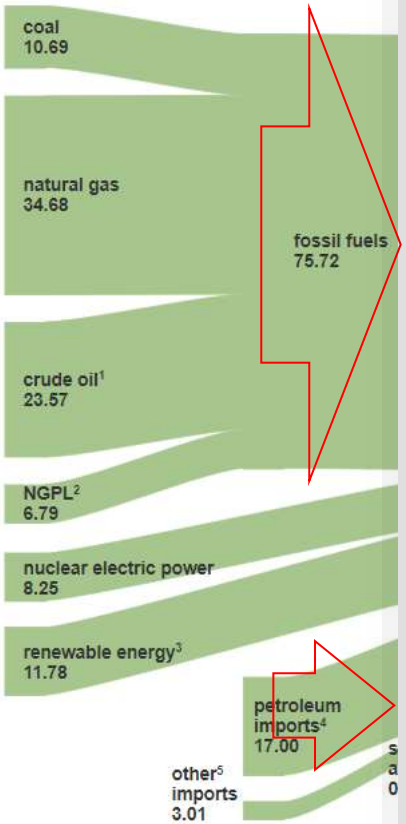
Oil and petroleum products: 672,118 tank cars (Jan-Oct 2014)

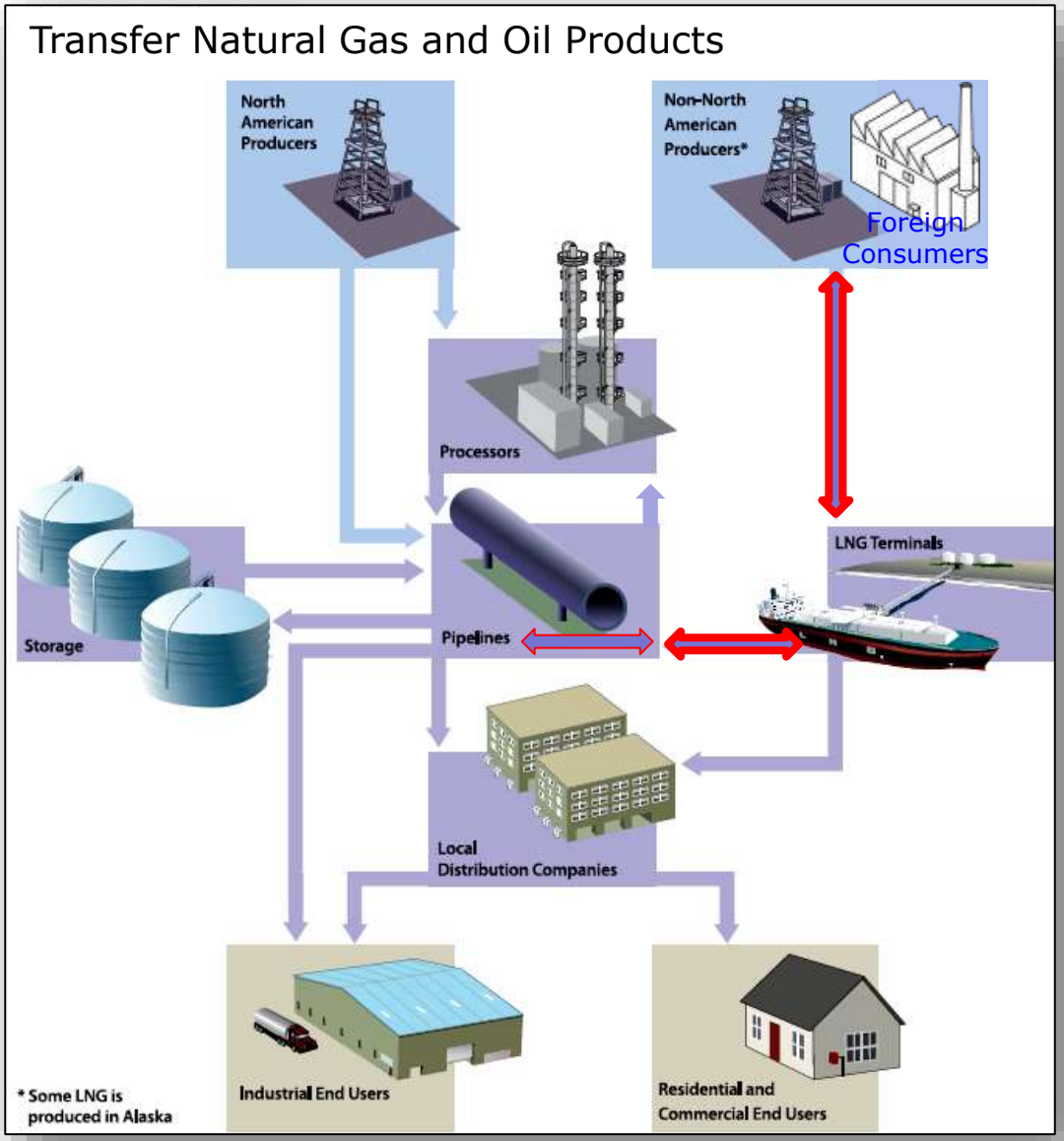
Coal transport by river barges (1,500 t/barge @ $5/t). Typical: 15-barge tows (1/4 mi). Less used for oil/petroleum.

2022: Low water level in major US rivers

# Primary Fossil Fuel Carrier Flow

2020: Quad BTU =EJ (Input)



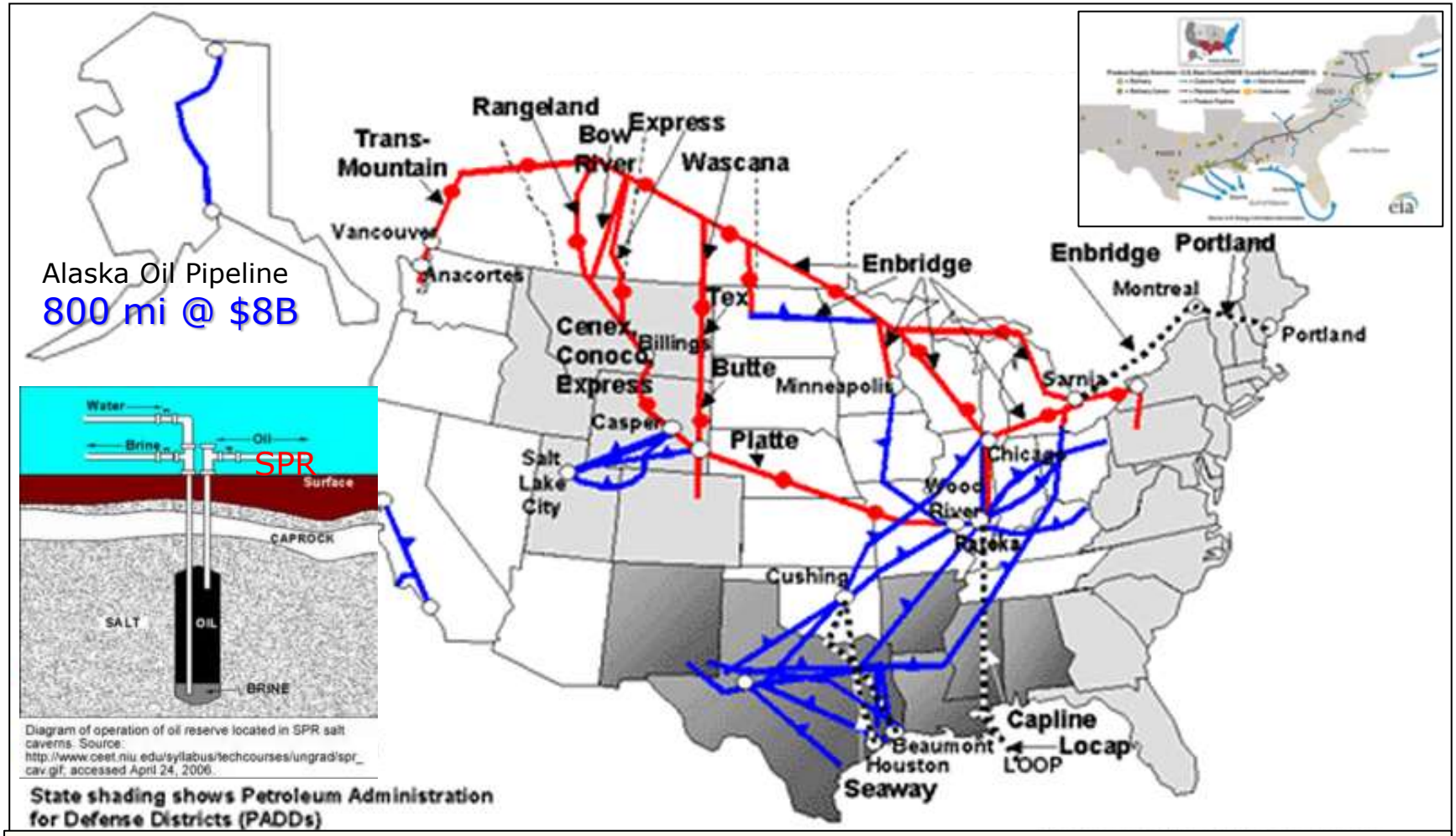

U.S. oil & gas import/export (net export)

Pipeline net, Keystone XL, N Dakota Access (1,172mi)

Oil and LNG Supertankers

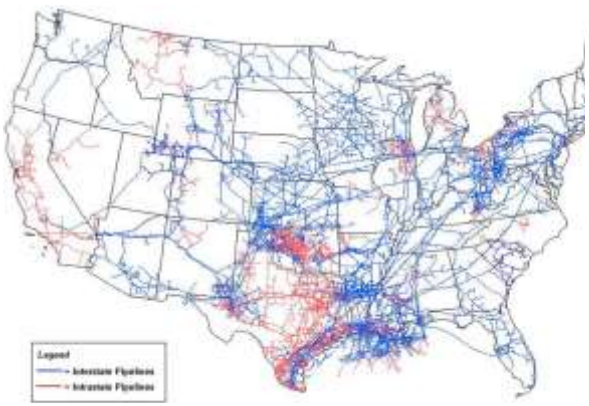
Concern: chemical safety, safety of sea lanes (protected convoys?)

# U.S. Major Crude Oil Pipeline (Trunkline) Network




55,000 mi of crude oil trunk pipelines connecting regional markets,
30,000-40,000 mi of gathering lines (Texas, Louisiana, Wyoming, ….)
Gathering and larger trunk pipelines: transfer crude oil from production wells to refineries.
Several new major, large volume oil pipelines under design/construction (Canada, Europe, Asia)

# U.S. Natural Gas Pipeline Grid



U.S. Natural Gas Pipeline Network


U.S. Regions (PADDs)

Compressor Stations

- More than 210 natural gas pipeline systems.
- 305,000 miles gas transmission pipelines.
- > 1,400 compressor stations → continuous flow.
- > 11,000 delivery points, 5,000 receipt points, 1,400 interconnection points .
- 24 hubs or market/distribution centers.
- 100 LNG peaking facilities (see map).
- 400 underground natural gas storage facilities.
- 49 import/export via pipeline terminals.
- 8 (➔20?) LNG import/export facilities.

| Size (in.) | Right of Way | Material | Labor | Misc. | Total |
|---|---|---|---|---|---|
| 8 | $ - | $ - | $ - | $ - | $ - |
| 12 | $ 68,779.00 | $ 188,942.00 | $ 737,056.00 | $ 438,626.00 | $ 1,433,403.00 |
| 16 | $ 267,288.00 | $ 415,979.00 | $ 1,937,269.00 | $ 1,473,663.00 | $ 4,094,199.00 |
| 20 | $ 199,333.00 | $ 329,680.00 | $ 2,728,127.00 | $ 1,740,590.00 | $ 4,997,730.00 |
| 24 | $ 134,000.00 | $ 337,650.00 | $ 2,021,810.00 | $ 836,247.00 | $ 3,329,707.00 |
| 30 | $ 736,129.00 | $ 920,316.00 | $ 4,919,086.00 | $ 3,406,645.00 | $ 9,982,176.00 |
| 36 | $ 504,104.00 | $ 895,253.00 | $ 3,301,095.00 | $ 2,763,844.00 | $ 7,464,296.00 |

Source: Oil and Gas Journal (2016).

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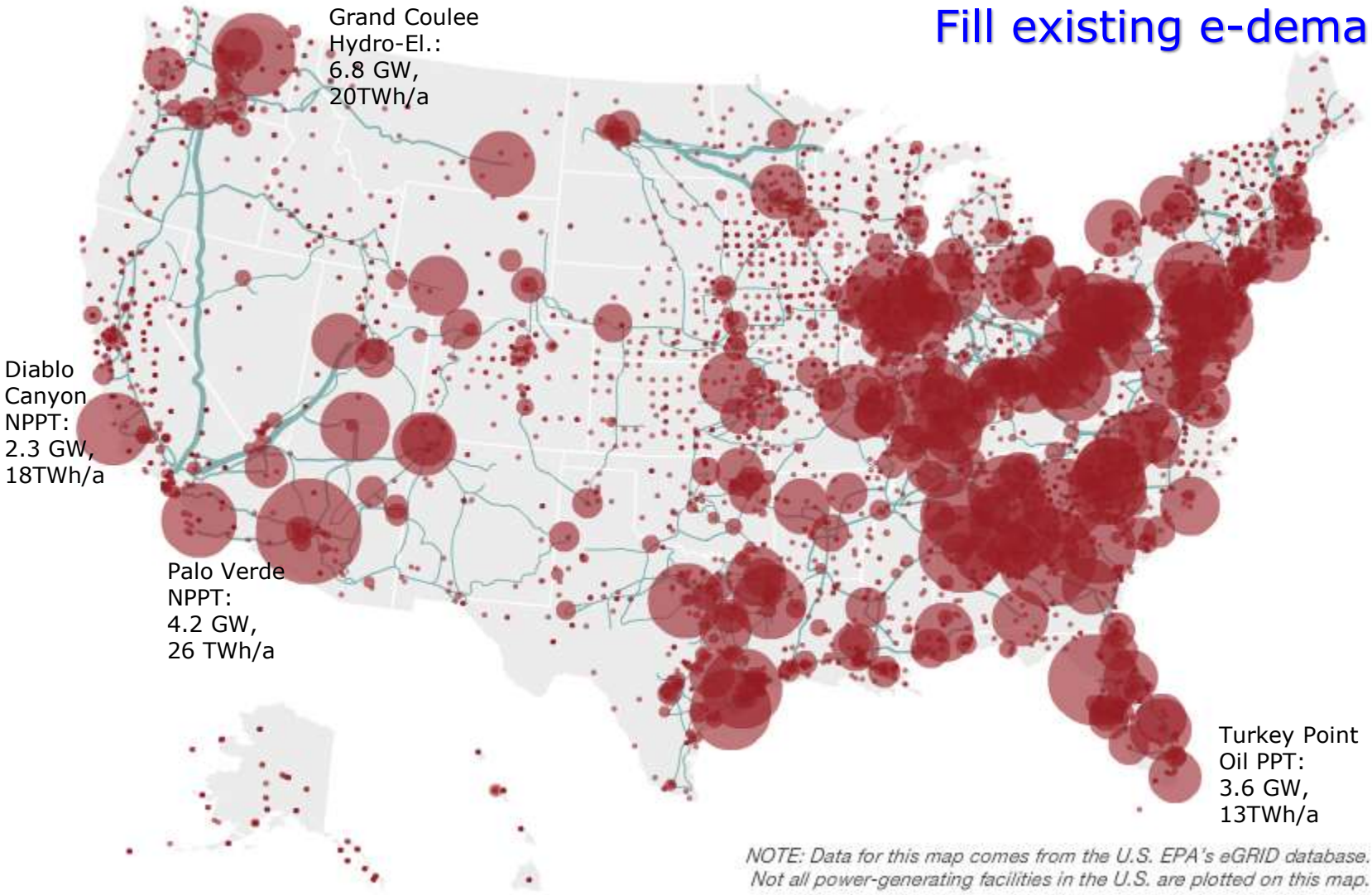
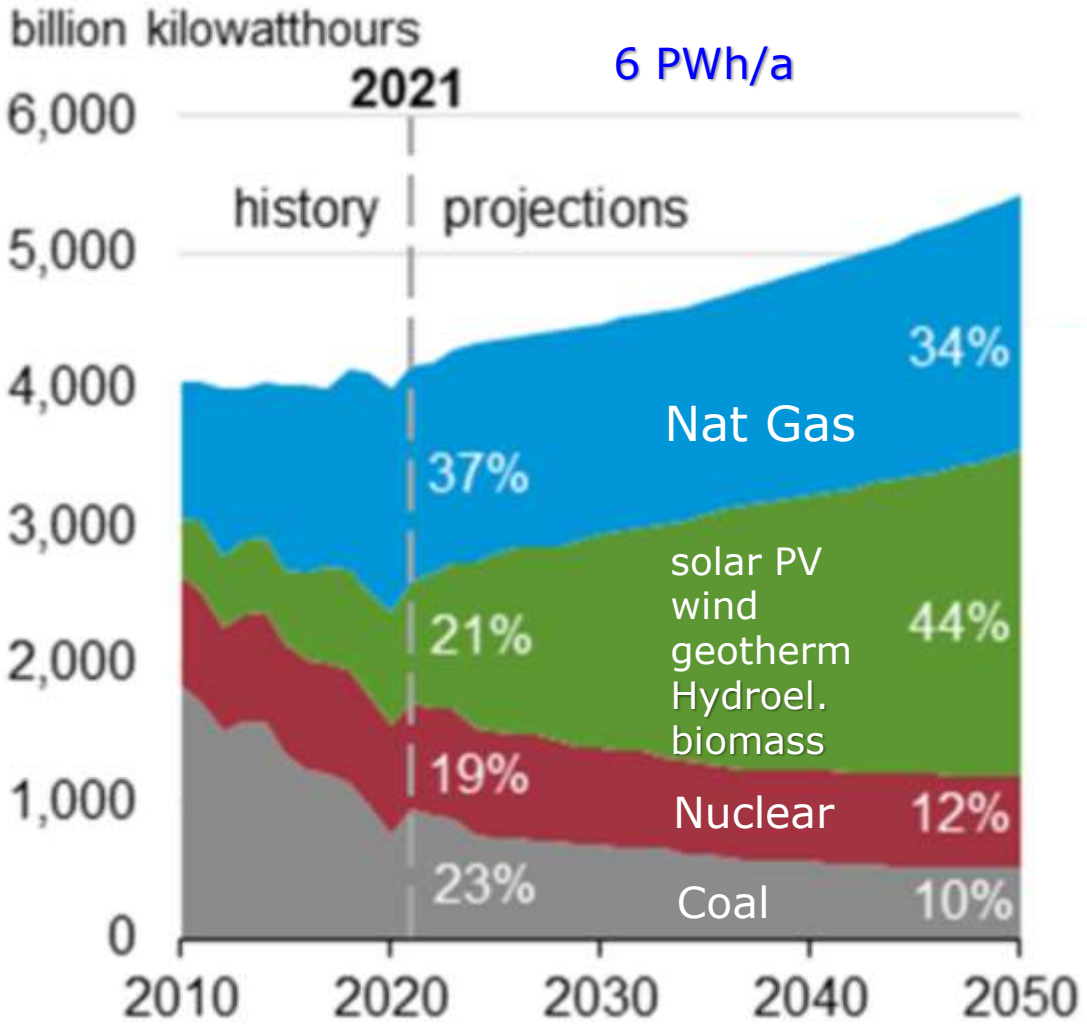
# U.S. Electrical Power Plants (2009, All Types)

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



# 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)

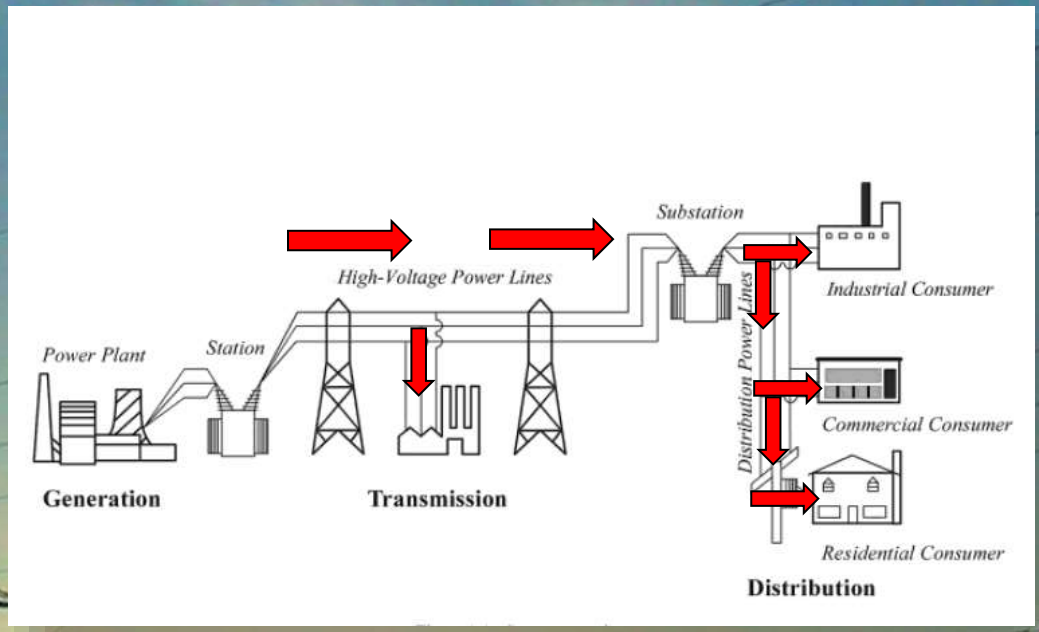
Generation: BAU + new policies
Tax credits, C tax ?

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.

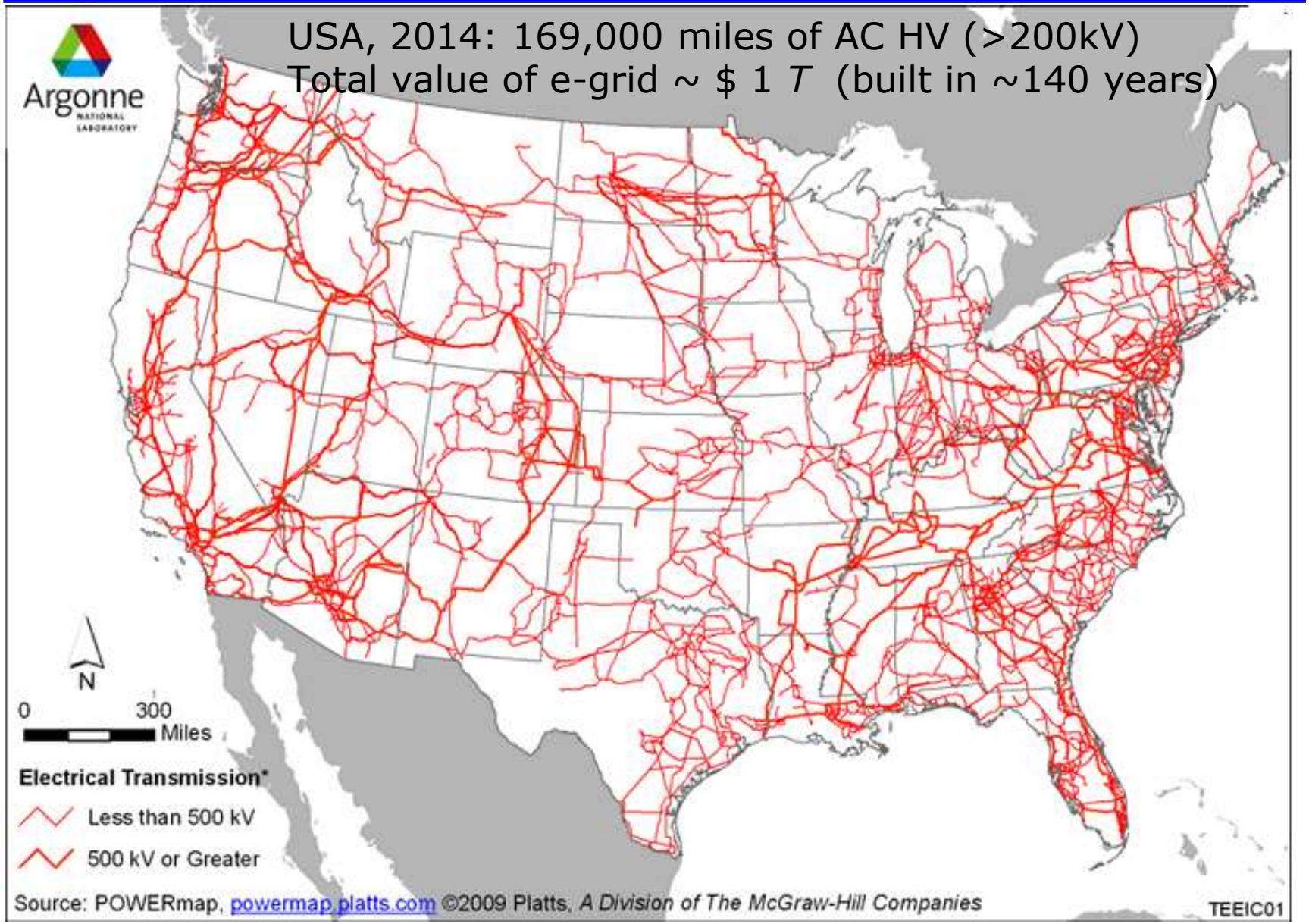
# The Current U.S. Electrical Grid

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

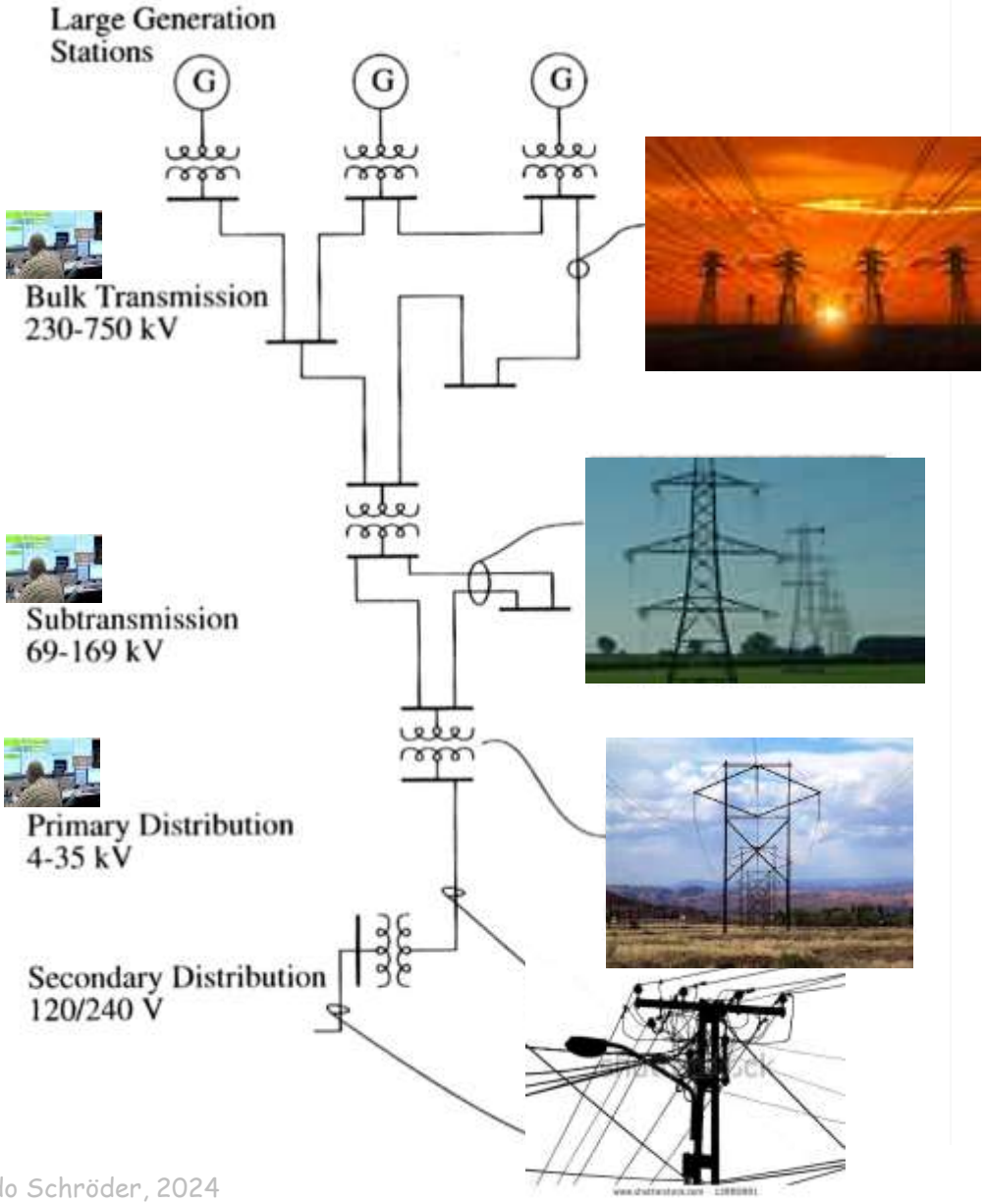



Video Grid History

# U.S. Electrical Transmission Lines



# Basic U.S. Power Transmission












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

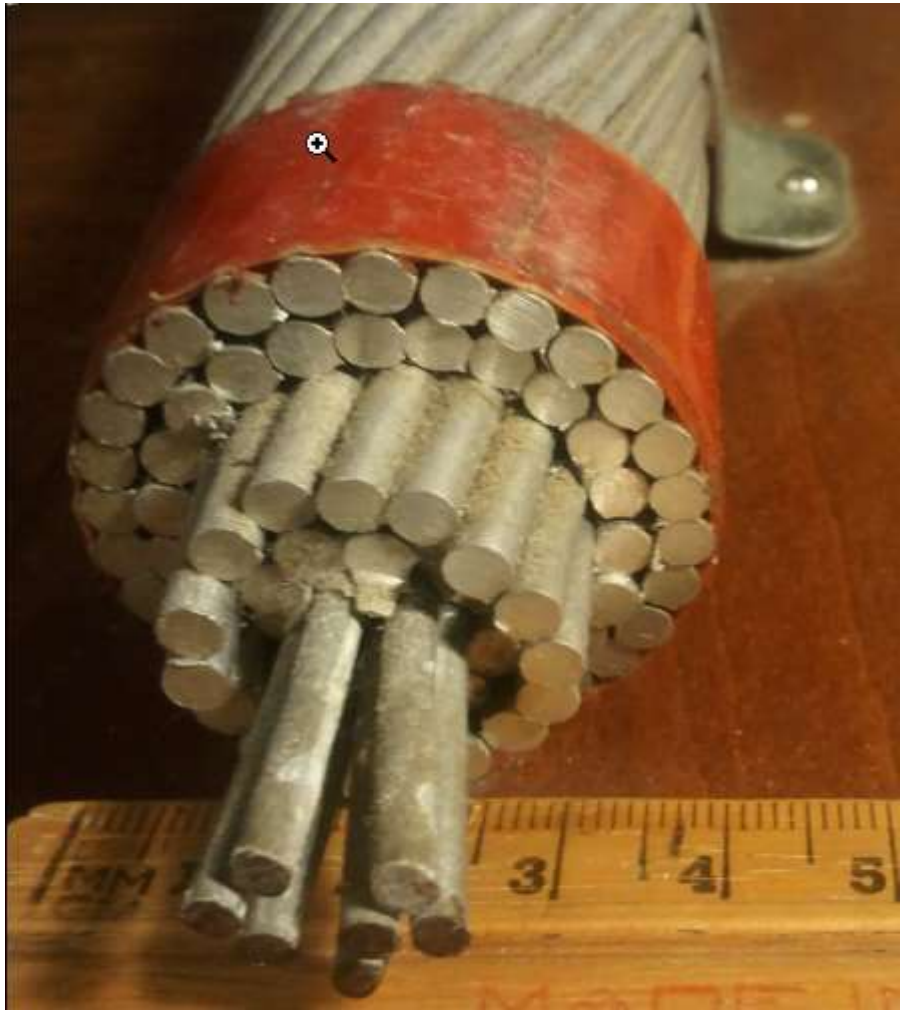
Easy conversion, switching, control, reliability, maintenance.
AC motors and generators are simpler and cheaper than DC.

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)




Main conductors:

4 twisted strands of aluminum.

Metal wires conduct electron currents only on the surface → optimize/maximize surface.

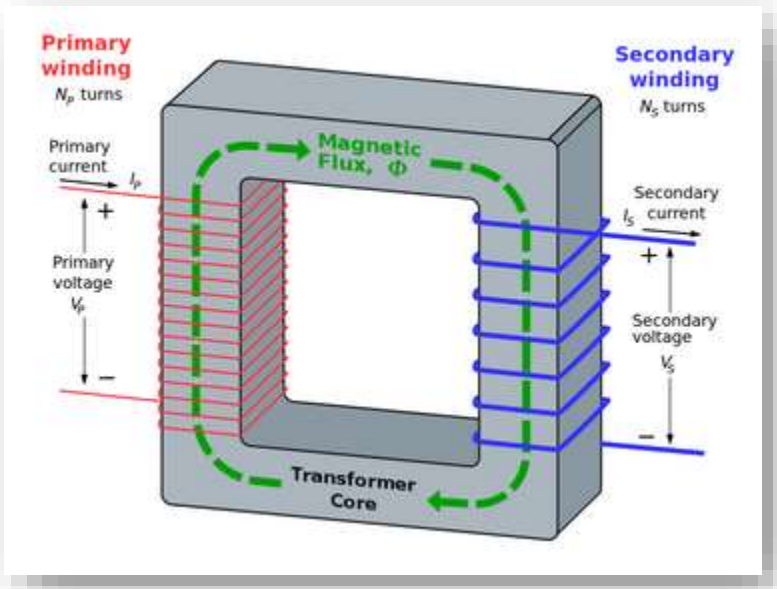
Better conductors are Cu, Ag, Au but not economical.

Steel strands form core bundle, for stability. HV overhead conductors are not insulated.

(carbon fibers in future?)

Different wire standard gauges (**A**merican **W**ire **G**auges)

# AC Transformer Substations




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

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

$$V_{secondary}/V_{primary} = N_{secondary}/N_{primary}$$

⇒ *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

Transformers, changes V amplitude

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# Main Tasks: Balance Electrical Power Distribution

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

Reliable instantaneous power **supply(t) $\overset{!}{=}$ demand(t)**

**Stability**: Regulated voltage ($\lesssim$ 1%)

Regulated frequency (~ 0.1 Hz)

Load imbalance → frequency change

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)

| Protection | Generator Primary Control and AGC | Economic Dispatch | Unit Commitment | Mid-Term Planning | Expansion Planning |
|---|---|---|---|---|---|
| Milliseconds | Seconds | Minutes | Hours | Days | Weeks | Years |

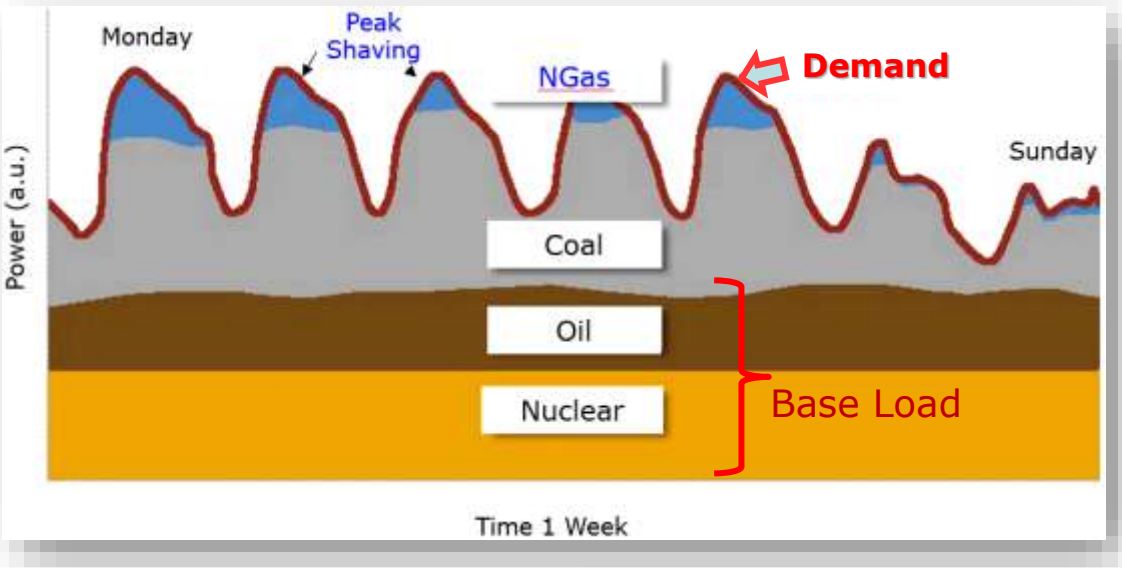
The Wires

video

The Brain (Computer Assisted)

video

# Balancing Agencies: Diurnal Tasks




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

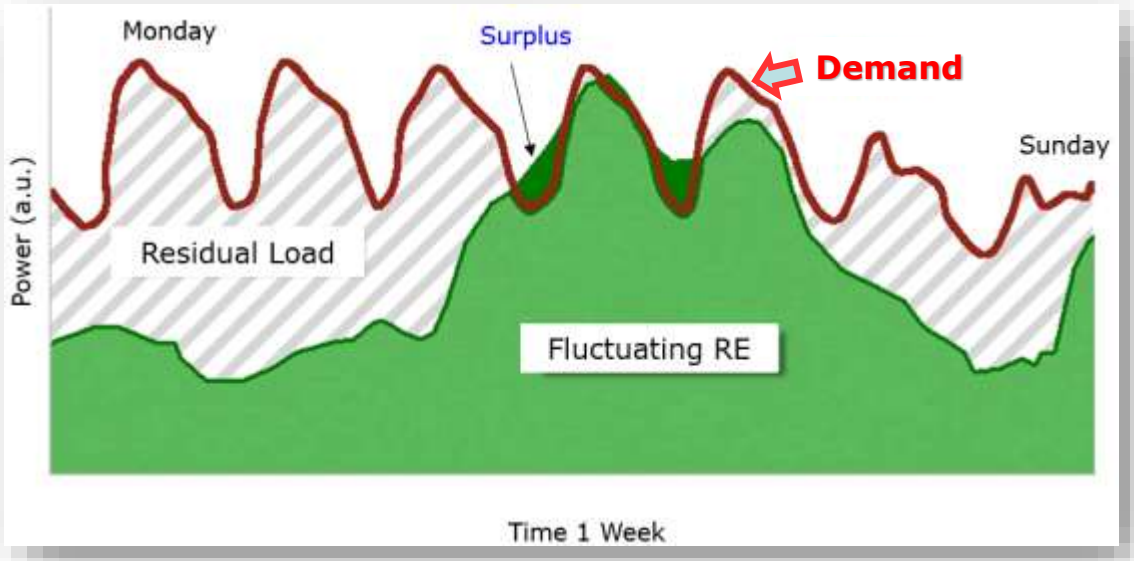
Peak power demands needs quick-responding generators (natural gas, LNG) for "peak shaving."

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

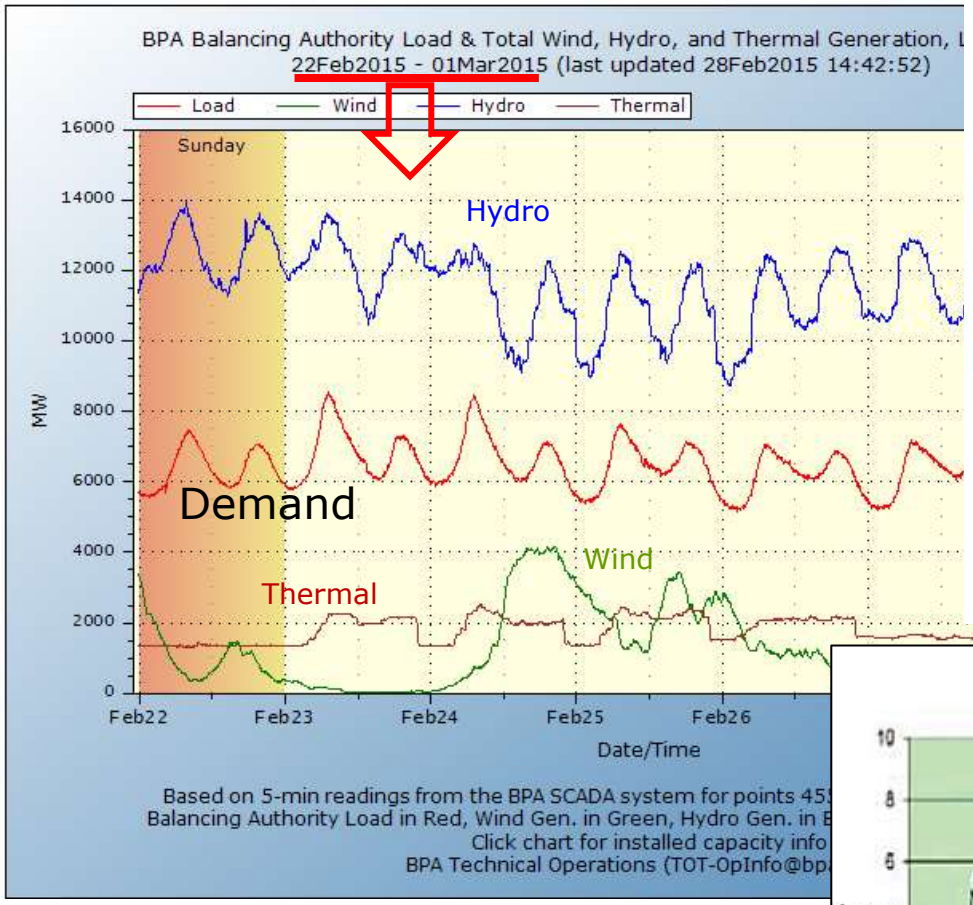
Accepting large fractions of variable renewable sources (wind/solar) with few traditional base load generators → great potential "residual loads."

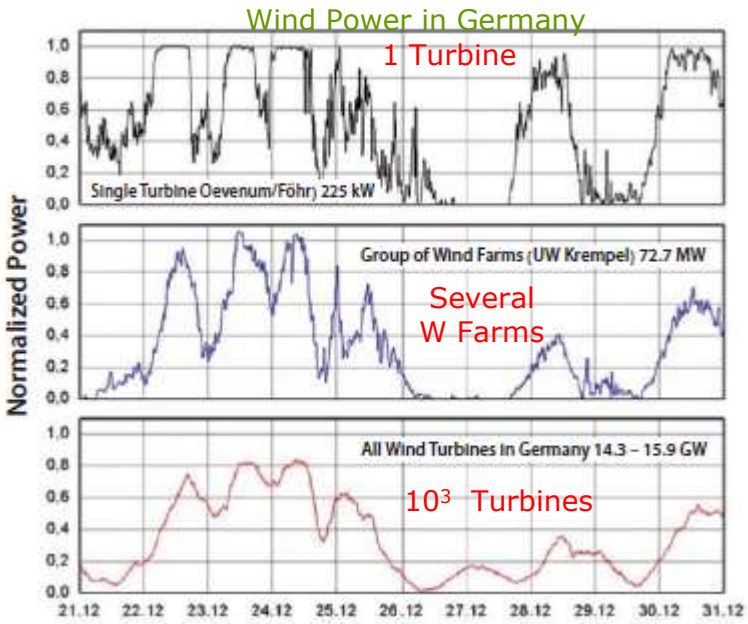
Base load →
Storage or idling fossil fuel, hydro or nuclear generators.

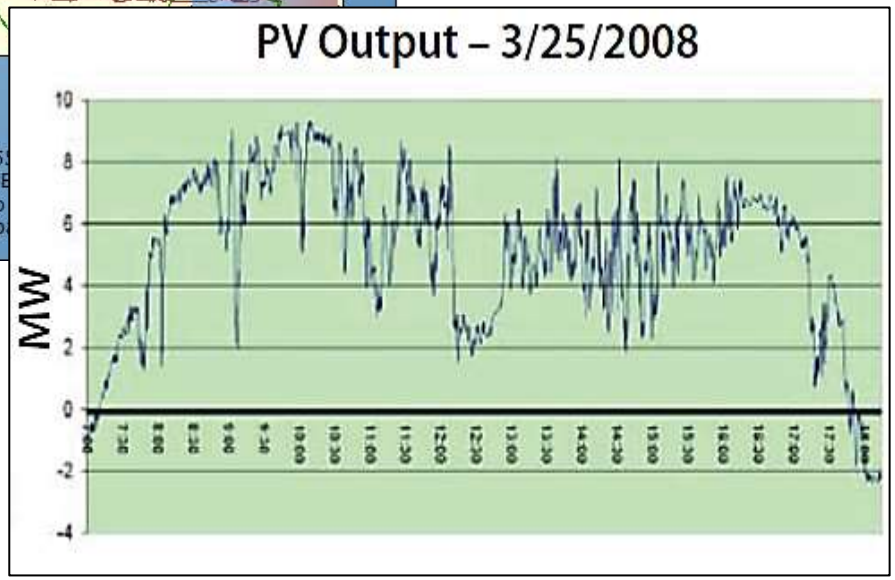
Good planning requires good RenEnergy/weather forecasts.



# Actual BA Records



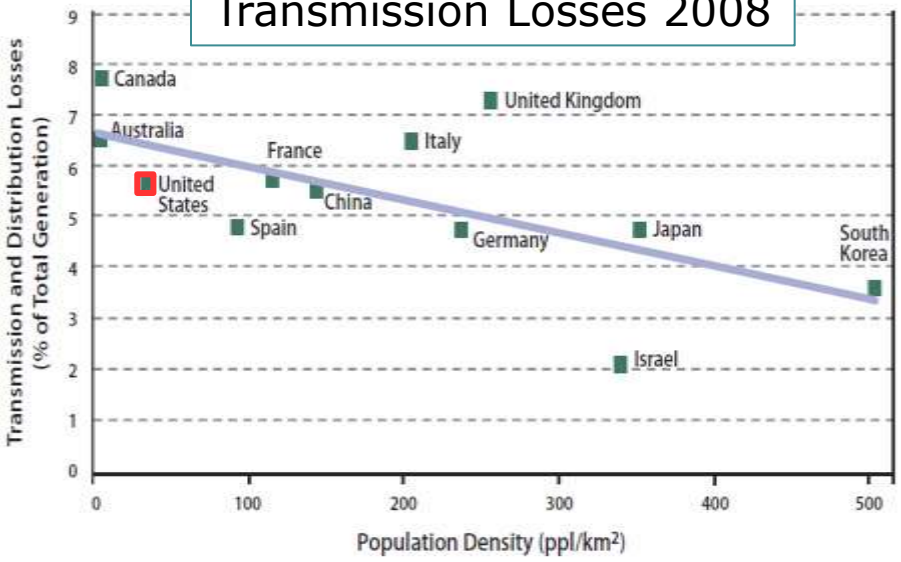

http://transmission.bpa.gov/business/operations/wind/baltwg.aspx

# Transmission Performance

| Line Type | Voltage (kV) | Miles |
|---|---|---|
| Alternating Current (ac) | 200–299 | 84,000 |
| | 300–399 | 54,000 |
| *AC* | 400–599 | 26,000 |
| | ≥ 600 | 2,400 |
| | Total ac | 161,000 |
| Direct Current (dc) | 200–299 | 700 |
| | 300–399 | 0 |
| *DC* | 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: > 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.

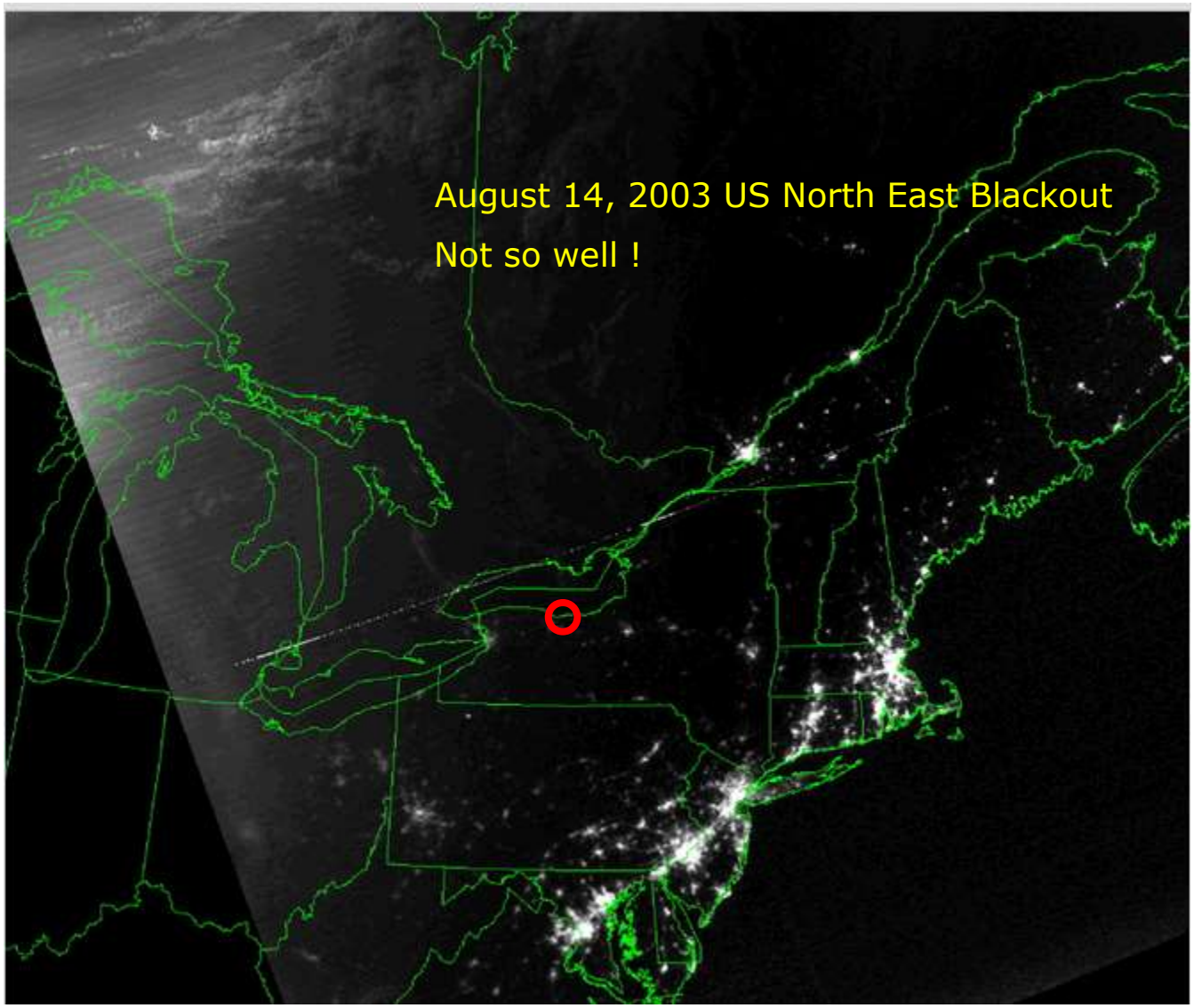
Grid performance: low losses (heat),

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

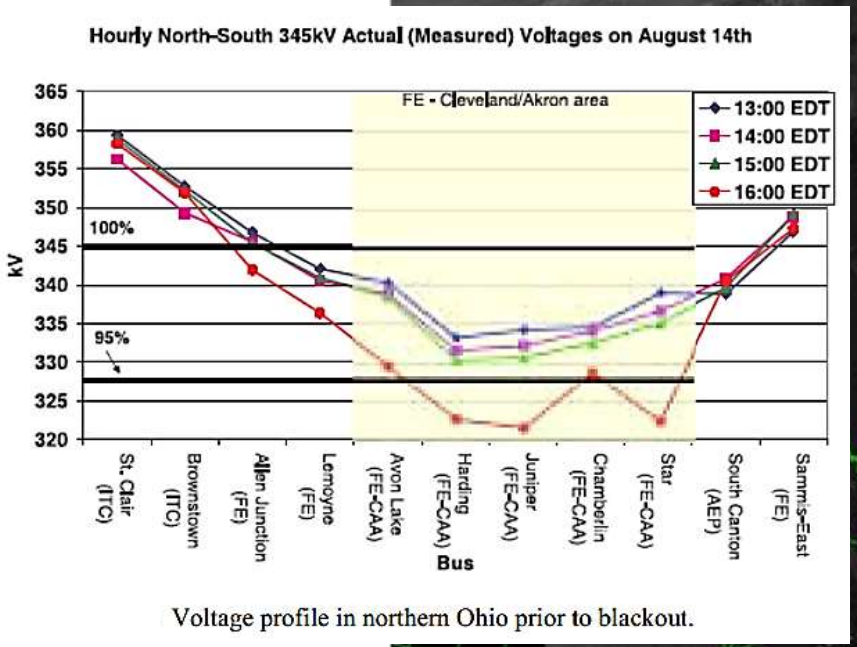
*U.S. e-Grid Performance*

# 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.

August 14, 2003 US North East Blackout

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

Tasks for network R&D !

# Cyber Vulnerabilities Of e-Grid

1st 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

# Fin Distribution Grids