

# Distribution Networks



# Agenda

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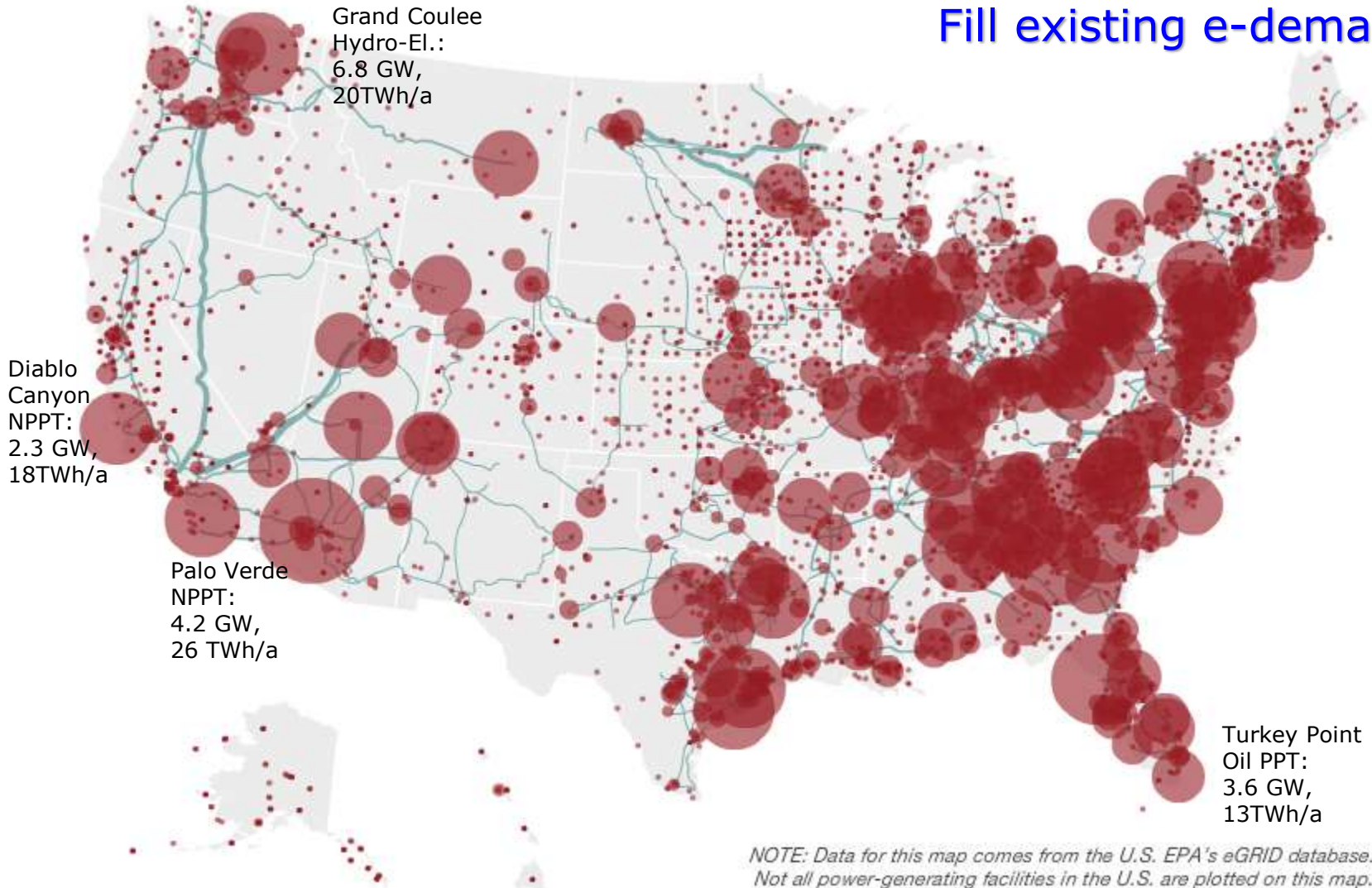
## Distribution Grids for primary fuels and electricity

- 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

# 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>

Fill existing e-demand

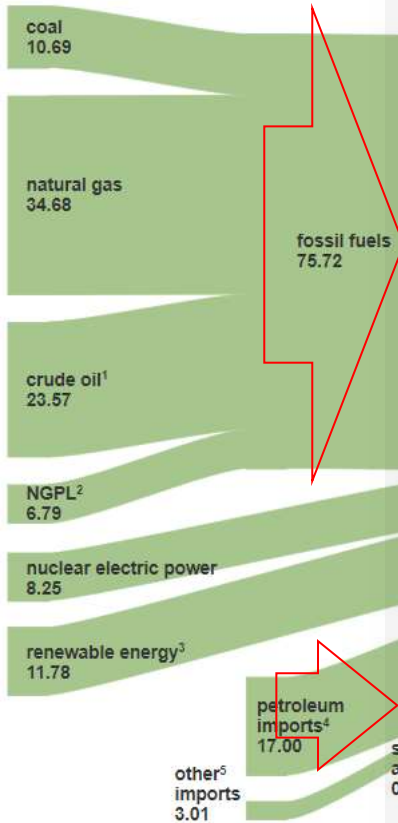


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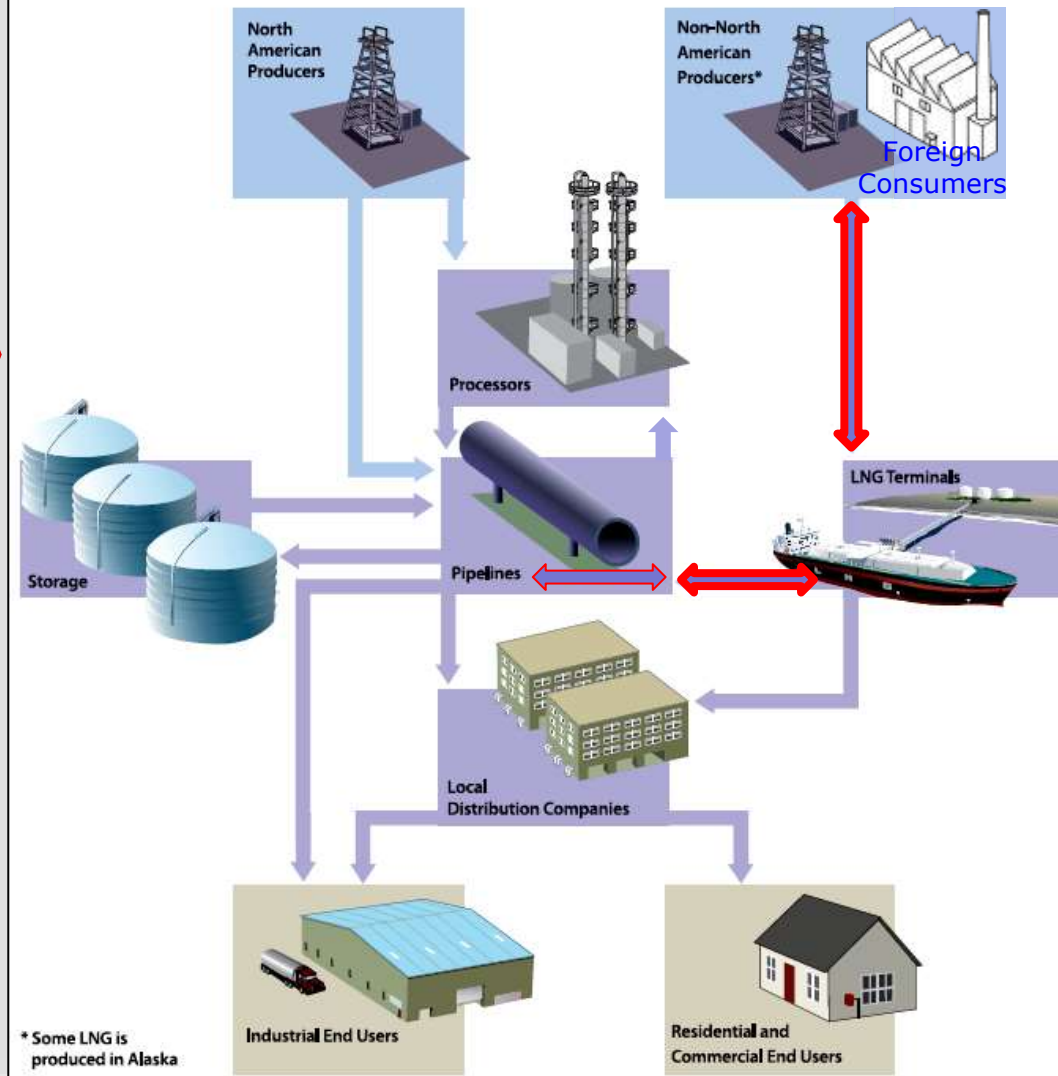
Distribution\_Grids

# Primary Fossil Fuel Carrier Flow

2020: Quad BTU  
=EJ (Input)



Transfer Natural Gas and Oil Products



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?)

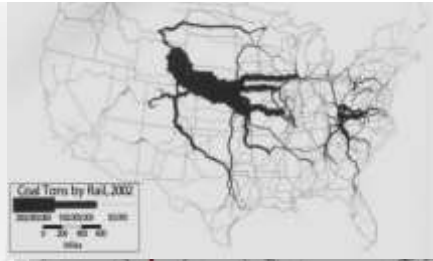
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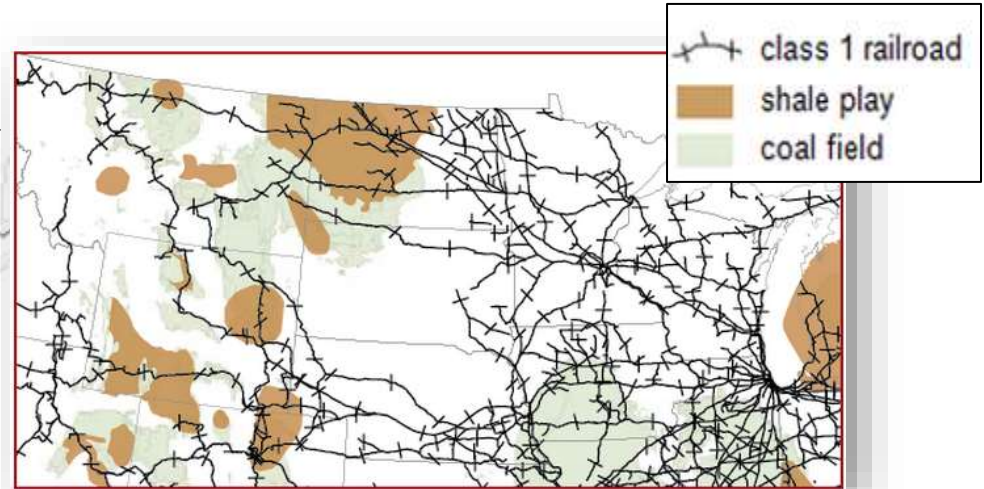
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# Coal Transport by Rail/Barge

## 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)

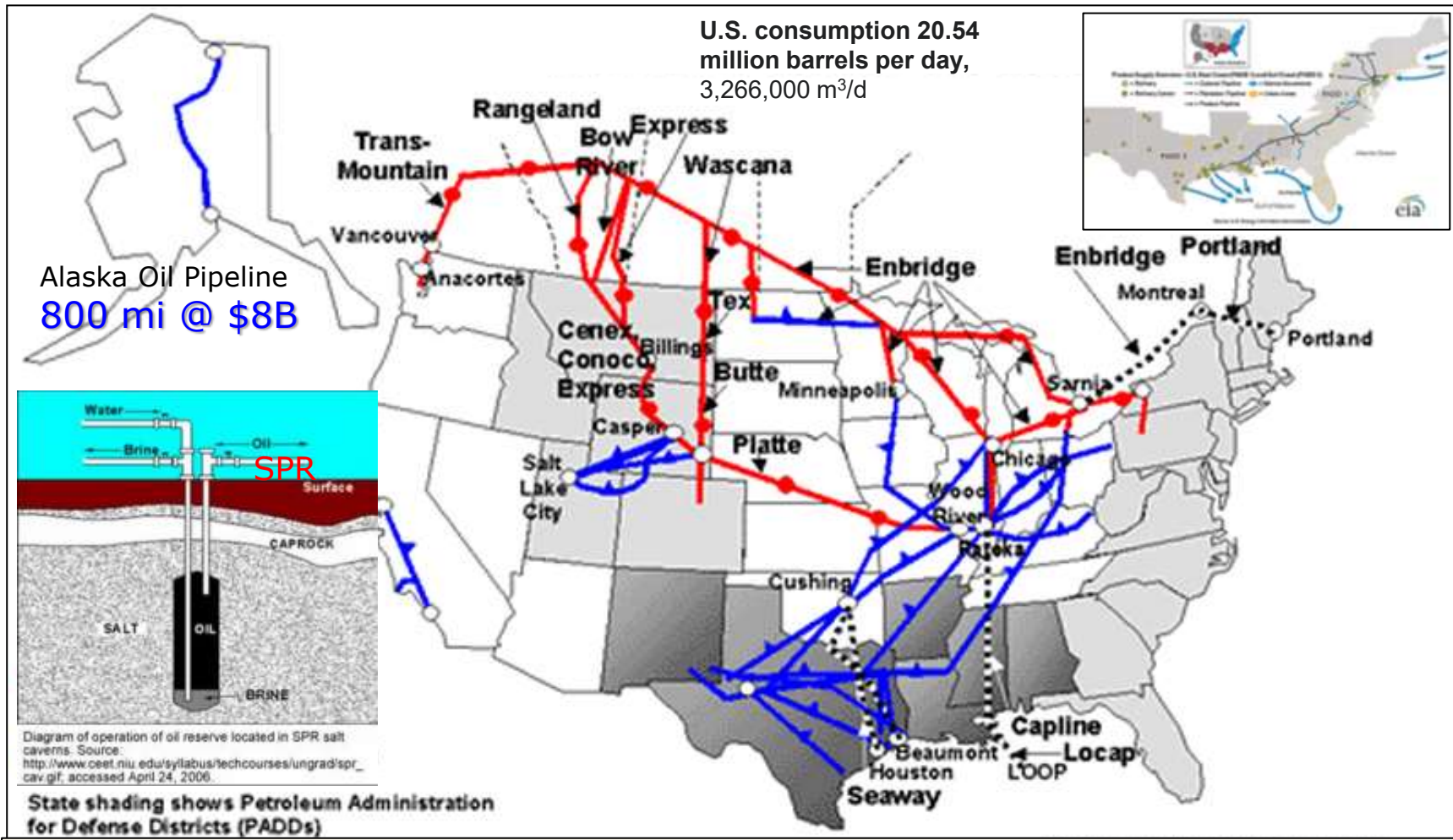
Coal transport by river barges (1,500 t/barge @ \$5/t). Typical: 15-barge tows (1/4 mi). Less used for oil/petroleum.



**2022: Low water level in major US rivers**



# 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)

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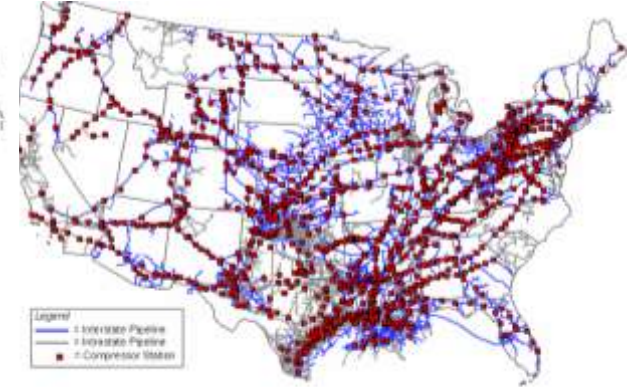
# U.S. Natural Gas Pipeline Grid



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.

➔ **Strategic Issue: Methan leakage.**



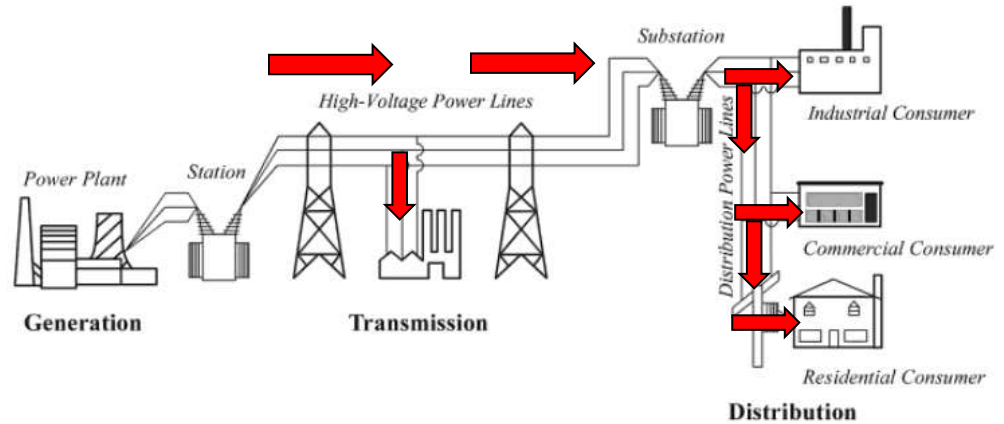
Size (in.)	Right of Way	Material	Labor	Misc.	Total
8	\$ -	\$ -	\$ -	\$ -	\$ -
12	\$ 68,779.00	\$ 188,942.00	\$ 737,056.00	\$ 438,626.00	\$ 1,433,403.00
16	\$ 267,288.00	\$ 415,979.00	\$ 1,937,269.00	\$ 1,473,663.00	\$ 4,094,199.00
20	\$ 199,333.00	\$ 329,680.00	\$ 2,728,127.00	\$ 1,740,590.00	\$ 4,997,730.00
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).

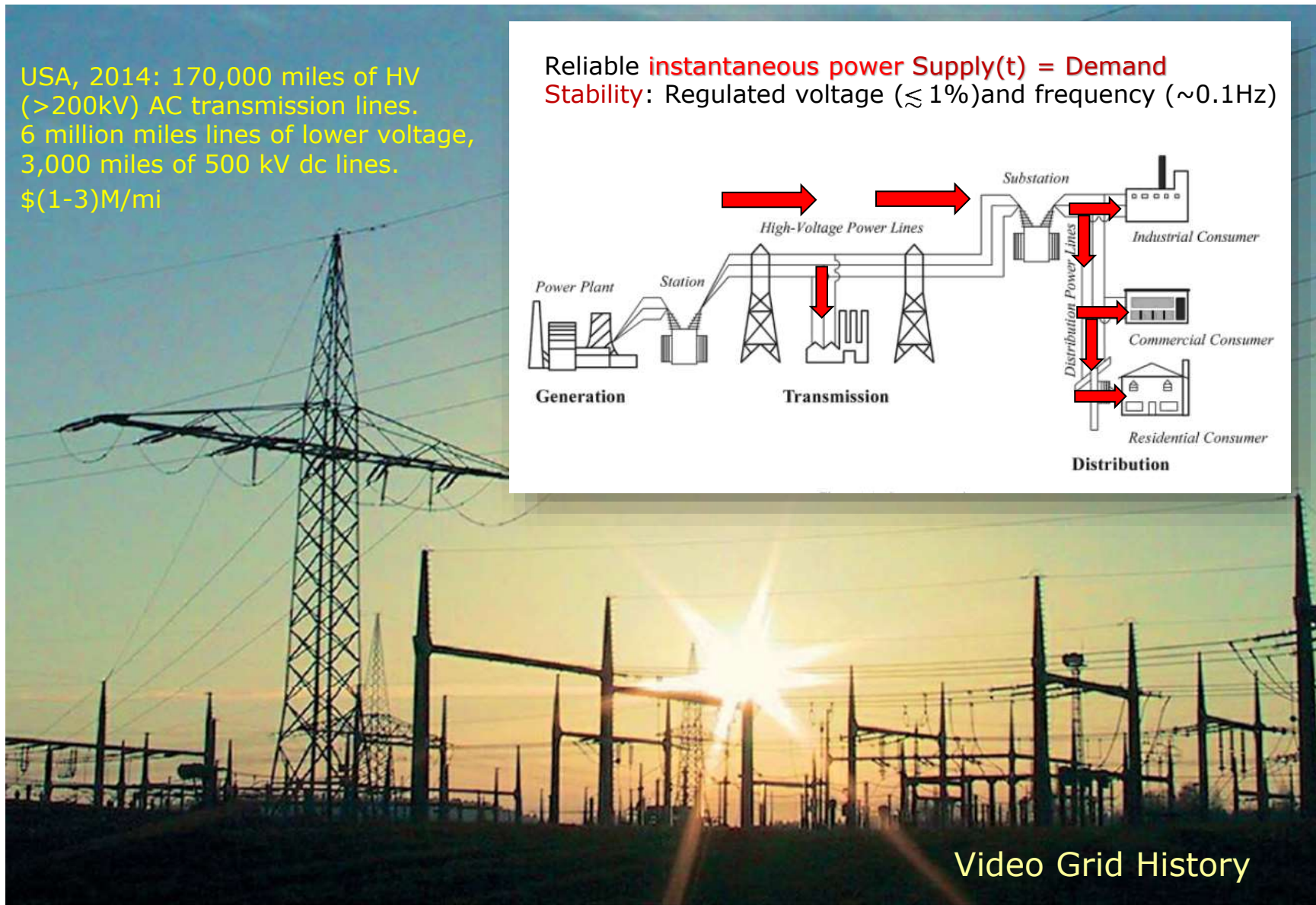
# The Current U.S. Electrical Grid

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

Reliable **instantaneous power Supply(t) = Demand**  
**Stability:** Regulated voltage ( $\lesssim 1\%$ ) and frequency ( $\sim 0.1\text{Hz}$ )

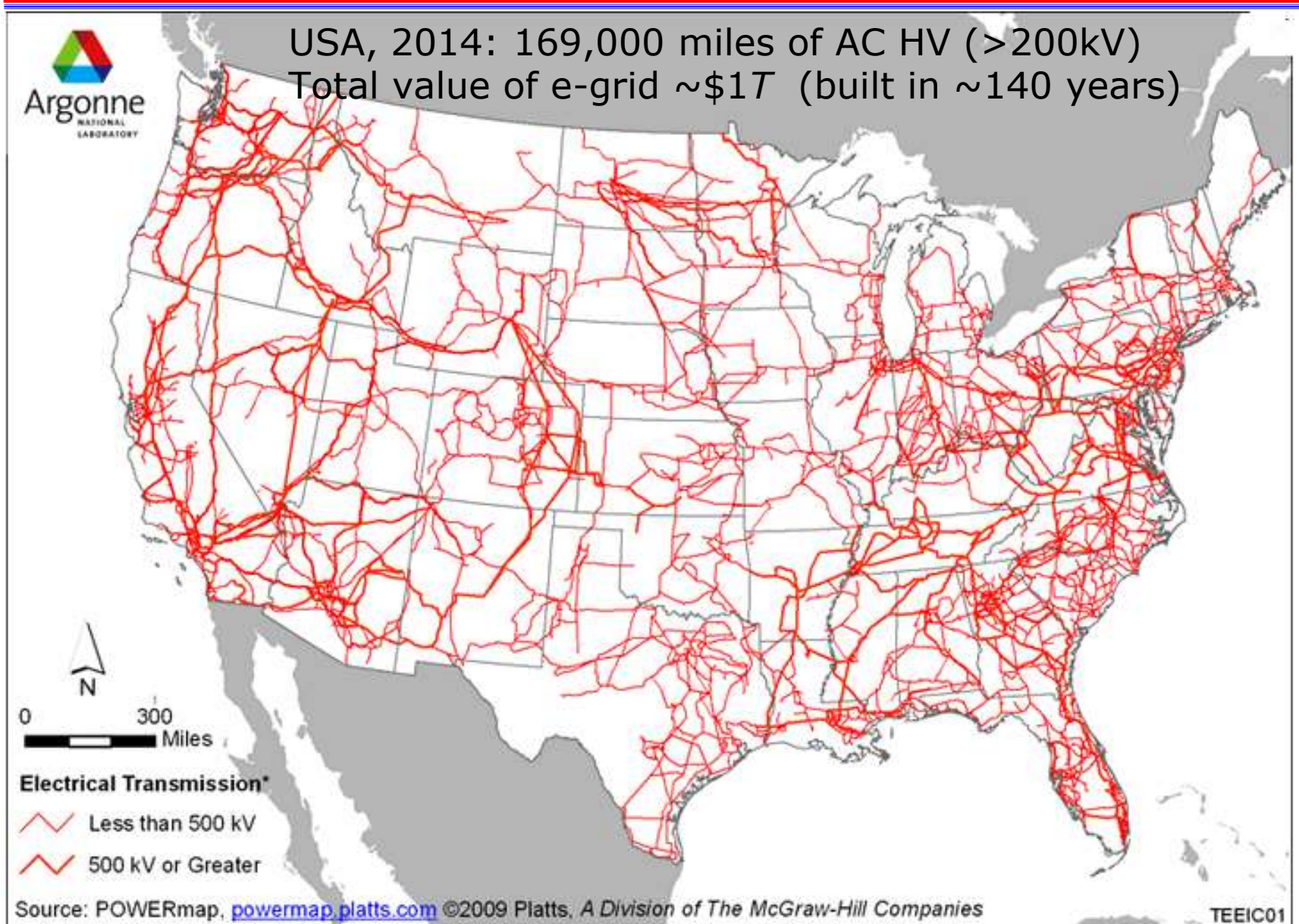


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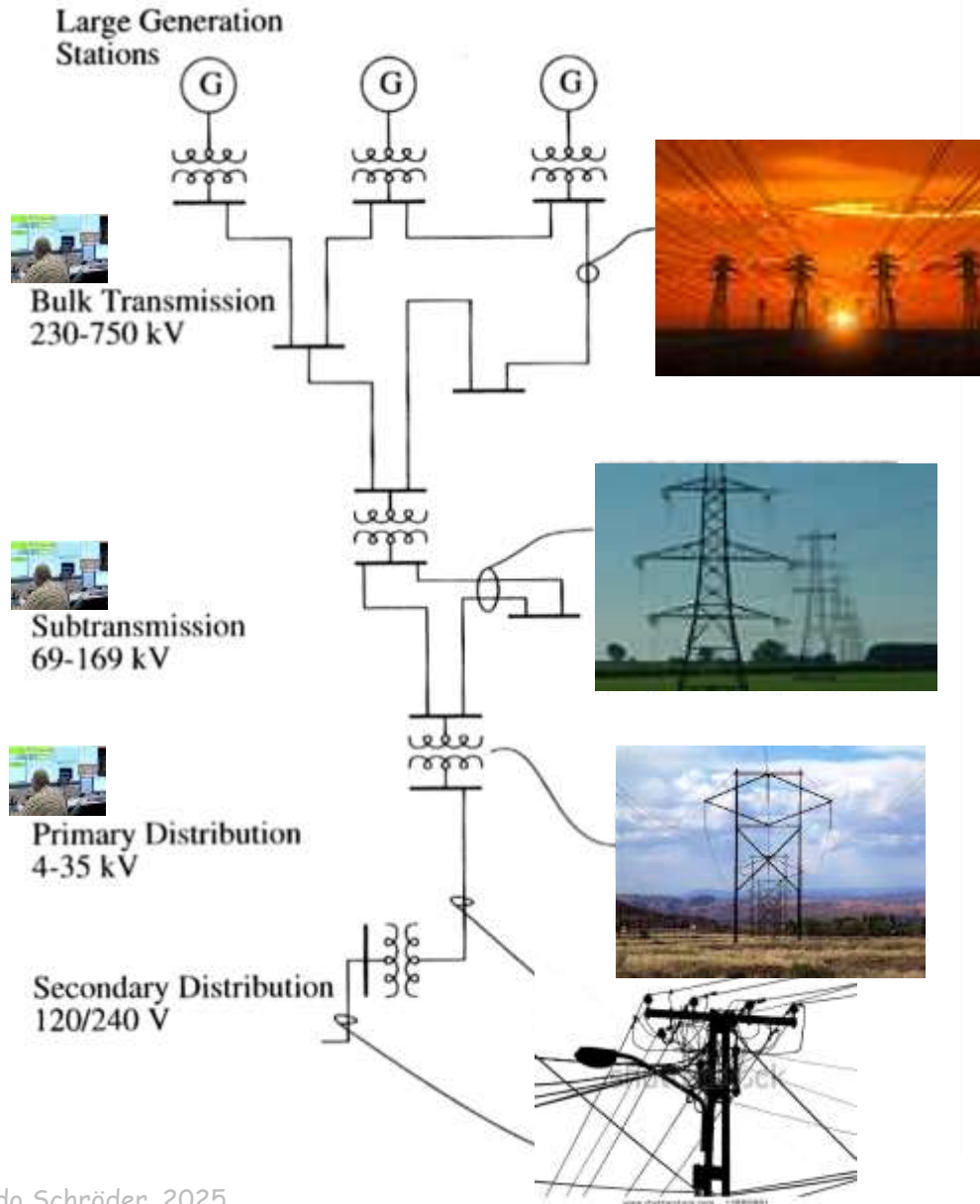


Video Grid History

# 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 economically preferred:**

115, 138, 161, 230 kV

Extra High Voltage (EHV):

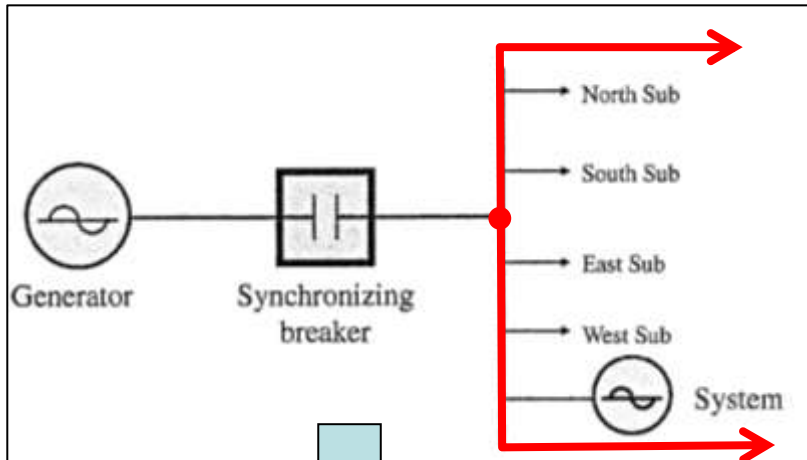
345, 500, 765 kV

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

High Voltage DC (HVDC):

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

# Generator Grid Matching



Reliable instantaneous power  
**supply  $\equiv$  demand**

**Synchronize** before connection:

- Frequency ( $60\text{Hz}$ ,  $\Delta v < 0.1\text{Hz}$ )
- Voltage ( $\approx$  voltage of grid side)
- Phase angle ( $\Delta\phi < 15^\circ$ )
- Rotation (matching 3-phases)



# Transmission Conductors (Aluminum Conductor Steel-Reinforced)

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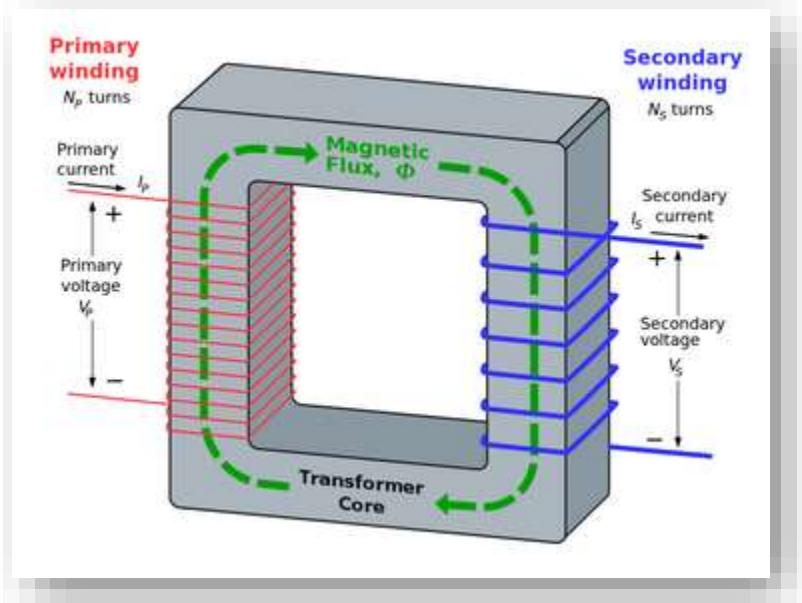
Steel strands form core bundle, for stability. HV overhead conductors, not insulated. Different standard gauges (AWG)

Main conductors:  
4 twisted strands of aluminum.

Better conductors Cu, Ag, Au not economical

Underground conductors are insulated → cooling problem

# 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



# Main Task: Balance Electrical Power Distribution

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

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

**Stability:** Regulated voltage ( $\lesssim 1\%$ )  
 Regulated frequency ( $\sim 0.1 \text{ Hz}$ )

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

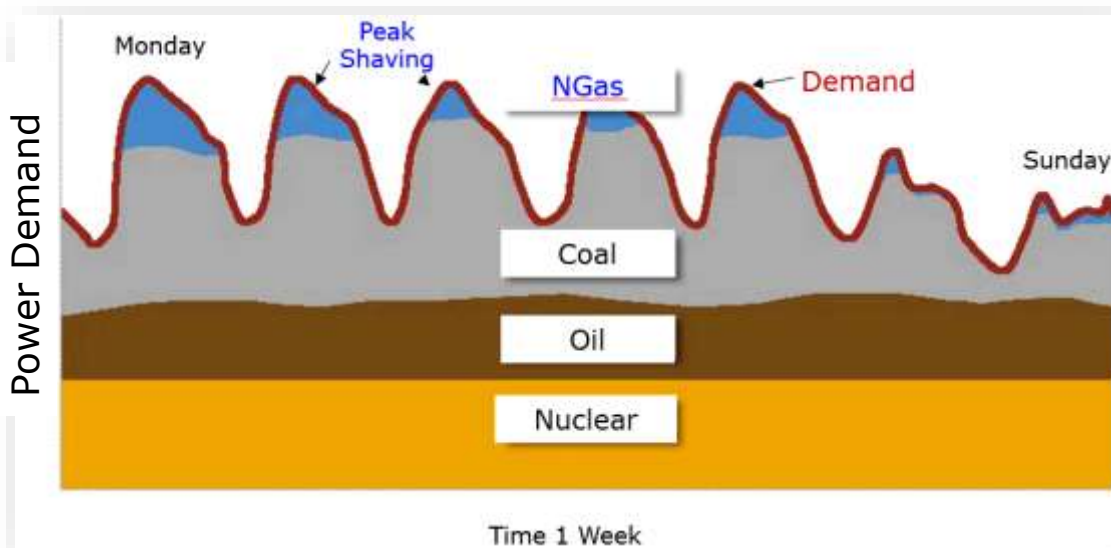
The Brain (Computer Assisted)



video

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

# Tasks of the Balancing Agencies



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

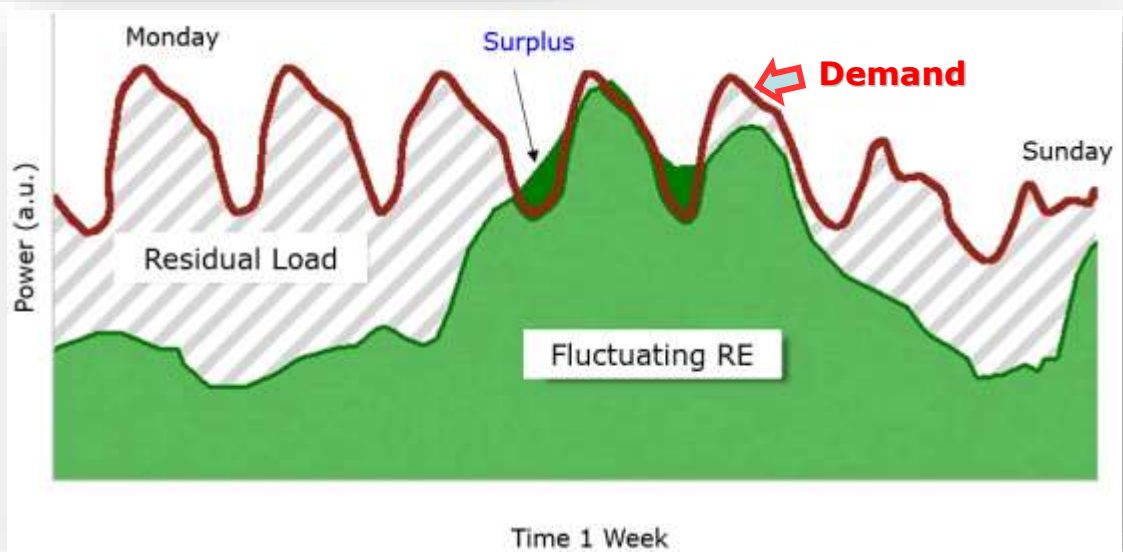
Peak power demands needs quick-responding generators (natural gas, LNG) for "peak shaving."

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.



# Cyber Vulnerabilities Of e-Grid



1<sup>st</sup> 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

# 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
<b>Total</b>		<b>169,000</b>

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

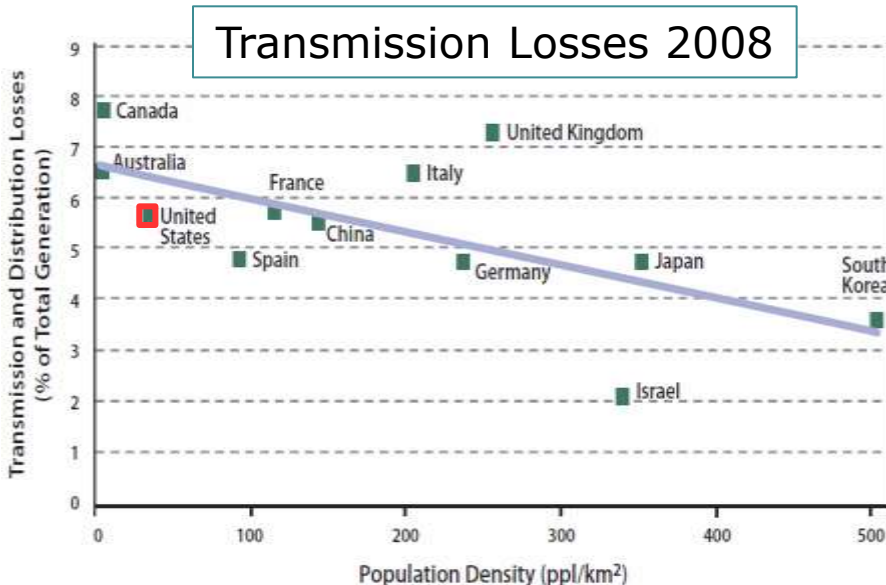
169,000 mi HV (> 200kV) lines  
6,000,000 mi HV (< 200kV) lines

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

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.



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

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# Fin Distribution Grids

