Turbines III: Wind, beg. of grid

GEOS 24705/ ENST 24705

What are constraints of having a very high turbine?

- No mechanical linkages up the tower – whole generator must be on top of tower.

Generator mounted in nacelle

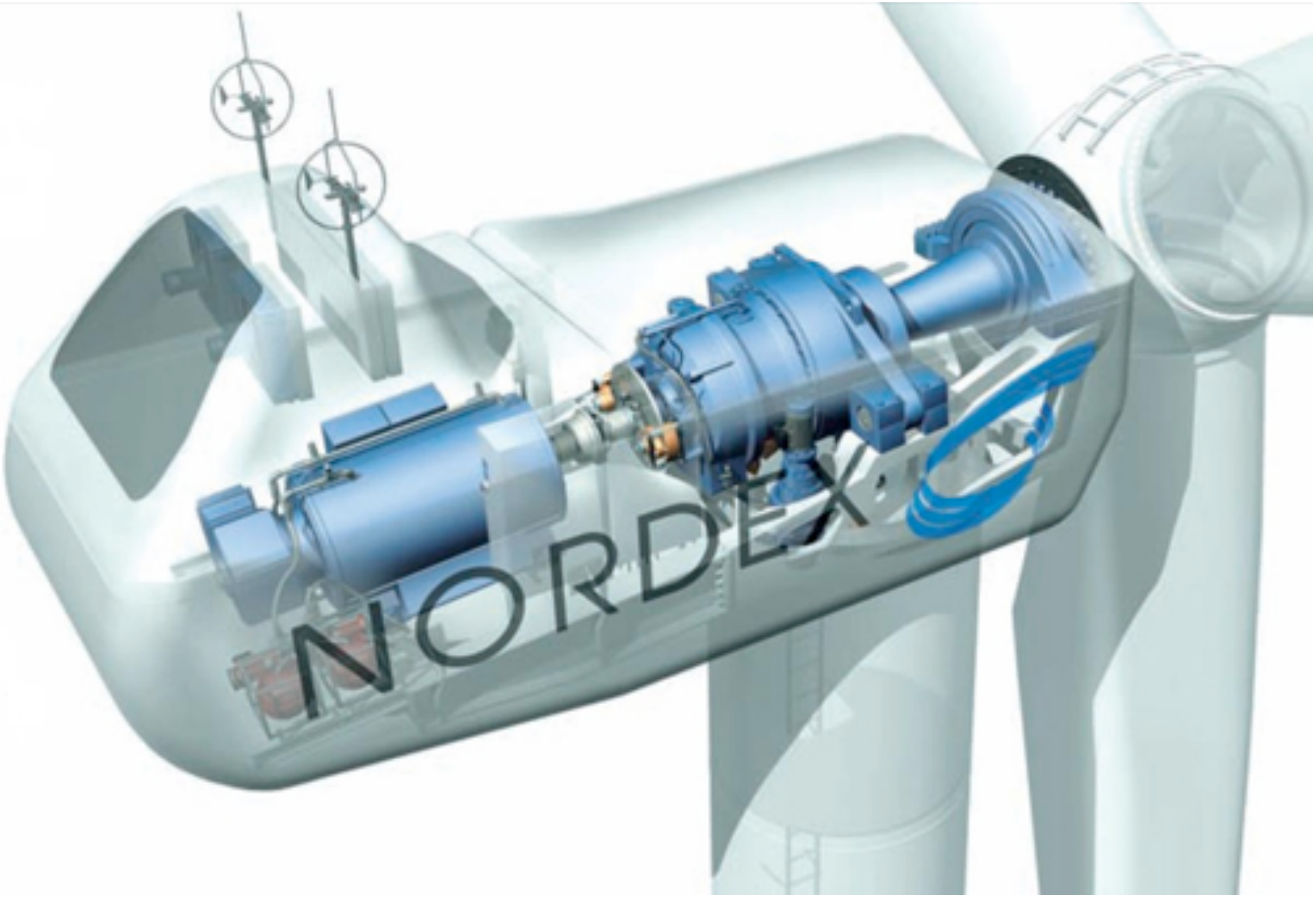


Diagram source: Nordex

Generator mounted in nacelle

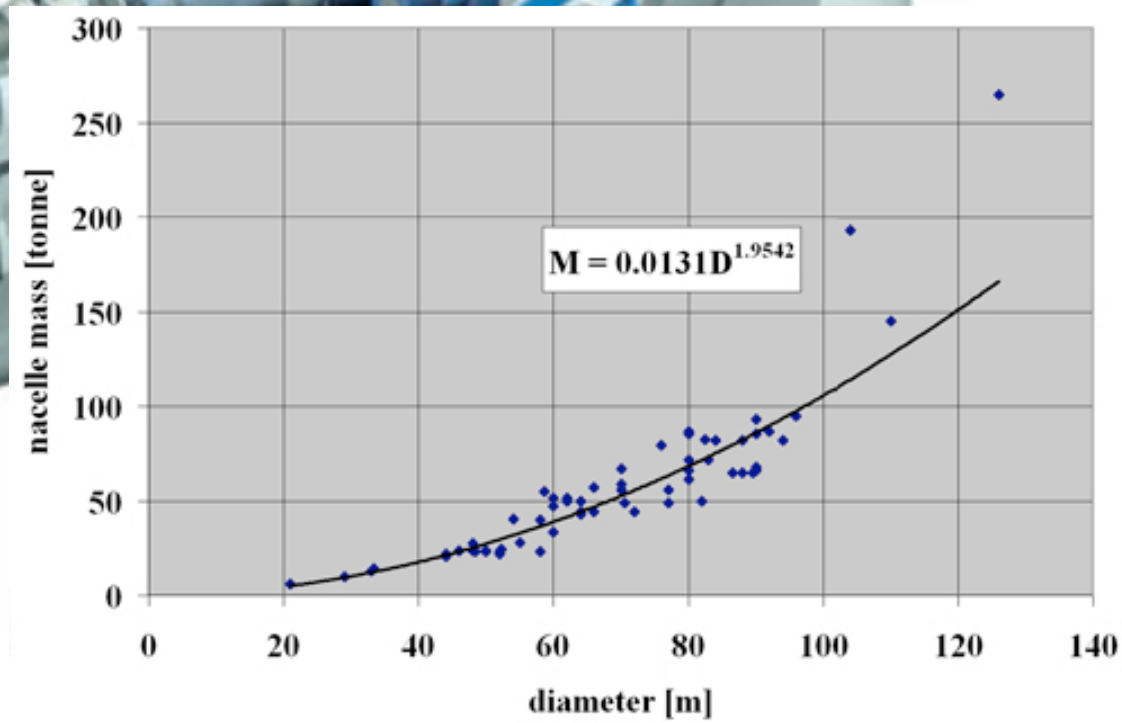


Diagram source: Nordex

Generator mounted in nacelle:

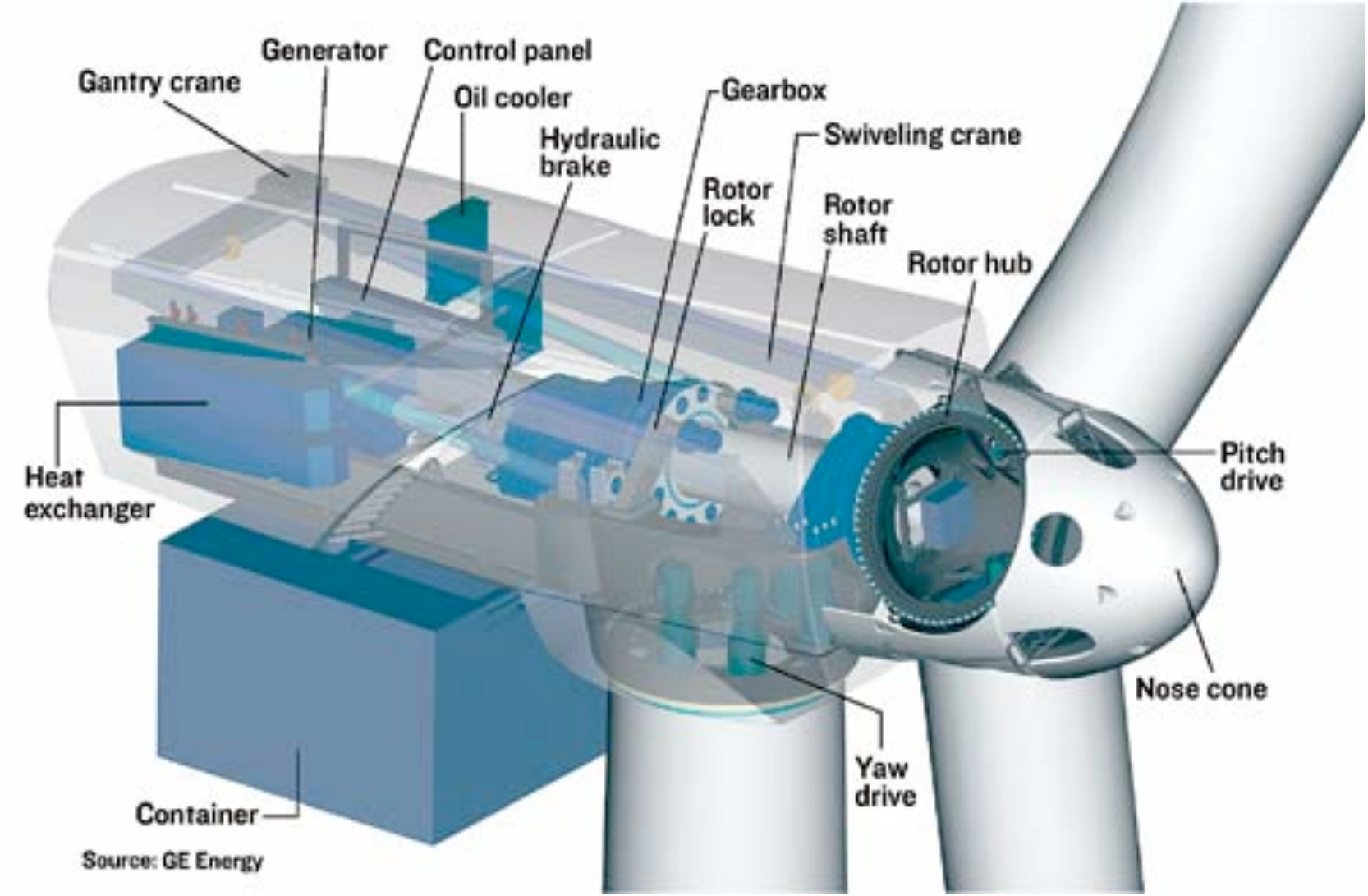
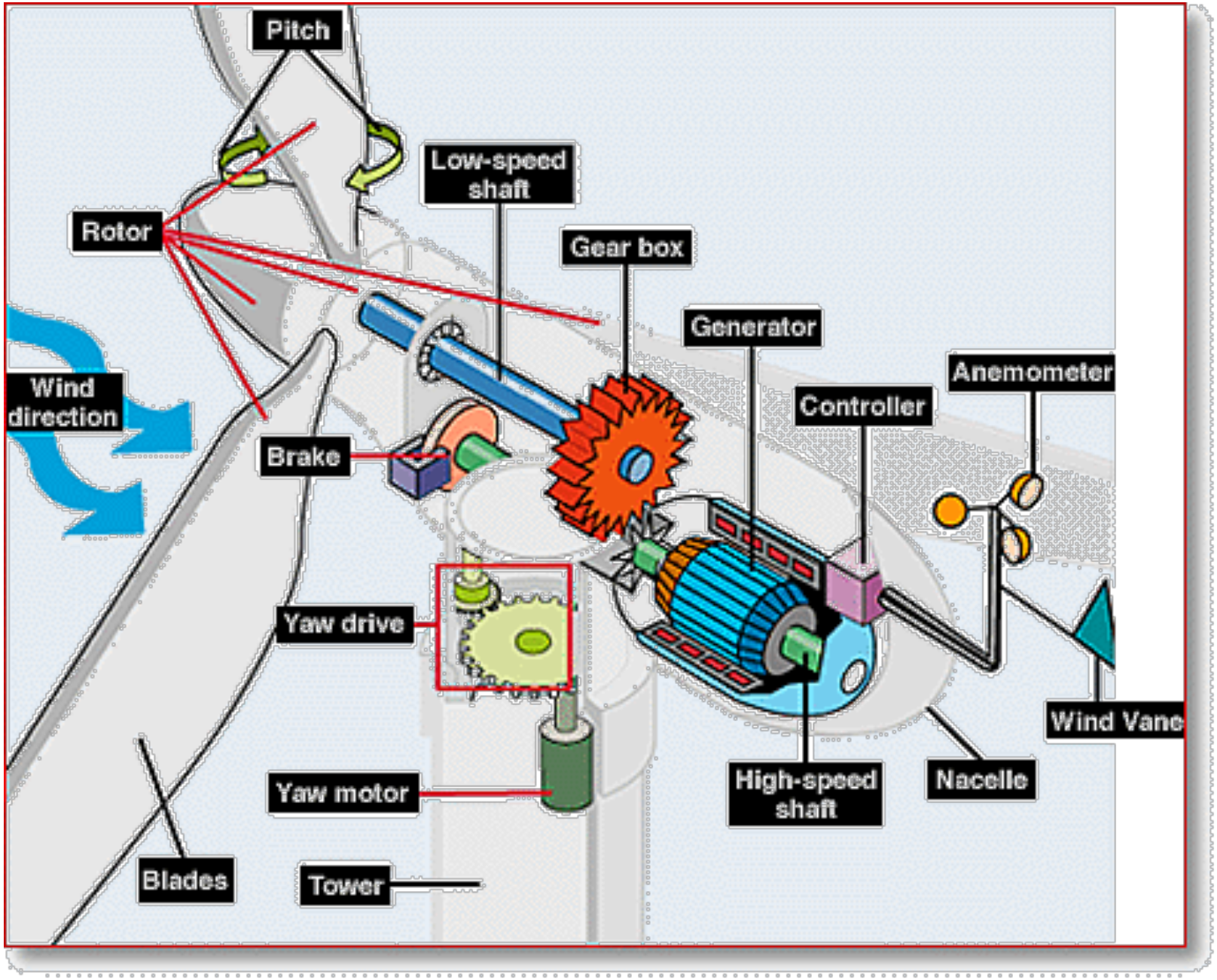


Diagram source: Nordex

Generator mounted in nacelle:



What are constraints of having a very high turbine?

- No mechanical linkages up the tower – whole generator must be on top of tower
- Therefore want minimal maintenance, so need very simple generators – minimize chance of **breakage**
  - No electrical connection to rotor
    - **Induction generators** – no brushes on rotor

      Drawback – asynchronous (power is out of phase)
    - **Permanent magnet generators** – must use neodynium

      Drawbacks – heavy, + exacerbates shortage of rare earth elements.
  - No gearbox
    - New trend toward **direct-drive generators.**

      Drawback – generators must be even bigger (ca. 4 m diameter), so nacelle is even heavier.

Wind growth not driven by (unsubsidized) cost alone

Turbine install cost is actually rising slightly and elect. prices are down

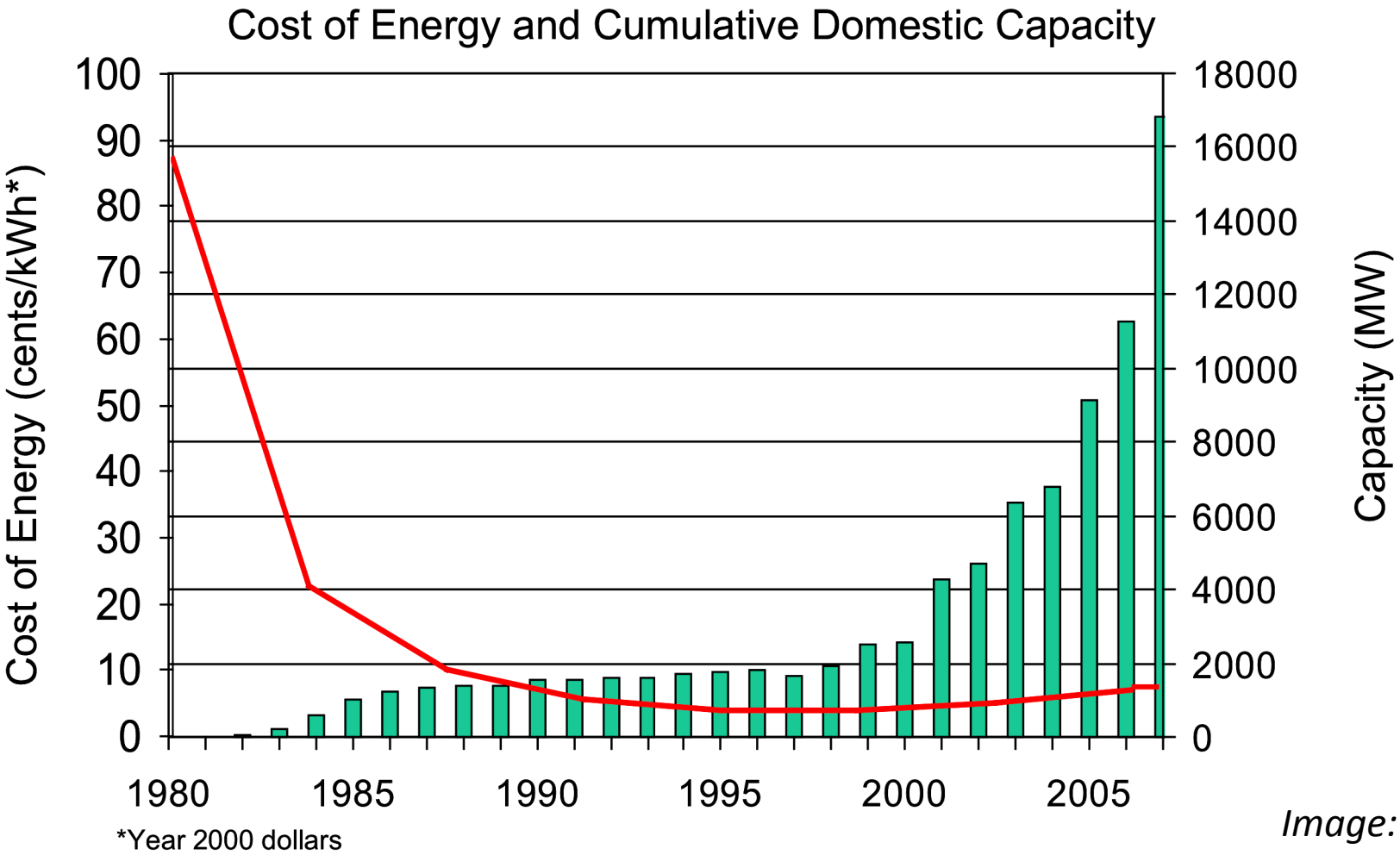
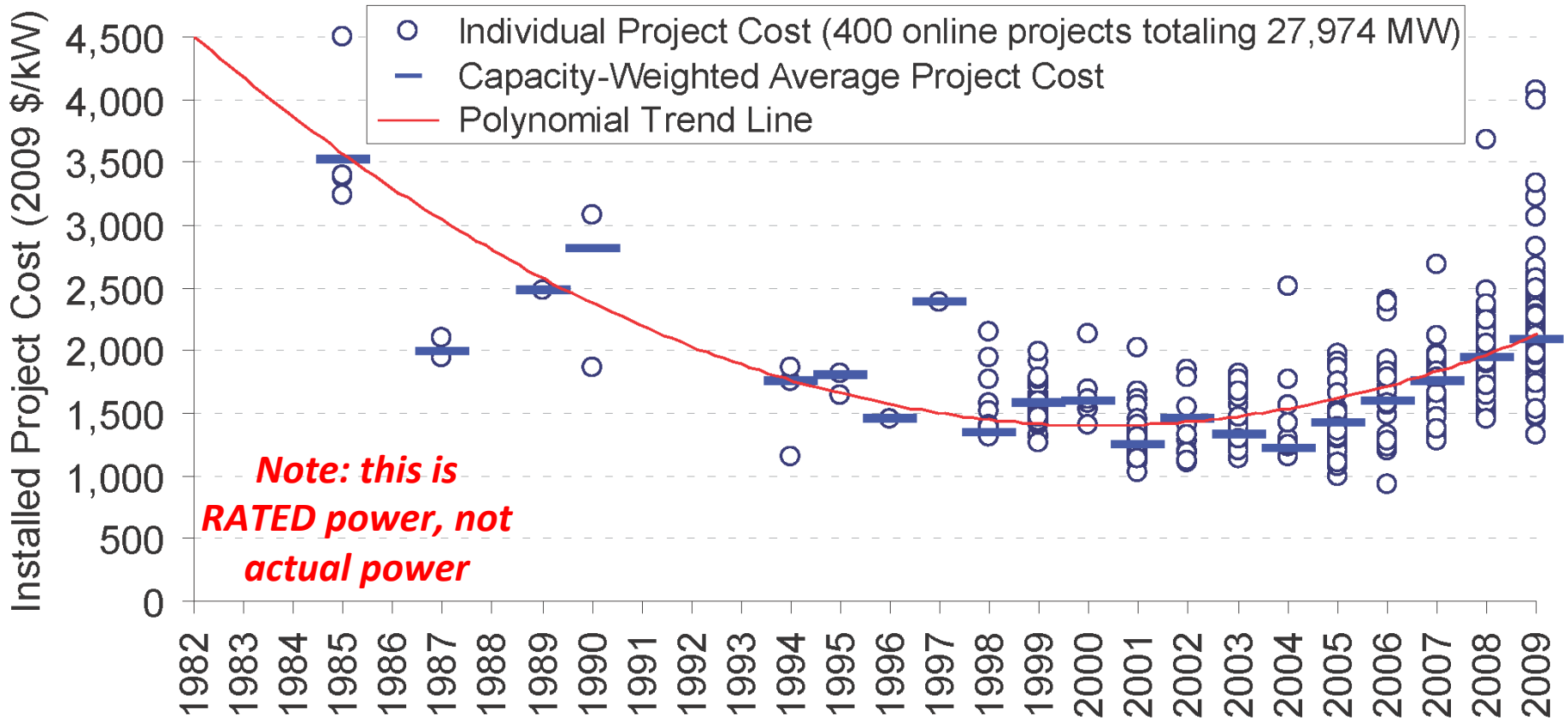


Image: NREL

Increased Turbine Size - R&D Advances - Manufacturing Improvements

Wind growth not driven by (unsubsidized) cost alone

Turbine install cost is actually rising slightly and elect. prices are down

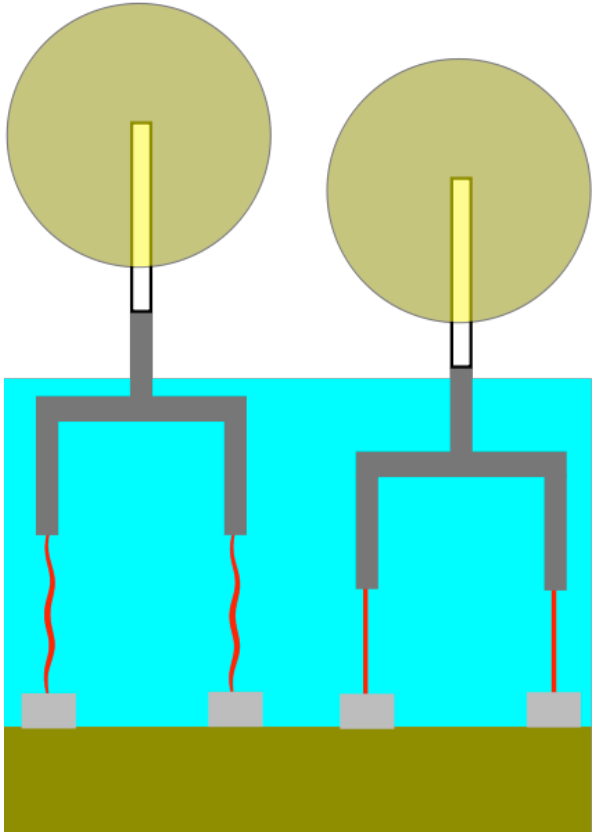


Project costs bottomed out in 2001-2004, and have risen by roughly $800/kW, on average, through 2009

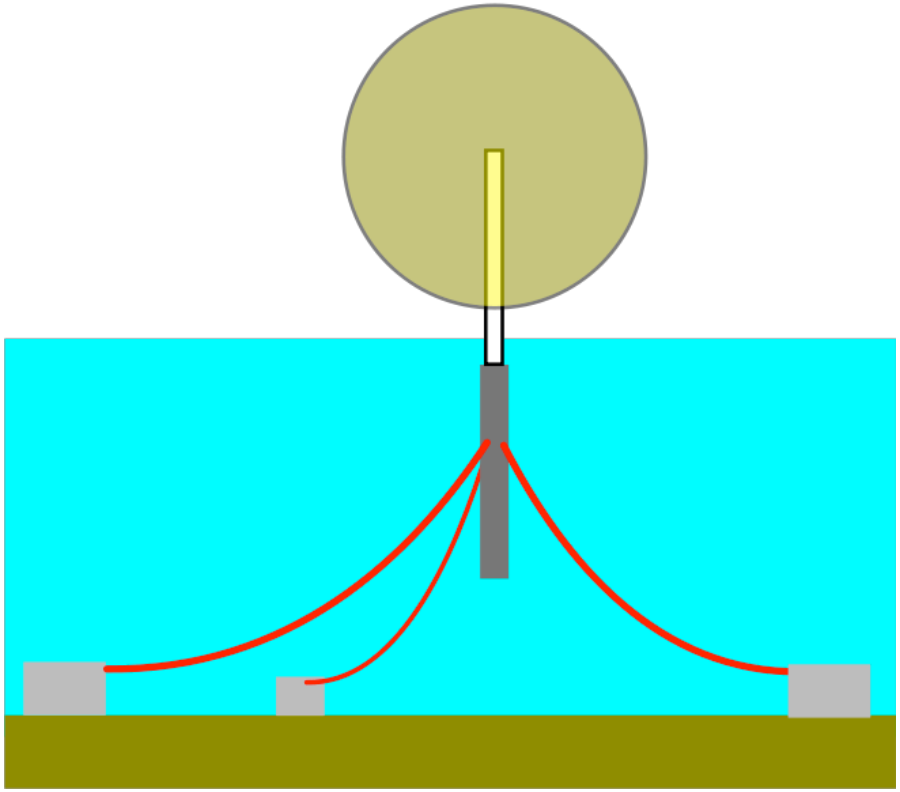
2009 Wind Market Report, LBNL

Slide: NREL

Offshore turbine platforms are expensive



Tension-leg mooring

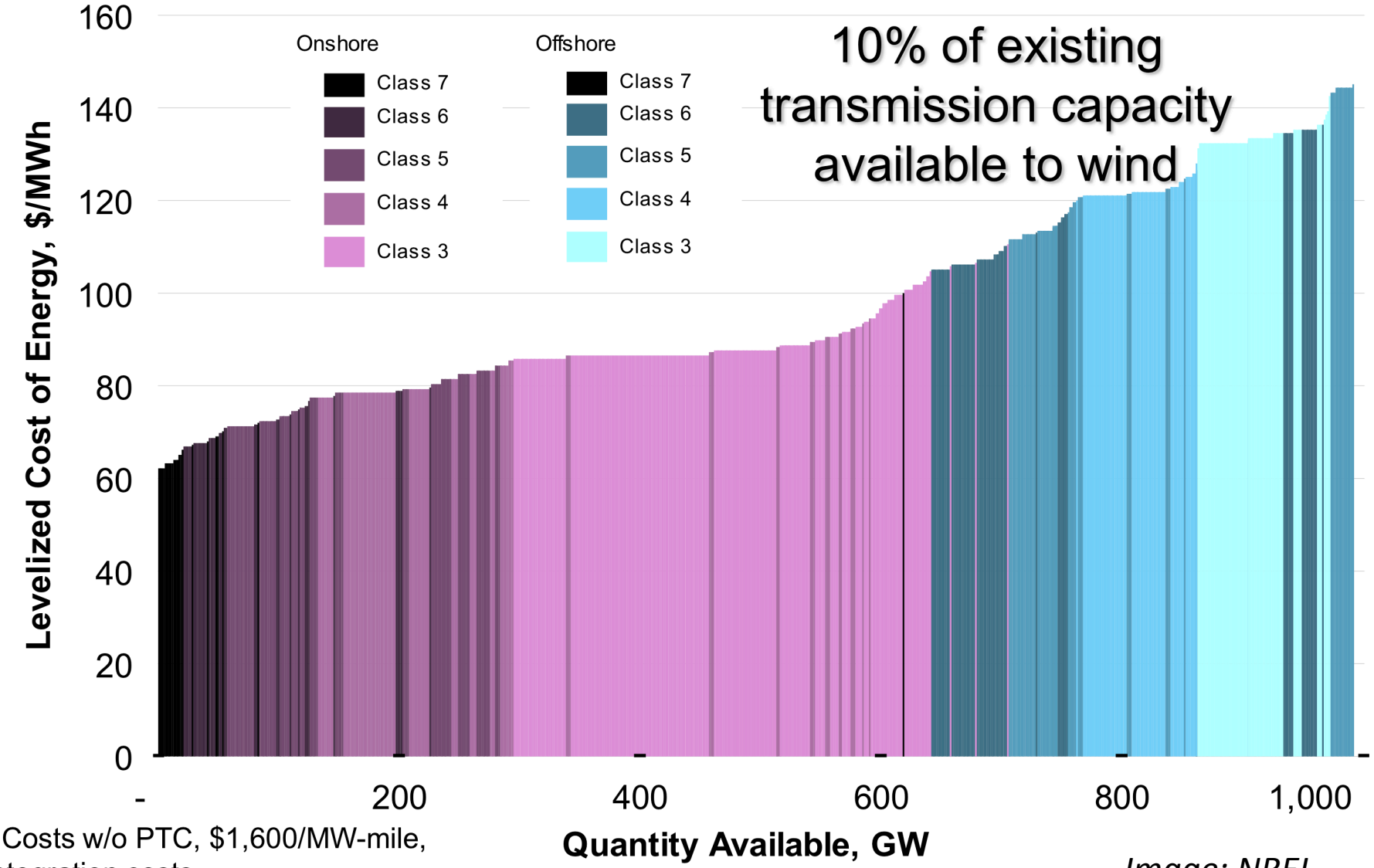


Catenary cable mooring

First operational deep-water high-capacity turbine operational Sept. 2009 (Hywind, 2.3 MW rated turbine, North Sea, 220 m deep water).

Install cost is $26/W rated, $90/W actual (!!!) Compare to $1-2/W for fossil or hydro, ~$1-2/W rated ($3-6/W actual) for onshore wind

Even relatively bad on-shore wind is more cost-effective than almost all offshore wind



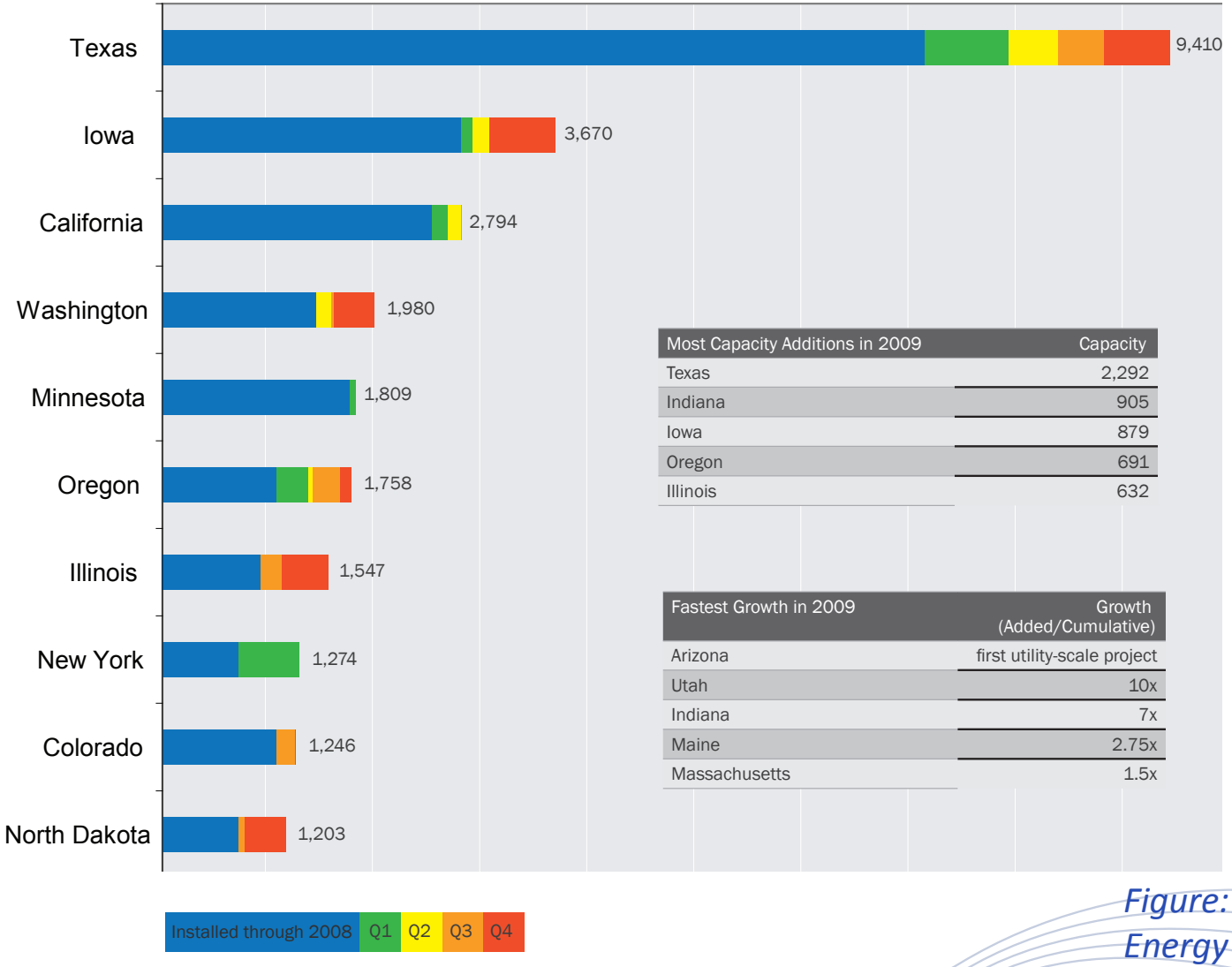
2010 Costs w/o PTC, $1,600/MW-mile, w/o Integration costs

Image: NREL

What's driving wind power growth in U.S.?

Wind is biggest installation type, but not always in obvious locations

Wind Project Installations by State (Top Ten States) in 2009



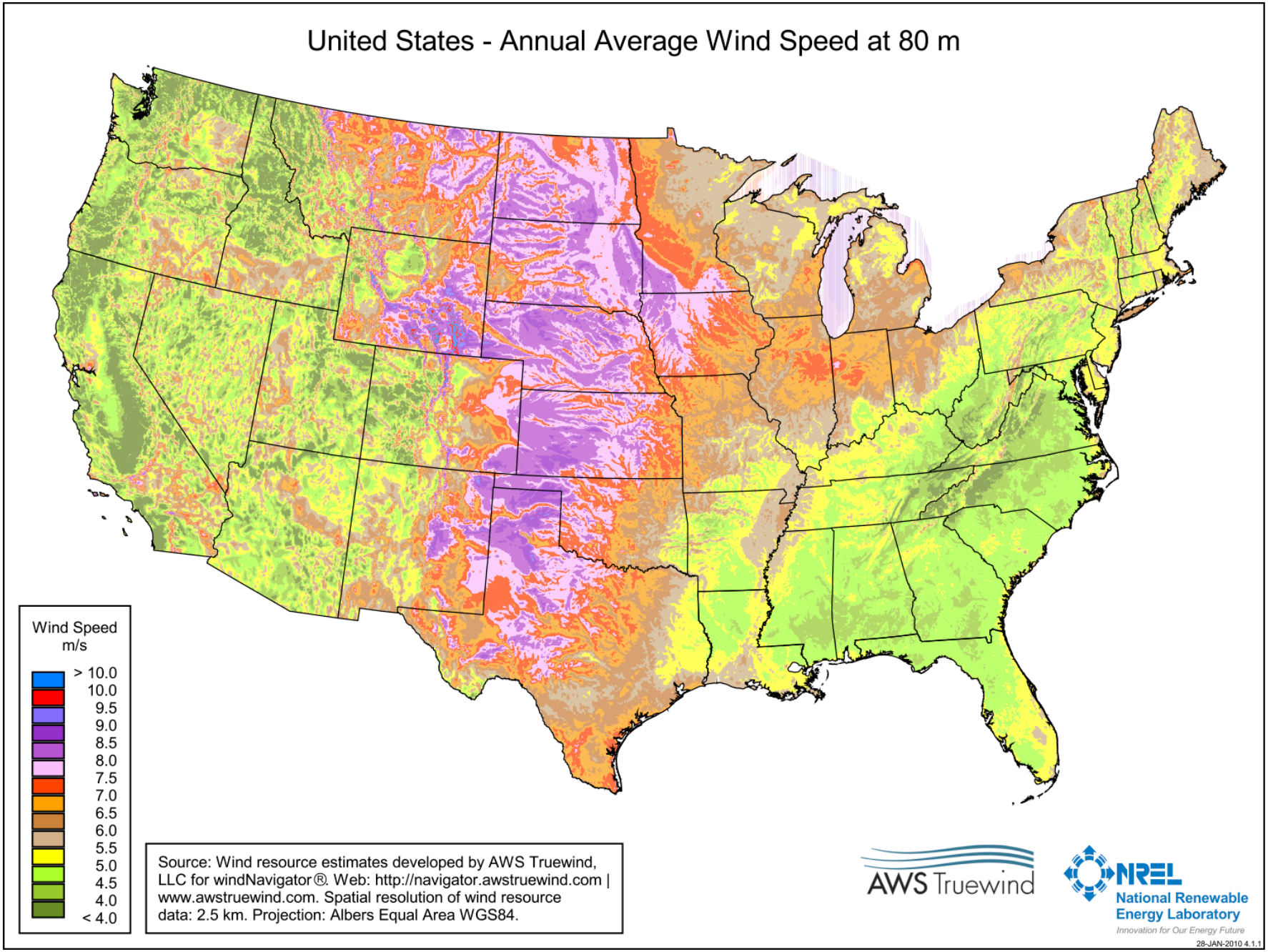
Most Capacity Additions in 2009	Capacity
Texas	2,292
Indiana	905
Iowa	879
Oregon	691
Illinois	632

Fastest Growth in 2009	Growth (Added/Cumulative)
Arizona	first utility-scale project
Utah	10x
Indiana	7x
Maine	2.75x
Massachusetts	1.5x

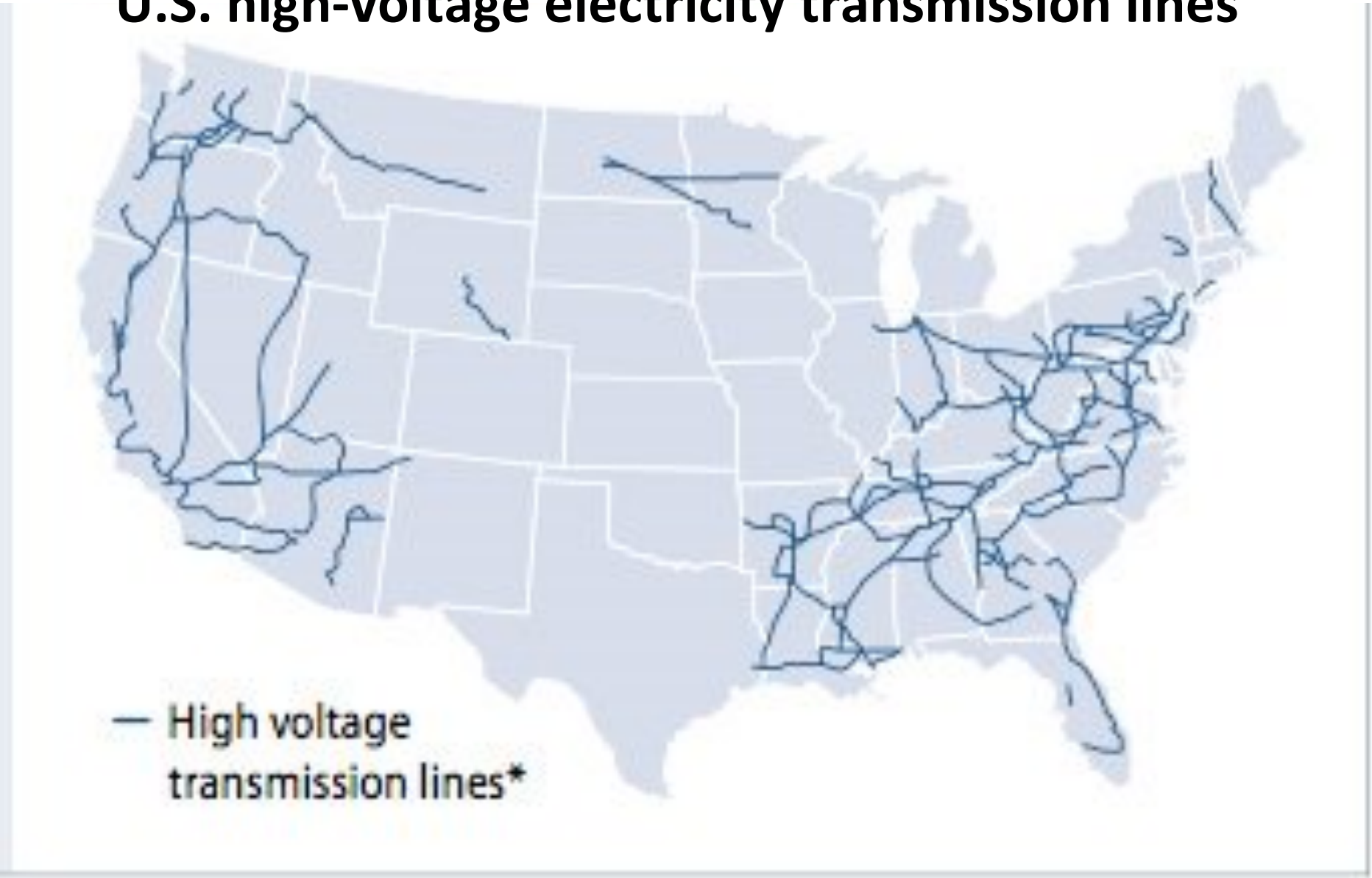
State	Added in 2009 (MW)
Texas	2,292
Indiana	905
Iowa	879
Oregon	691
Illinois	632
New York	568
Washington	542
North Dakota	488
Wyoming	425
Pennsylvania	388
Oklahoma	299
California	277
Utah	204
Kansas	199
Colorado	178
Missouri	146
Maine	128
South Dakota	126
Montana	104
New Mexico	100
Nebraska	81
Idaho	71
Arizona	63
Minnesota	56
Wisconsin	54
Michigan	14
Massachusetts	9
Alaska	5

Figure: American Wind Energy Association

“Wind belt” runs through the middle of the U.S.



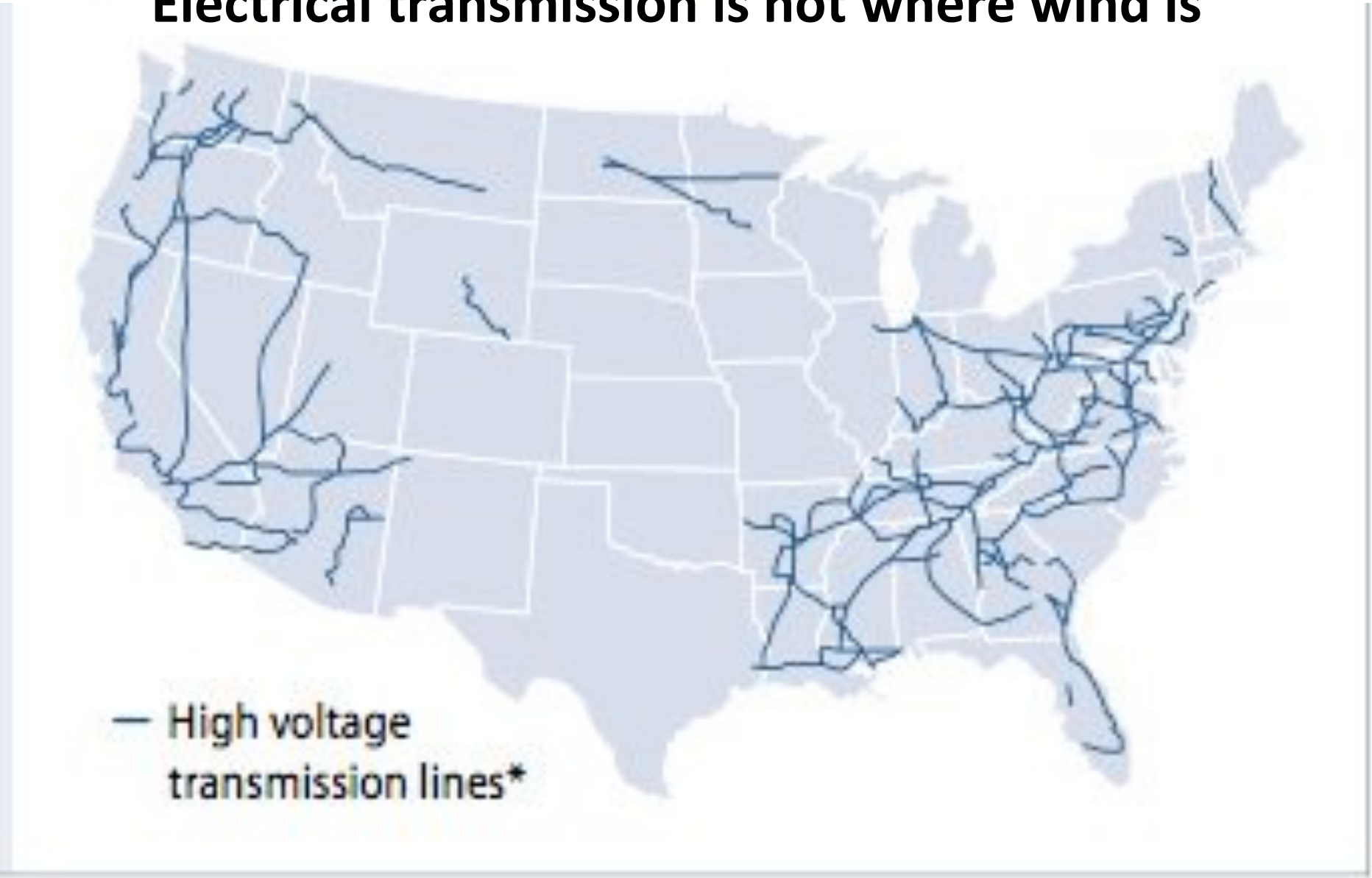
U.S. high-voltage electricity transmission lines



* Depicted lines are 500 kV–999 kV and DC.

Source: Platts POWERmap, www.maps.platts.com.

Electrical transmission is not where wind is



* Depicted lines are 500 kV–999 kV and DC.

Source: Platts POWERmap, www.maps.platts.com.

The electrical grid: link between generation and consumption

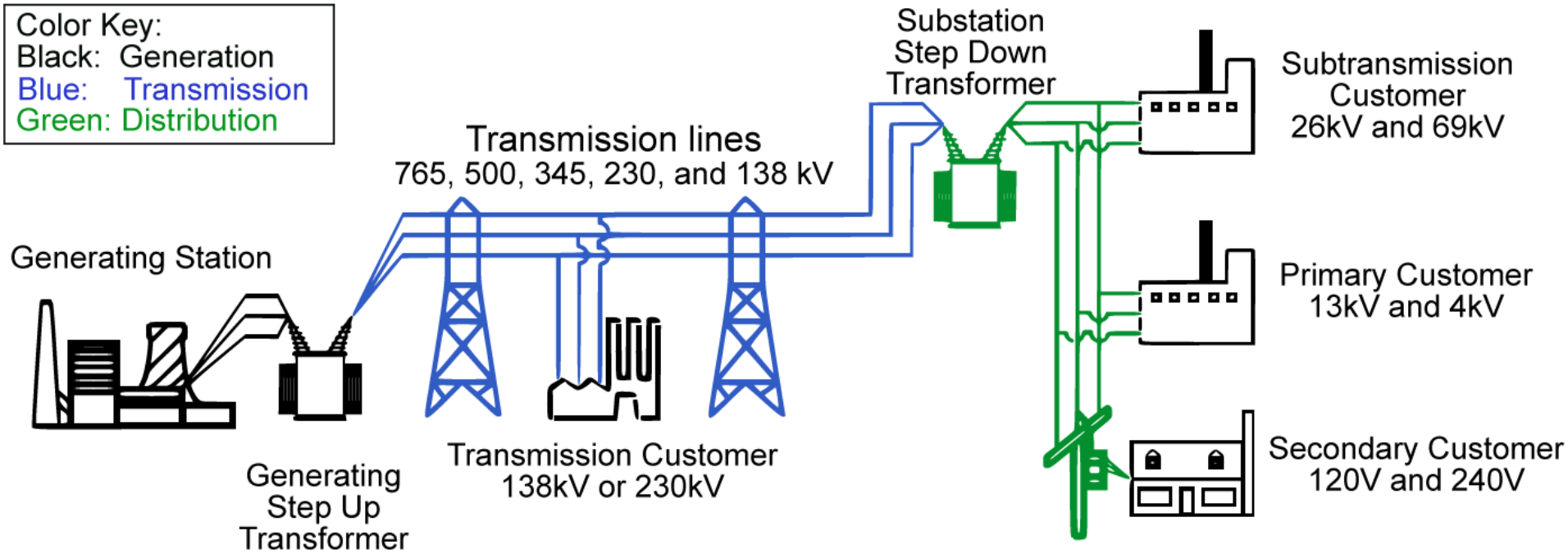
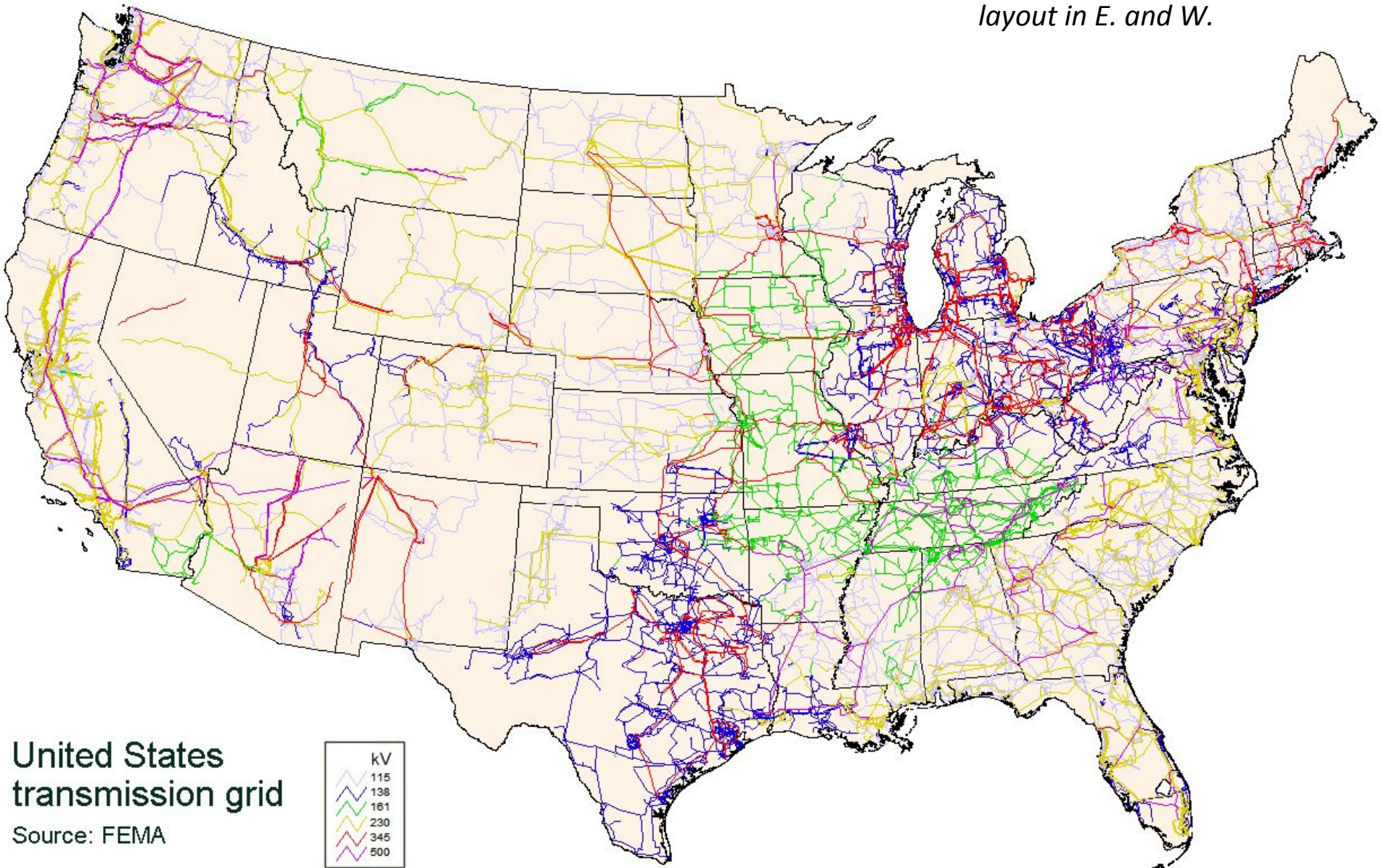


Image: Wikipedia

Electrical grid operation: basic questions

- Why so many different voltages?

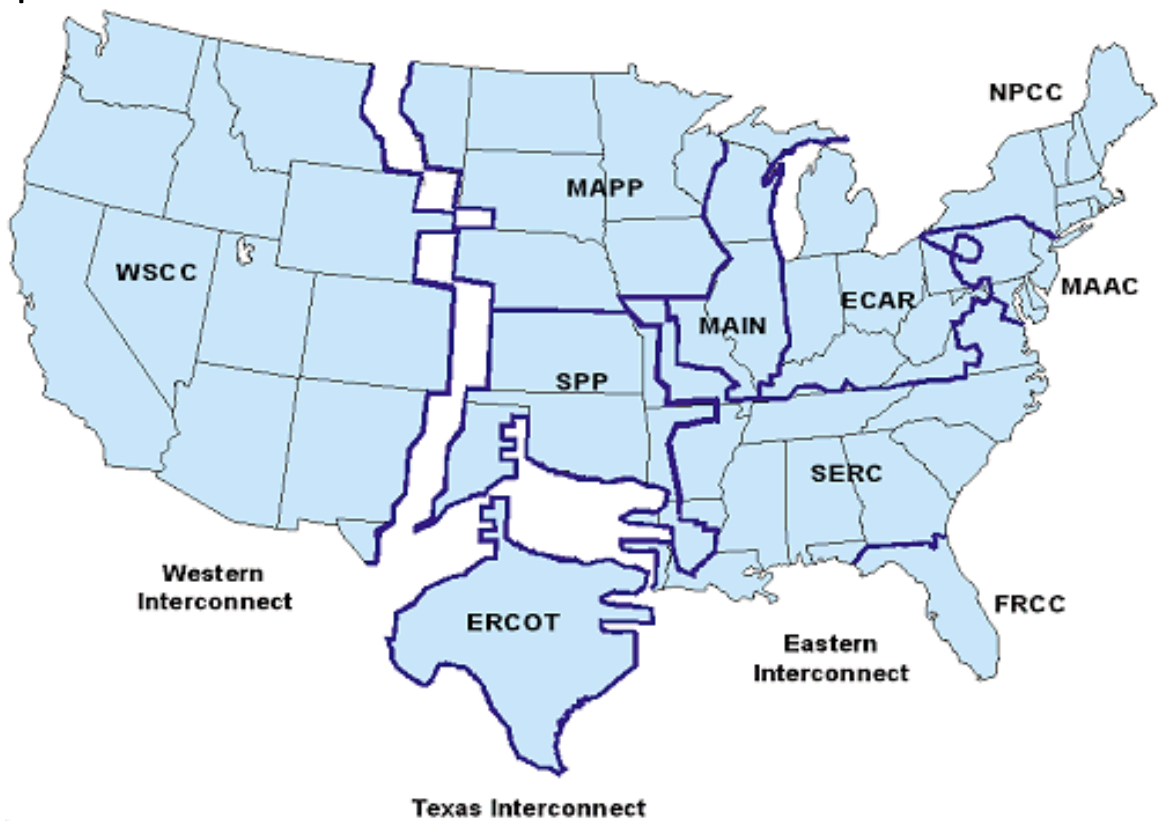
Note also different layout in E. and W.



Electrical grid operation: basic questions

- What controls how much power flows, and where?

Nothing except the balance of generation and demand – an 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



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.

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

Electrical grid operation: basic questions

- Why so many different voltages?

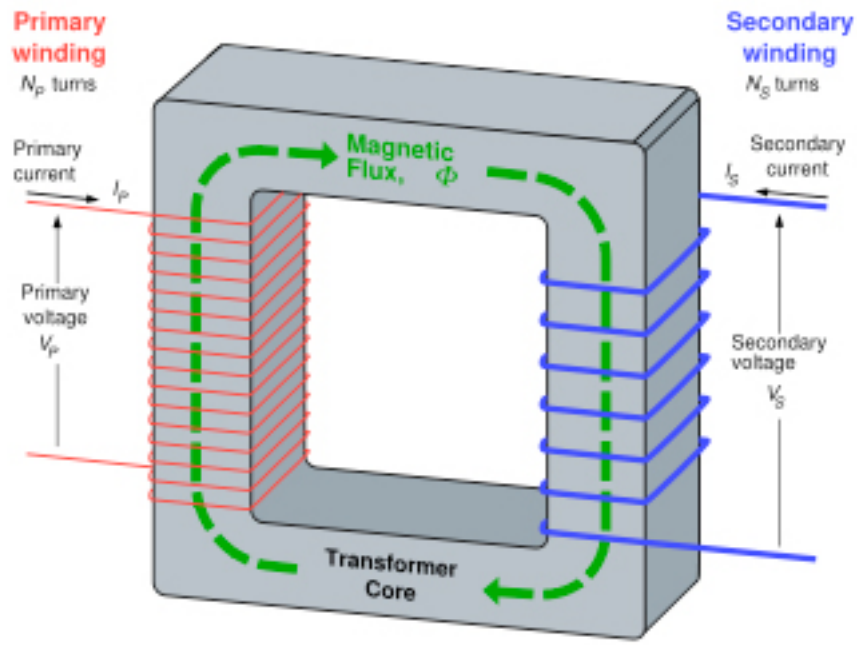
To some extent is logical – don't want to waste $ building big transformers for lines running a short distance, if can get away with lower voltage

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

For historical reasons, typical voltages are different in Eastern and Western U.S.

Electrical grid operation: basic questions

- How is voltage transformed? Why is DC transmission OK now?



AC transformers work on Ampere's and Faraday's laws: changing AC current generates magnetic field, and changing magnetic field in turn generates current. Inside giant box is just a core with 2 wire windings.

DC transformer must operate via power electronics – but now that is possible, unlike in Edison's day

Images from ATSI Engineering Services (L) and The Electricity Forum (R)

Electrical power transmission: why are lines in multiples of 3?

Image: PennLive.com

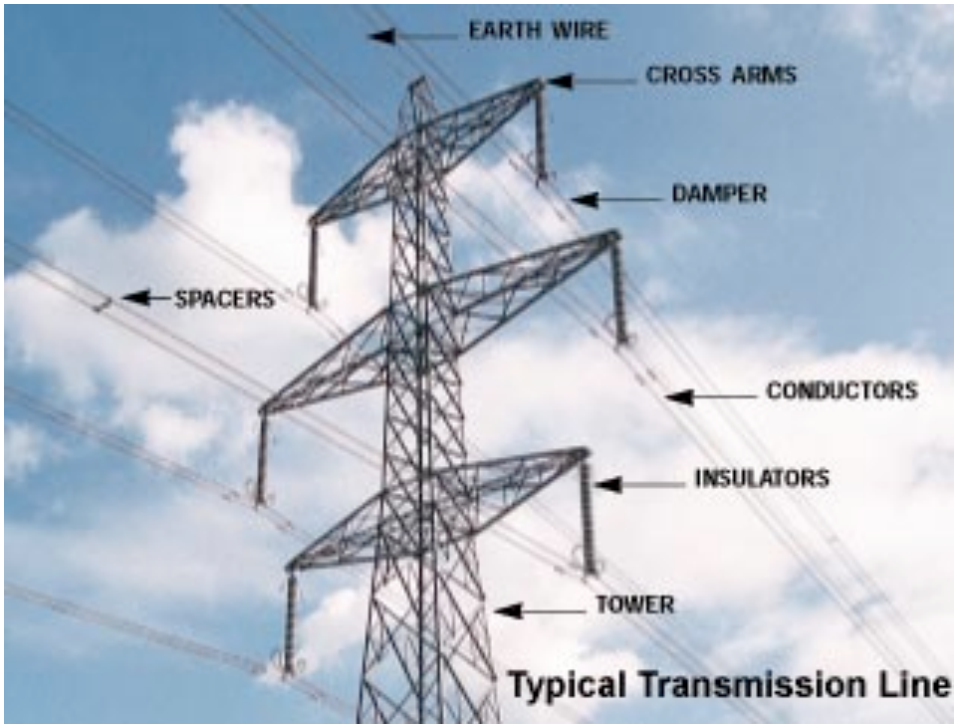
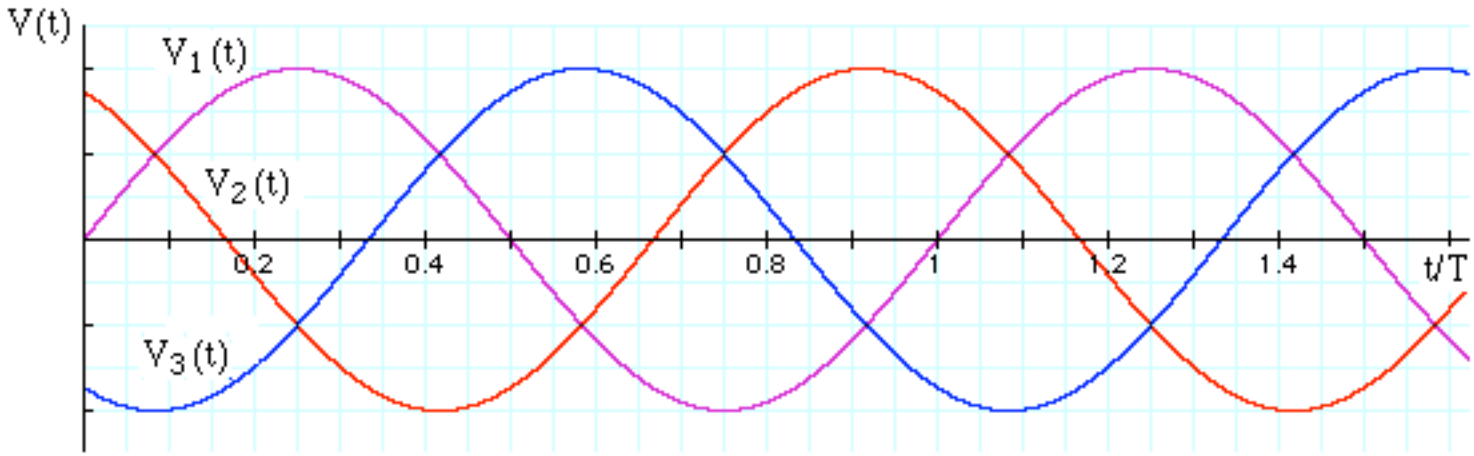
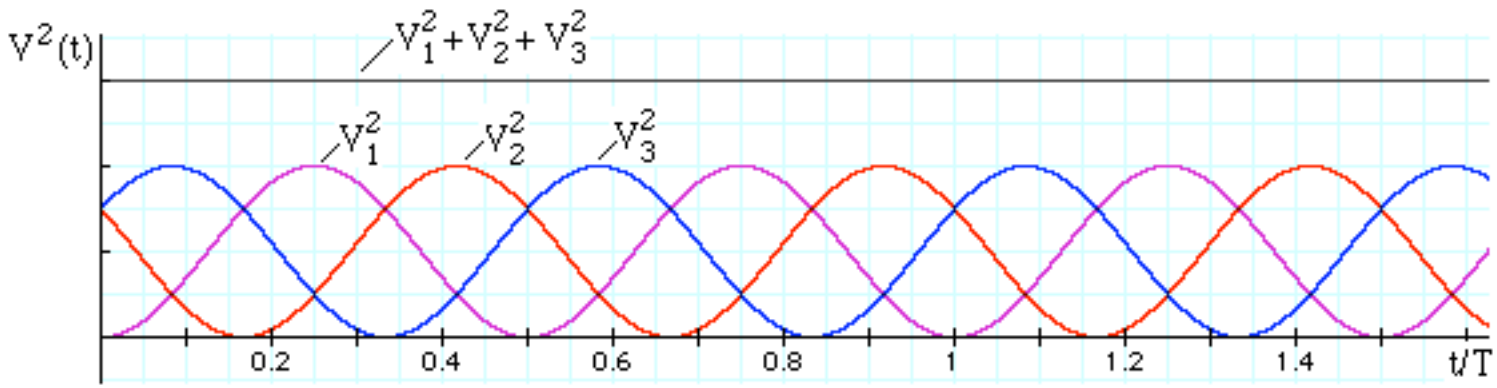


Image: NationalGrid

Electrical power transmitted as 3-phase power

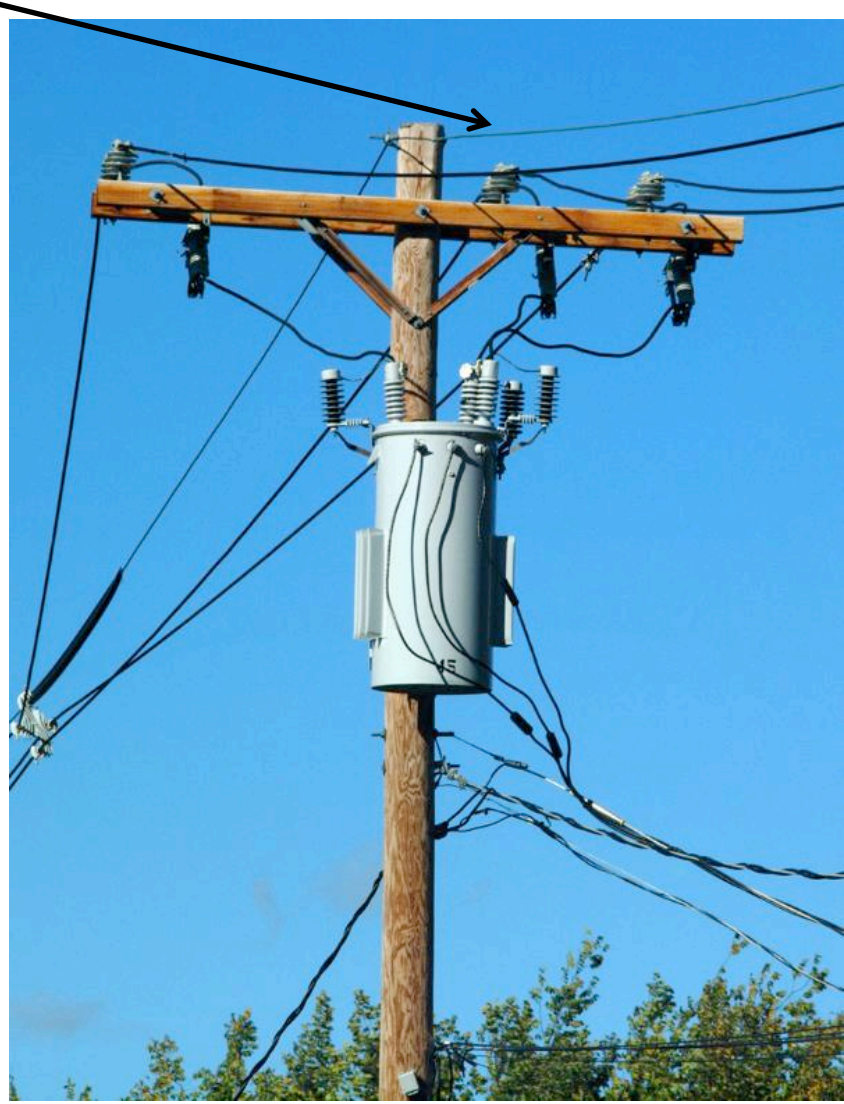




Why 3-phase? Because voltages (and current) sum to 0 if perfectly balanced – meaning there is no need for a return wire, which saves costs.

*Also power (I*V, prop. to V^2) sums to a constant – there are no fluctuations in the power transmitted.*

Distribution: why 4 wires now?

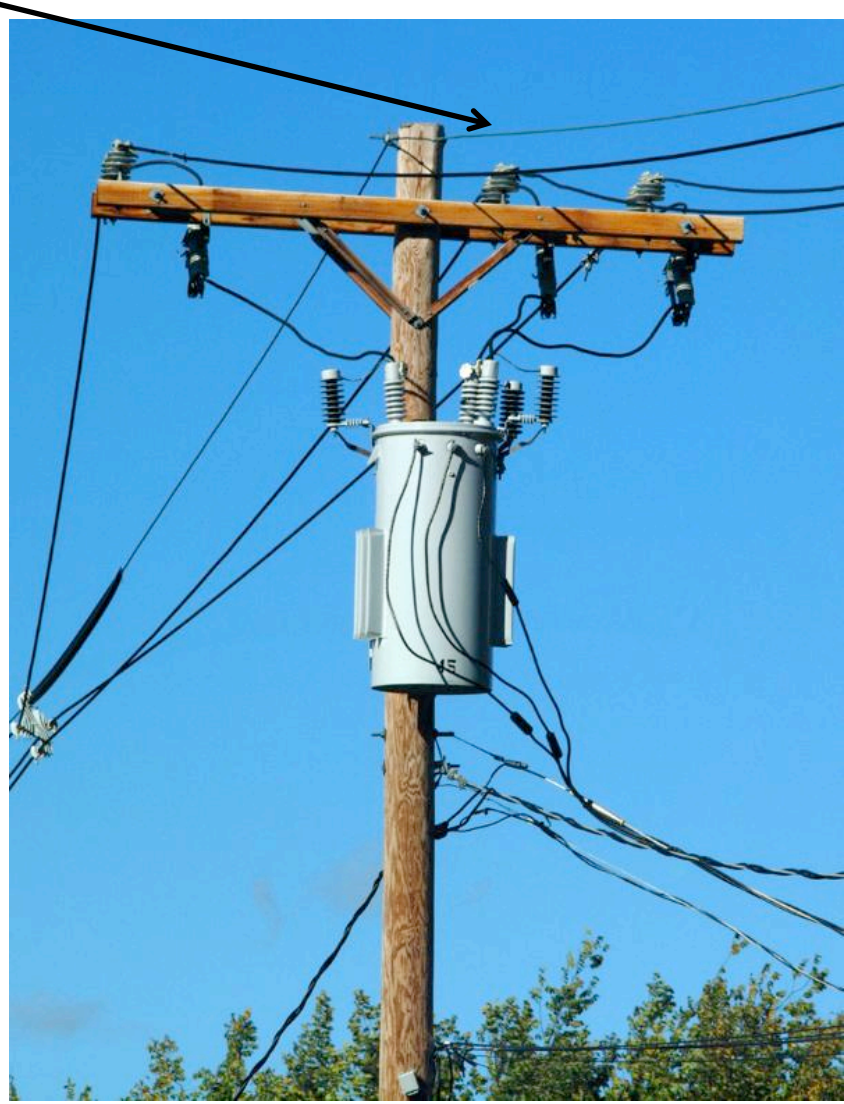


Distribution: neutral wire is added

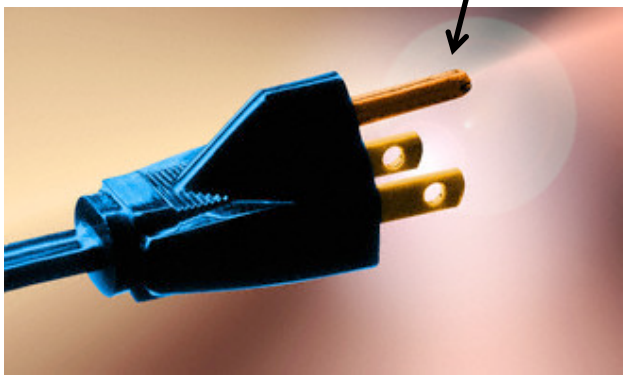
Each household circuit uses only ONE of the three AC phases transmitted. That means that three different phases could see different loads (could have different power demand).

If demand becomes unbalanced, the three-phase transmission won't cancel the current - a net flow of current would occur. A neutral (return) wire is therefore added at some point.

The return loop of current is not all the way back to the generator but (usually) just to the substation, or sometimes even just to the local transformer.

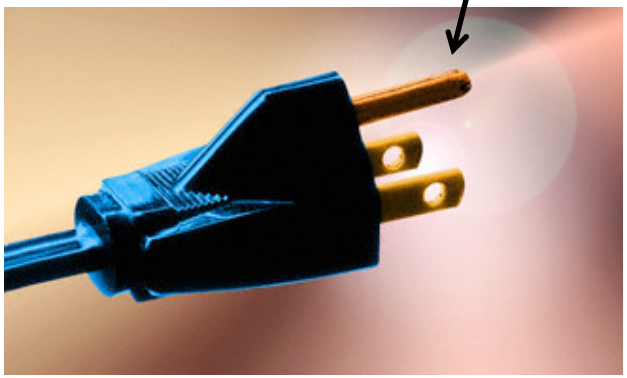


Distribution: what is the 3rd prong on a 3-prong plug?



If each household circuit uses only ONE of the three AC phases transmitted, why does it need three prongs?

Distribution: what is the 3rd prong on a 3-prong plug?



Third prong is neutral grounding wire to to "earth ground" – separate connection to ground – never carries current except in emergencies. Ensures that the electrical device itself can't carry a voltage.

Physical grid infrastructure: what's unusual about this picture

Long-distance transmission line, Western U.S.

DC lines carry 4% of U.S. electricity (identifiable by only 2 conductors)

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 a steel core

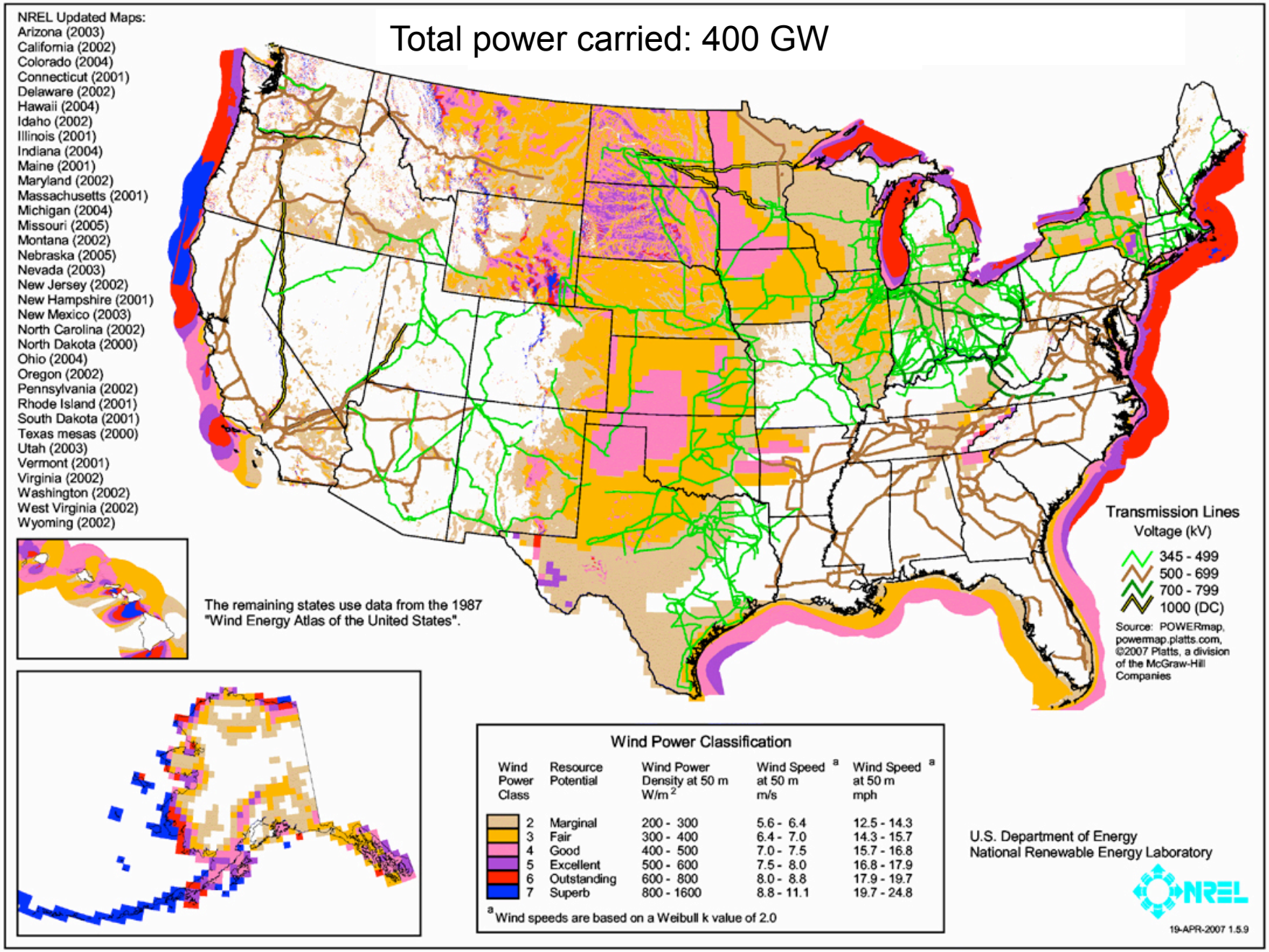
Losses in DC transmission are lower than those in AC since no inductive reactance – only direct I^2R Joule heating.

Losses on this line = 8% *(that’s ~ U.S. average even if line is longer)*

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 from Inga Dam in D.R.C. to Shaba copper mine (1700 km)

DC lines in U.S. go from single power sources to big users



Electrical grid operation: basic questions

- How big is the grid?

Total U.S. network: ~ 300,000 km

Most of this is high-voltage
(> 250,000 km are > 230 kV

TABLE 1. CAPACITY LIMITS FOR ELECTRICAL TRANSMISSION LINES

Voltage (kV)	Length (miles)	Maximum capacity (GW)
765	100	3.8
	400	2.0
500	100	1.3
	400	0.6
230	100	0.2
	400	0.1

Data from *Transmission Planning for a Restructuring U.S. Electricity Industry*, by Eric Hirst and Brendan Kirby, June 2001, prepared for Edison Electric Institute, Washington, DC.

How long are lines? Longest individual HVDC transmission line are > 1000 km
(mostly in China, carrying > 3 GW each)

Suggested practical limits to transmission length:
~ 7000 km DC, 3-4000 km AC (Paris et al., 1984).
Size of continental U.S. is ~ 4600 km x 2000 km
So could transmit across the country, barely.

Check numbers: 3 x 105 km/300 km = 1000 lines. If each line carries ~ 1 GW that's 1 TW max power carried.

*U.S. electrical use: we have 300 M people * 3000 W/ person in electric sector (*50% efficiency) ~ 0.5 TW*

Clase enough to feel consistent

Electrical grid operation: basic questions

- How much does it cost to build a transmission line?

… about $1M/km in practice on average

Example: Arrowhead-Weston line in Minnesota cost > $1.1 M/ km in 2002. Original estimate ~ $0.7M/ km, but cost nearly doubled because of environmental safeguards and payments to landowners, plus two-year delay caused by opposition and permit issues

… but bigger / more expensive lines can carry more power

Rule of thumb = $500-700 /MW*km

Projected total costs in future are high

Estimates of annual cost in U.S. that will need to be spent in next 10 years just to keep pace with rising electricity demand: $9-12 B/yr
(Report Card for America's Infrastructure, ASCE, 2005)
To replace existing grid: 300,000 km * $1M/km = $300 B
If power lines last 50 years that means $6B/yr just for maintenance

Electrical grid operation: basic questions

- How much power is lost in transit?

Total ~ 7% of power lost

Losses due to:

- Joule heating (I^2R) (resistive losses)
- Coronal discharge losses
- Inductance and capacitance (reactive power)

- Conductor size is large and V high to minimize resistive losses
- Coronal discharge sets upper limit on V
- Inductance and capacitance losses are not a factor for DC