GEOS 24705 ENST 24705 ENSC 21100

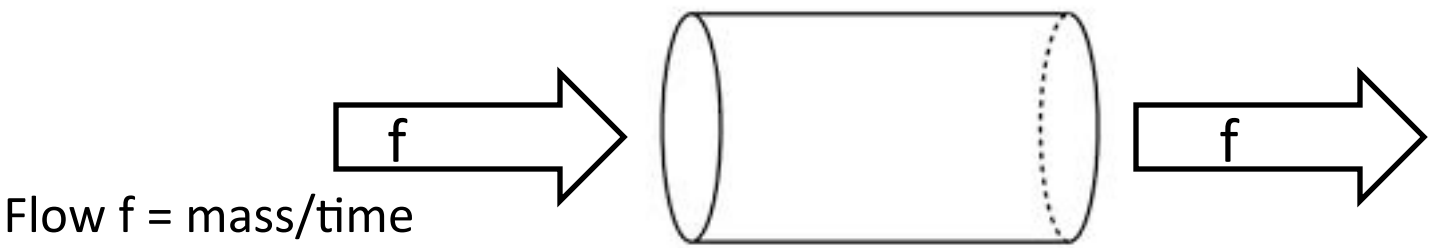
Lecture 15

Wind II, Hydro

Energy in a flow, wind power: v^3 dependence is strong!

$$\text{Energy/mass} = \underbrace{\tfrac{1}{2} v^2}_{\text{kinetic}} + \underbrace{g\,h}_{\text{gravitational}} + \underbrace{p/\rho}_{\text{pressure gradient}}$$

Power = energy/mass * mass/volume * volume/time



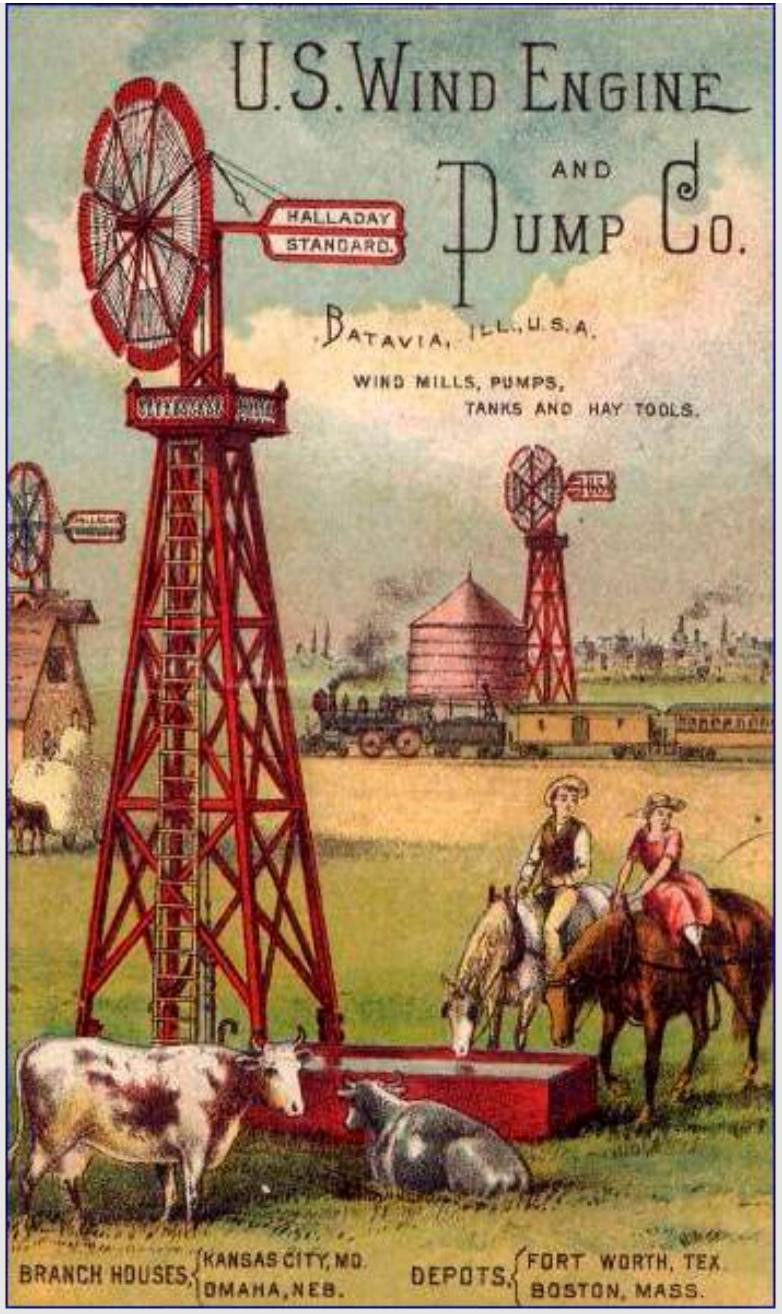
Flow f = mass/time

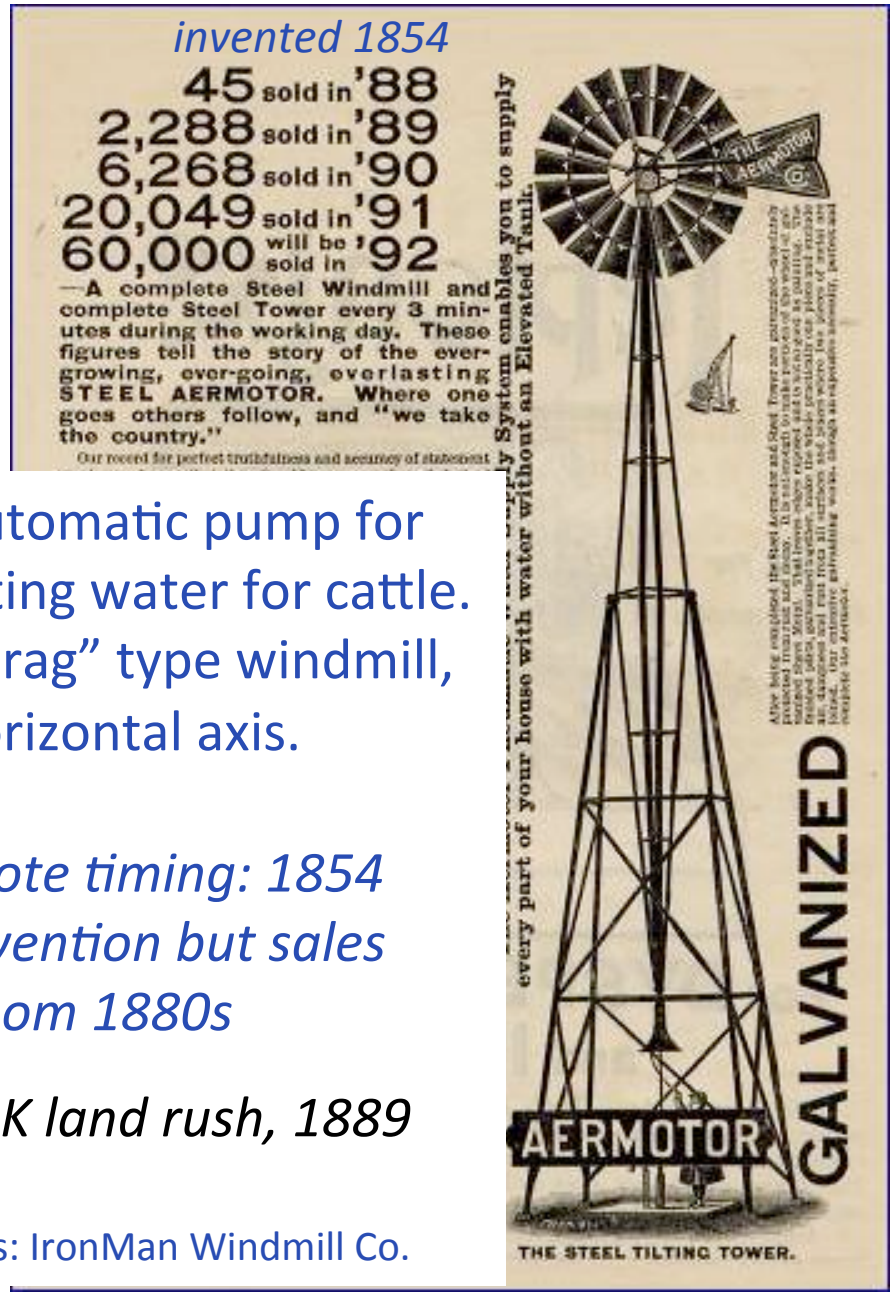
$$P = \varepsilon \cdot \rho \cdot A \cdot v$$

energy density is kinetic term: $\varepsilon = \tfrac{1}{2} v^2$

$$\mathbf{P = \tfrac{1}{2} \rho A v^3}$$

Early windmills symbolize American West





Automatic pump for lifting water for cattle. "Drag" type windmill, horizontal axis.

Note timing: 1854 invention but sales boom 1880s

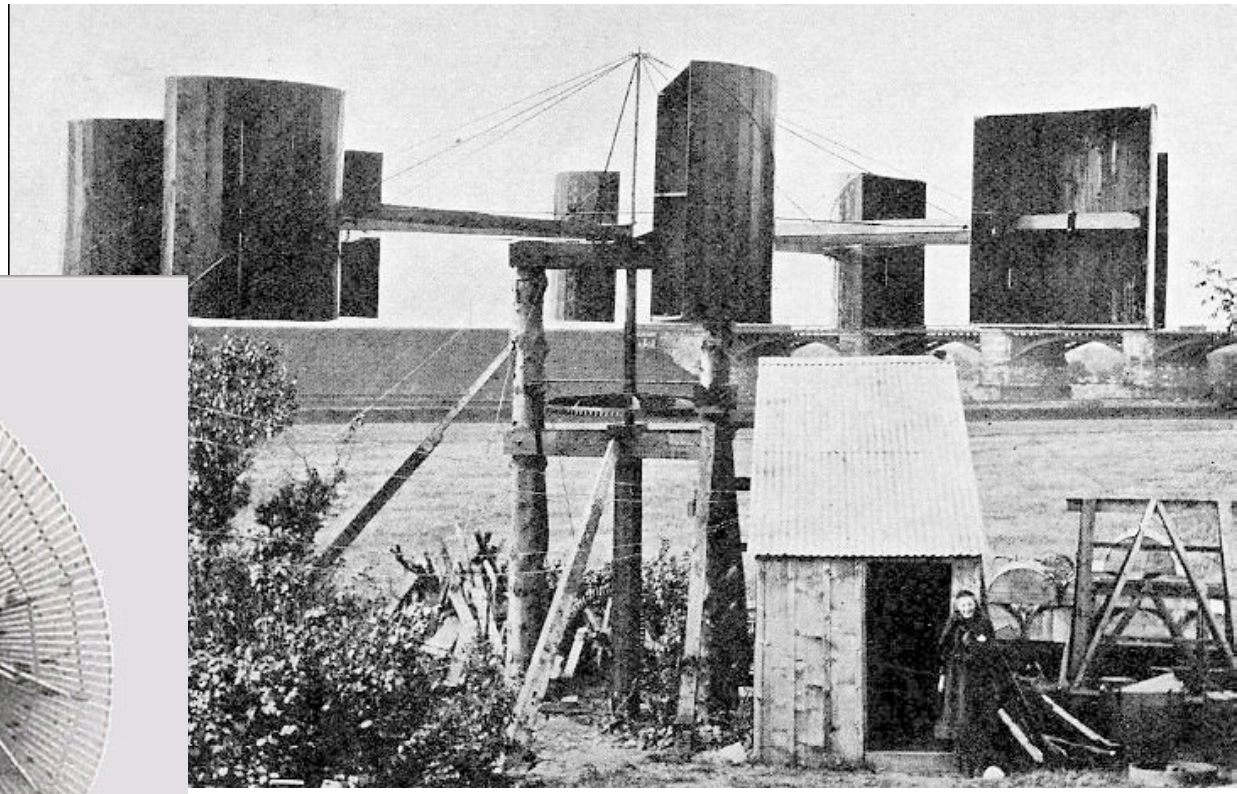
OK land rush, 1889

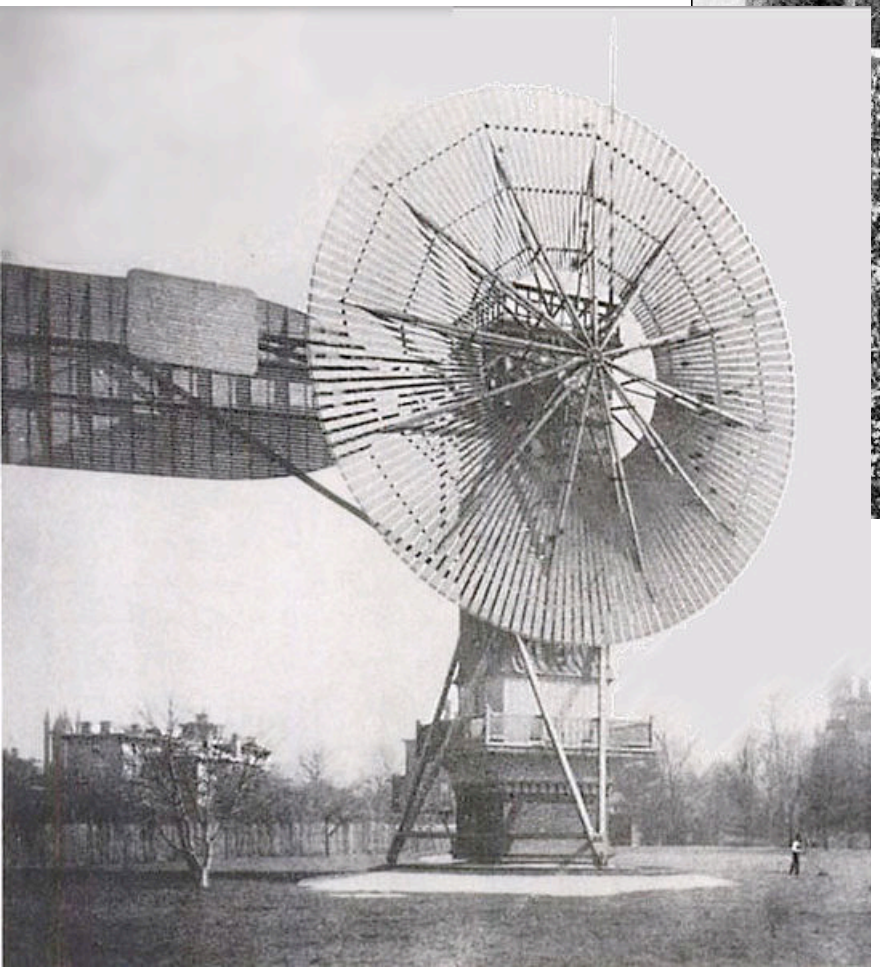
Images: IronMan Windmill Co.

All early wind turbines are “drag” turbines

Blades “pushed” around by impact of air striking them

James Blyth, Scotland, 1887
vertical axis“drag” type



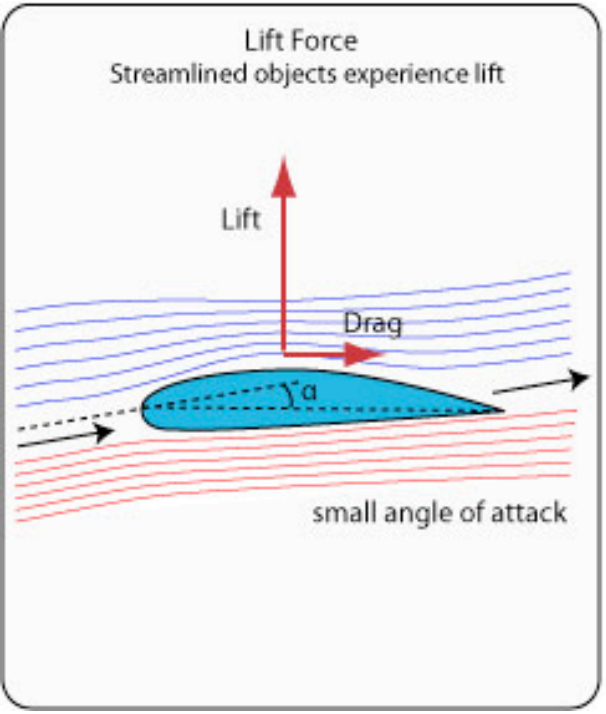


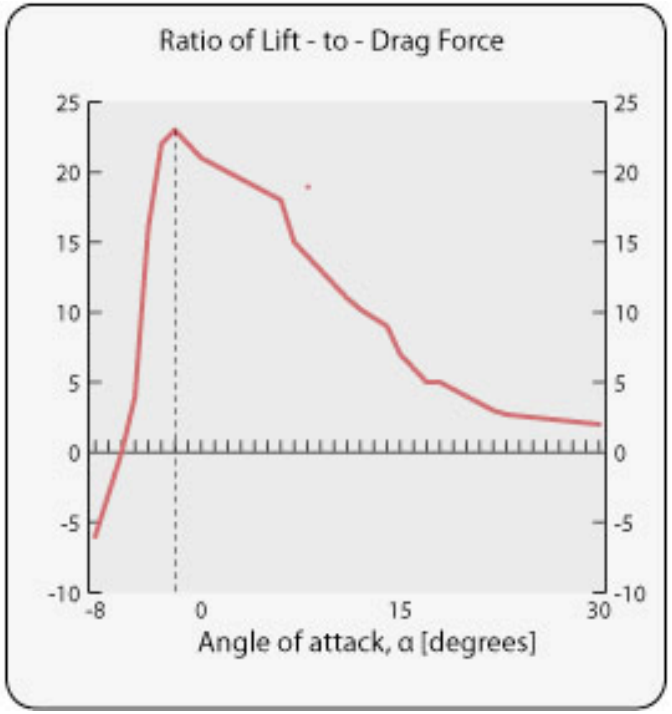
Charles Brush, Cleveland, 1888
17 m diameter
12 kW electricity

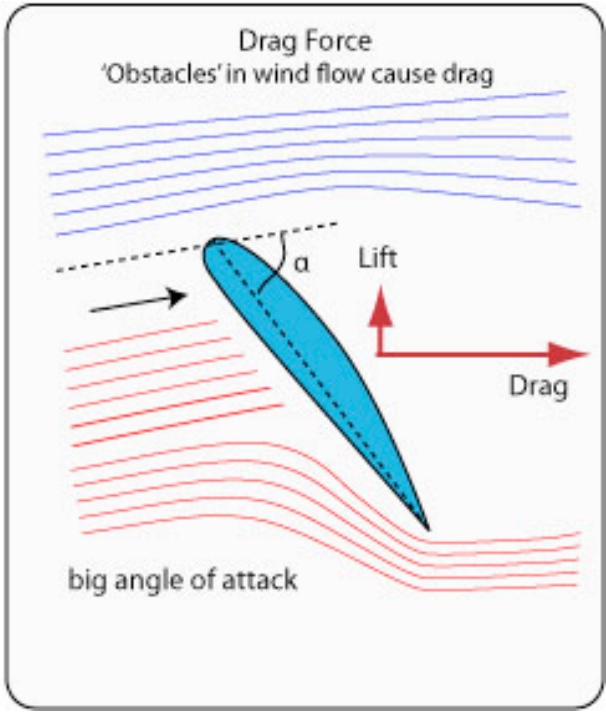
Images: Wikimedia

Modern wind turbines are “lift” turbines

Blades “pulled” around by low-pressure as air flows over airfoil shape
Don’t need to touch every air molecule







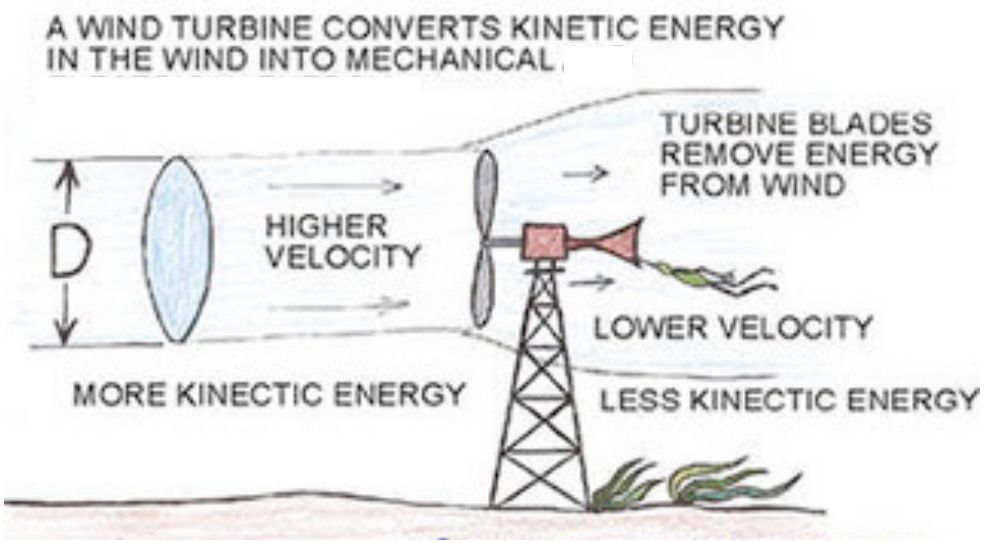
Lift blades can generate more force than drag turbines – extract more of wind’s energy

Much cheaper since need fewer blades

Image: Green Rhino Energy

Wind turbines extract energy by slowing wind

but can't get all the kinetic energy, would need to stop the flow

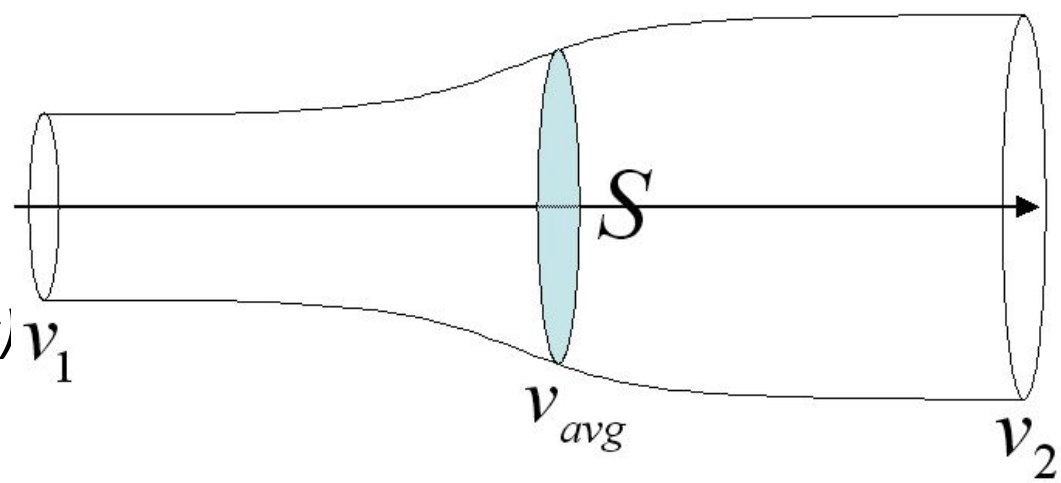


Wind turbine disturbs the flow, makes a "cone" of high -> low velocity

Max power extracted when slow flow down by 66%:

$v_2/v_1 = 1/3$

Limit to power extracted is then 16/27 = 0.59 *(Betz's law)*



Images: (T) FTexploring.com
(B) Wikimedia

Max efficiency only occurs for ideal blade speed

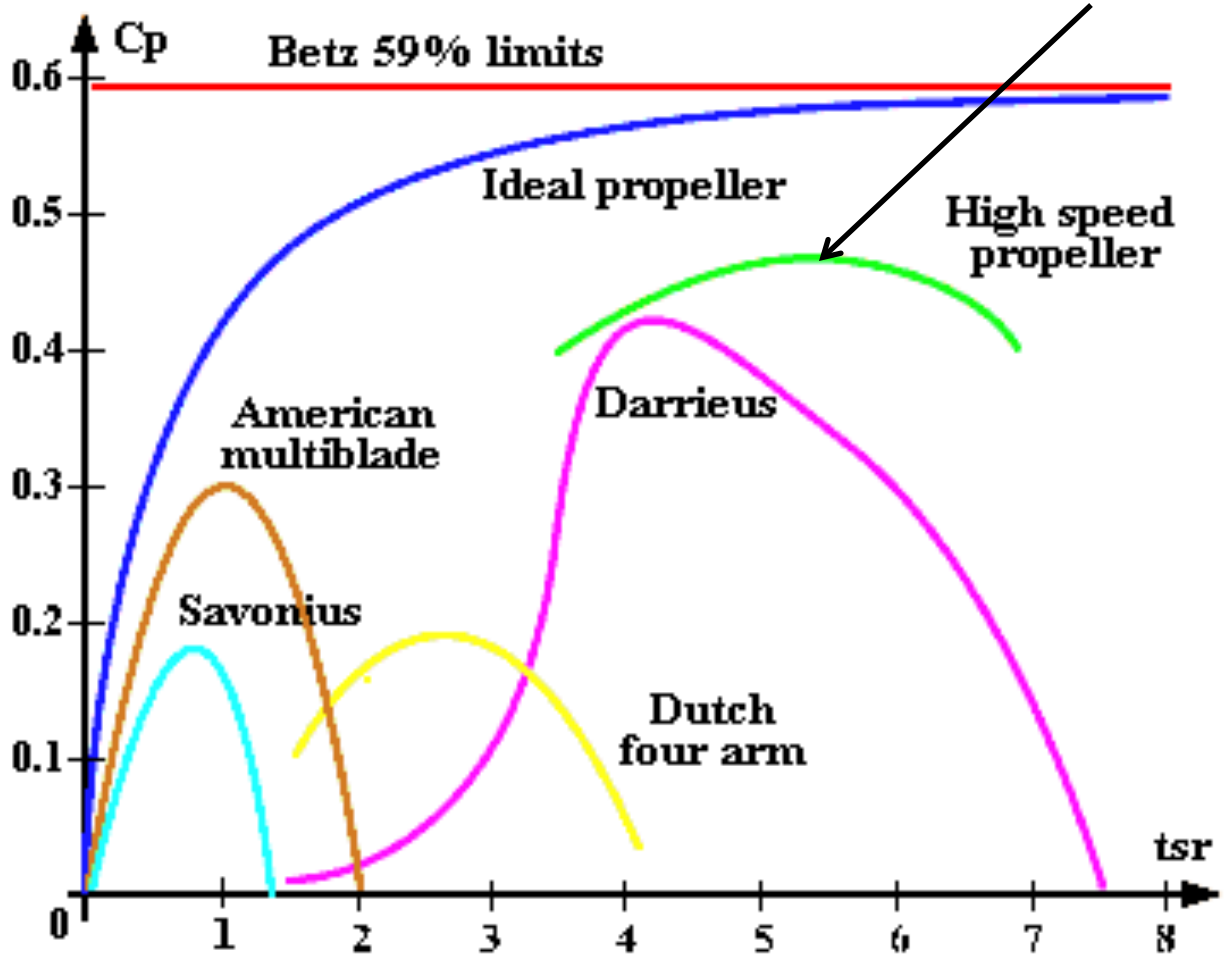
(tsr = "tip speed ratio", v_{blade}/v_{wind})

With ideal turbine tsr should be as high as possible.. In practice tsr of about 5-6 gives best performance

Betz's law limit only achievable if turbine goes fast –

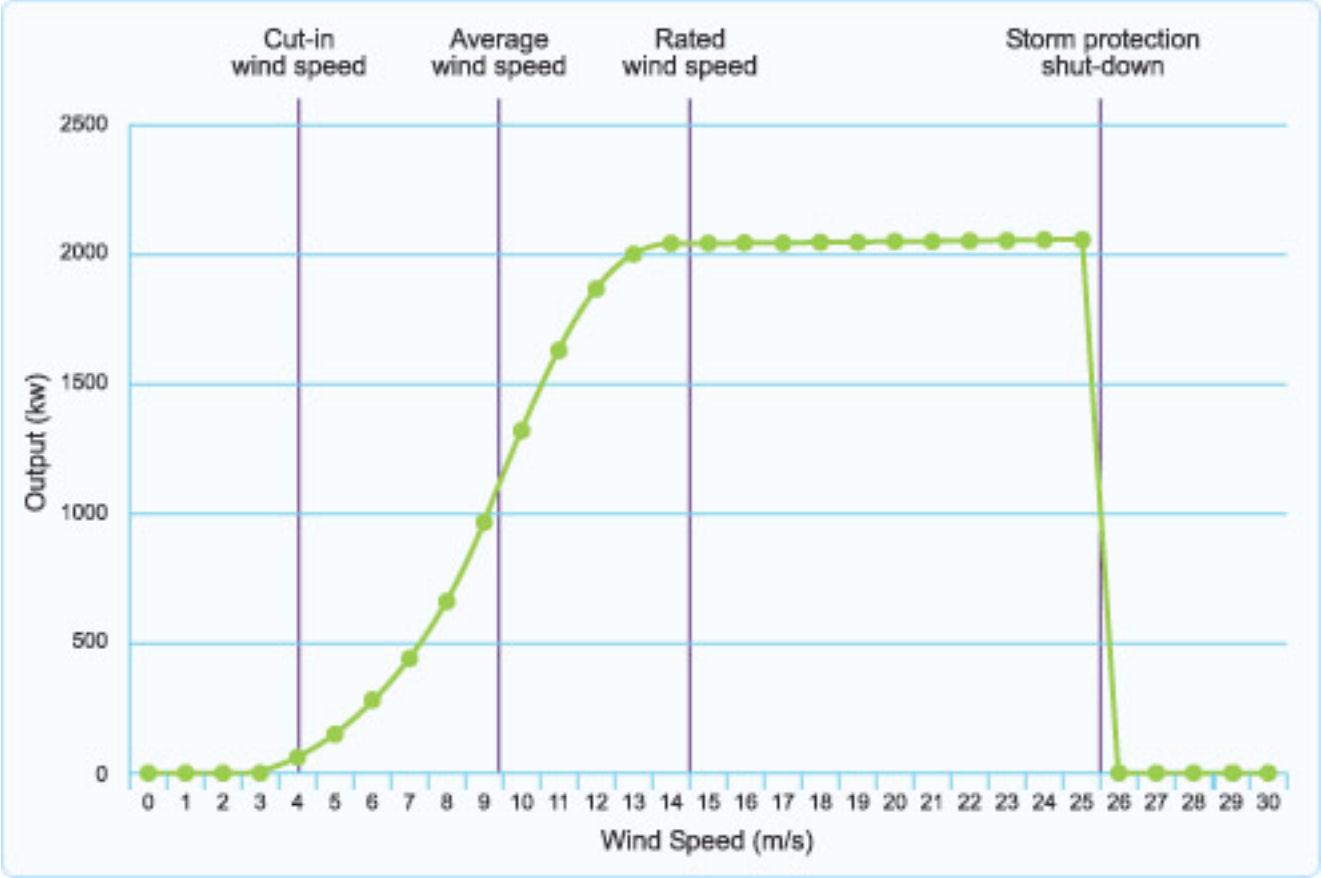
...if wait too long can't extract energy...

....but if go too fast wind can't adjust properly around blade



Actual windpower is less than rated power

Rated power is that under optimal (designed-for) wind



Betz' law: 59%, or ~ 50% in practice recoverable *(this is rated power)*

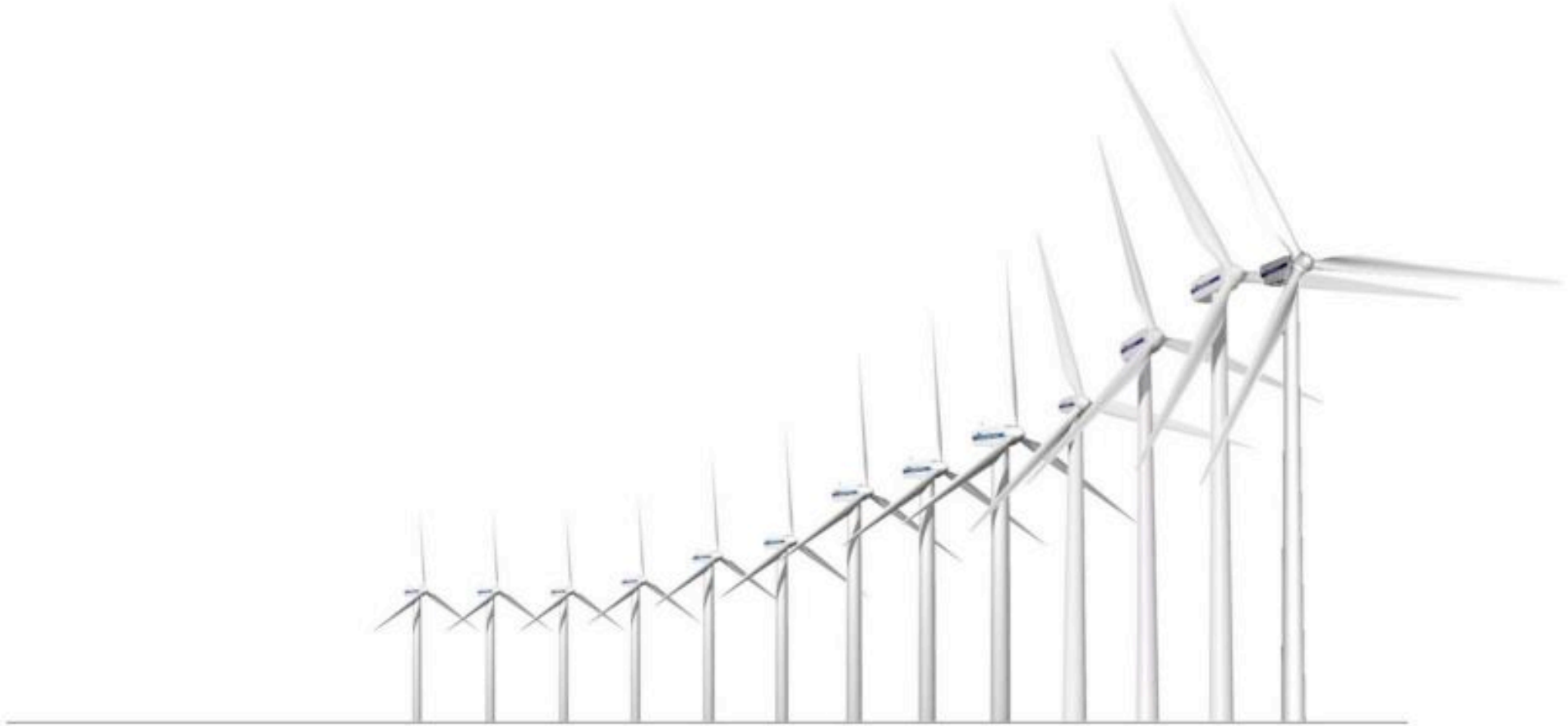
…. Then capacity factor ~ 30% *(of rated power)*

→Total recoverable from wind kinetic power ~ 15%

(Image from Partnerships for Renewables)

Low energy density drives wind turbines to be large

power extracted scales with cross-sectional area

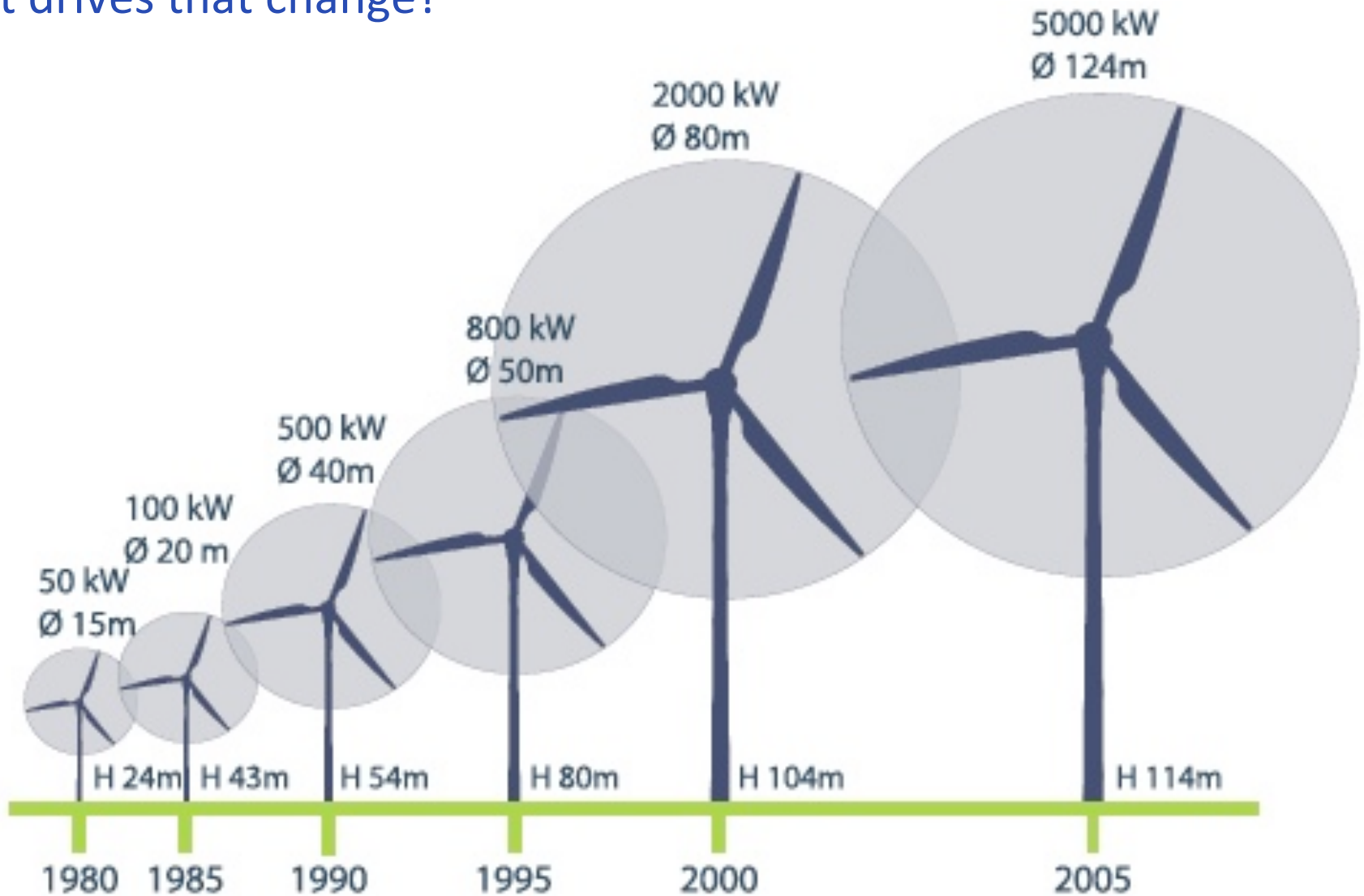


Product/Rotor diameter (m)	V15	V17	V19	V20	V25	V27	V39	V44	V47	V52	V66	V80	V90
Year of installation	1981	1984	1986	1987	1988	1989	1991	1995	1997	2000	1999	2000	2002
Capacity (kW)	55	75	90	100	200	225	500	600	660	850	1750	2000	3000
MWh/year	217	265	301	346	481	647	1304	1581	1947	2530	4705	6768	9152

Image: Vestas

Wind turbine size continues to increase

What drives that change?



2016 U.S. mean new-build rotor diameter = 108 m
(Wiser & Bolinger 2017)

Image: EWEA via Terra Magnetica

Wind turbine size continues to increase

What drives that change?

- More x-sectional area = more power
- Higher wind speeds at altitude

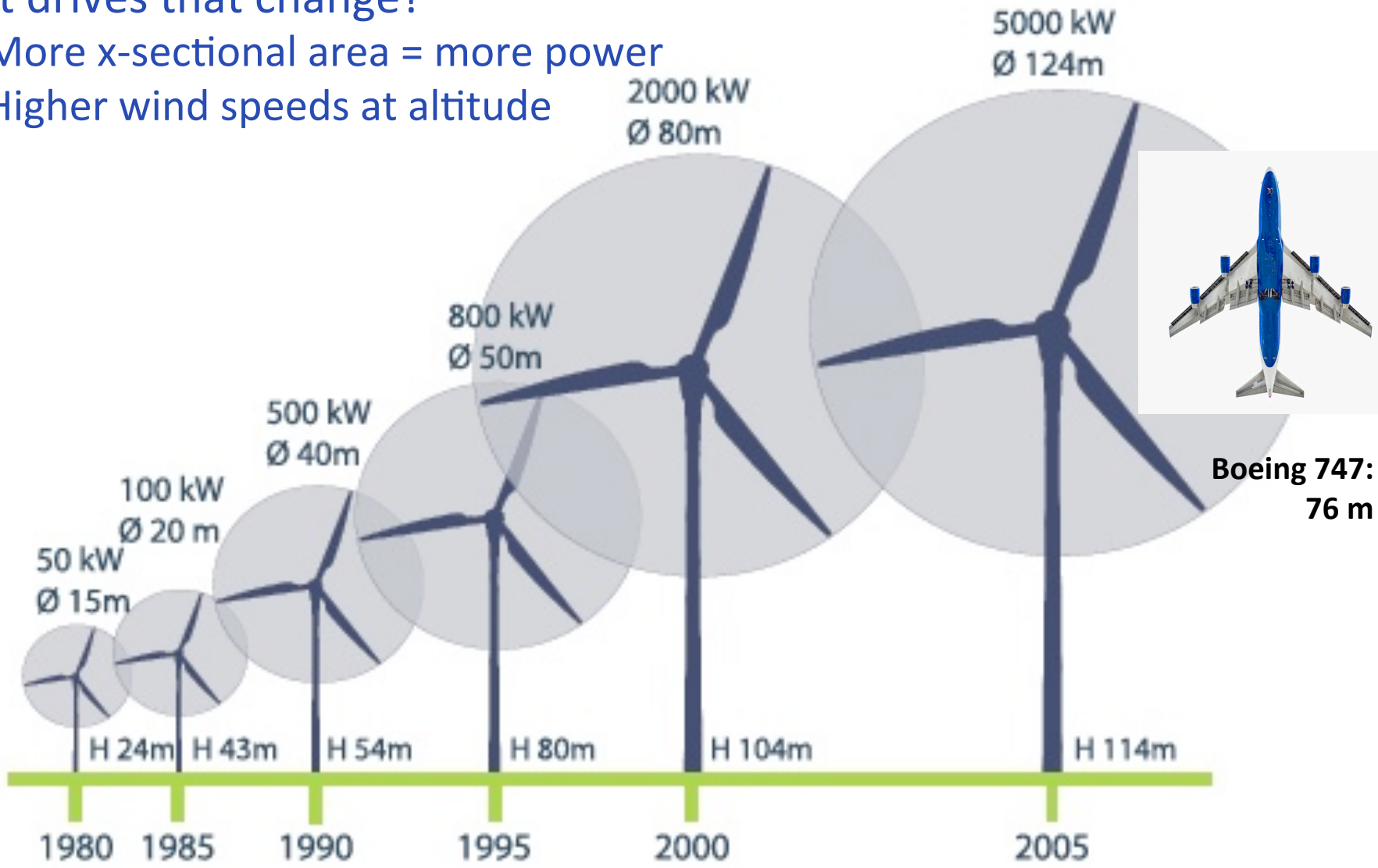
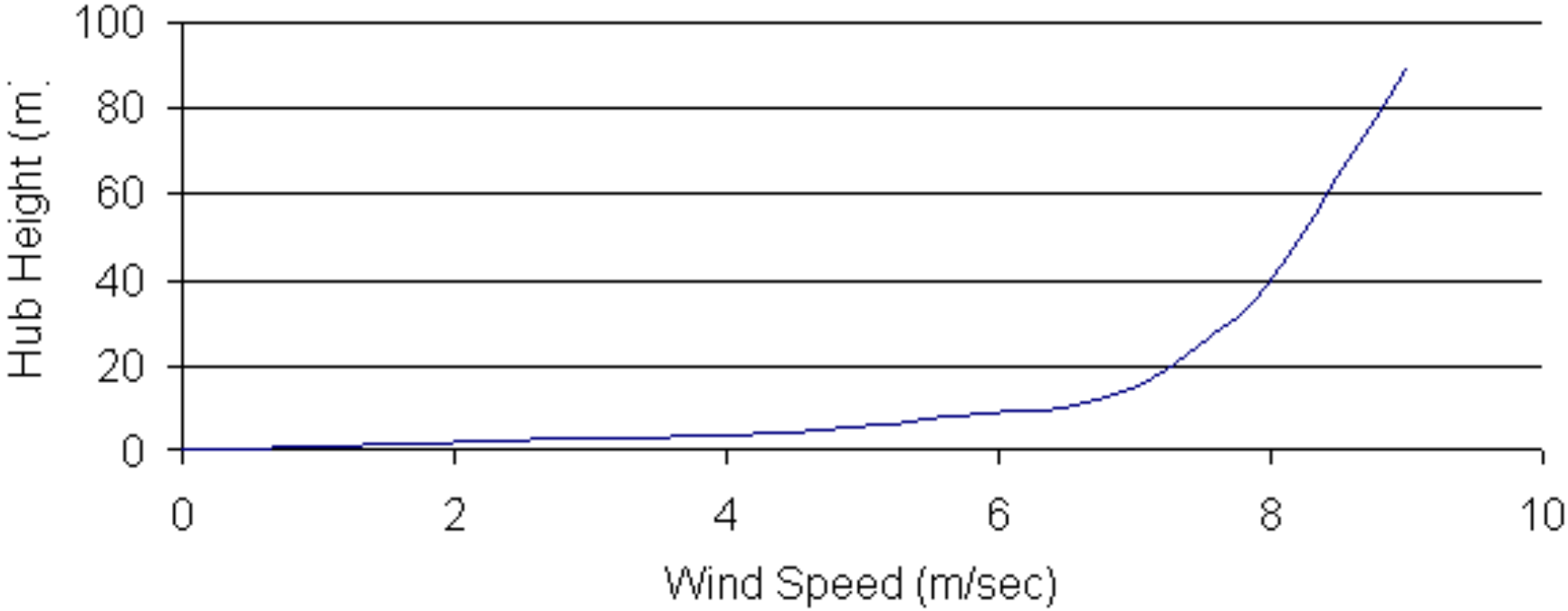


Image *(plane)*: Jeffrey Millstein

Image: EWEA via Terra Magnetica

Wind speed increases with altitude

Means turbines must be high to get good wind



Power carried by wind is a function of **cube** of wind speed

$$P = \frac{1}{2} \rho A v^3$$

Also area α square of diameter, and higher hub allows longer arms

Microwind (short towers) is **inherently** inefficient.

Wind scale is now huge

Most turbines now installed are ~2 MW.
Record is 8.8 MW (2018, Vestas V164)
9.5 MW to be installed off Belgium (V164)

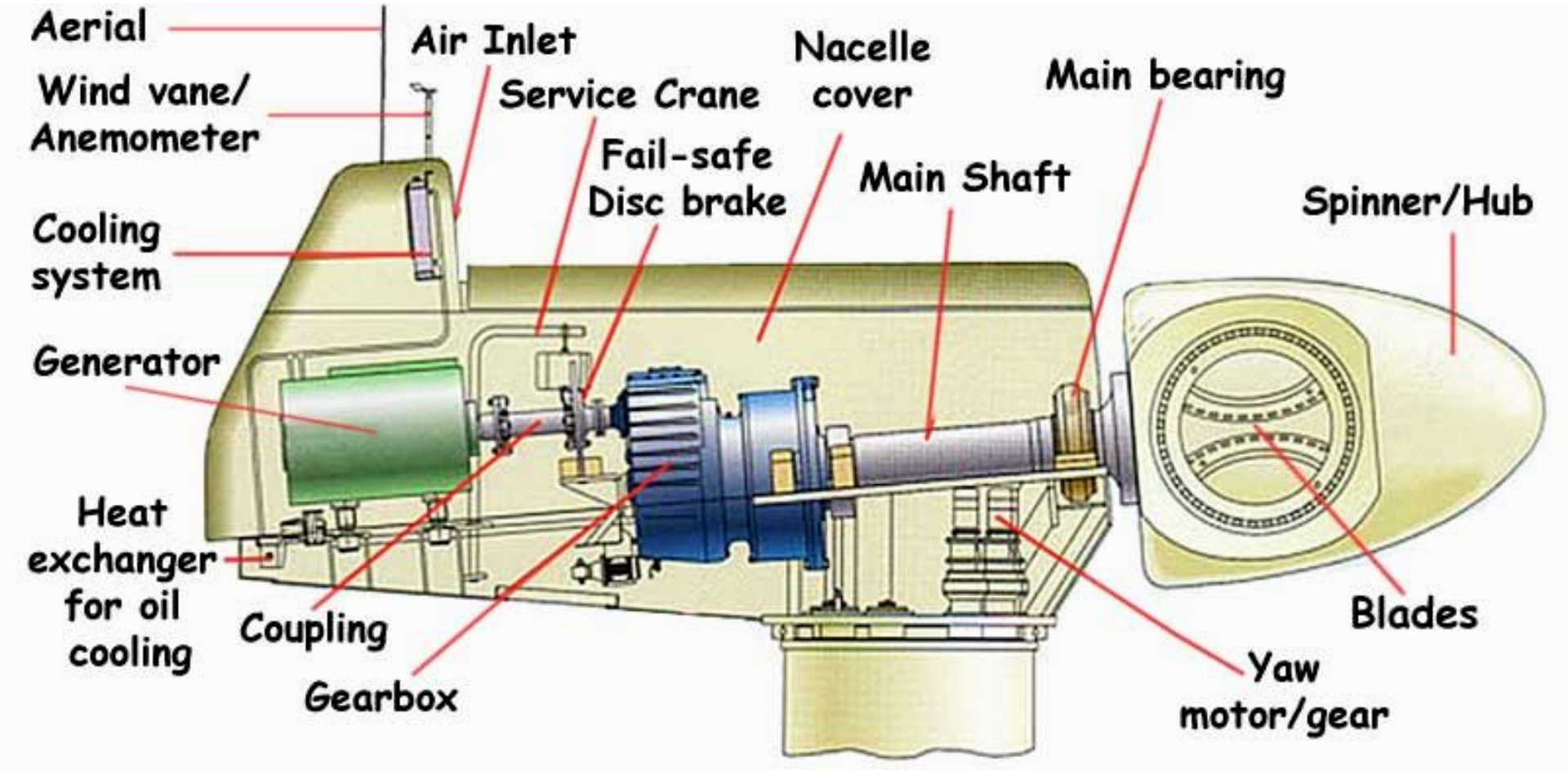
R. Enercon E-126, 126 m. rotor diameter (413 feet), 6 MW rated (likely 7+ in practice).

L. Clipper Liberty, 2.5 MW

Generator mounted in nacelle

Note gearbox to allow turning slowly, as needed for large turbine

Nacelle is heavy: 70 tons for Vestas 2.8 MW (excluding rotor and blades)



Generator is a minor component of cost

electronics (power converter/transformer) are over 3x generator cost

gearbox costs almost as much as the tower does

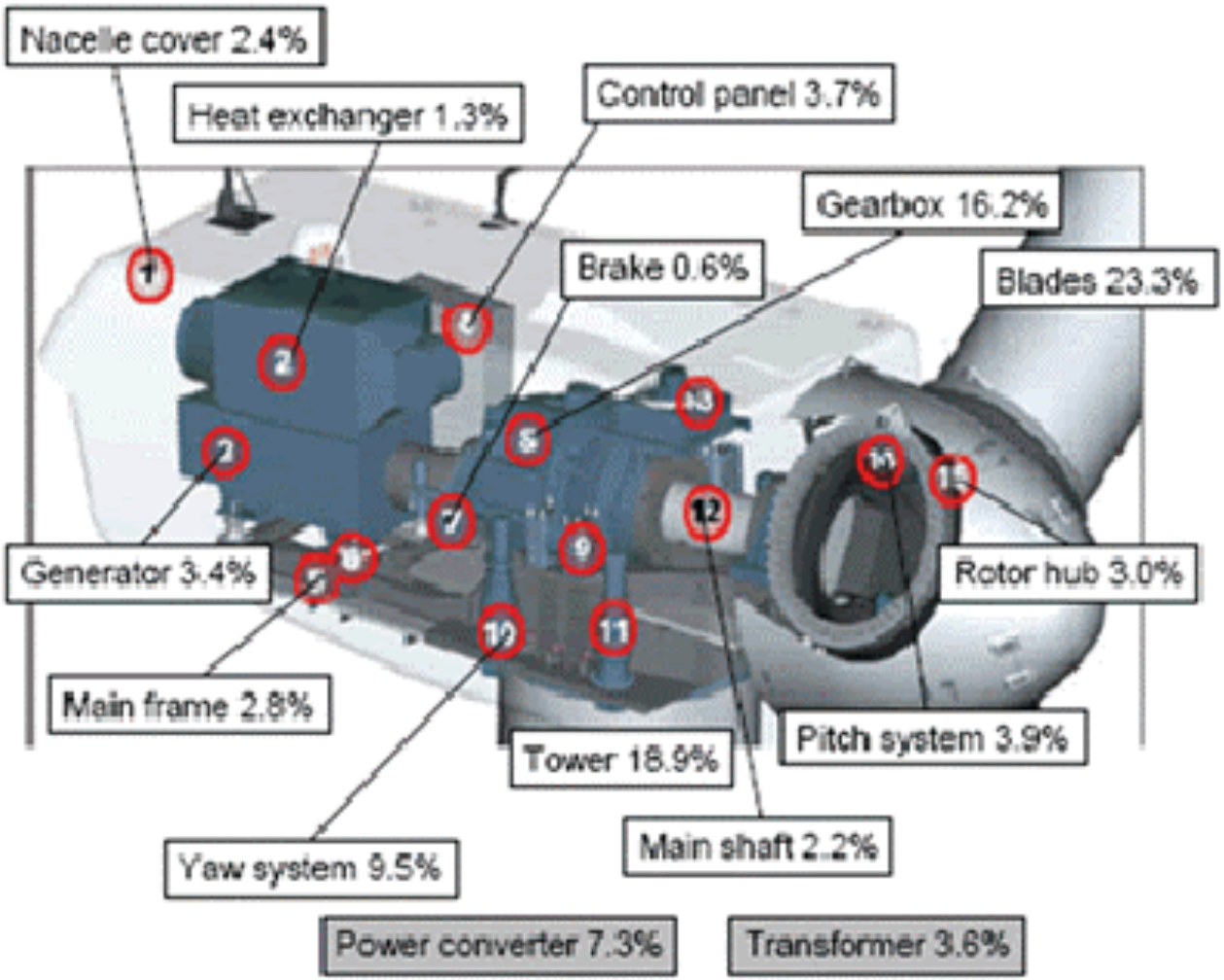
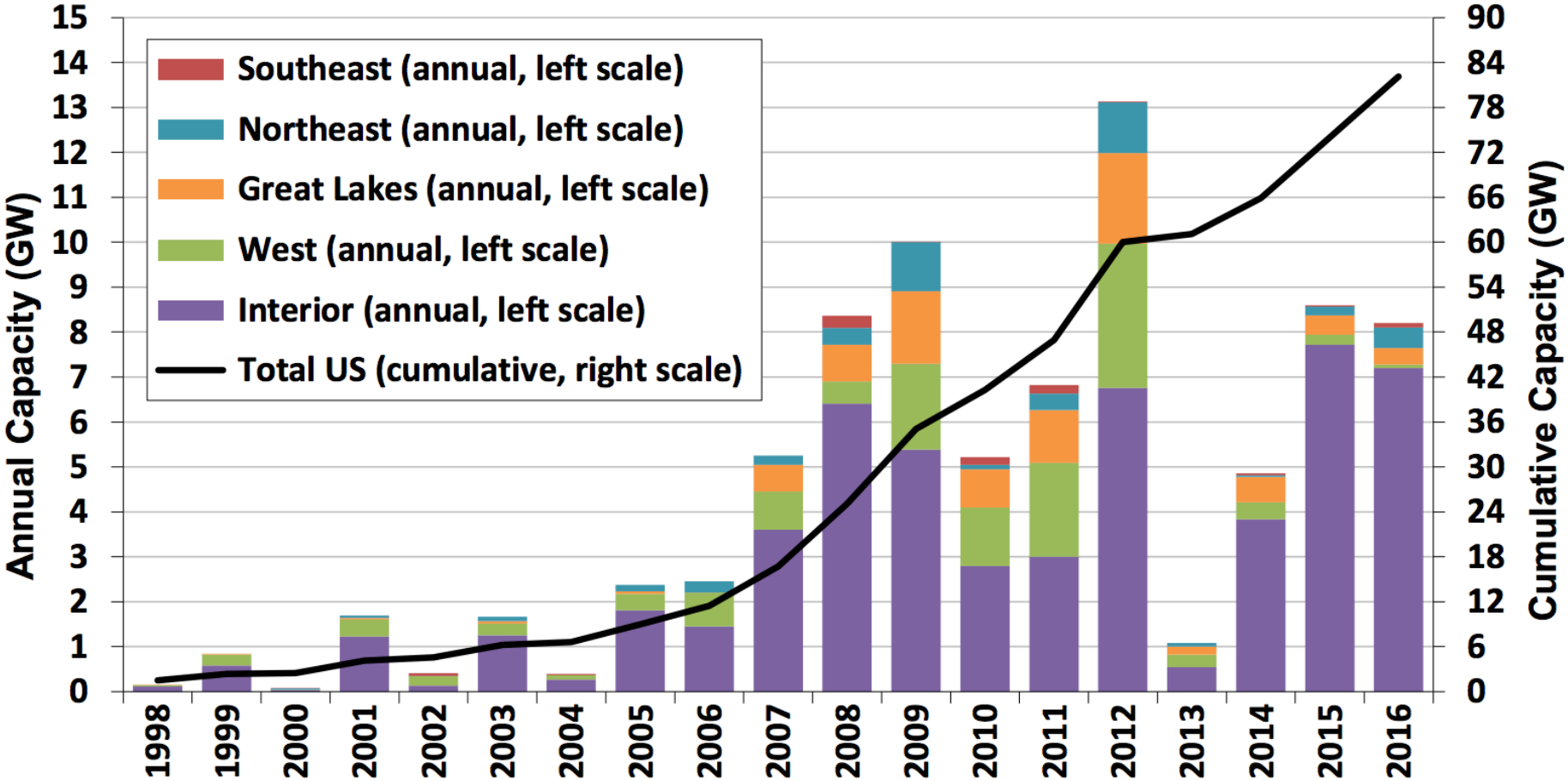


Diagram: Lilas et al, 2011.

U.S. windpower increases in fits and starts



Source: AWEA project database

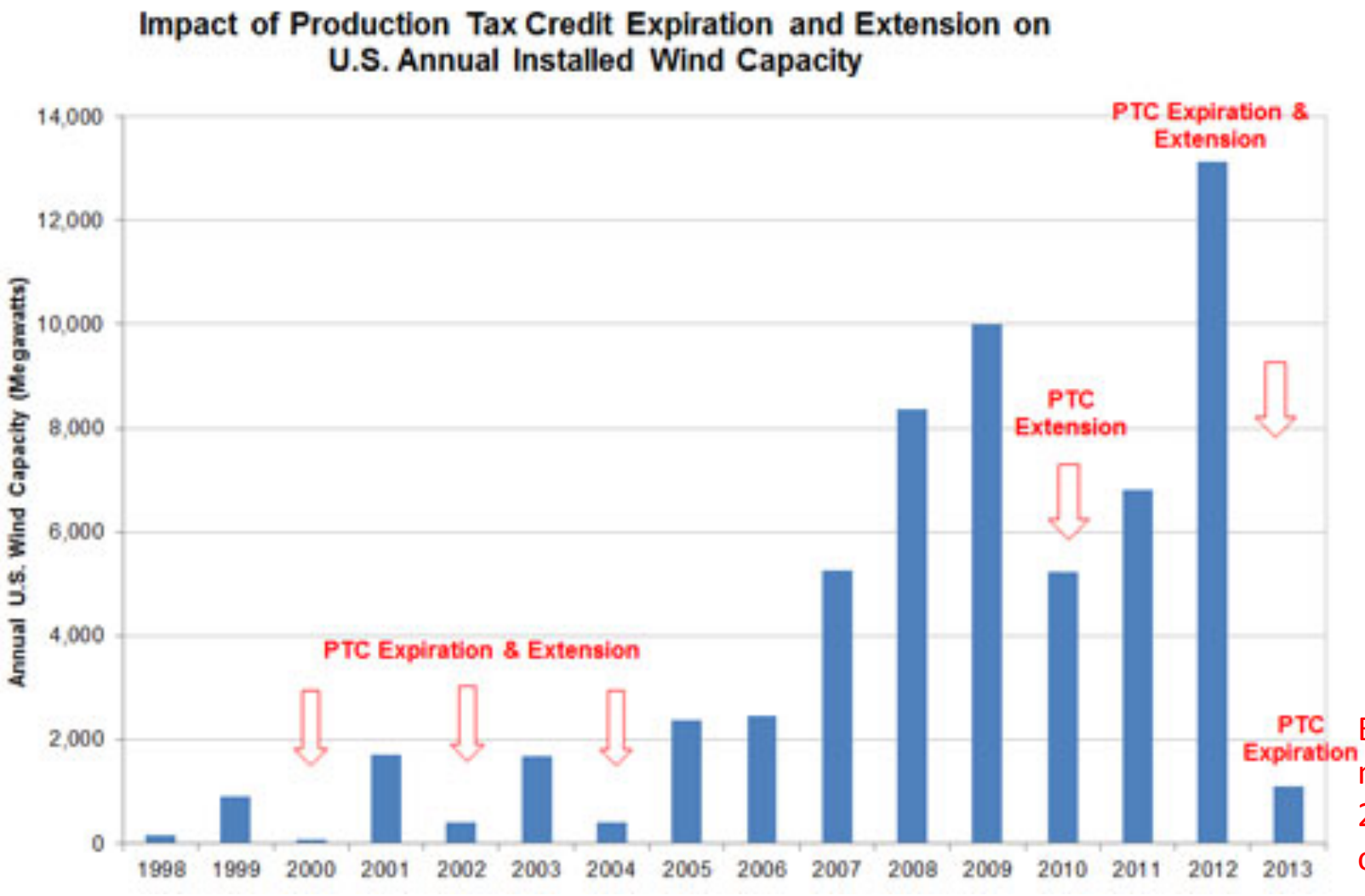
From: Wind Technologies Report 2016, Wiser and Bolinger

U.S. windpower increases in fits and starts

Development driven by presence /absence of federal subsidies:

Production tax credit = 2.3 c/kWh for 10 years (or take ITC, 30% upfront cost)

Now ramping down and will end after 2019 unless new legislation passed



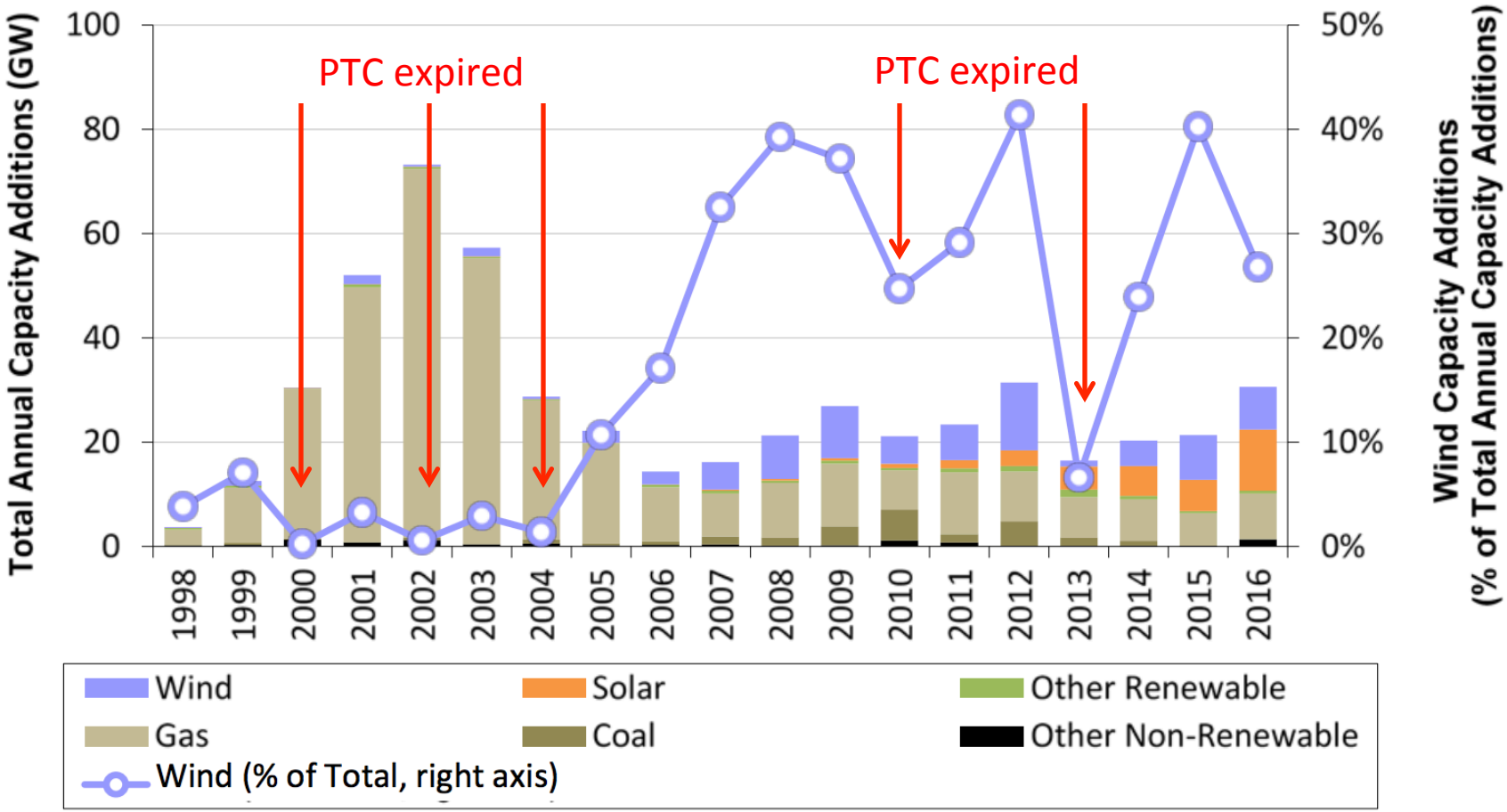
From: Union of Concerned Scientists, data from DOE 2013 and AWEA 2014

Extended 5 more years in 2014, phasing out 2017-2019

Wind now makes up ~ 1/3 of new electric generation

in Interior region, over 50% of installations in 2007-2016

but, windpower still makes up only 6% of electricity generation

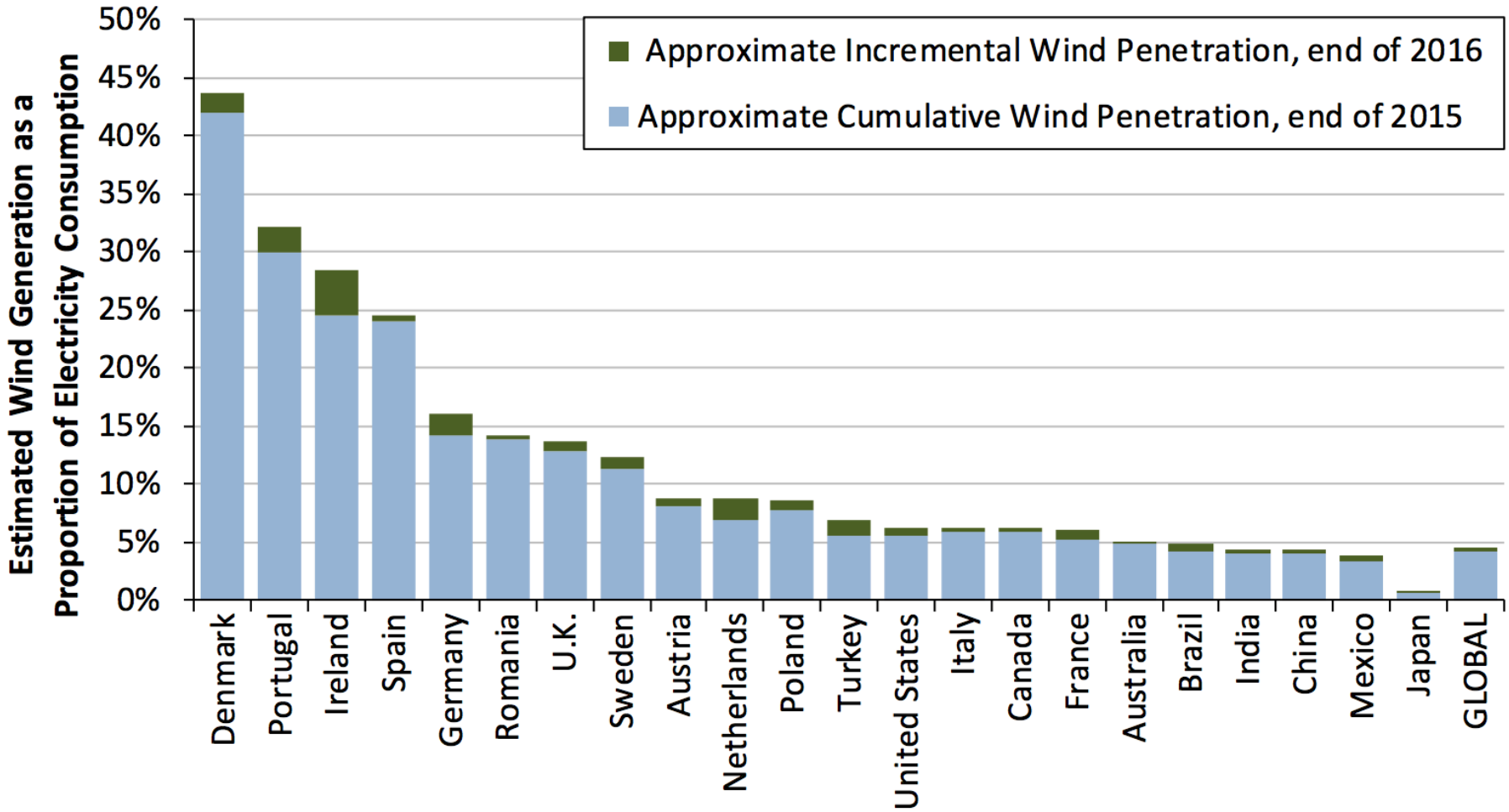


Source: ABB, AWEA, GTM Research, Berkeley Lab

From: Wind Technologies Report 2016, Wiser and Bolinger

U.S. isn't leading in wind penetration

Denmark, Portugal are small countries with backup from European grid



Source: Berkeley Lab estimates based on data from GWEC, EIA, and elsewhere

From: Wind Technologies Report 2016, Wiser and Bolinger

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

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

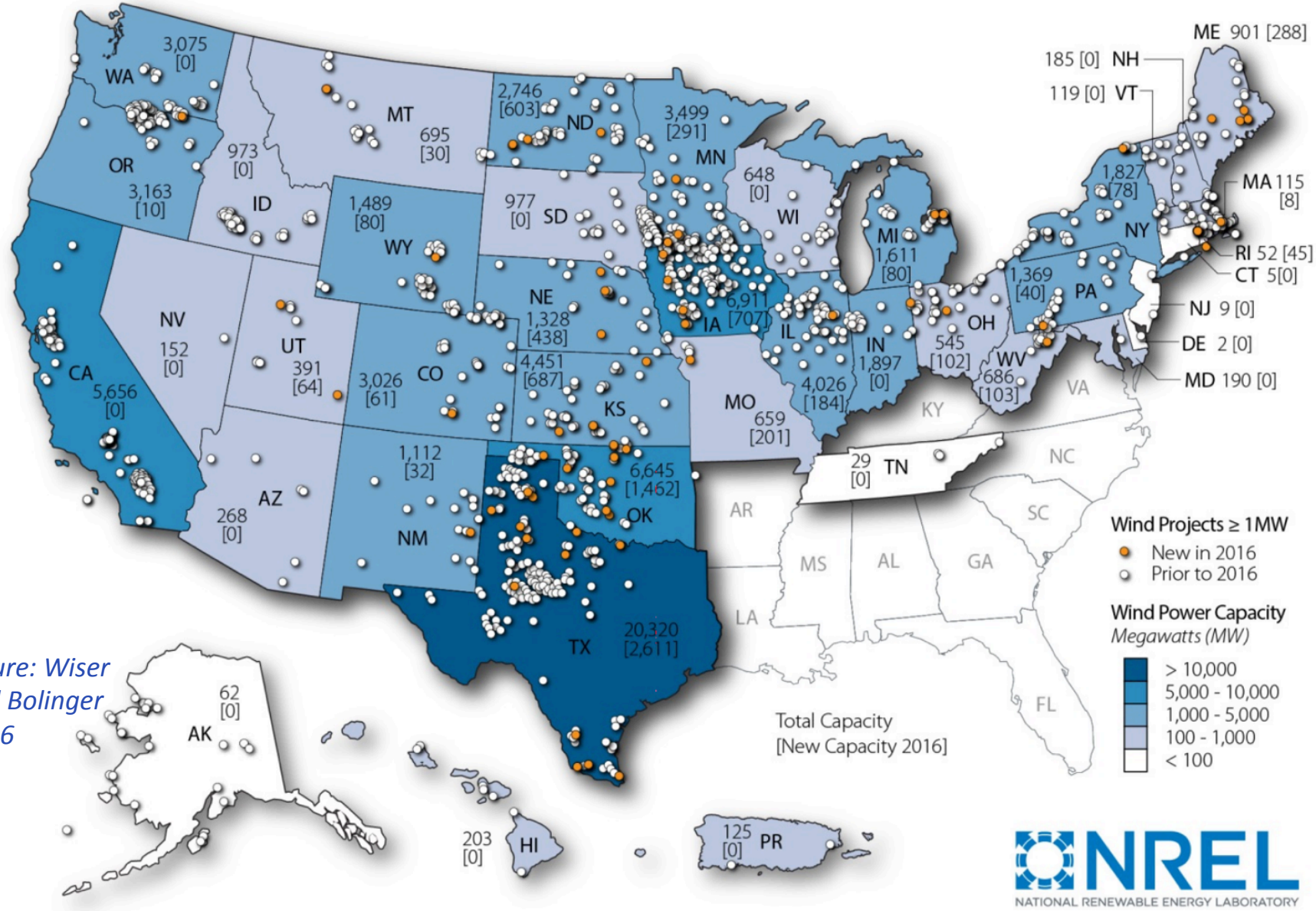
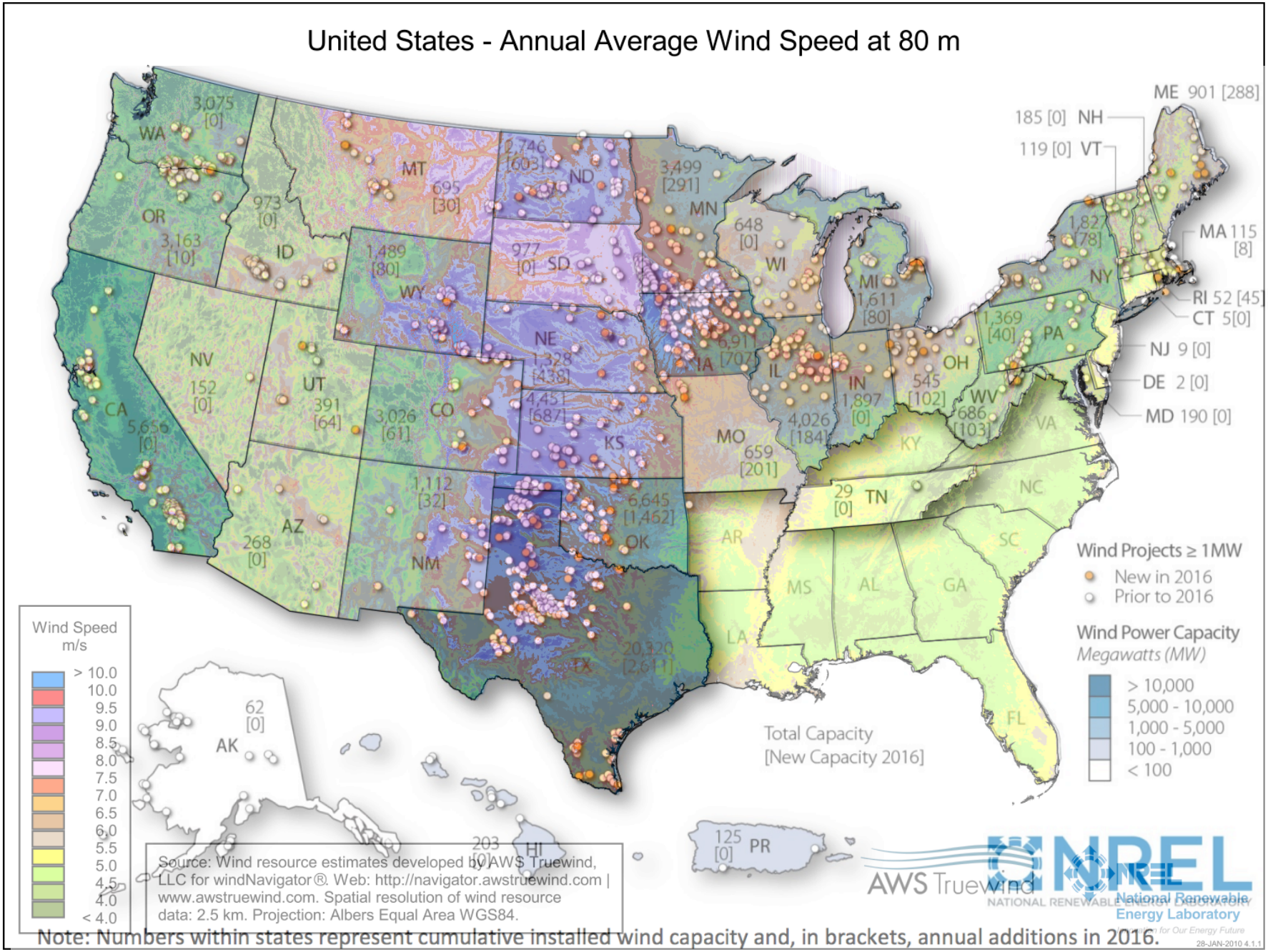


Figure: Wiser and Bolinger 2016

Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2016.

Wind installations follow wind resources



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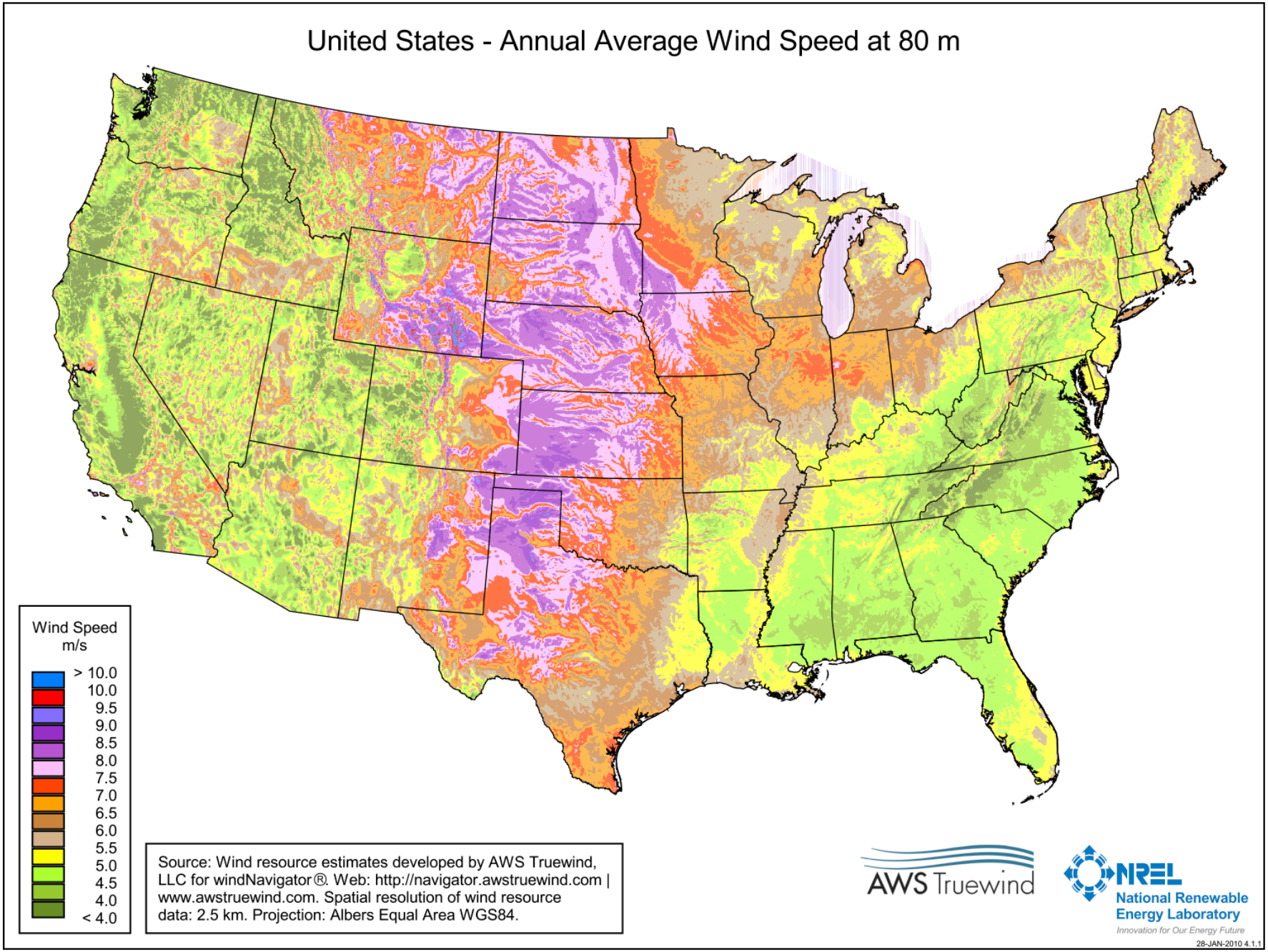
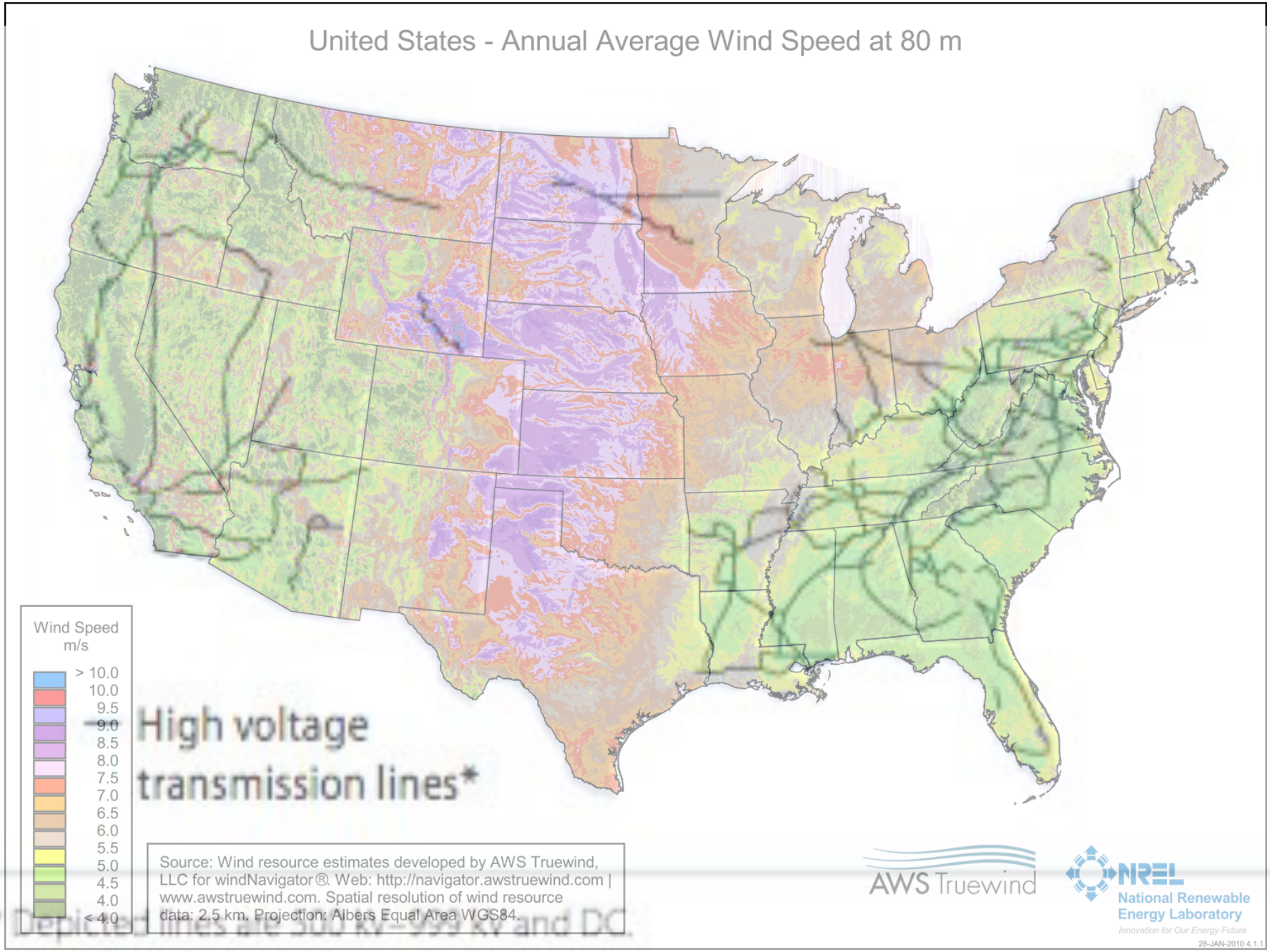
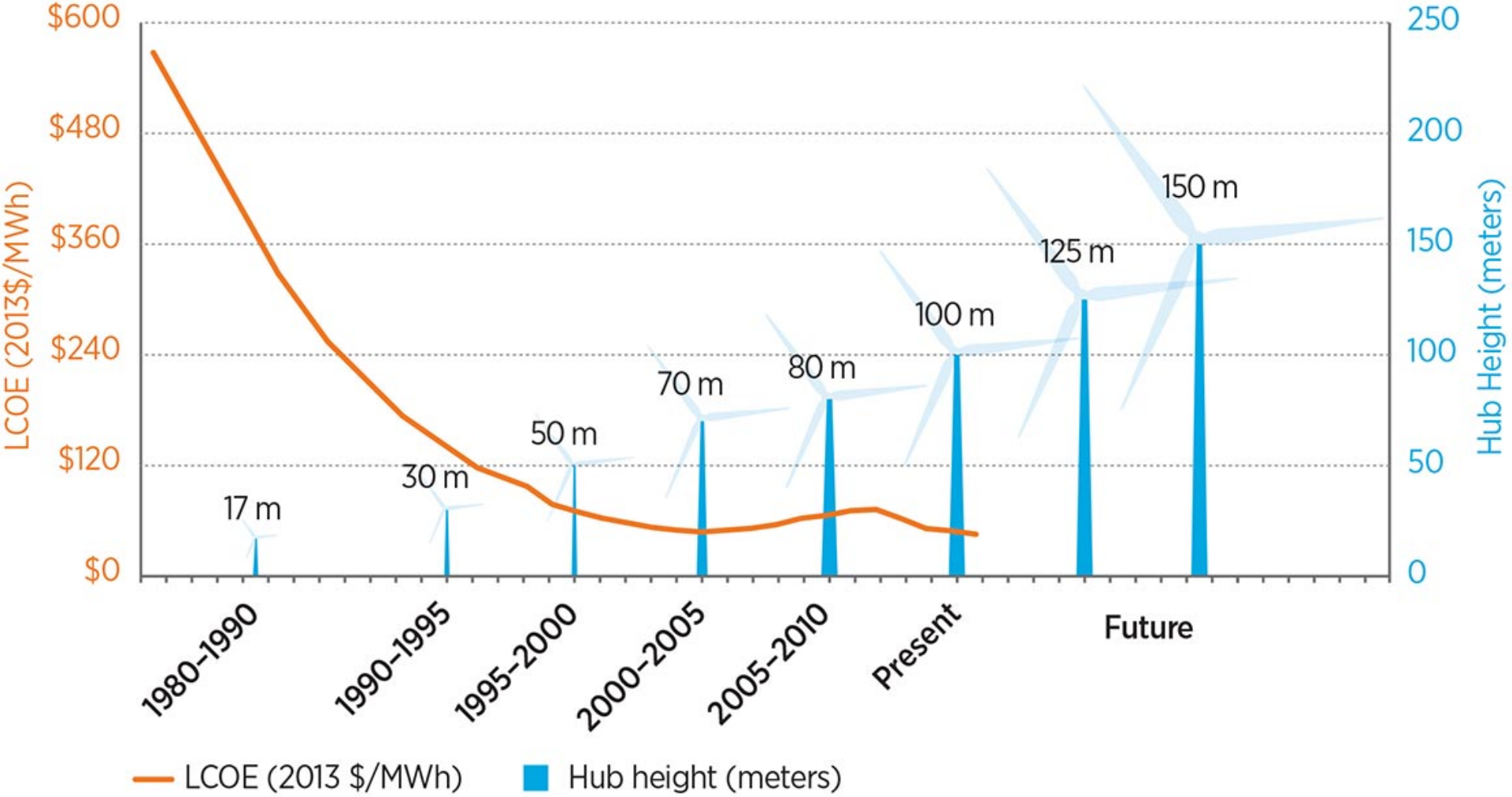


Electrical transmission is not where the wind is



Wind is increasing now because prices are competitive



LCOE = "levelized cost of electricity"

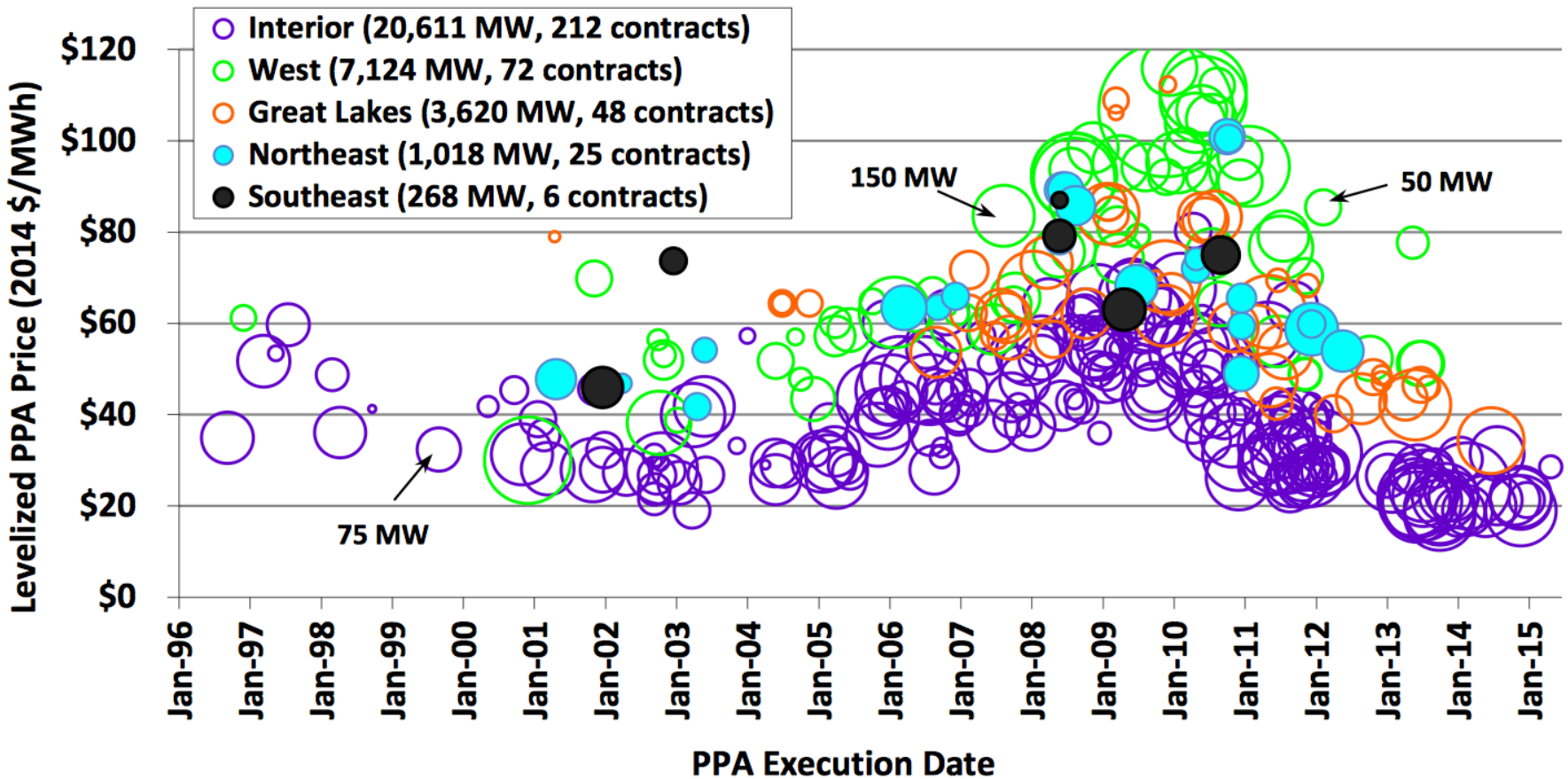
= capital cost * financing + discounted future (earnings − operation cost)

(Note that these costs are after subsidies, which lower costs ~ 30%)

Wind power levelized cost differs by location

costs cheapest in "wind belt" where wind speed is highest

stronger wind = more electricity from the same turbine



PPA is "power purchase agreement"

guaranteed price provided in long-term contract

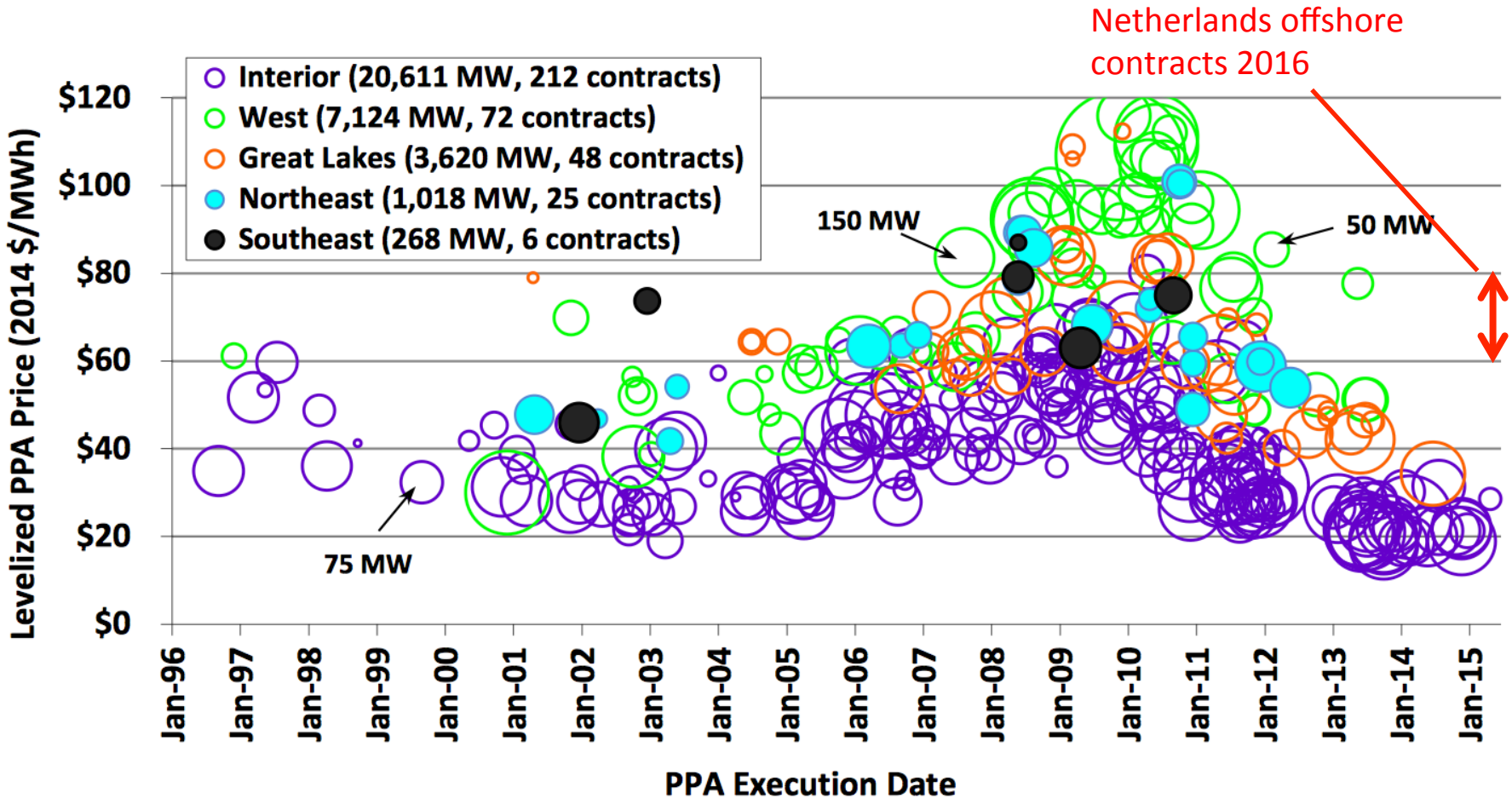
Offshore wind is much more expensive

wind is stronger but costs much larger

cheaper in Europe, but still exceeds onshore

U.S. Block Island

$240/MWh



PPA is “power purchase agreement”

guaranteed price provided in long-term contract

Why expensive? expensive towers, undersea cables to land

Why expensive? also technology constraints because of location - maintenance extremely difficult, so need to make turbines reliable

- Want more power per tower: bigger turbines
- Very simple generators to minimize chance of breakage
  - No electrical connection to rotor. Either
    - **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
    - trend toward **direct-drive generators**

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

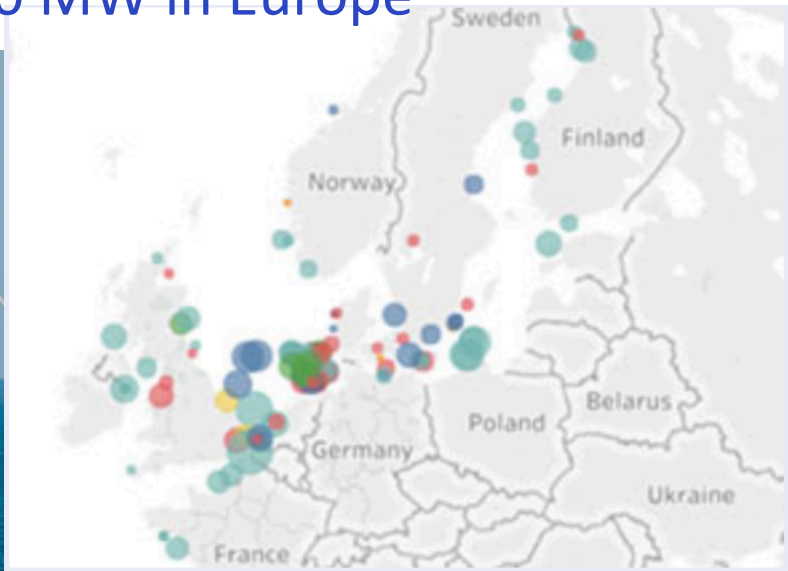
Only one offshore project in U.S., off Rhode Island

- Deepwater Wind (Block Island), 30 MW, completed 2016
  first conceived of as massive 385 MW
- Contracted electricity price 24.4 cents/kWh
  RI wholesale rate is typ. 3-4 cent/kWh, 6 times less

  Project does serve Block Island which had locally high rates, but costs borne by ratepayers throughout RI
- Contract initially rejected by RI Public Utilities Commission as excessive to ratepayers
- Approval required state law to remove the requirement that RIPUC approve only projects that are "commercially reasonable"

Why so much offshore wind in Europe?

30 MW in U.S. 15,780 MW in Europe



Top: Denmark, (Copenhagen)

Bottom: U.K., (Sheringham Shoal)

In Europe, cost discrepancies not so prohibitive for offshore

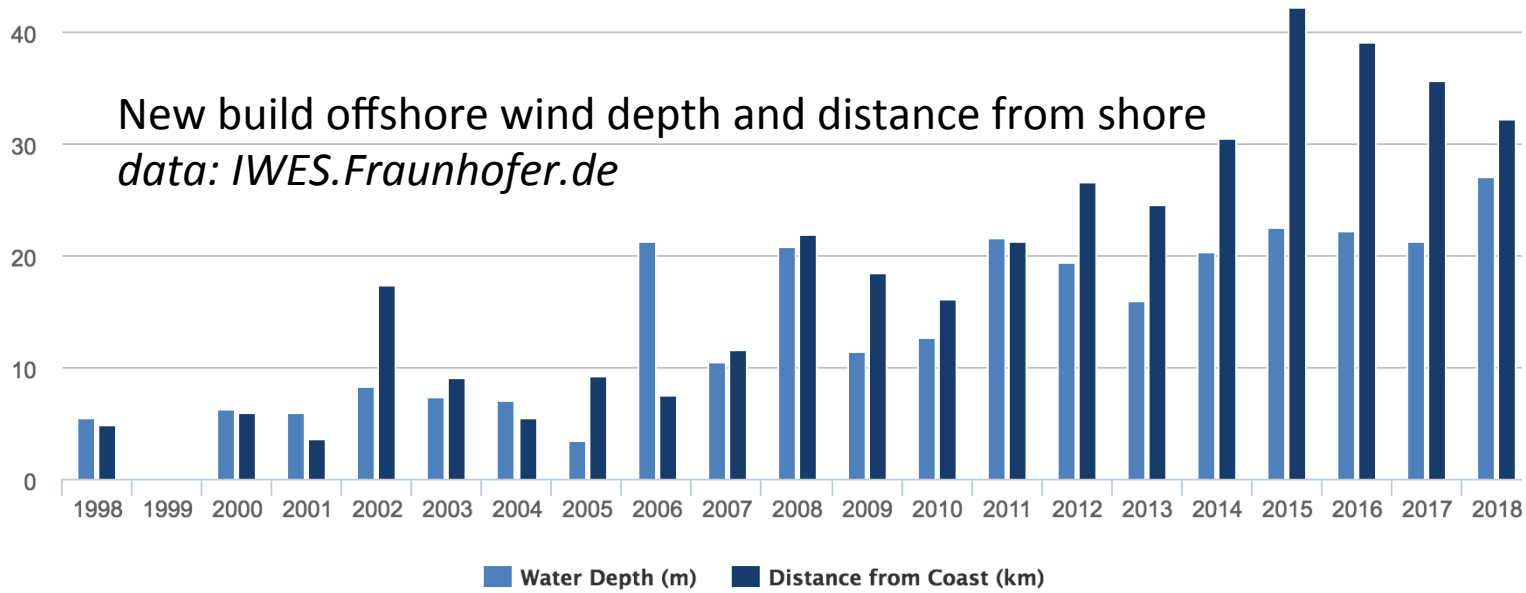
- offshore waters are shallow, easier to build than in U.S.

  Europe mean depth for new builds ca. 20 m, earliest farms < 5 m
  (but Block Island only 23-28 m, depth can't explain its much higher costs)

- land is crowded, so few locations for cheap onshore wind
- electricity by conventional sources is expensive

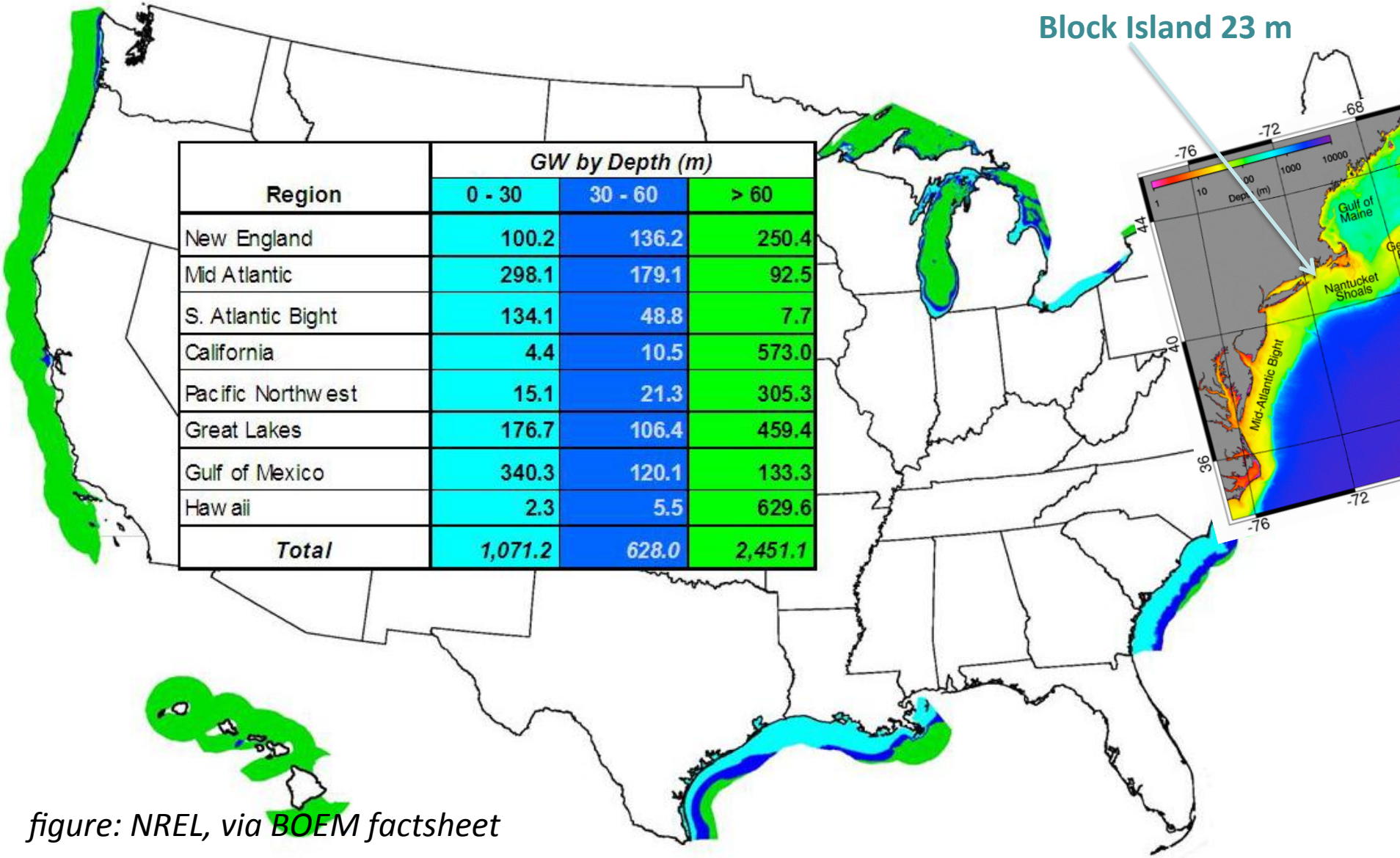
  no cheap natural gas to lower wholesale rates

- countries are willing to subsidize, & experience lowers costs



Very little of U.S. continental shelf is shallow

remember mean depth of European offshore farms < 20 m

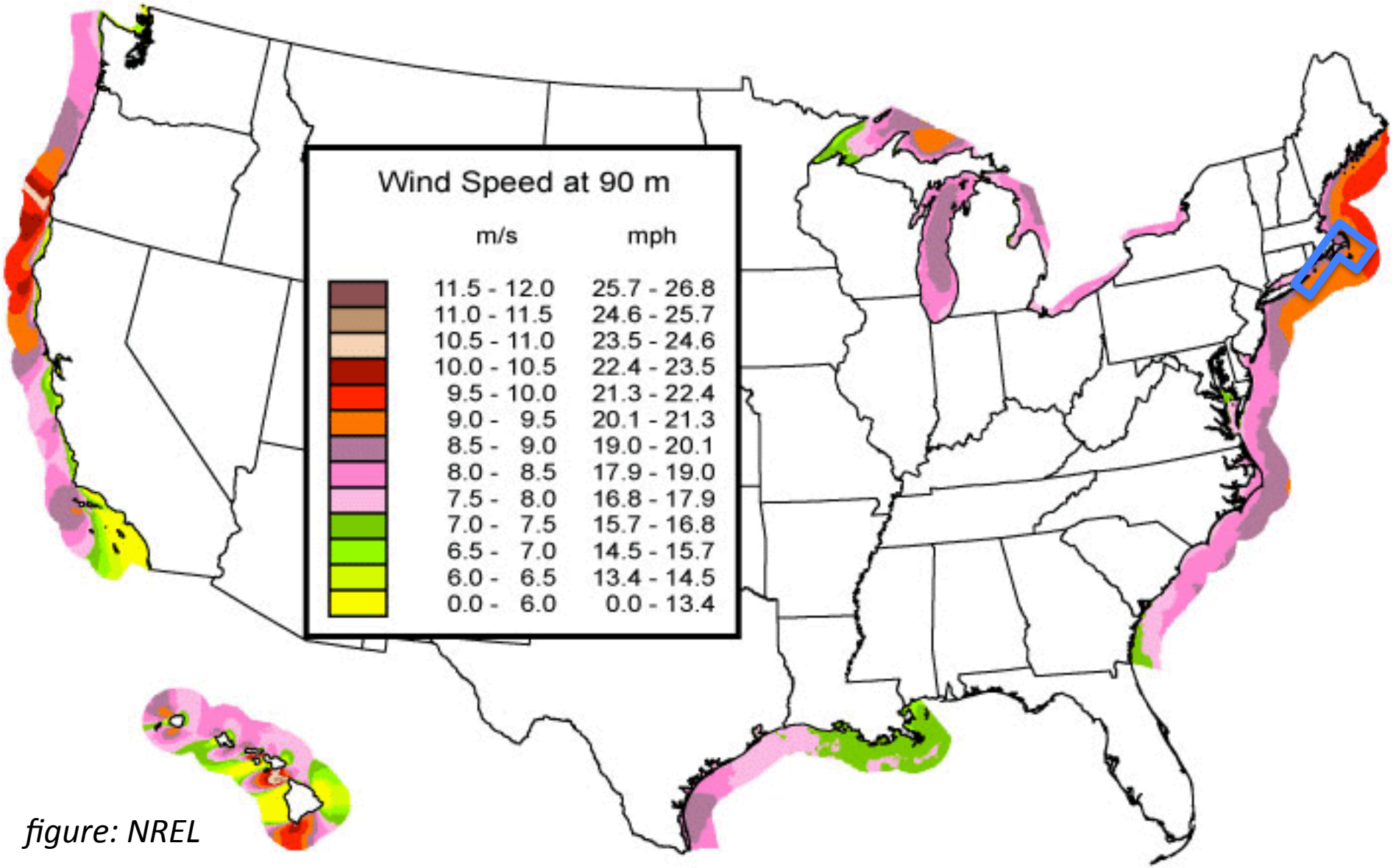


Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

figure: NREL, via BOEM factsheet

And winds are not strong in shallow U.S. shelf sites

7 m/s is about limit for onshore wind, must be higher to justify offshore
*the **only** overlap of shallow and windy is the MA, CT, RI shelf*



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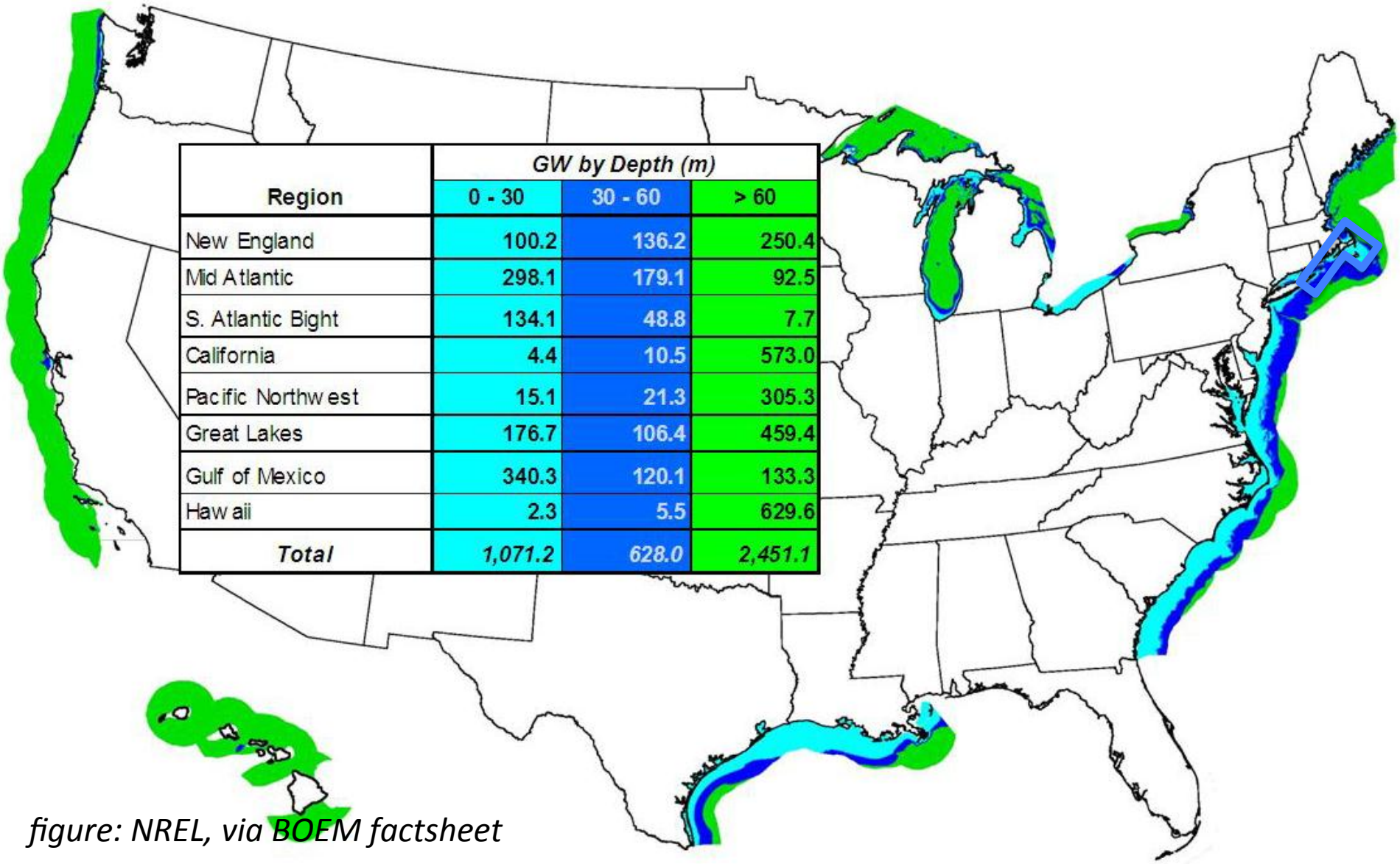

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