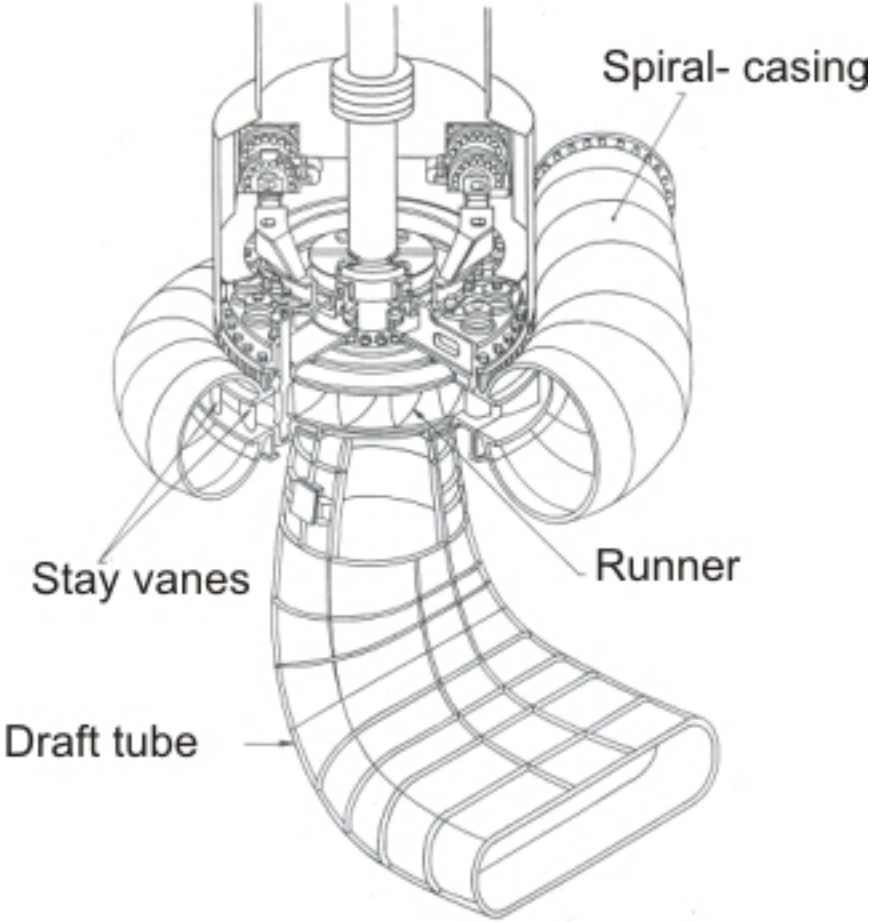
Turbines III: Hydro and Wind

GEOS 24705/ ENST 24705

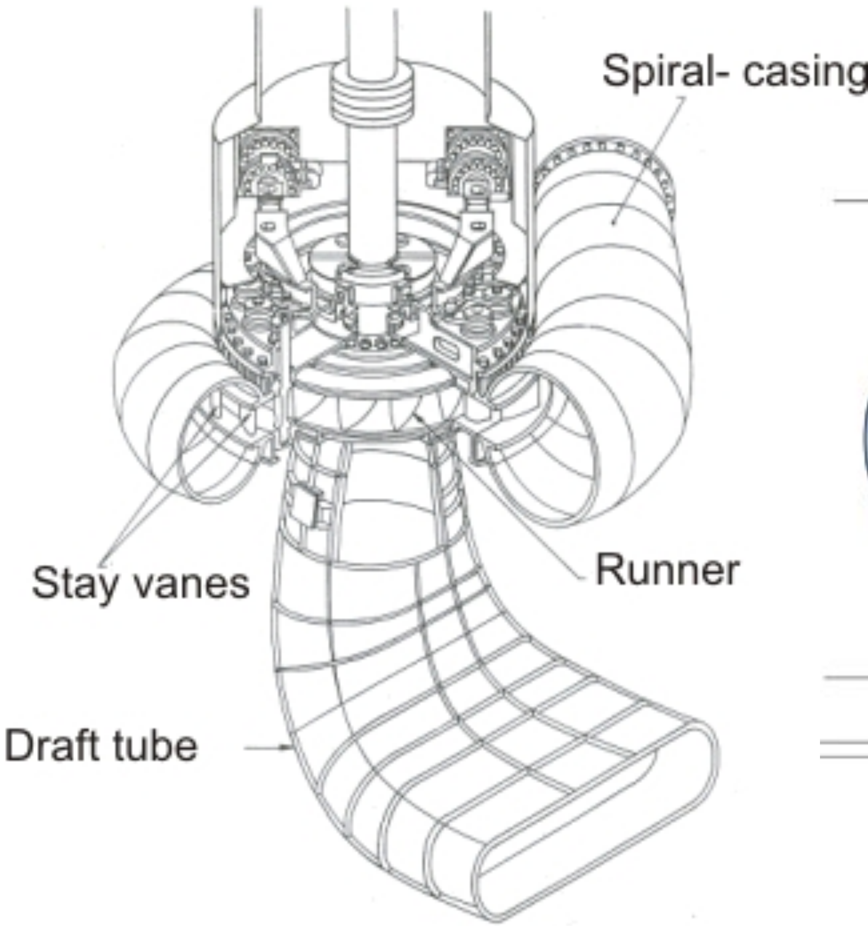
Turbine assembly contains more than just runner

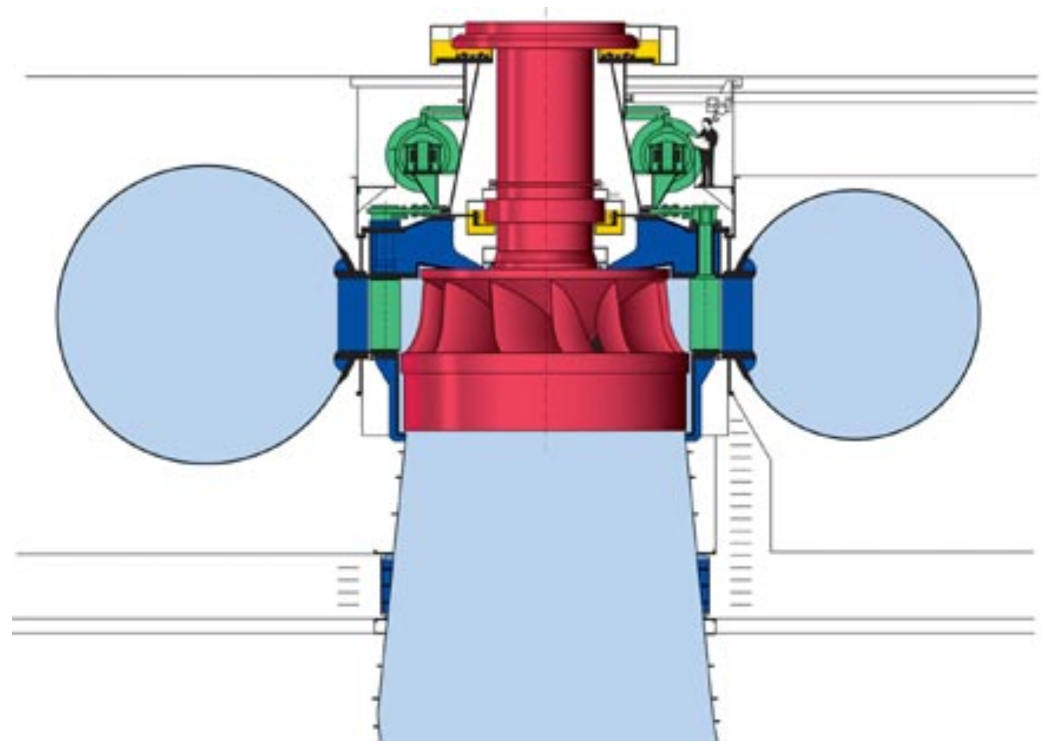


What is the input spiral for? Why does it decrease in radius?

What is the function of the draft tube? Why does it fan outwards?

Turbine assembly contains more than just runner





What is the input spiral for? Why does it decrease in radius?

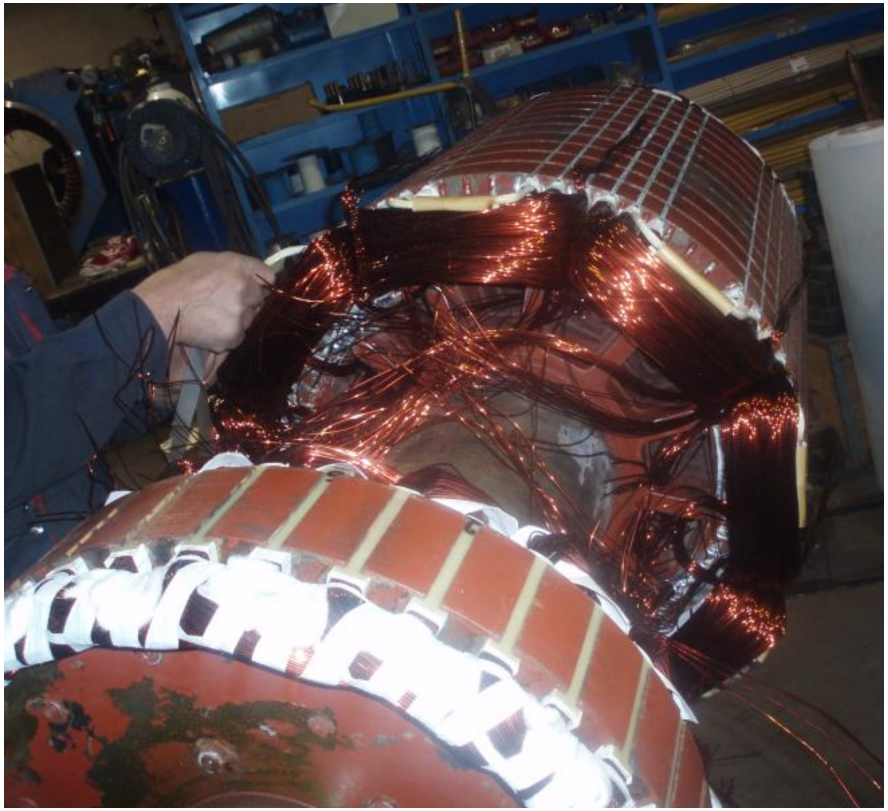
The spiral directs water **radially** to the runner. Because water flows in to center and is lost, the diameter has to narrow to keep velocity constant.

What is the function of the draft tube? Why does it fan outwards?

To produce a slow-down of motion and drop in pressure. (It's an "anti-nozzle")

How fast does the turbine rotate?

15 m rotor for 400 MW generator at Son La hydroelectric facility, Vietnam (L). Rewinding the rotor for a small hydroelectric plant (R)



Design questions:

Will a hydro turbine rotate as fast as a gas or steam turbine?

If not, how does it make 60 Hz AC electricity?

How fast does the turbine rotate?

15 m rotor for 400 MW generator at Son La hydroelectric facility, Vietnam (L). Rewinding the rotor for a small hydroelectric plant (R)

Design questions:

Will a hydro turbine rotate as fast as a gas or steam turbine?

No – gas turbines rotate at 60 Hz but hydro turbines rotate more slowly, sometimes nearly 1 Hz

If not, how does it make 60 Hz AC electricity?

By increasing the number of poles in the rotor magnet

Pelton wheel:

impulse turbine

large-scale OR small-scale

Even in micro-hydro use, control fluid pressure and velocity with inlet nozzles rather than putting wheel in river and letting it spin.

Free-stream turbine

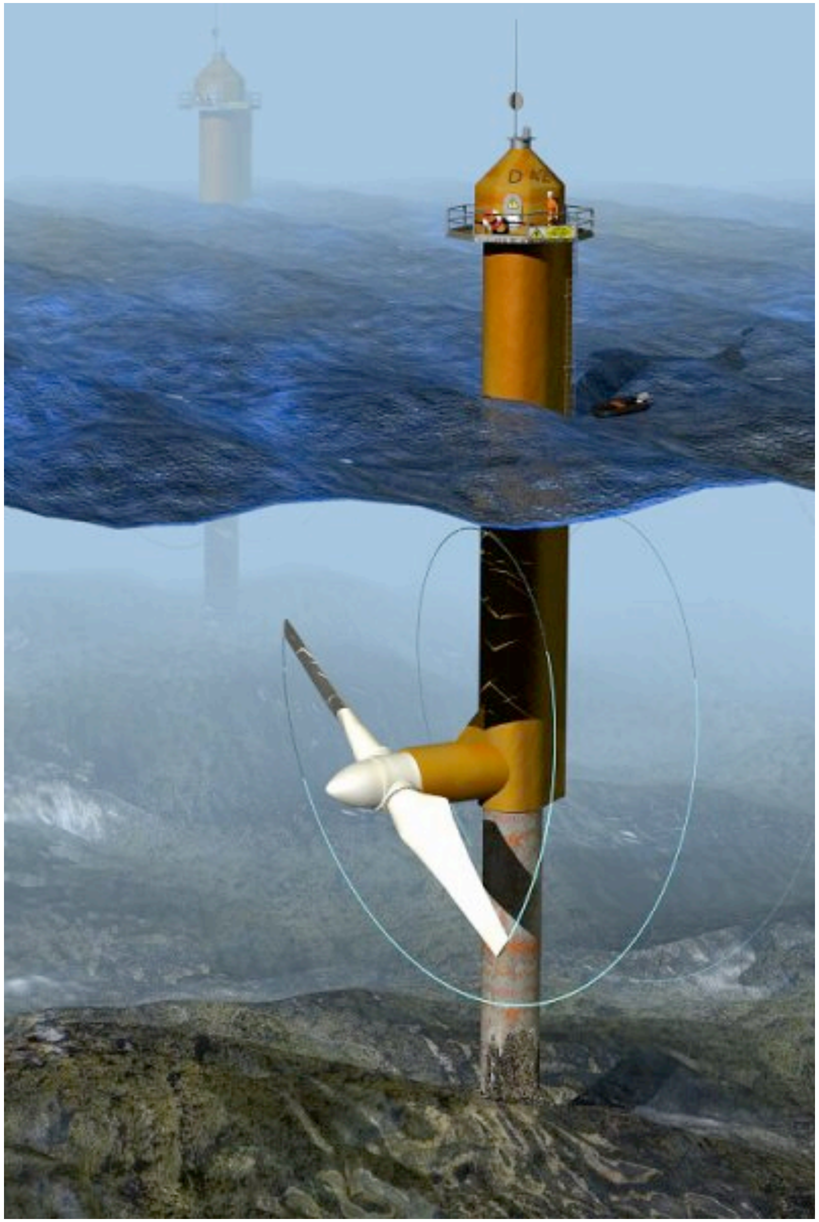
DEFINITIONS

"Run-of-river" = no dam

"free stream" = not even a penstock,
so no pressure drop at all

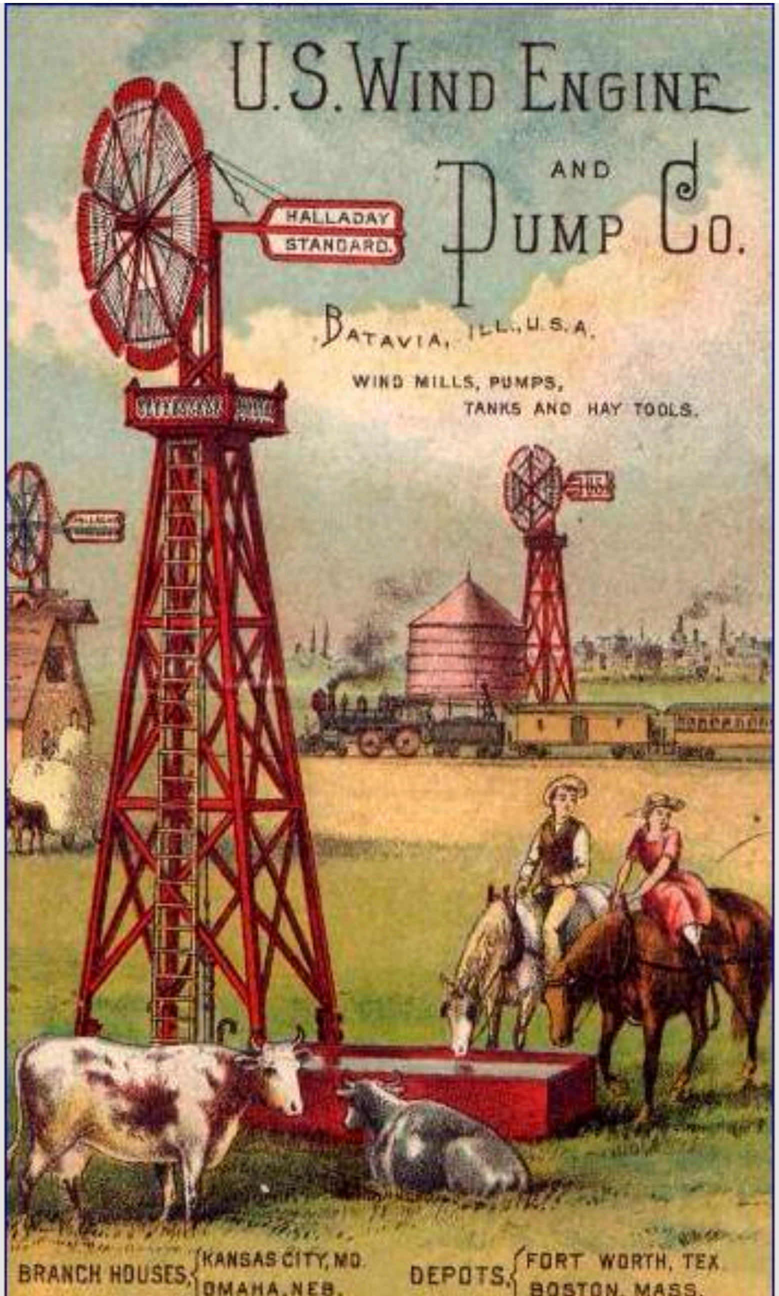
No pressure gradient
= impulse turbine only

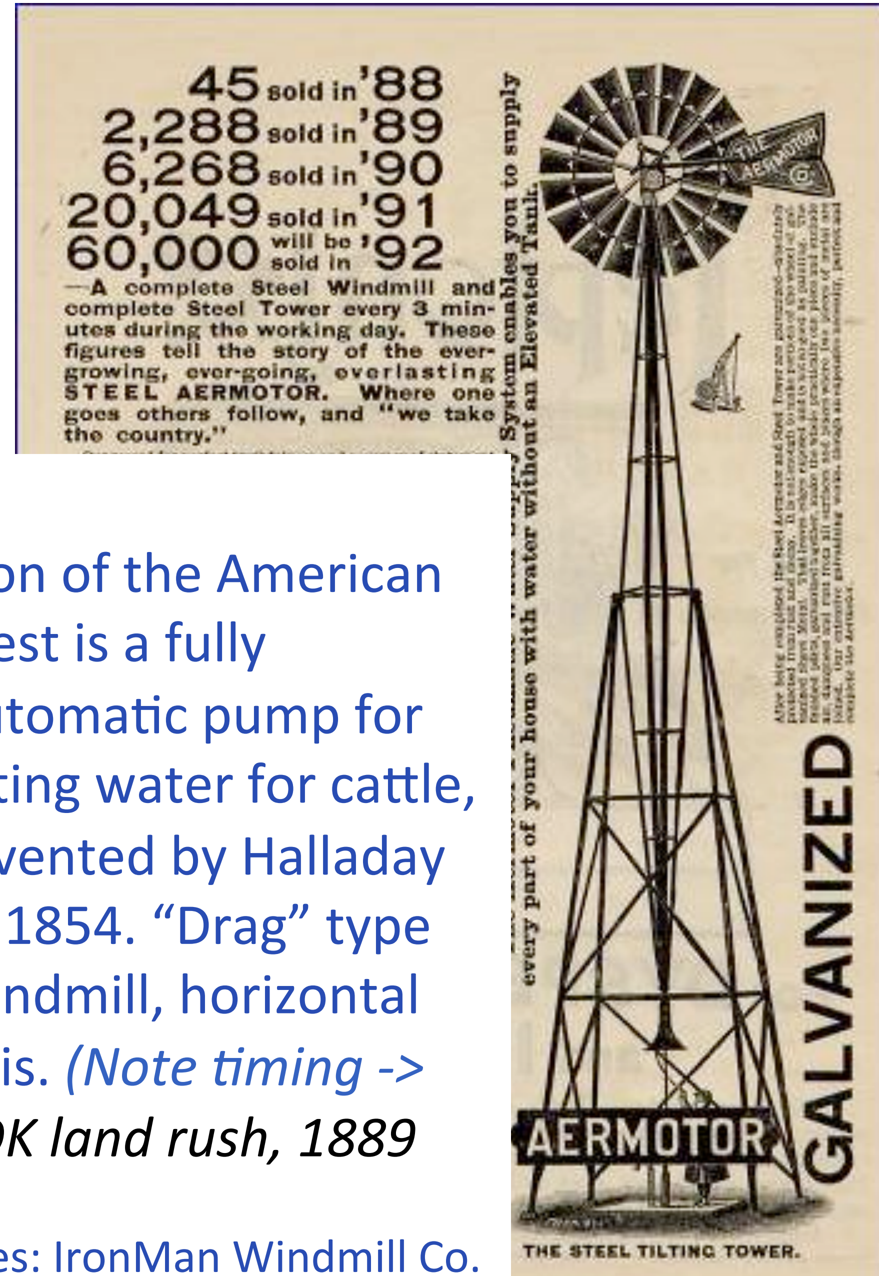
These start to look even more like propellers… a lot like wind turbines…



Artist's rendition of marine current turbine for extracting energy from tidal flows (Tidal Stream Inc.). No control of pressure at all.

Early windmills run mechanical pumps only



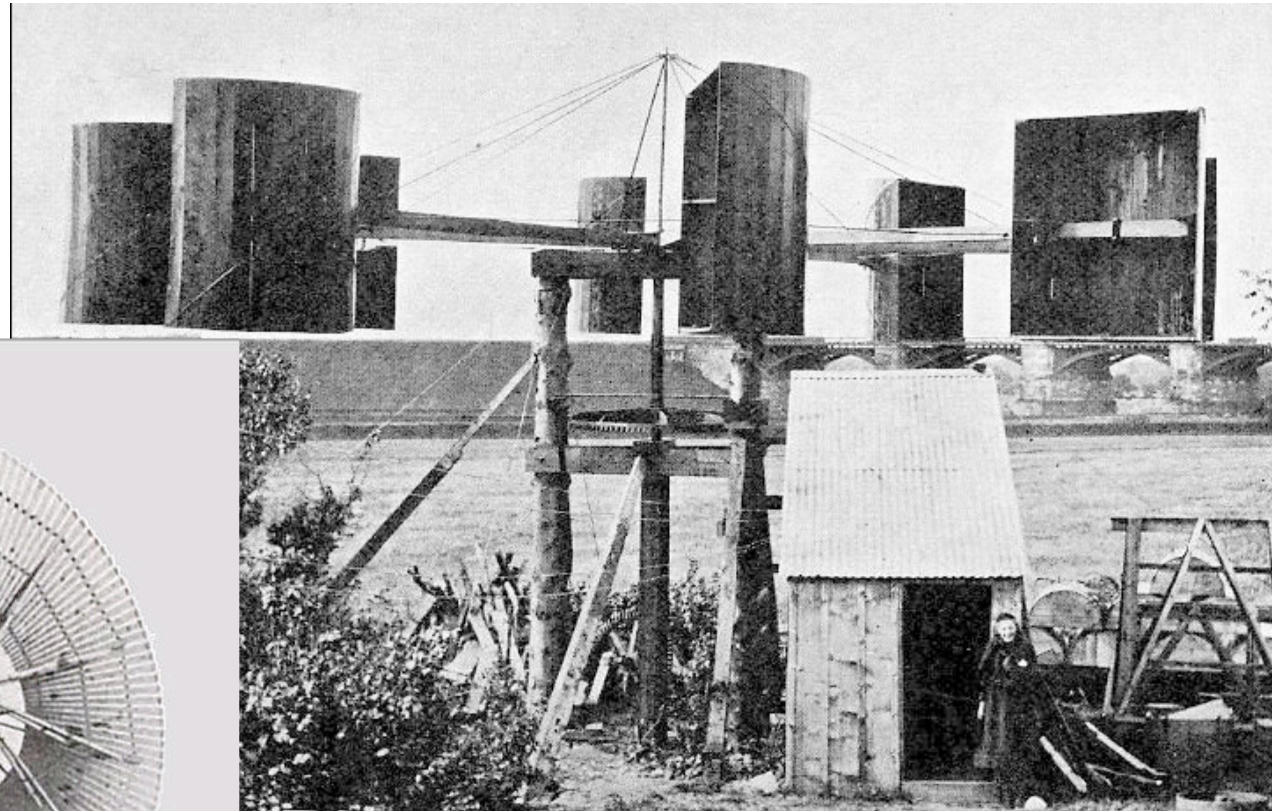


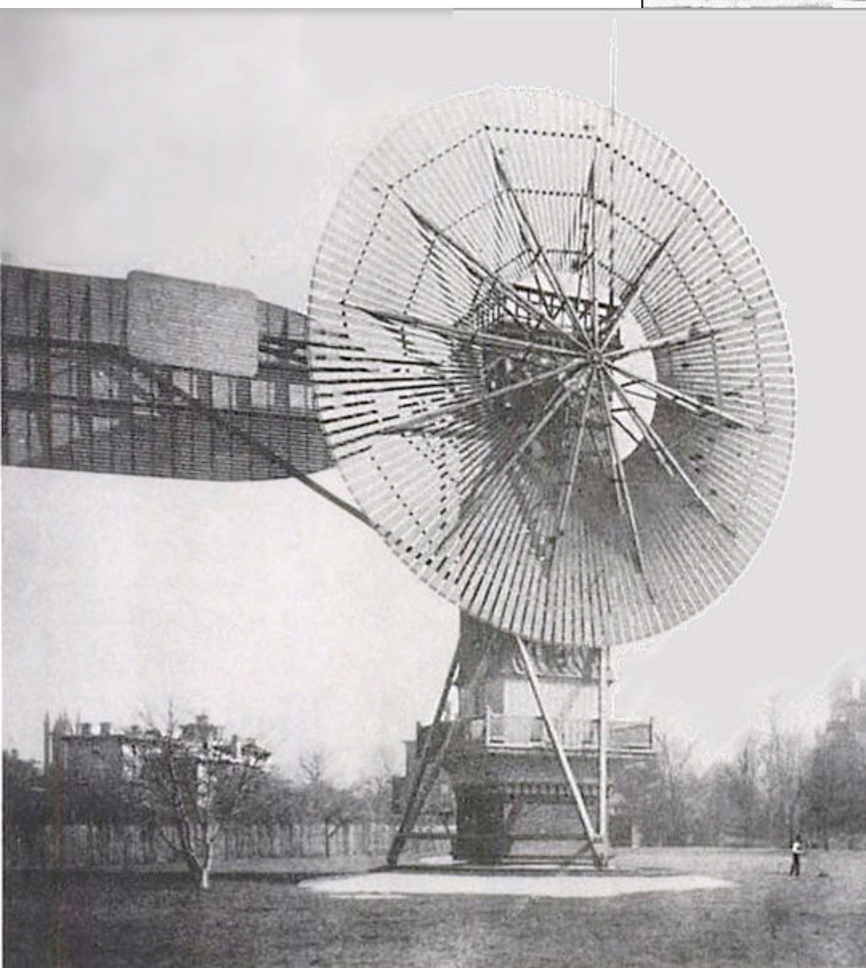
Icon of the American west is a fully automatic pump for lifting water for cattle, invented by Halladay in 1854. "Drag" type windmill, horizontal axis. *(Note timing -> OK land rush, 1889*

Images: IronMan Windmill Co.

All early wind turbines are "drag" turbines

James Blyth,
Scotland, 1887
vertical axis
"drag" type





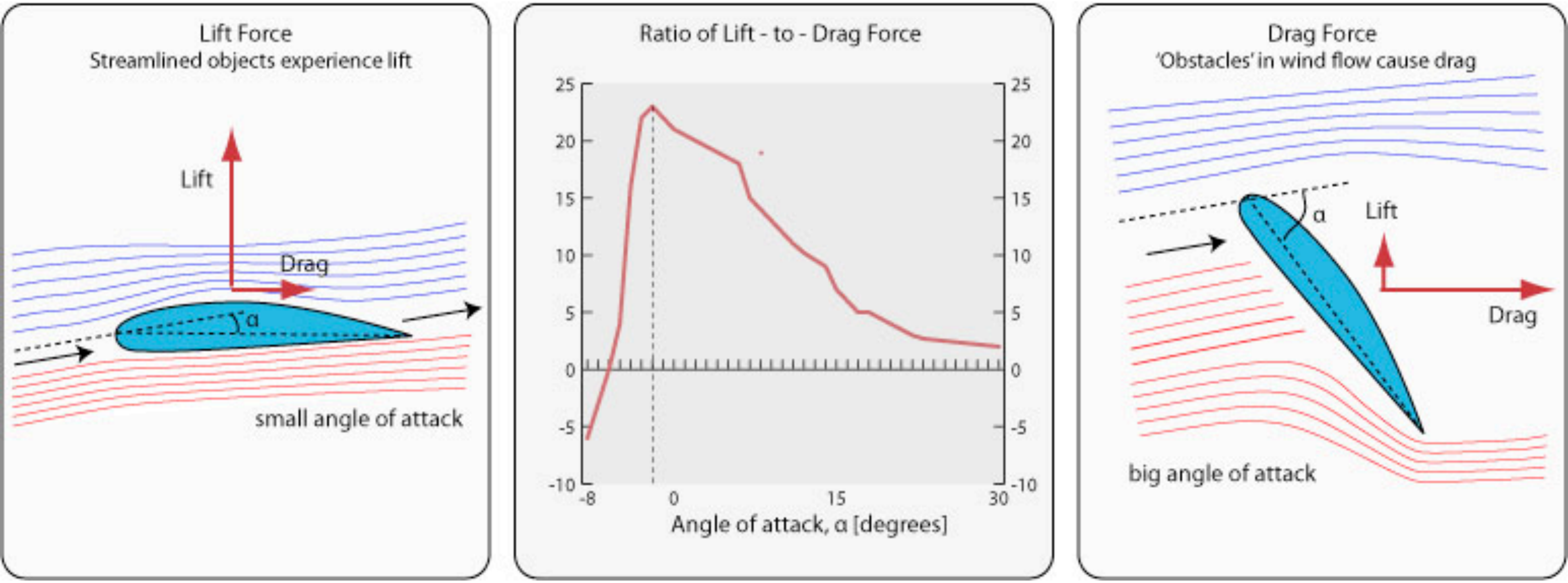
Charles Brush,
Cleveland, 1888
17 m diameter
12 kW, used for
electricity gen.

Blades "pushed" around by impact of air striking them

Images: Wikimedia

Modern wind turbines are "lift" turbines

Blades "pulled" around by low-pressure as air flows over airfoil shape



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

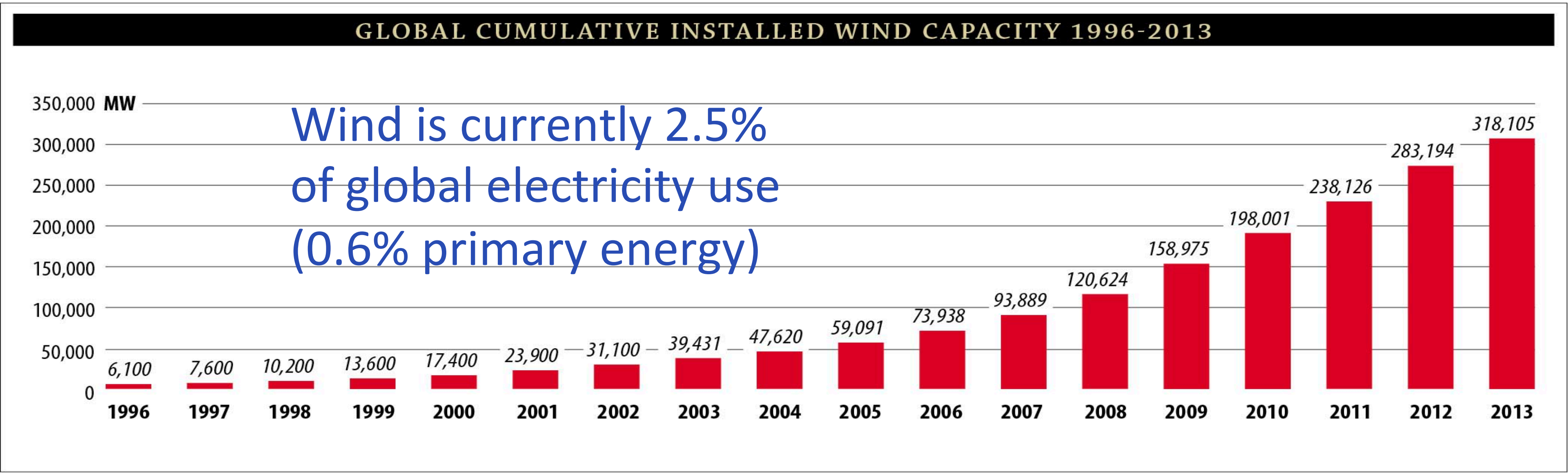
Image: Green Rhino Energy

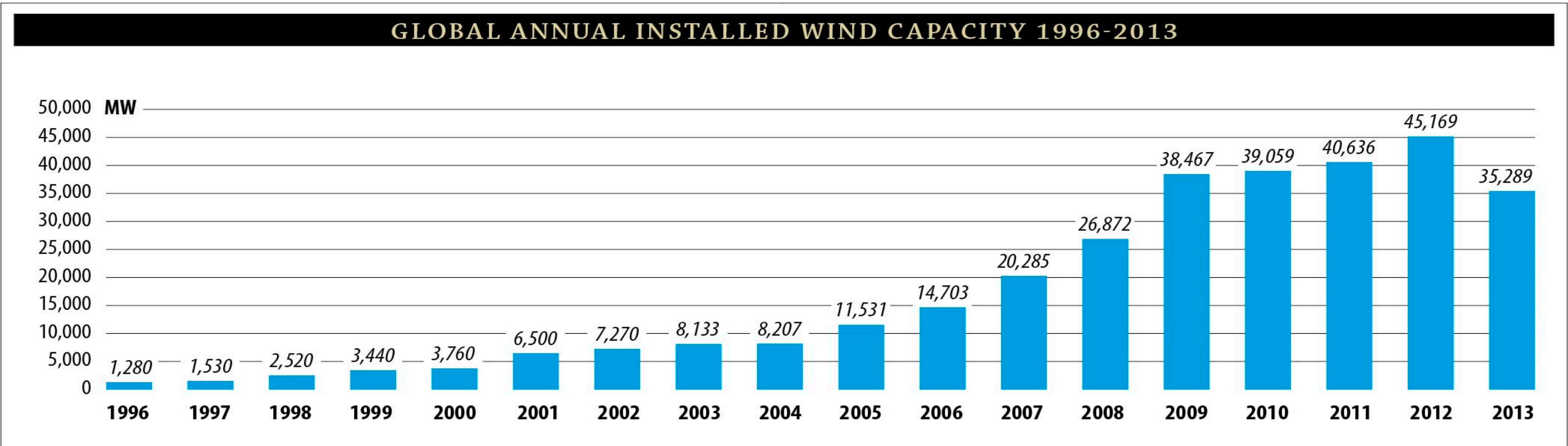
World windpower increasing rapidly

Wind increasing by > 15%/yr. (doubling in 4 years);

Energy use increasing at 2%/yr (doubling in 35 years)

Figs: Global Wind Energy Council

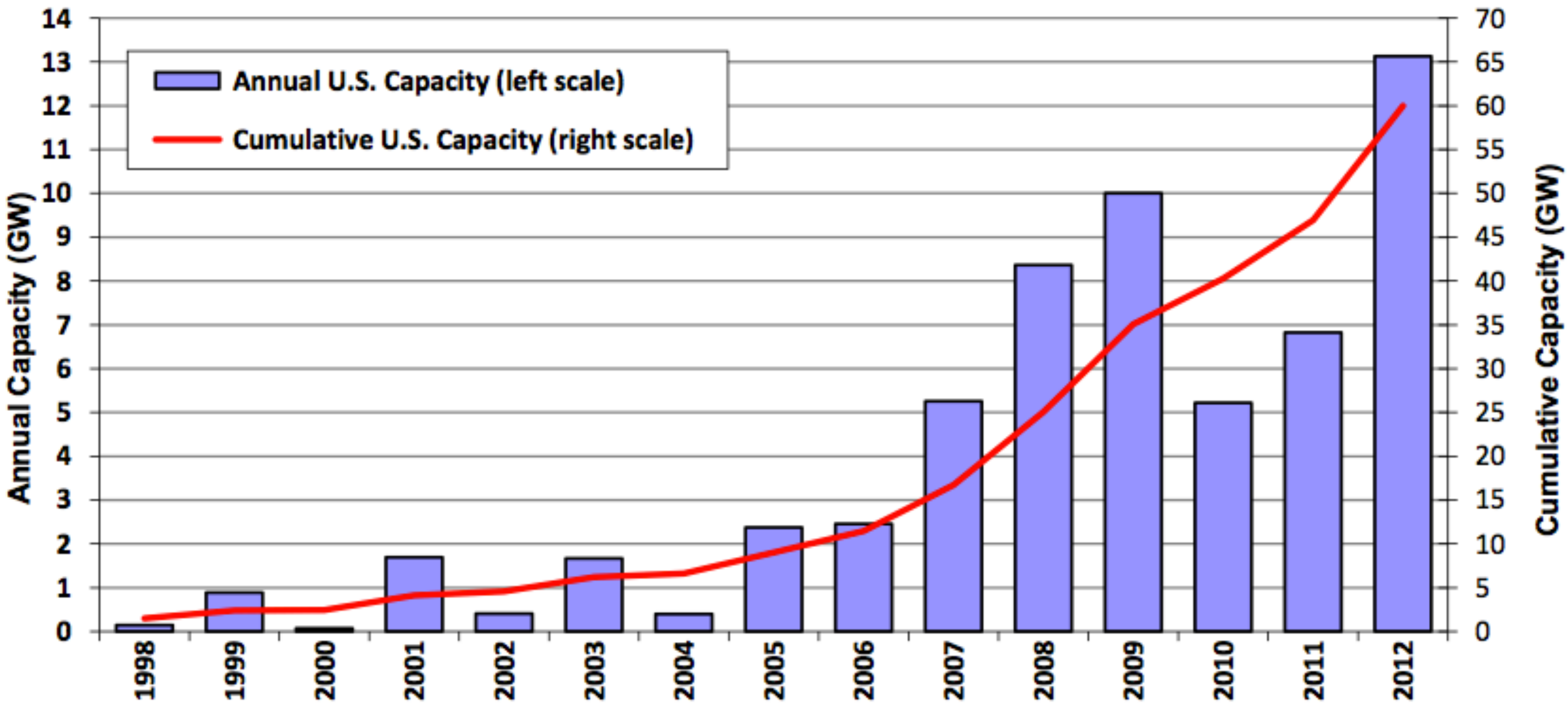




U.S. windpower increasing rapidly

Wind capacity grew by 28% in 2012

Now nearly 5% of electricity production



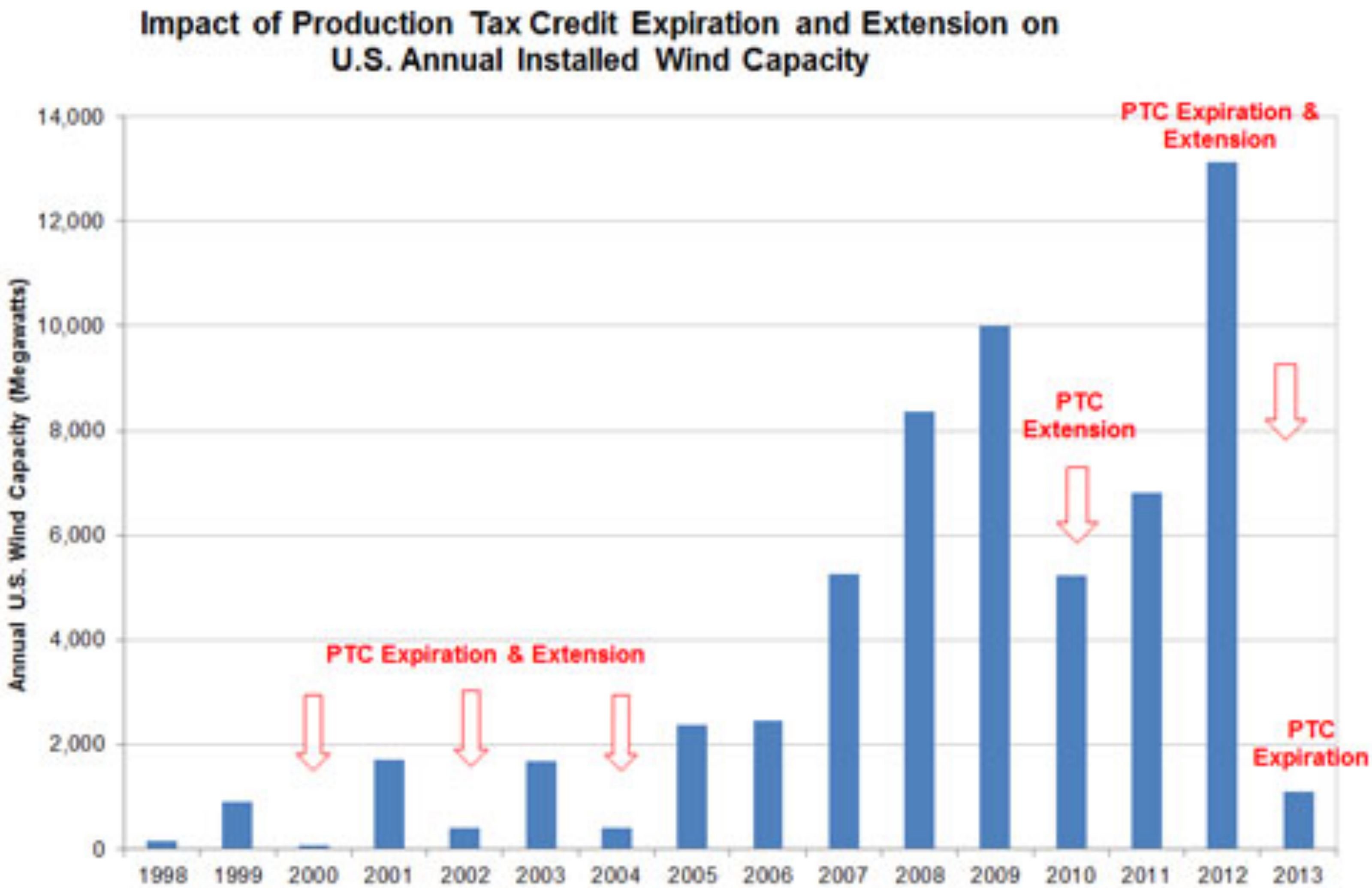
Source: AWEA project database

From: Wind Technologies Report 2012, Wiser and Bolinger

U.S. windpower increasing irregularly

Development driven by presence /absence of federal subsidies:

Production tax credit = 2.3 c/kWh for 10 years or 30% upfront cost



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

Wind turbine size also increasing

What drives that change?

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:

Wind turbine size also increasing

What drives that change?

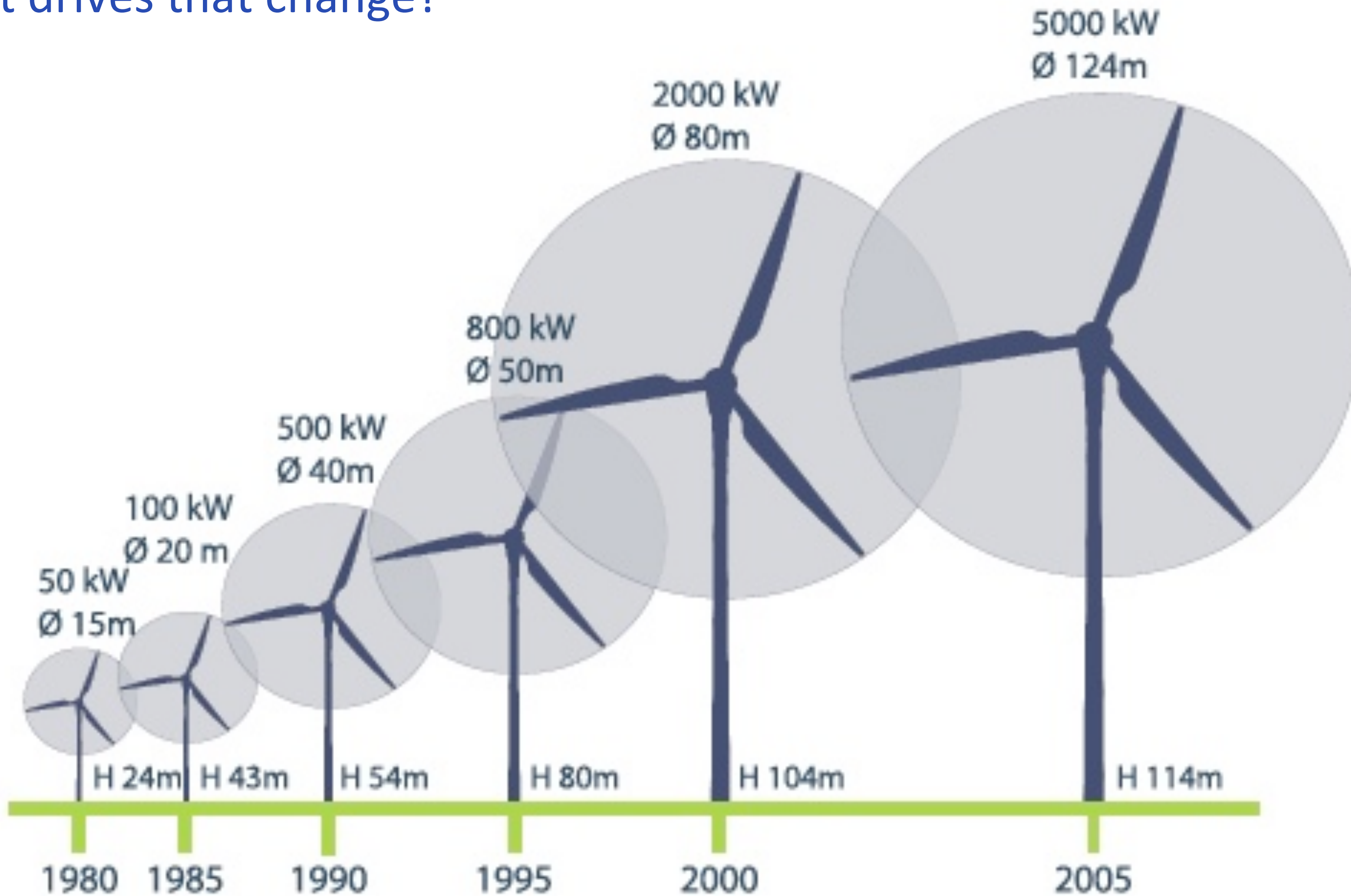


Image: EWEA via Terra Magnetica

Wind turbine size also increasing

What drives that change?

- Longer blades – more power per turbine built
- Higher wind speeds at altitude

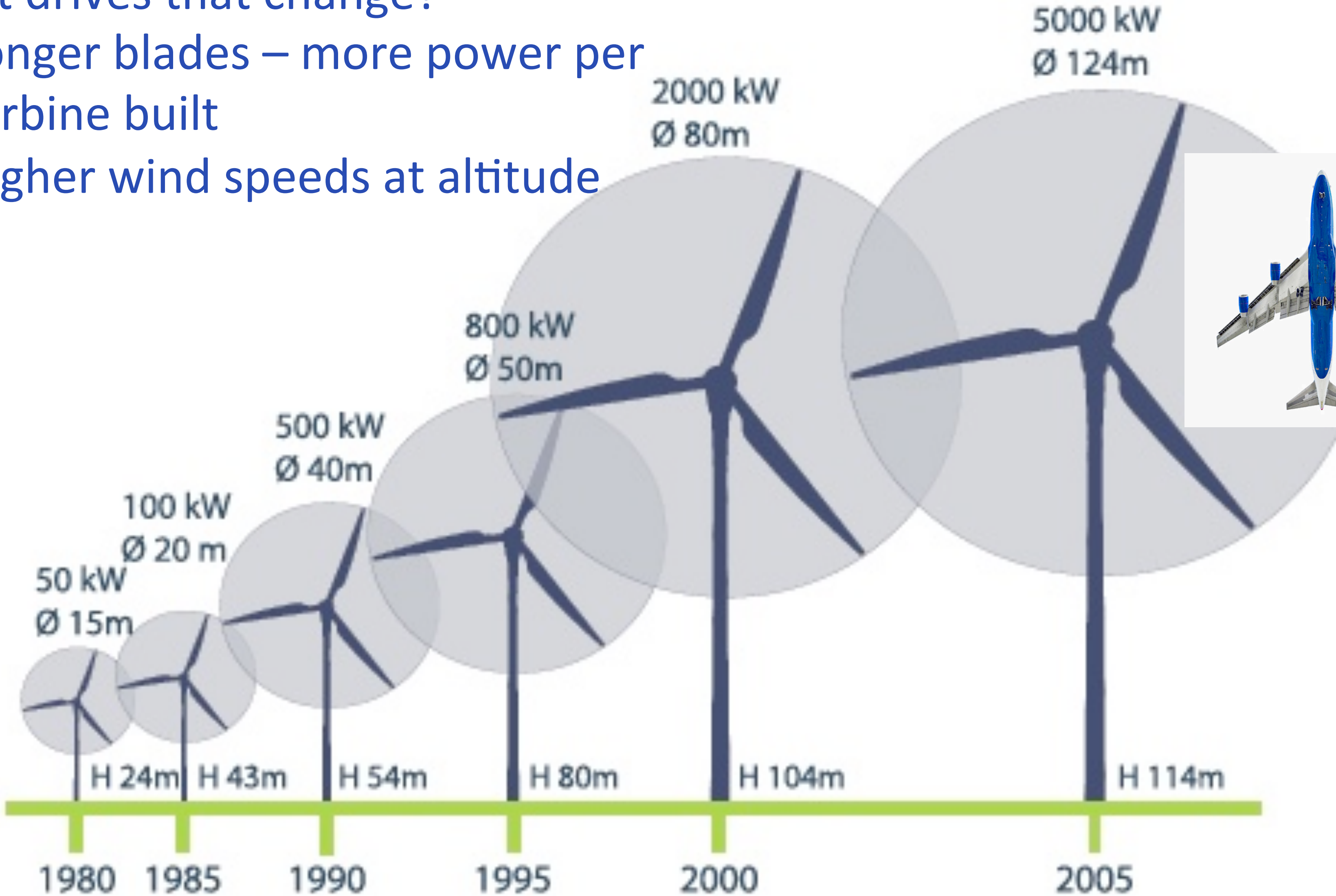


Image *(plane)*: Jeffrey Millstein

Image: EWEA via Terra Magnetica

Wind scale is huge

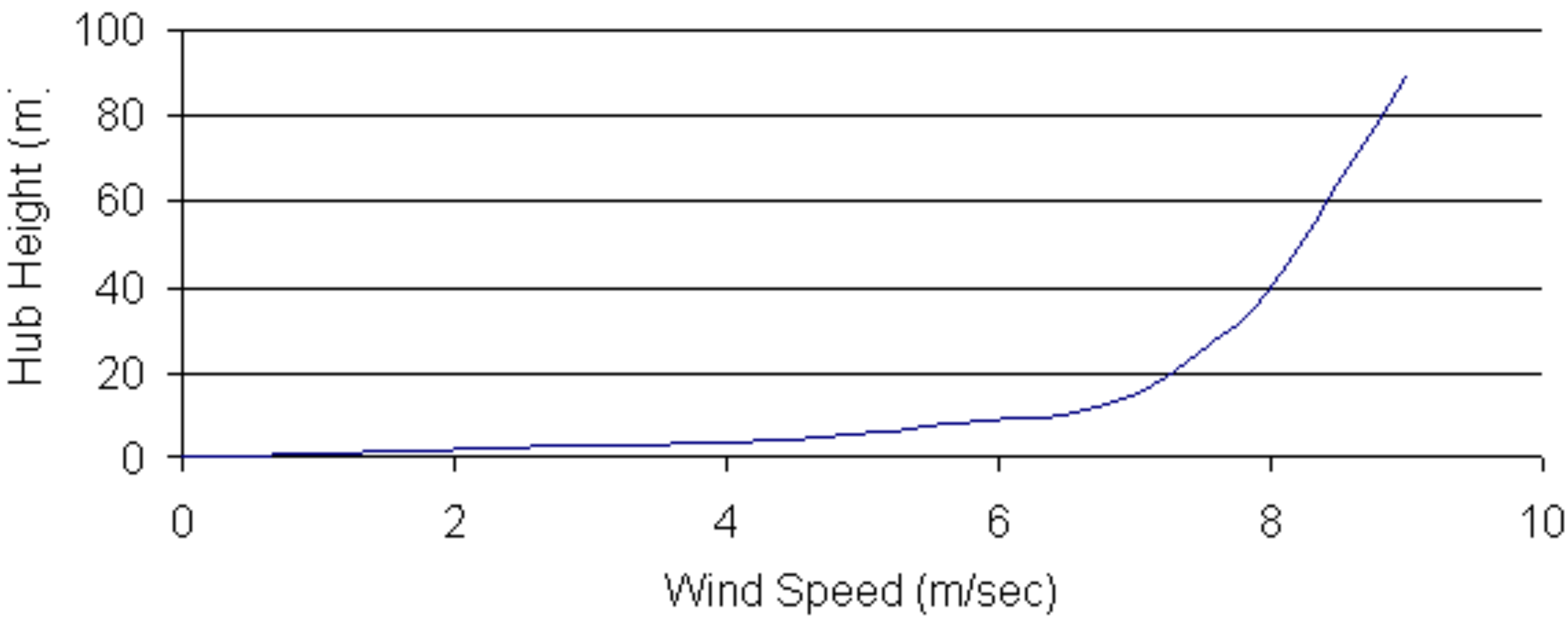
Most turbines now installed are > 1 MW.
Record is 8 MW (Vestas V164, Jan 2014).

R. Enercon E-126, 126 m. rotor diameter (413 feet), 6 MW rated (likely 7+ in practice).
L. Clipper Liberty, 2.5 MW

Images: source, copyright unknown

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

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

Max area A α square of hub height (higher hub allows longer arms).

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

Why only three blades?

Blades do not touch all air molecules that pass through turbine x-section

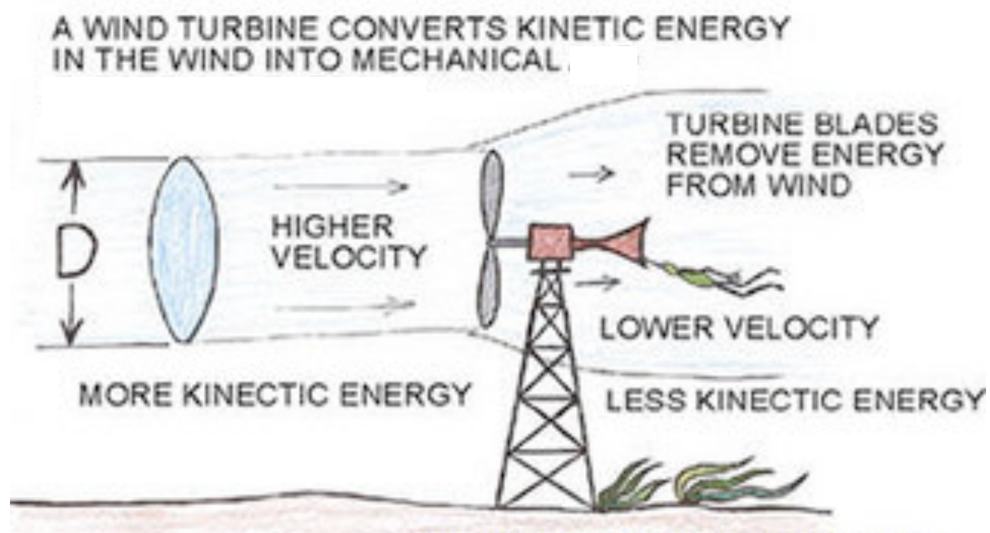
Answer:

blades can affect flow of all air that passes through x-section without touching every molecule

Can’t get all the energy out of a flow

To get all the kinetic energy you’d need to stop the flow

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

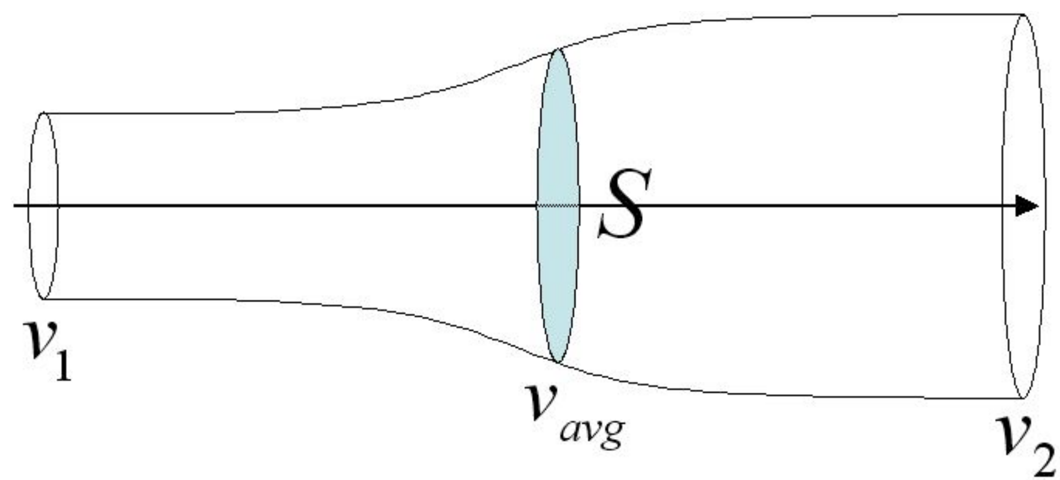


Rotor velocity is average of upstream and downstream

$$v_{rotor} = ½ (v_1 + v_2)$$

Max power extracted when slow flow down by 66%:

$$v_2/v_1 = 1/3$$
$$v_{rotor} = 2/3\ v_1$$



Max energy extracted is then $(2/3)^3$ or 59% of total

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

But max efficiency only occurs for ideal blade speed

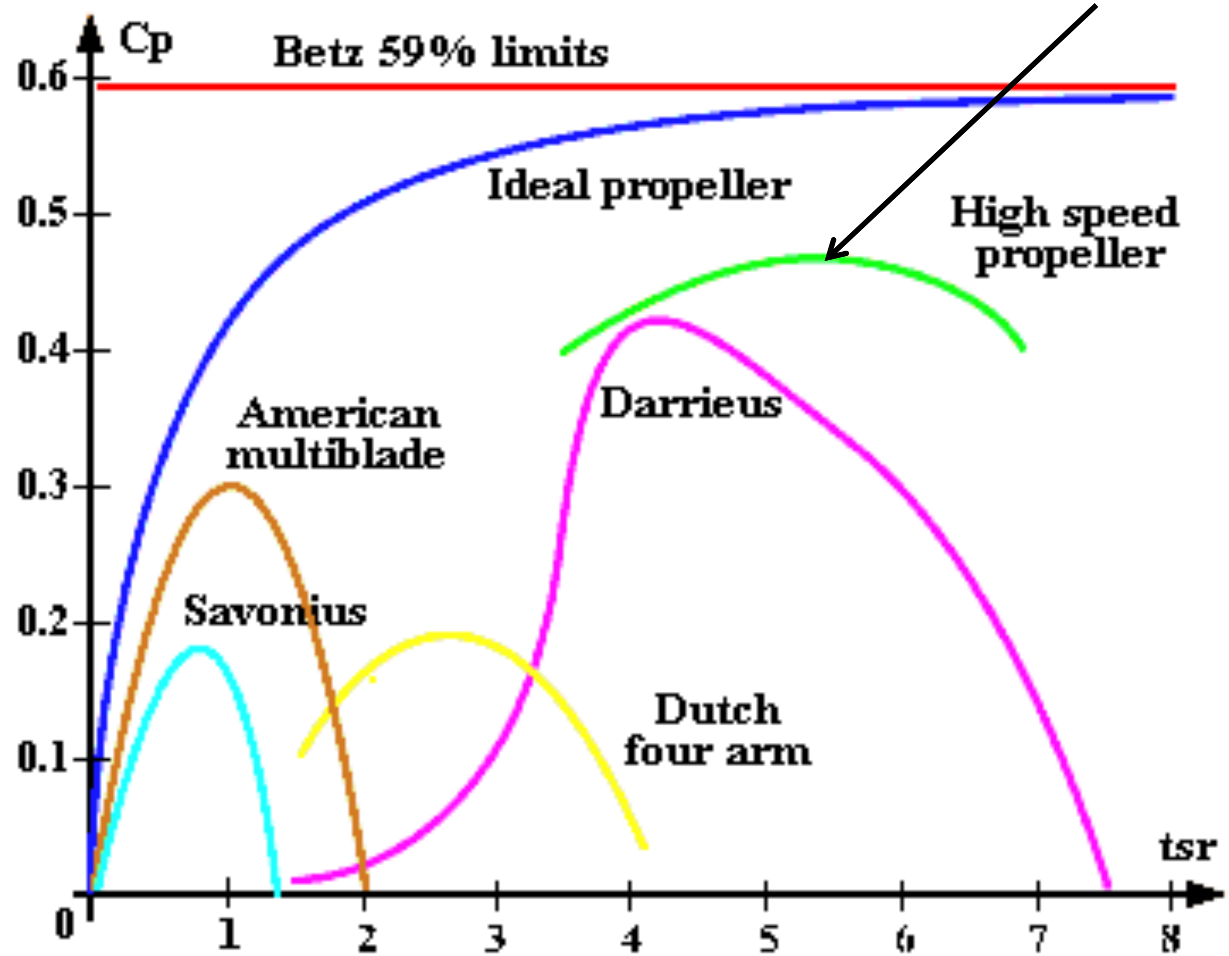
(tsr = "tip speed ratio", v_{blade}/v_{wind})

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



TSR guidelines set how fast blades rotate

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

$tsr = v_{blade}/v_{wind}$

$v_{blade} = \omega R = 2 \pi f R$

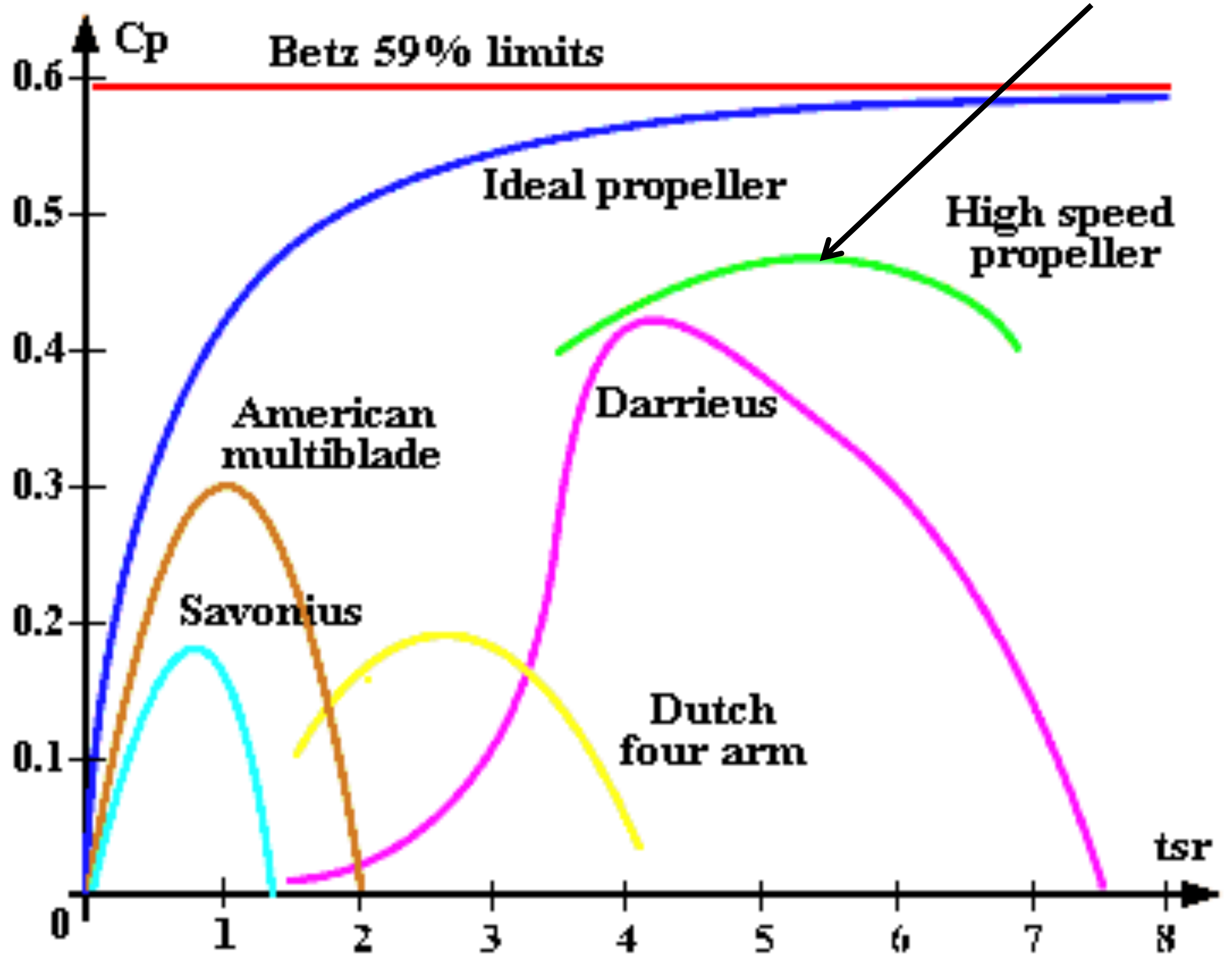
or $f = tsr \cdot v_{wind}/(2\pi R)$

the longer the blade,
the slower the turbine!

For 40 m blades, 10 m/s wind (high), tsr of 6:
$f \sim 60/240\ s^{-1}$
~ (1/4) revs. per sec.

i.e. ~ 4 s per revolution
or ¼ Hz

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



How to meet AC grid requirements with wind?

- *Synchronous generator matched to 60 Hz grid , no gearbox?*
  No – would require too many poles on generator
  Can't go from ¼ Hz rotation to 60 Hz electrical oscillation

- Constant low velocity matched to grid via gearbox
  …how it mostly used to be done

- "Wild" AC converted to DC then back to AC via inverter *("variable-speed" wind).*
  New common strategy. Important side benefit: no need to maintain constant turbine speed.

Can't extract wind power at all wind speeds

- ***Too low:*** *you're a motor, not a generator*
- ***Too fast:*** *mechanical failure*

- In low-wind regime

  adjust blade pitch for optimal torque (optimal power generation)

- In high-wind regime

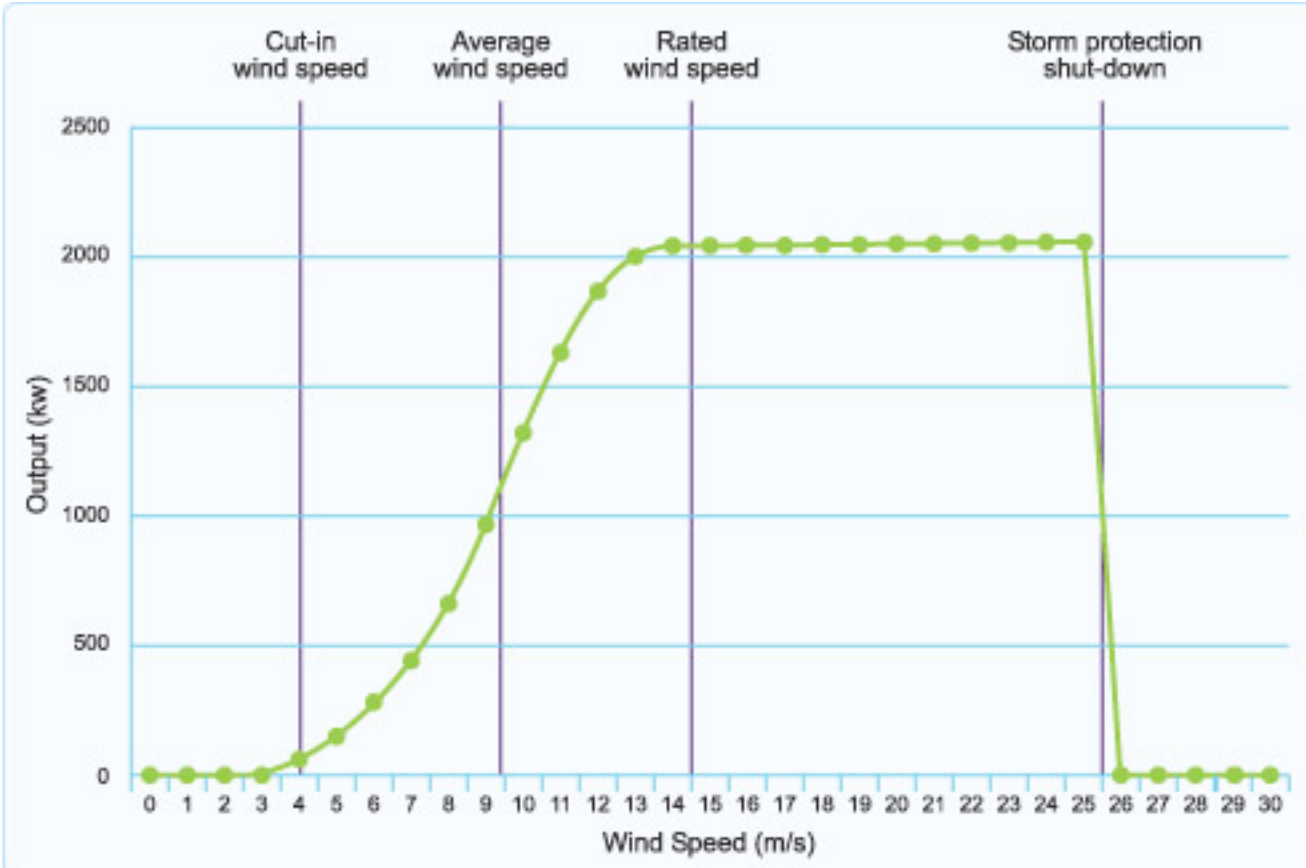
  protect turbine from too much torque with sub-optimal blade pitch

- In very high-wind (or very low-wind) regime

  feather blades, disconnect from the grid, and apply brake.

Brake failure consequences

Can’t extract wind power at all wind speeds

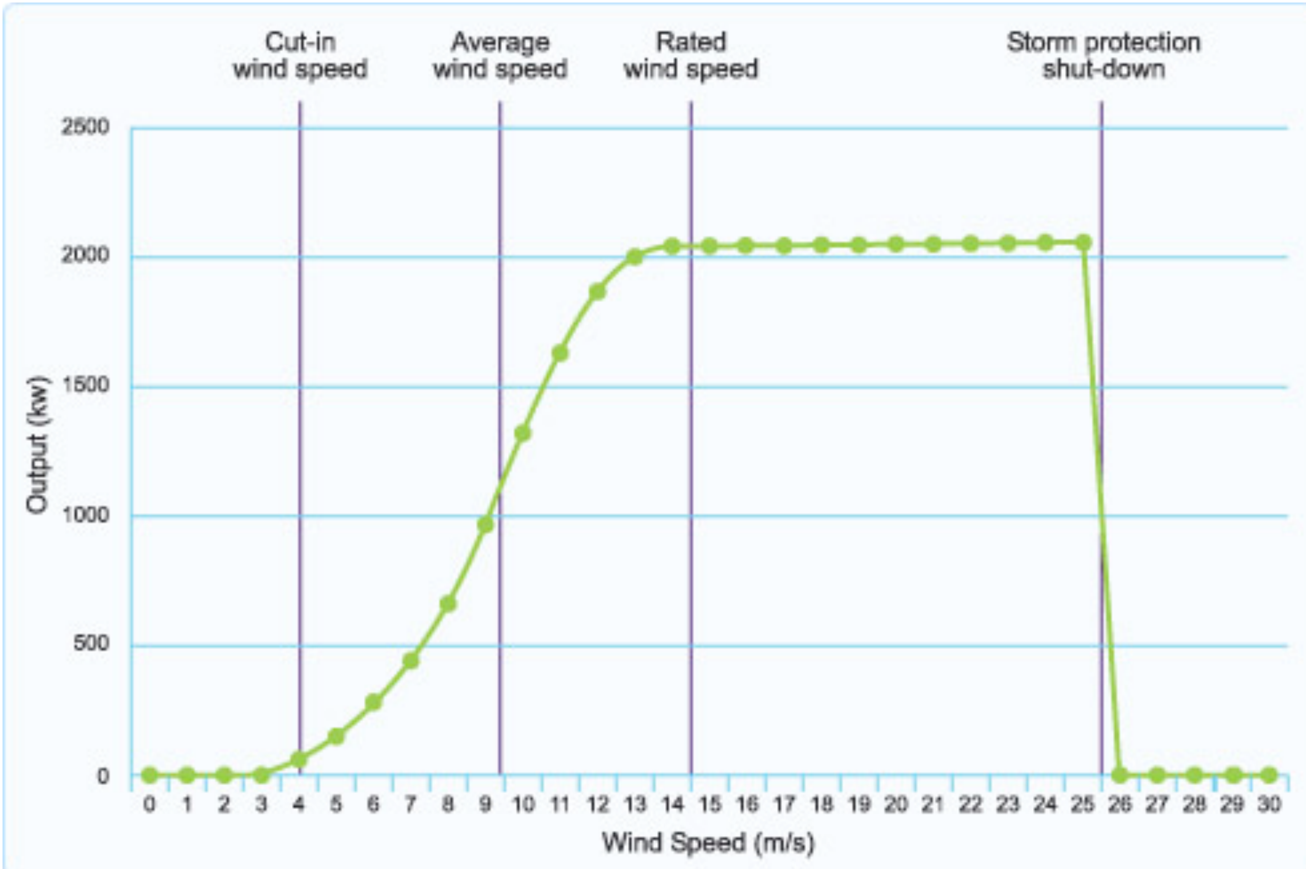


- Note that “rated” wind is > typical wind - produces *maximum* power
- Note also average wind doesn’t give average power (power depends on v^3, so turbines are designed for higher-than-average winds).

(Image from Partnerships for Renewables)

…actual power is less than rated power

(and rated power is itself less than power in 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)

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

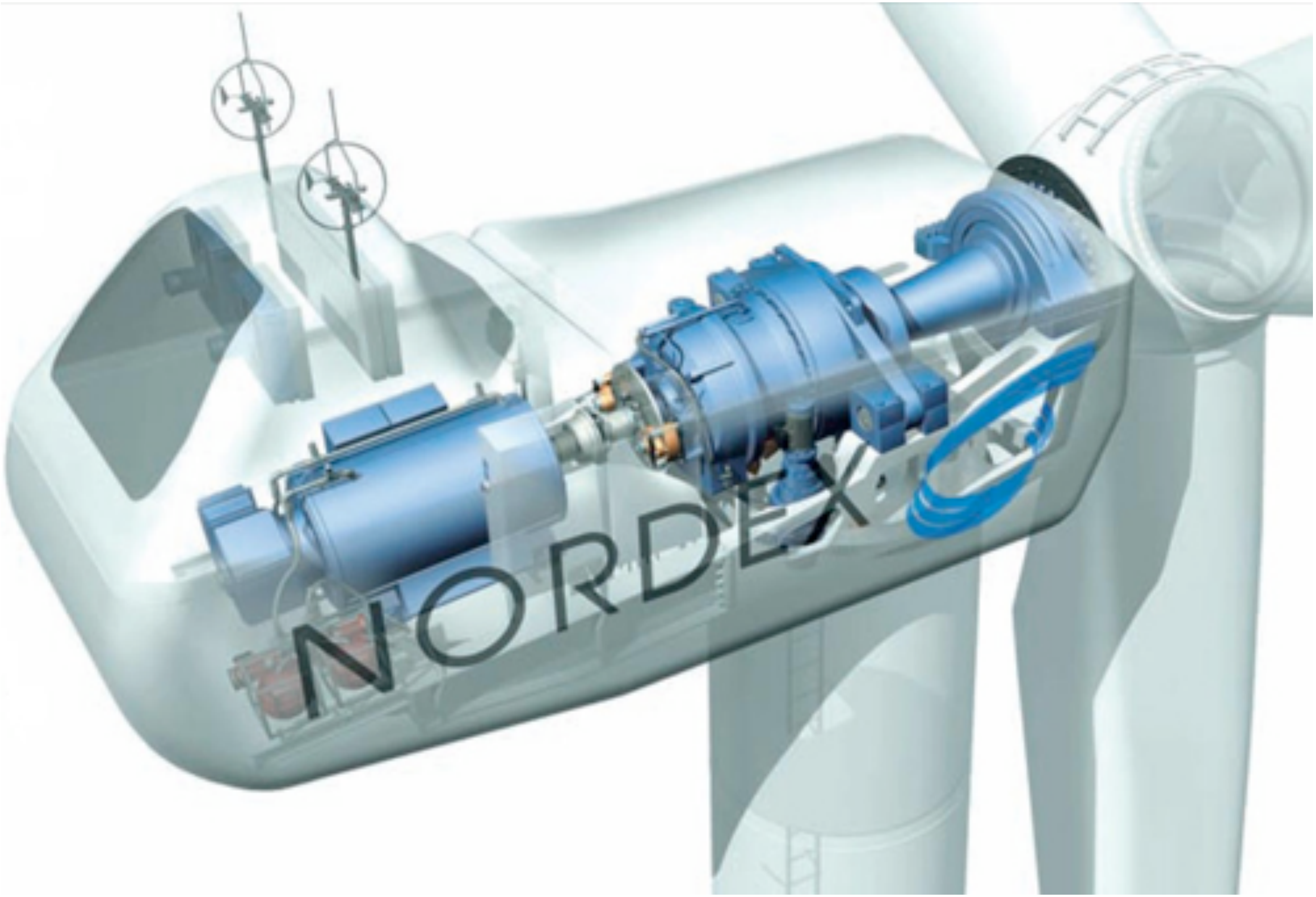


Diagram source: Nordex

Generator mounted in nacelle:

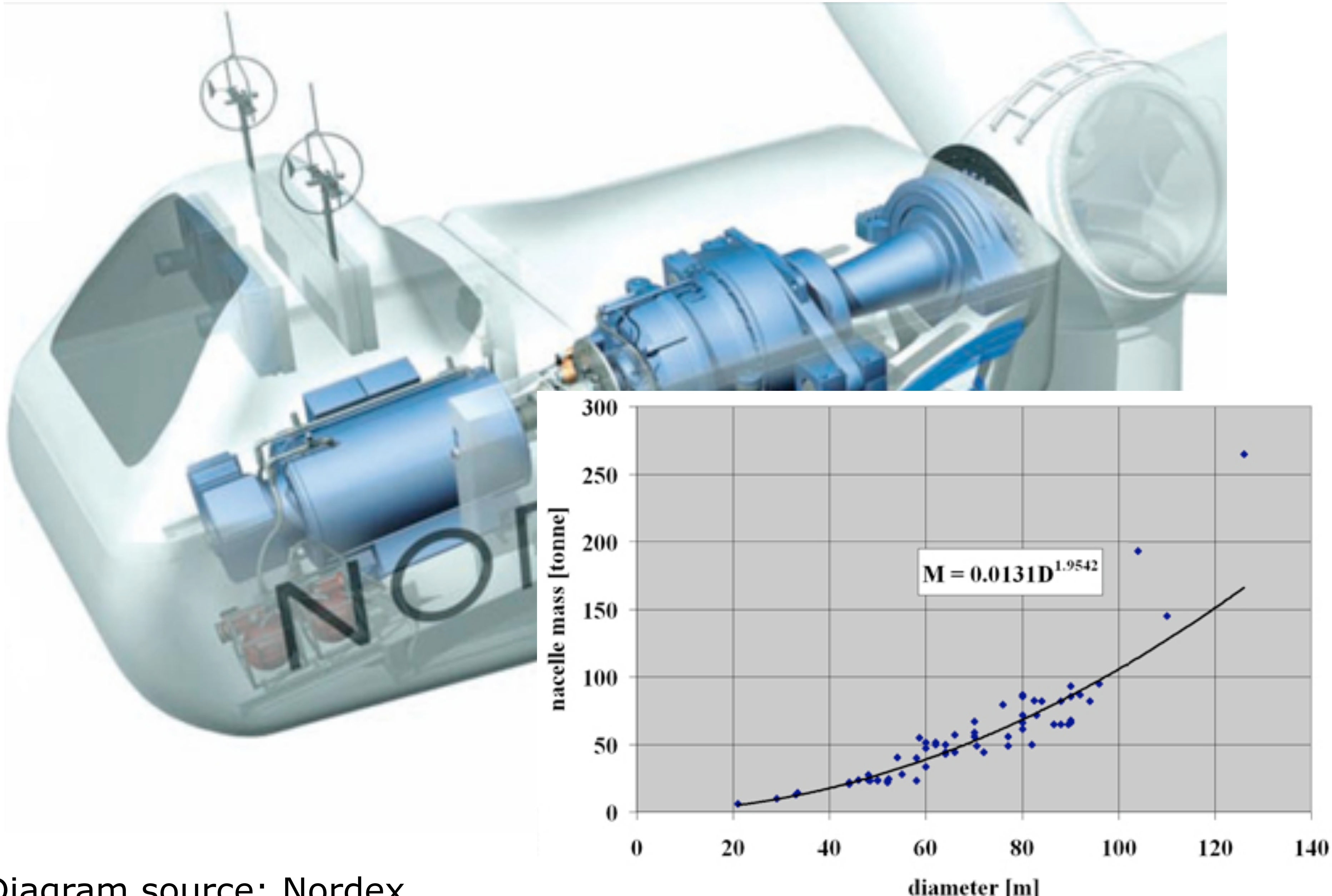


Diagram source: Nordex

Generator mounted in nacelle: *(with gearbox)*

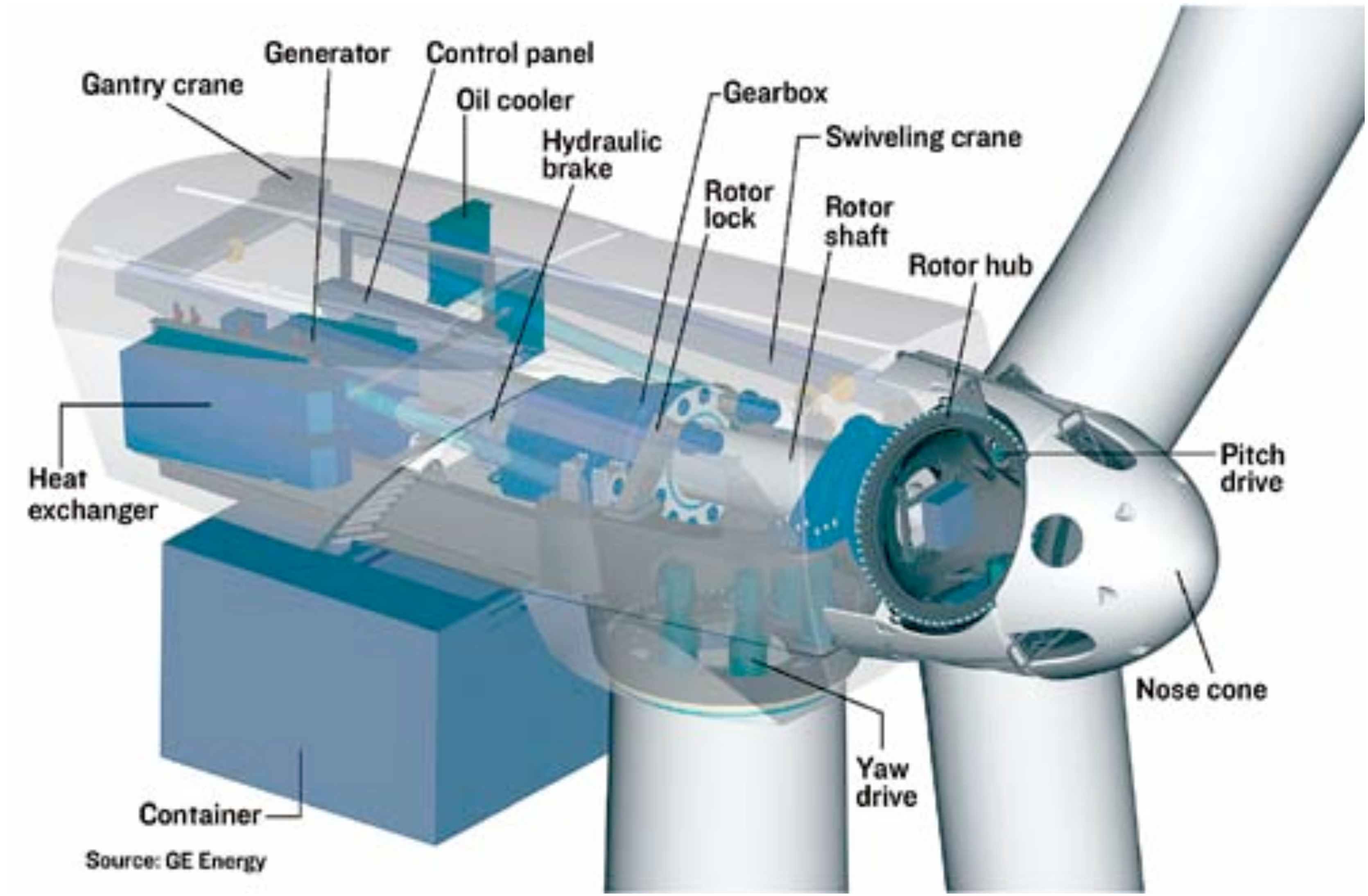


Diagram source: Nordex

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

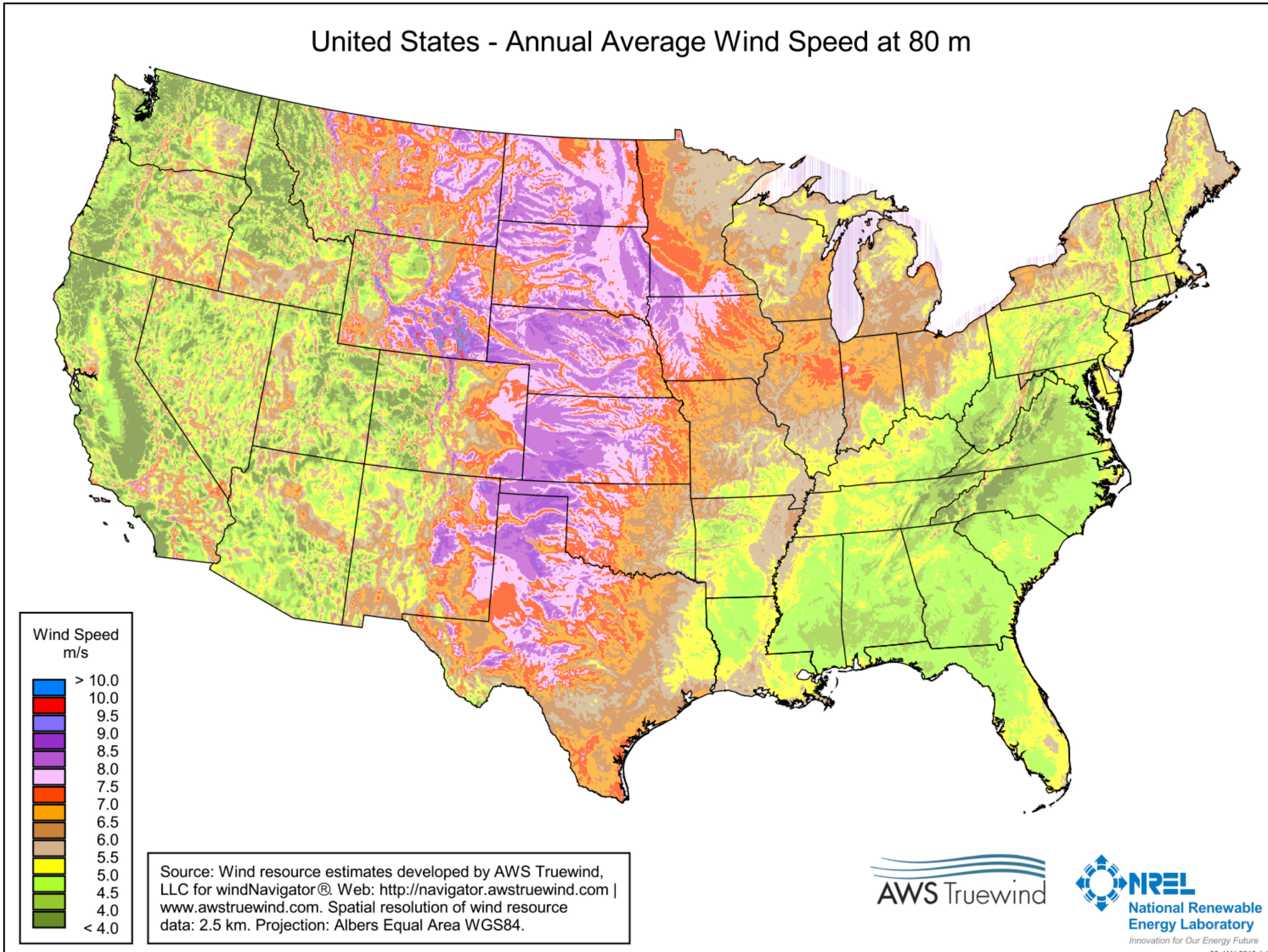
          Drawbacks – heavy, + exacerbates shortage of rare earth elements.

    - No gearbox

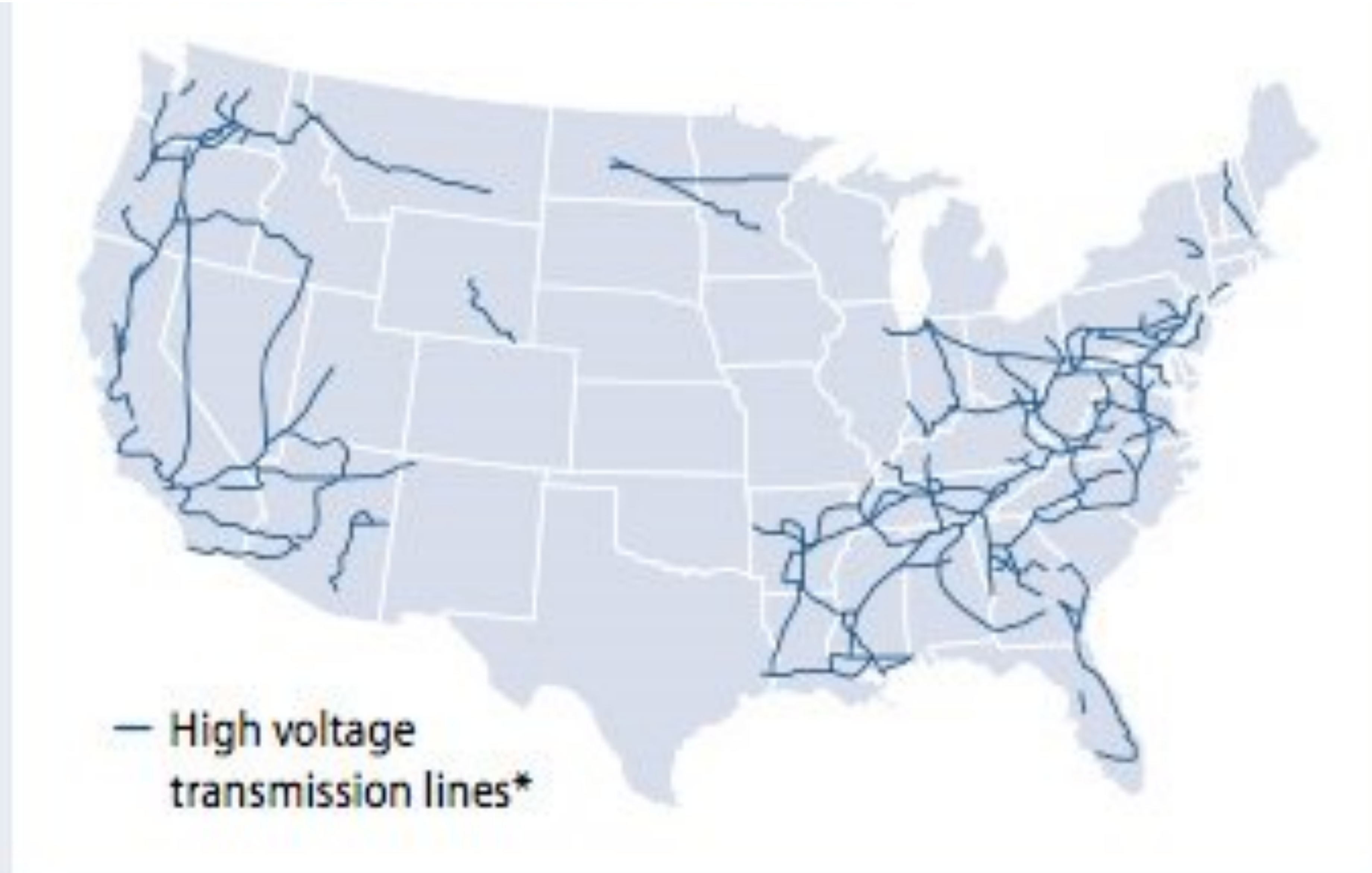
        - New trend toward **direct-drive generators.**

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

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



Electrical transmission is not where wind is



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

Source: Platts PowerMap