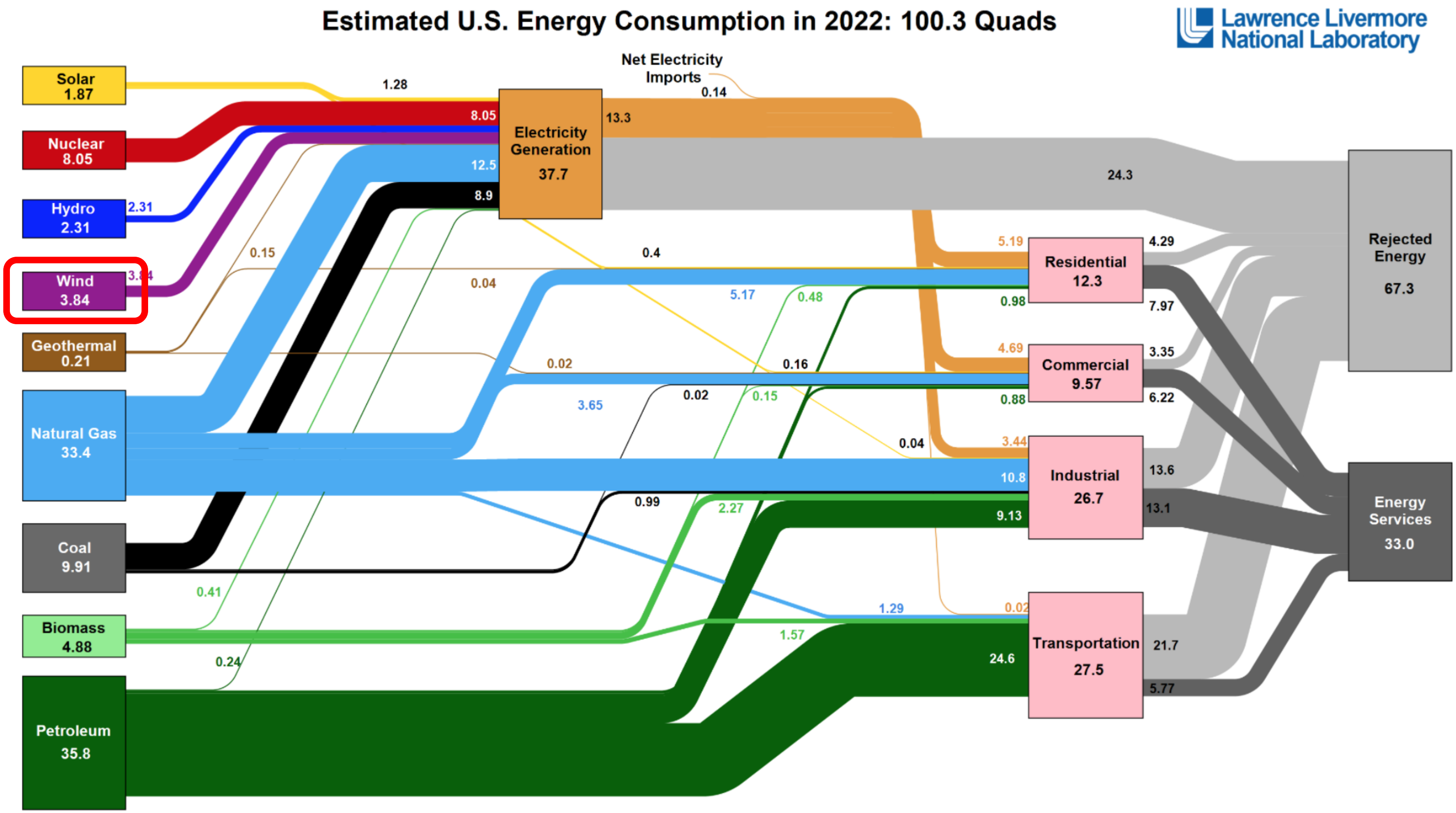
# ECE 530: Contemporary Energy Applications

## Wind

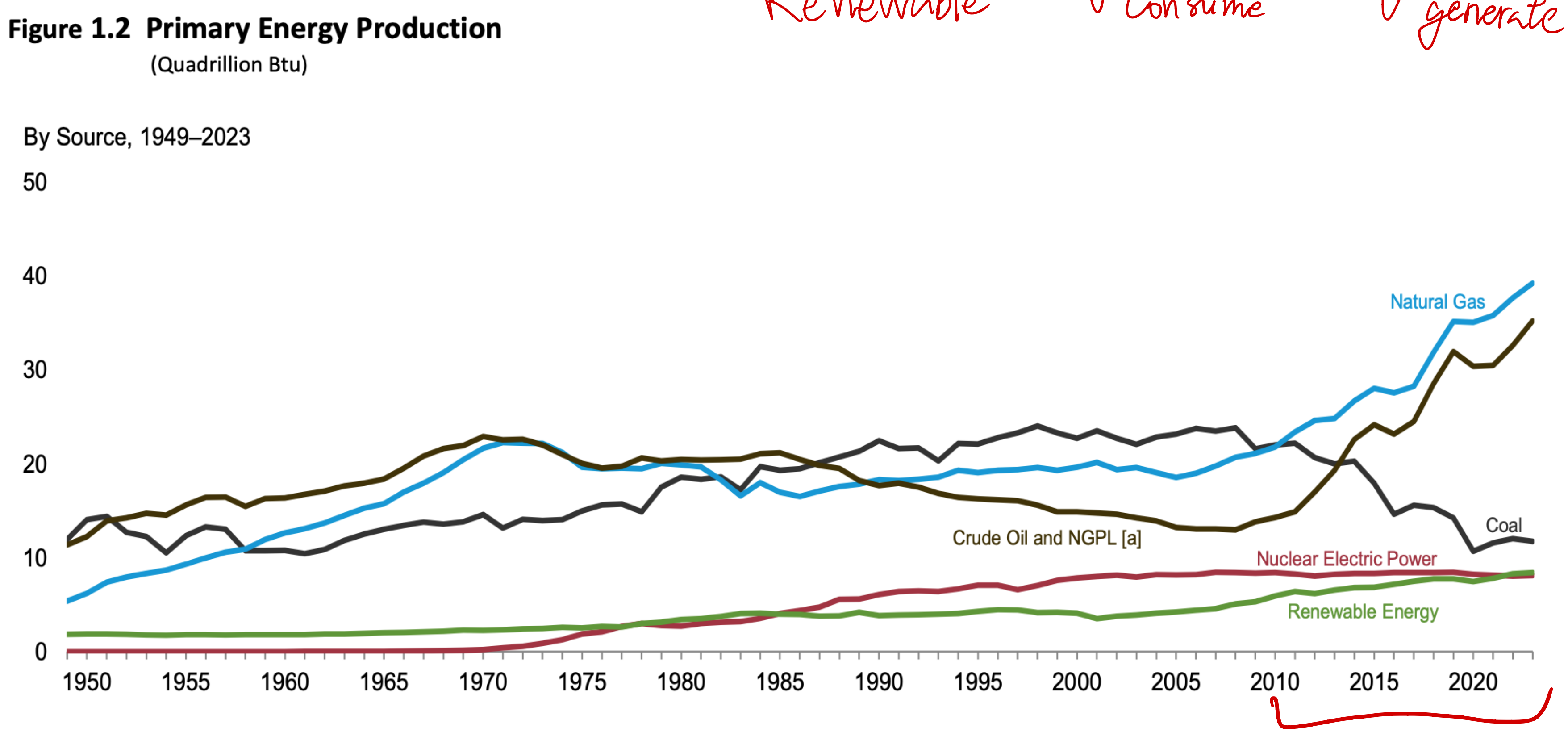
# US Energy Flow




Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

# US Trends

Renewable: $V_{consume} = V_{generate}$



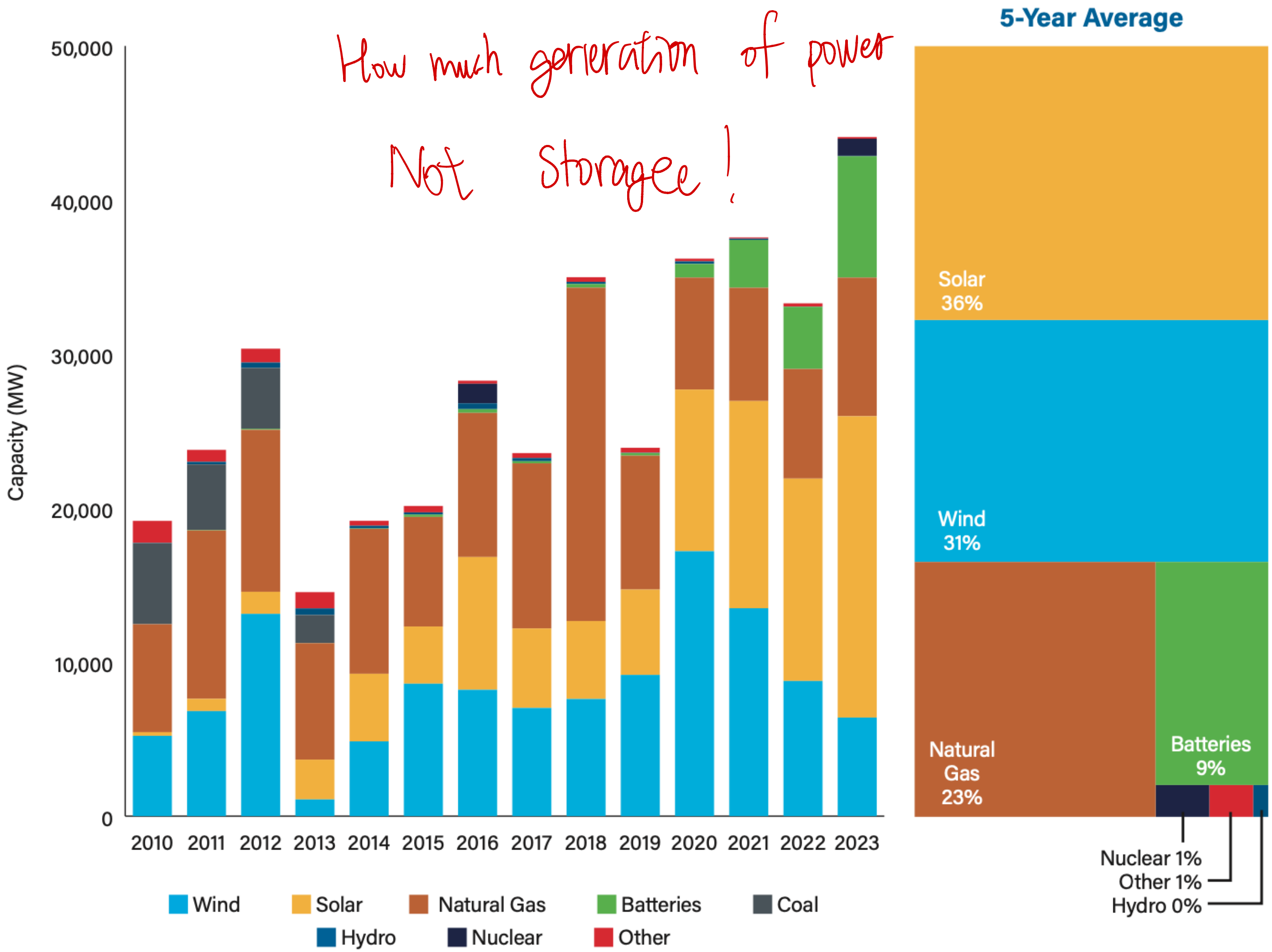

[Aug 2024, Monthly Energy Review, Energy Information Administration]

# Electrical Capacity Growth

## Utility-Scale Power Capacity Additions

How much generation of power

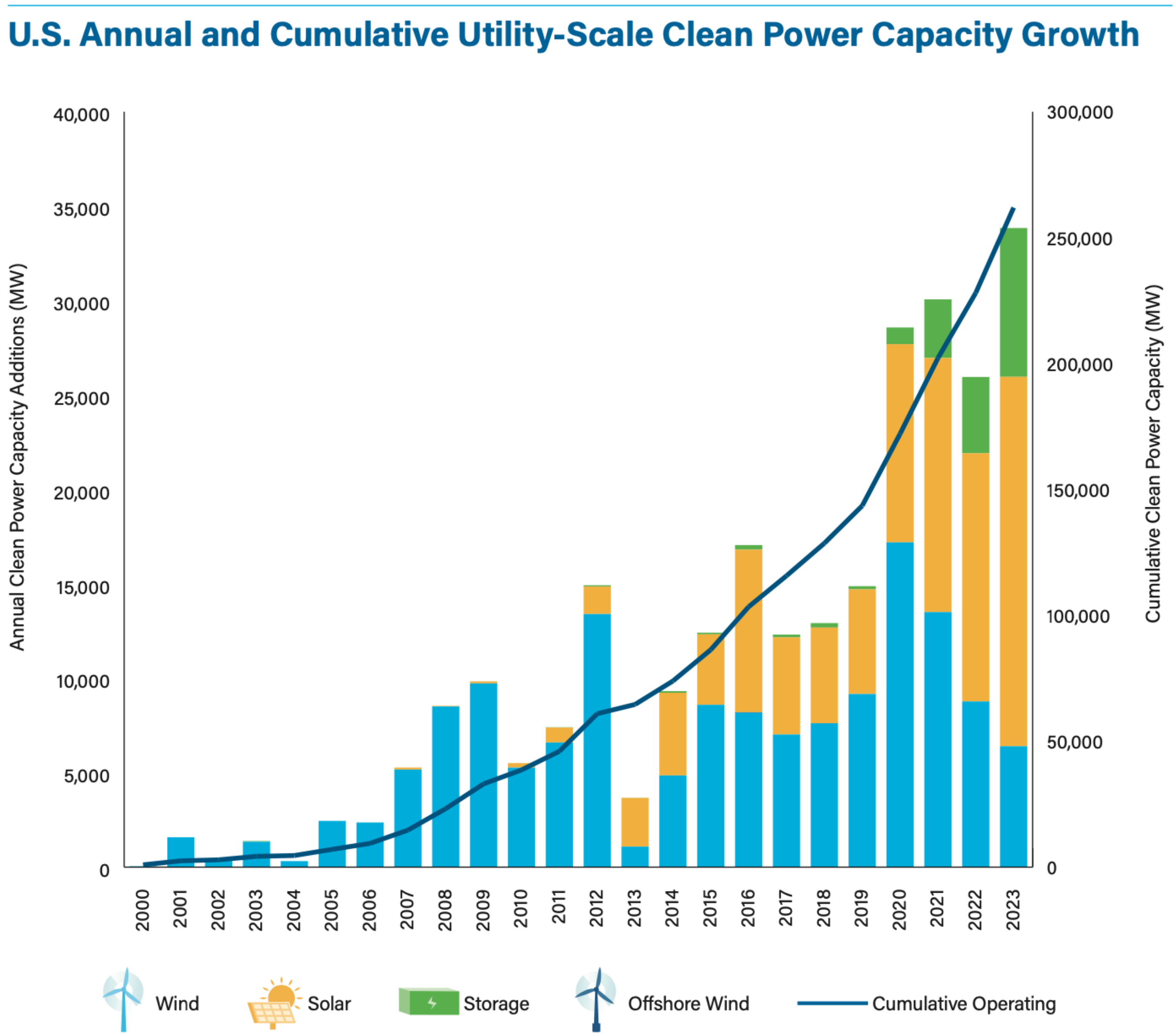
Not storagee !




Source: ACP, EIA

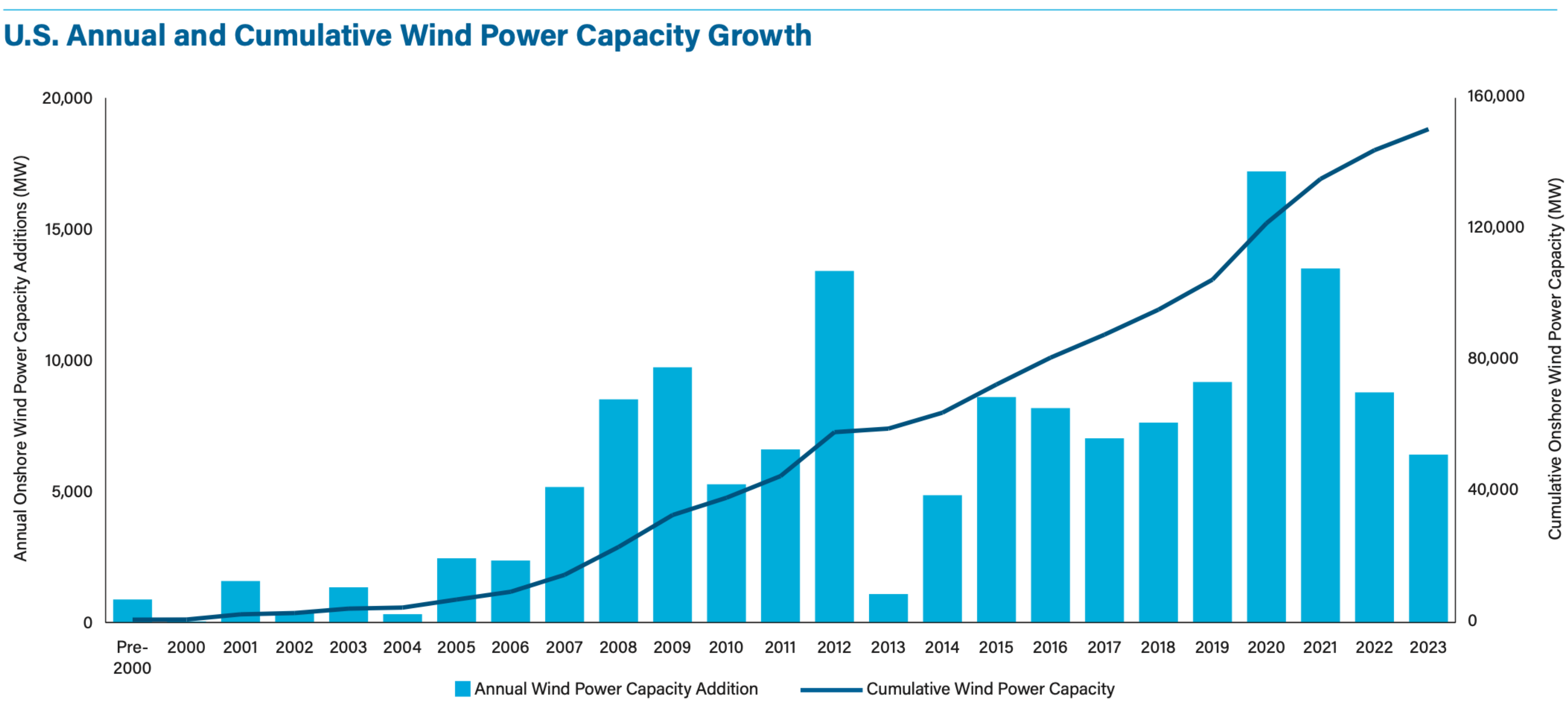
[American Clean Power, "Annual Market Report 2023"]

# Renewable Growth




[American Clean Power, "Annual Market Report 2023"]

# Wind Growth




[American Clean Power, “Annual Market Report 2023”]

# Wind Turbine Designs

push power

Lift power

[Pixabay]

Savonius (vertical axis)

inefficient


[CC BY-SA 3.0]

Darrieus (vertical axis)

[Pixabay]

Horizontal Axis

# Wind Turbine Technology

- Airflow produces lift on the blades, which is translated to torque on a generator in the nacelle
- Typically 80 meters high
- Swept diameter of 80 m
- Each turbine: 2 MW to 5 MW Dozens or hundreds in a single wind farm.
- Reach maximum power at wind speeds of around 15 m/s
- Rotational speed of around 10-20 revolutions per minute
- Variable speed and blade pitch → control by computers
- Energy Return on Investment (EROI) of around 20 20 is excellent !!
- Avian mortality rate is very, very low compared to buildings, traffic, and cats
- Peak coefficient of power of around 50%
- Capacity factor of around 30% to 40%

If a turbine generate 1 MW

→ Actually 0.3 ~ 0.4 MW

Cp is kind of efficiency

[Pixabay]

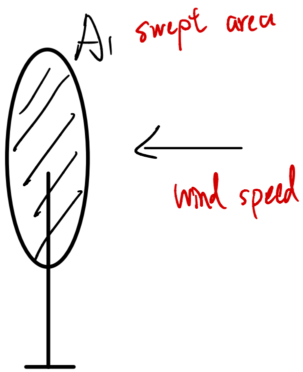
# Kinetic Energy of Wind

$J/s = W$

- Power is proportional to the square of the blade length and the cube of wind speed
- The coefficient of power, $C_p$, is the percent of wind energy devices can capture

焦耳

Kinetic Energy $\rightarrow \frac{1}{2} m v^2 \quad \left[ J = Kg \cdot (m/s)^2 \right]$




Airmass speed

$\rightarrow \rho \cdot A_1 \cdot U_0$

$[Kg/m^3]\,[m^2]\,[m/s] = [Kg/s]$

$$P_{wind} = \frac{1}{2} (\rho \cdot A_1 \cdot U_0) \cdot U_0^2 = \frac{1}{2} \rho \cdot A_1 \cdot U_0^3 \quad [J/s = W]$$

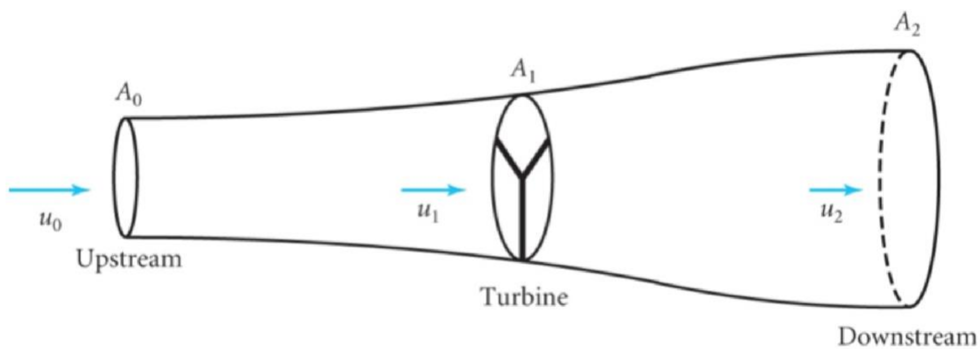
$$P_{Turbine} = C_p \times P_{wind}$$

Coefficient of Power.

≤60%

# Betz Limit

- The Betz limit shows that only a maximum of 16/27 (59%) of the energy in in the wind is harvestable by the turbine, assuming unrestricted airflow. In otherwords, $C_{pmax} = 0.59$.




$$m_0 \qquad m_1 \qquad m_2$$

$$\rho \cdot A_0 \cdot U_0 = \rho \cdot A_1 \cdot U_1 = \rho \cdot A_2 \cdot U_2$$

$$[\mathrm{kg}/s]$$

$P_{turbine}$ Method 1: How hard time how fast

$$F = m \cdot a = m \cdot \partial V / \partial t = \frac{m}{\partial t} \partial V = \rho \cdot A_1 \cdot U_1 \cdot (U_2 - U_0)$$

force

$$P_{turbine} = \rho \cdot U_1 \cdot A_1 (U_2 - U_0) \cdot U_1$$

$P_{turbine}$ Method 2: $P_{end} - P_{start}$

$$P_{turbine} = \frac{1}{2} m_0 \cdot U_0^2 - \frac{1}{2} m_2 \cdot U_2^2 \quad (\text{given } m_0 = m_1 = m_3)$$

$$= \frac{1}{2} \cdot m_1 \cdot (U_0^2 - U_2^2) = \frac{1}{2} \rho \cdot A_1 \cdot U_1 (U_0^2 - U_2^2)$$

# Betz Limit (pt 2)

$$P_{turbine} = \rho \cdot U_1 \cdot A_1 \, (U_2 - U_0)\, U_1$$

$$= \frac{1}{2}\rho \cdot \underline{\underline{U_1}} \cdot A_1 \, (U_0^2 - U_2^2)$$

$$\boxed{U_1 = \frac{1}{2}(U_2 + U_0)}$$

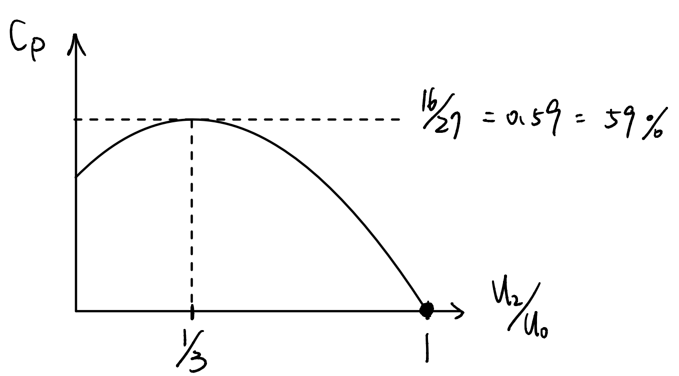
Average

$$P_{turbine} = \frac{1}{2}\rho \cdot \left[\frac{1}{2}(U_2 + U_0)\right] \cdot A_1 \cdot (U_0^2 - U_2^2)$$

No fraction loss

$$P_{wind} = \frac{1}{2}\rho \cdot A_1 \, U^3$$

$$C_p = \frac{P_{turbine}}{P_{wind}} = \frac{1}{2}\left[1 - \left(\frac{U_2}{U_0}\right)^2\right]\left[1 + \left(\frac{U_2}{U_0}\right)\right]$$

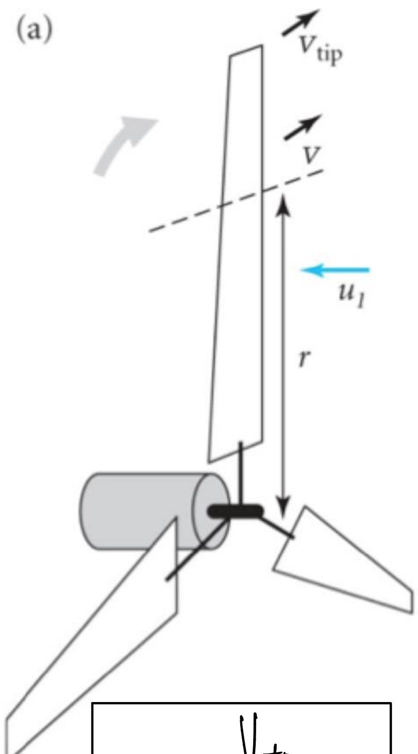


# Blade Design and Operation

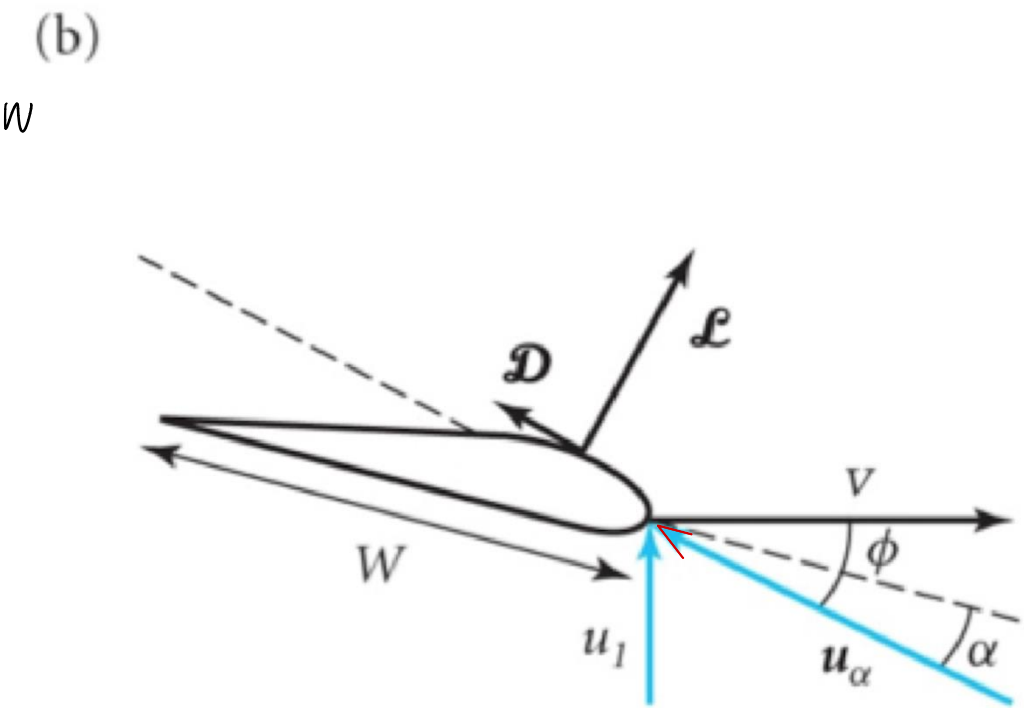
difference between blade point direction and vector sum

- The tip speed ratio is tip velocity over wind speed. Typically around 7.
- g is the ratio of drag to lift and it is a function of the blade design. Typically 1/50.
- Blades are twisted because the angle of attack is a function of the radius.
- There is an optimal angle of attack, which, for a given wind speed, is equivalent to an optimal blade pitch and rotational speed (i.e. tip speed ratio). In other words, tip speed ratio is a proxy for angle of attack.

change rotational speed (tip speed) to maintain optimal $\alpha$




$V_{tip} = r \cdot w$




$$\boxed{\lambda = \frac{V_{tip}}{U_0}}$$

* maintain $\lambda$ at $\lambda_{opt}$

tip speed ratio

$U_\alpha$: Vector Sum

$\alpha$: angle of attack

If $\lambda_{opt} = 10$ $\quad U_o = 10 \ m/s$ , $V_{tip} = 100 \ m/s$

$U_o = 20 \ m/s$ , $V_{tip} = 200 \ m/s$

Q.29

$$\lambda_{opt} = 7 = \frac{V_{tip}}{U_o} = \frac{r \cdot W}{U_o} = \frac{40 \times 1.05}{6} = 7$$

$$W = \frac{\lambda_{opt} \times U_o'}{r} = \frac{7 \times 9.1}{40} = 1.5925 \ rad/s$$

$$RPM = \frac{rad/s \times 60}{2\pi} = \frac{1.5925 \times 60}{2\pi} = 15.20722$$

$$\approx 15.21 \ \#$$

# Coefficient of Power

- There is an optimal angle of attack, which means that for a given wind speed and blade pitch there is an optimal tip speed ratio.

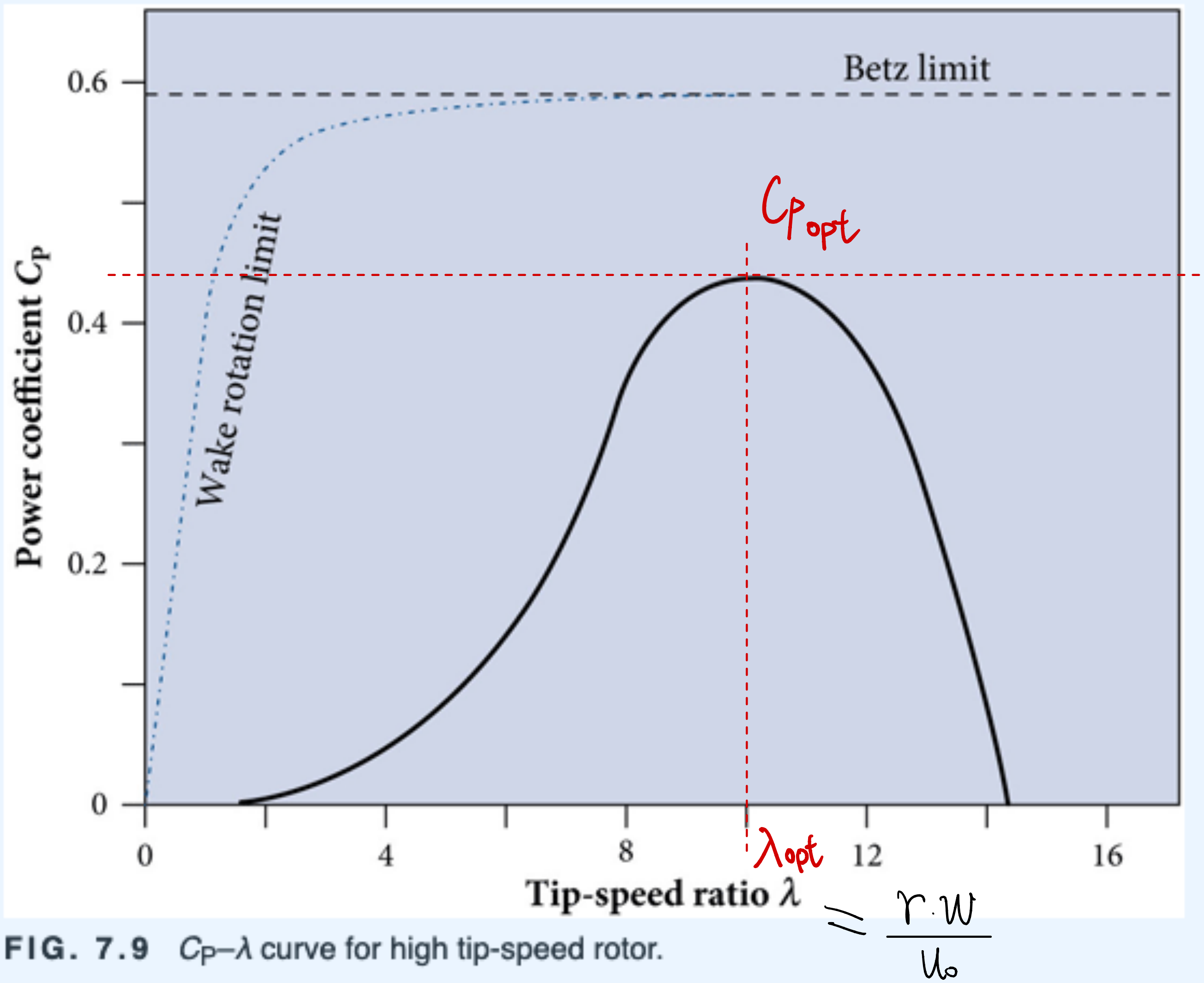
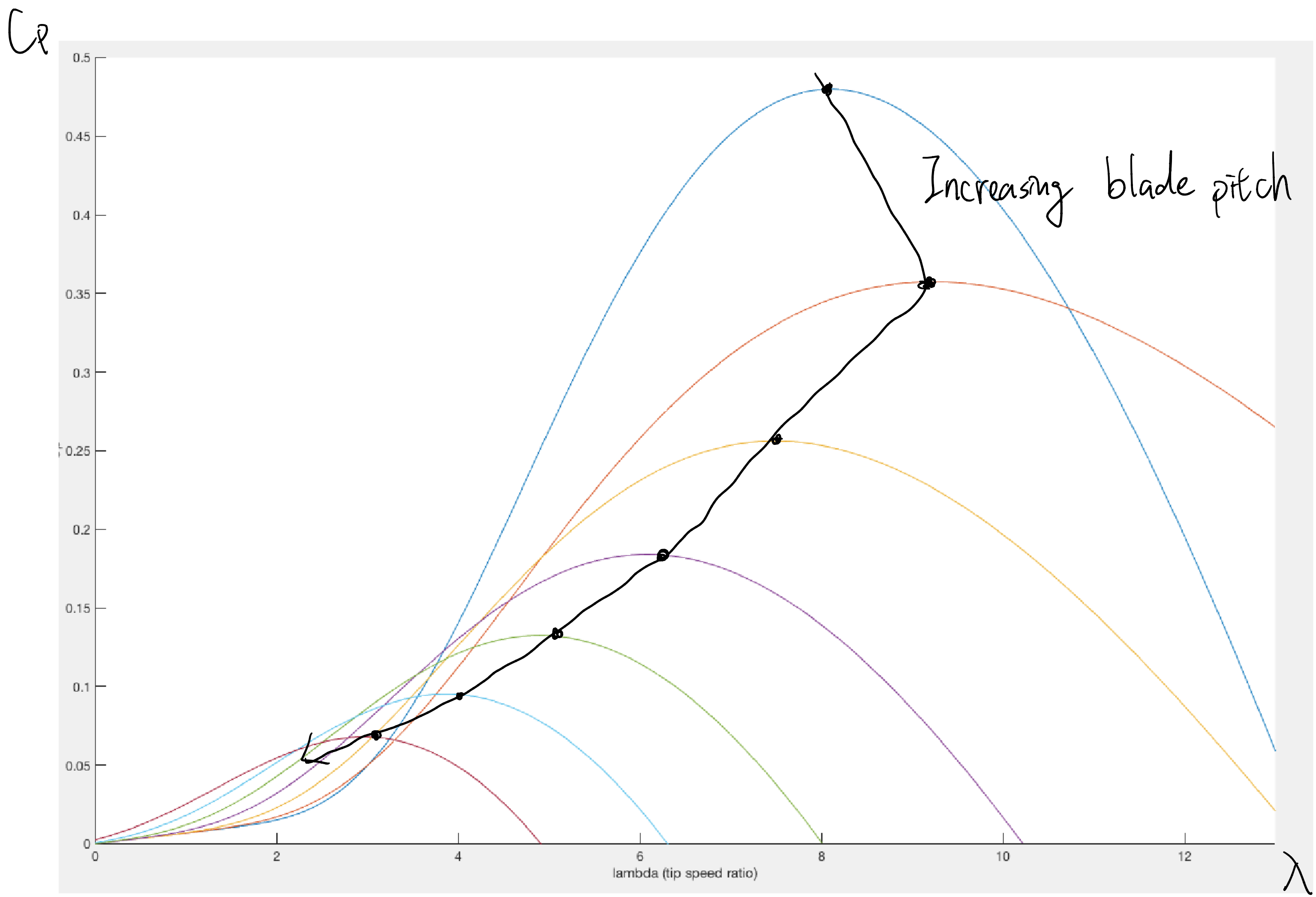



**FIG. 7.9** $C_P$–$\lambda$ curve for high tip-speed rotor.

[Andrews and Jelley, "Energy Science"]

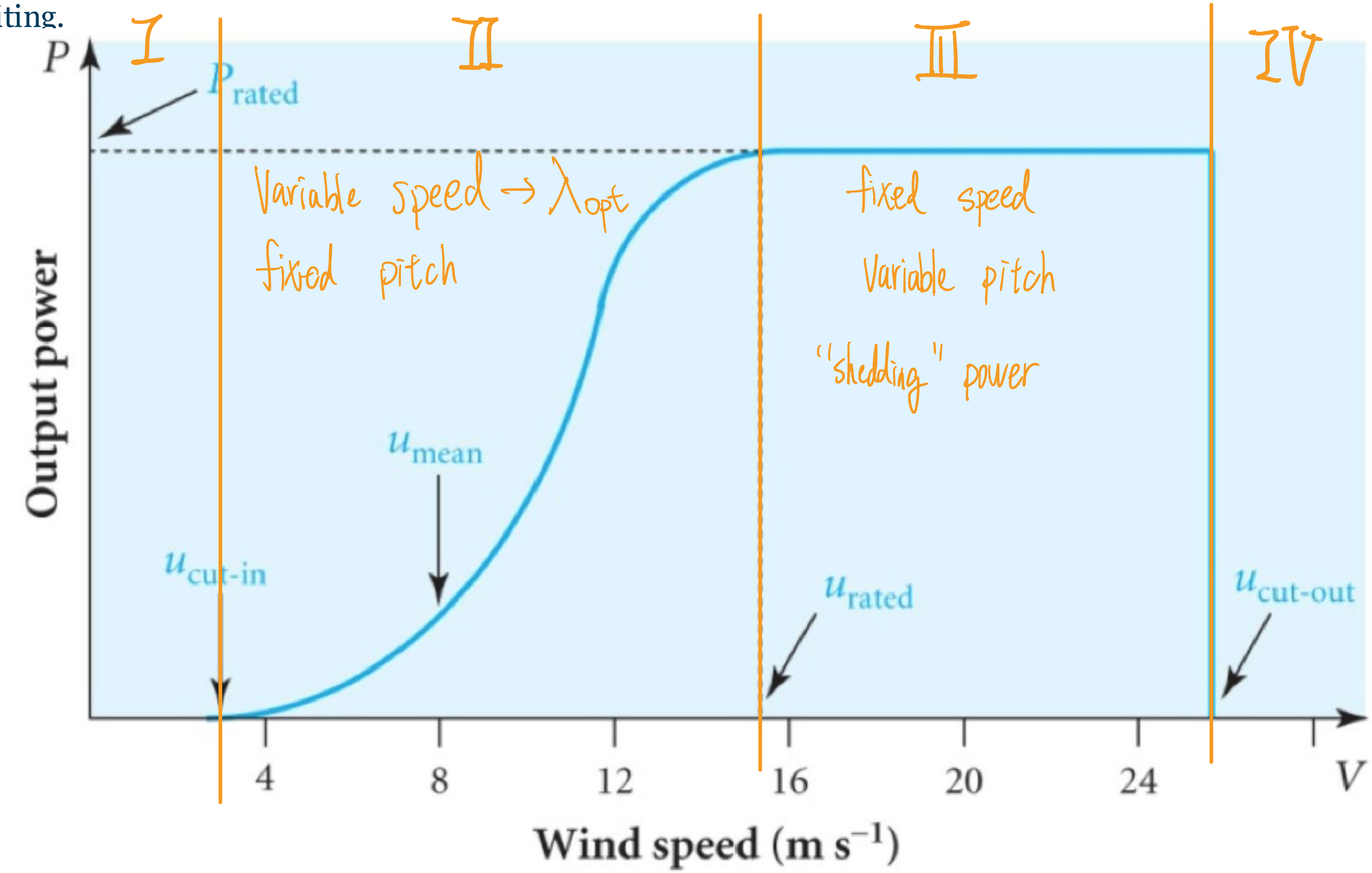
# Coefficient of Power as a Function of Blade Pitch

- Increasing blade angle (beta) decreases the peak $C_p$
- Increasing blade angle moves peak $C_p$ to higher wind speeds (lower tip speed ratio)



# Typical Power Curve

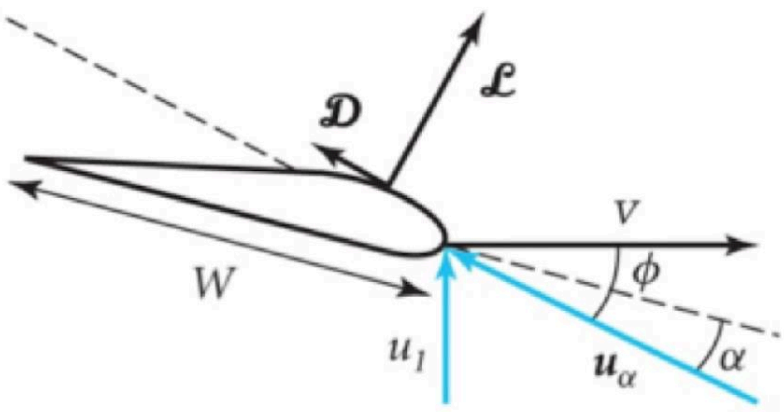
- Between the cut-in wind speed and the rated wind speed, the tip speed ratio is kept at optimum by adjusting the turbine rotational speed by controlling the generator torque.
- Between the rated wind speed and cut-out wind speed, the rotational speed is kept constant and the blades are pitched to "spill" the extra power.
- To avoid spilling the extra power, the generator must be rated much larger than its average output. This is uneconomical.
- The generator typically has a rating 3 times its average output. This ratio is called the "capacity factor." It is dependent on siting.

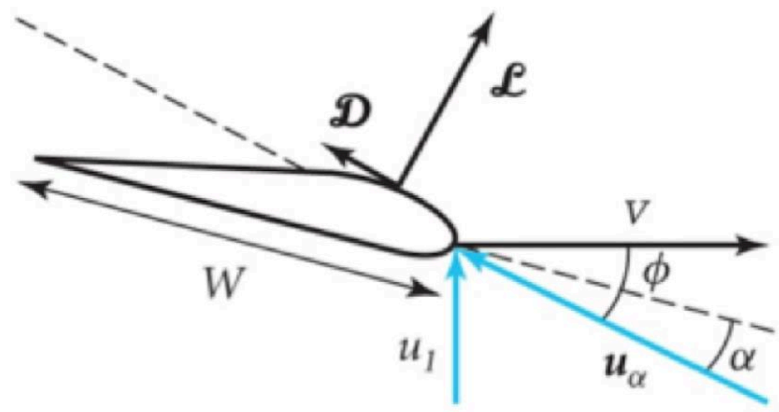



[Andrews and Jelley, "Energy Science"]

# Blade Feathering and Passive Stall

- Feathering decreases the angle of attack to reduce torque. This avoids stall but makes the system vulnerable to rapid increases in wind speed.
- Stall techniques can be passive or active. Stalling produces more vibration and noise.

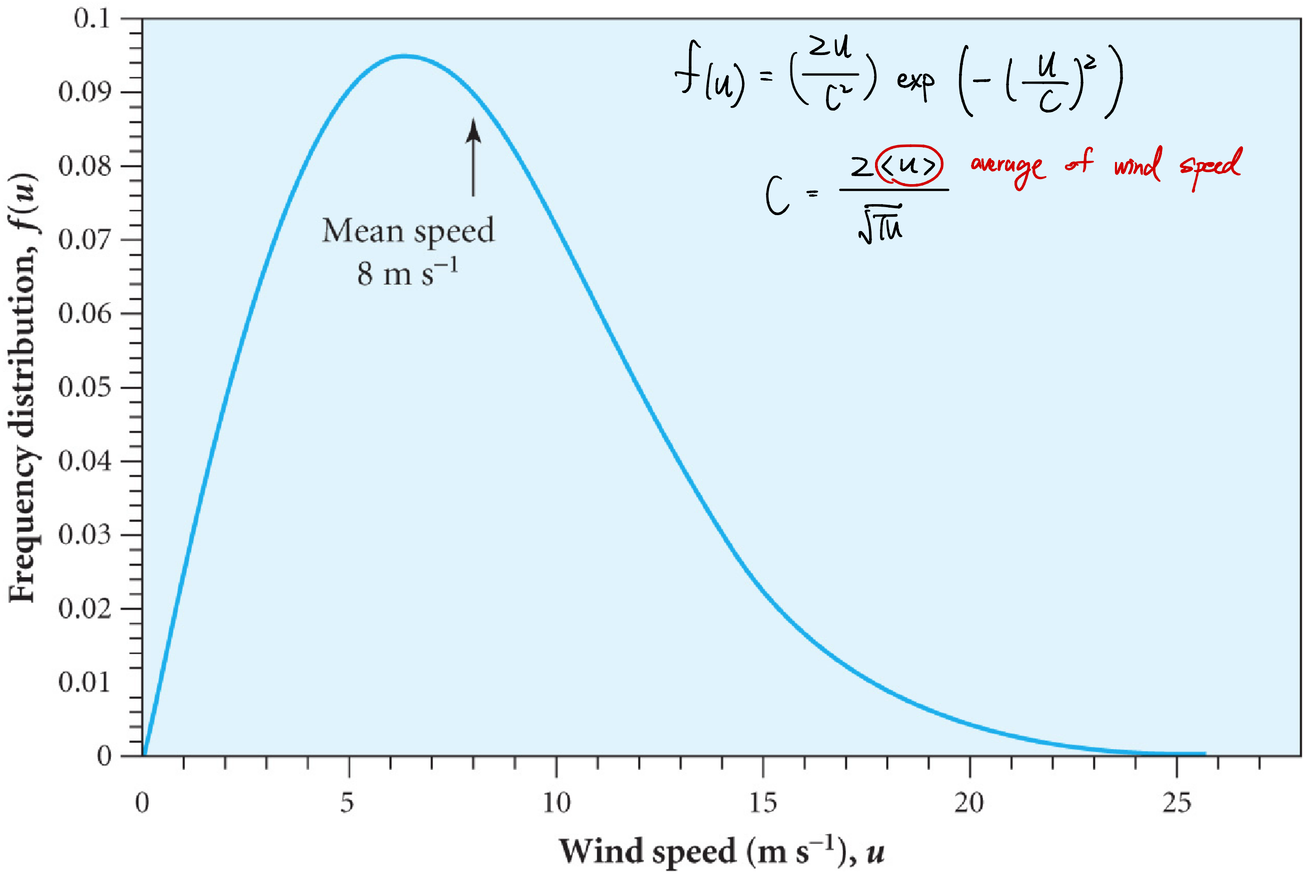



[Andrews and Jelley, “Energy Science”]

# Rayleigh Distribution

- To find average raw wind power, weight wind power as a function of speed with frequency as a function of speed.
- To find average turbine power, weight turbine power curve as a function of speed with frequency as a function of speed.

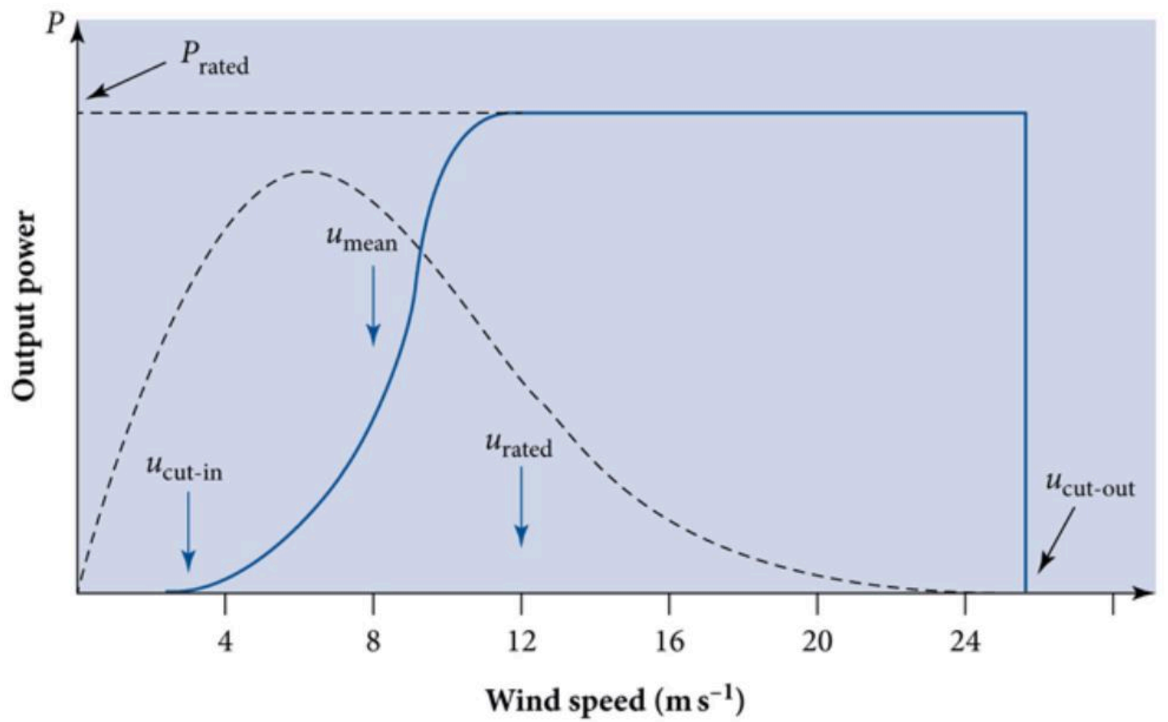



[Andrews and Jelley, "Energy Science"]

$$\frac{1}{2}\rho \cdot A \cdot u^3 \neq \frac{1}{2}\rho \cdot A \cdot \langle u \rangle^3$$

# Average Turbine Power

- The average turbine power is the integration of the turbine power vs wind speed weighted by the probability distribution.




[Andrews and Jelley, “Energy Science”]

$$\langle P_{turbine} \rangle = \int f(u) \cdot P_{turbine}(u) \cdot du \sim \frac{1}{3} P_{rated}$$

$$CF = \frac{\langle P_{turbine} \rangle}{P_{rated}} \sim 1/3$$

Capacity Factor

# Region 2 Control

- In region 2, we want the turbine speed to change with wind speed, such that we maintain a constant ratio.  For optimal power capture, this ratio should be the *optimal* tip speed ratio.
- We can enforce this by constraining a specific torque-speed characteristic.

In region II

blade length

$$\lambda = \lambda_{opt} = \frac{r \cdot w}{u_0} \Rightarrow C_{p\,opt}$$

If true

$$P_{gen} = T_{gen} \cdot w = P_{wind} \cdot C_{p\,opt}$$

$$= \frac{1}{2} \rho \cdot A \cdot u_0^3 \cdot C_{p\,opt}$$

$$T_{gen} \cdot w \cdot (w^2 \cdot r^3) = \frac{1}{2} \rho \cdot A \cdot u_0^3 \cdot C_{p\,opt} \, (w^2 \cdot r^3)$$

$$\rightarrow T_{gen} \cdot \frac{w^3 \cdot r^3}{u_0^3} = \frac{1}{2} \rho \cdot A \cdot C_{p\,opt} \cdot w^2 \cdot r^3$$

$$\rightarrow T_{gen} = \frac{1}{2} \cdot \rho \cdot A \cdot \frac{C_{p\,opt}}{\lambda_{opt}^3} \cdot r^3 \cdot w^2 = K_{opt} \cdot w^2$$

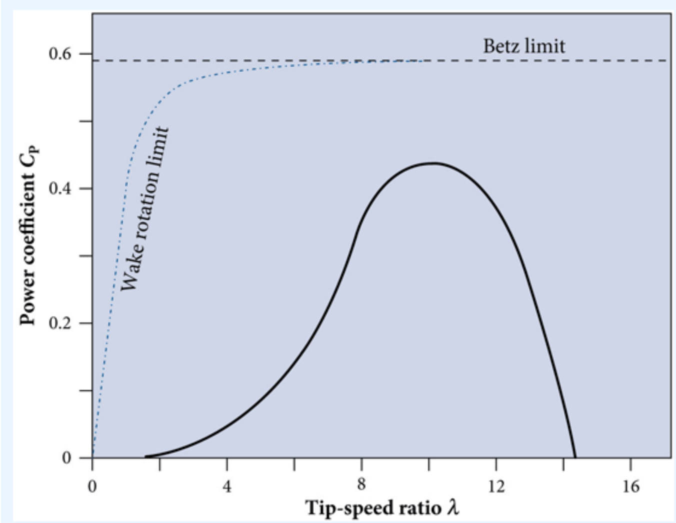
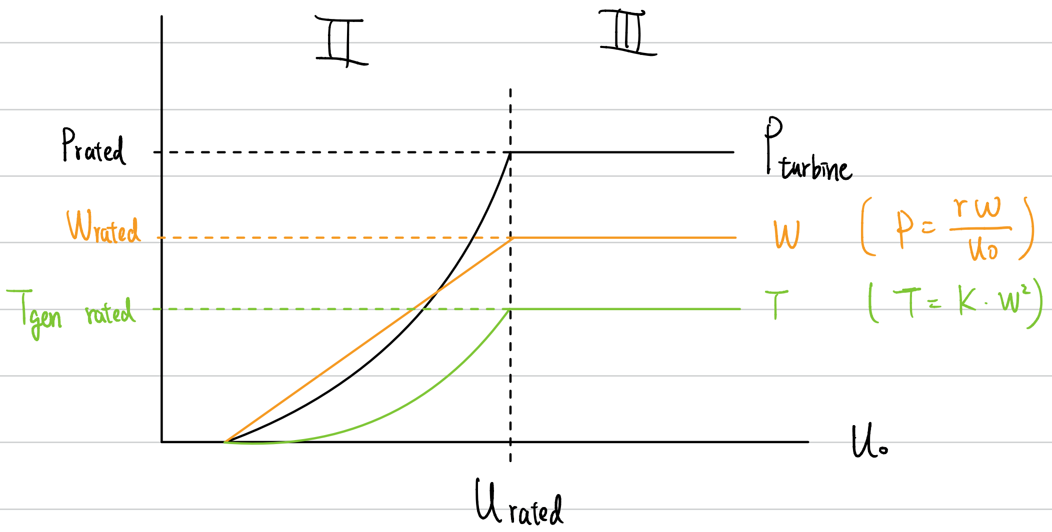



**FIG. 7.9** $C_P$–$\lambda$ curve for high tip-speed rotor.

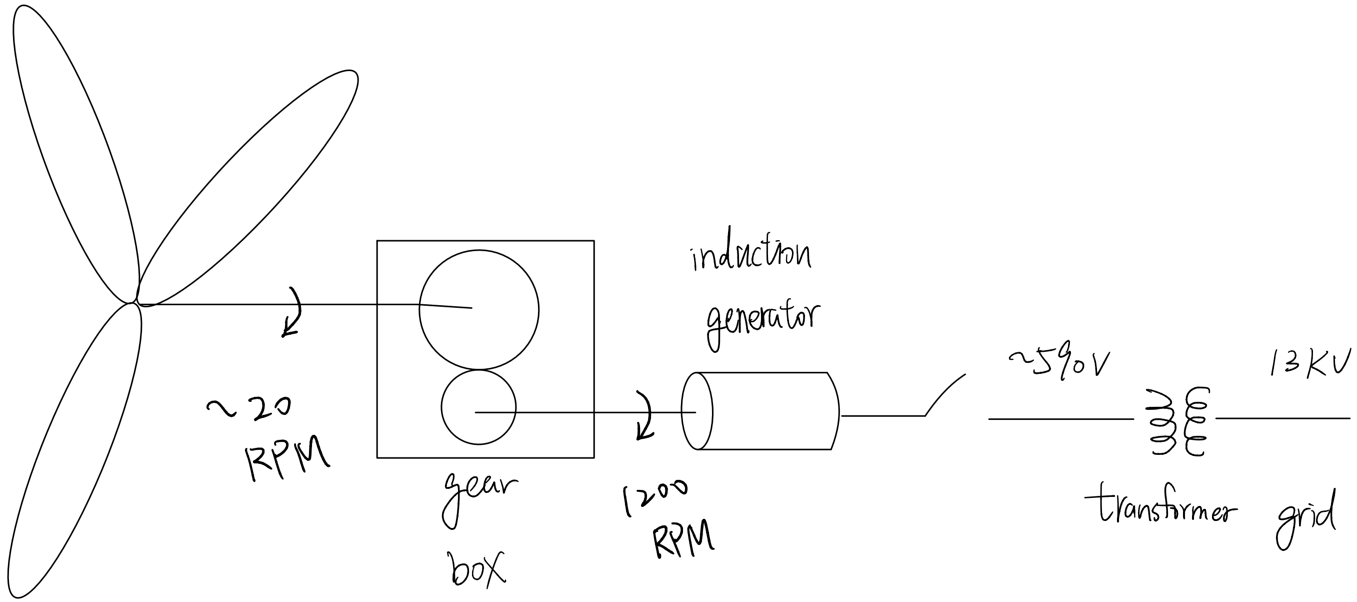
[Andrews and Jelley, "Energy Science"]

# Region II → III transition



# Wind Turbine Topologies: Grid Connected Cage Induction

- Fixed speed
- Fixed VAR

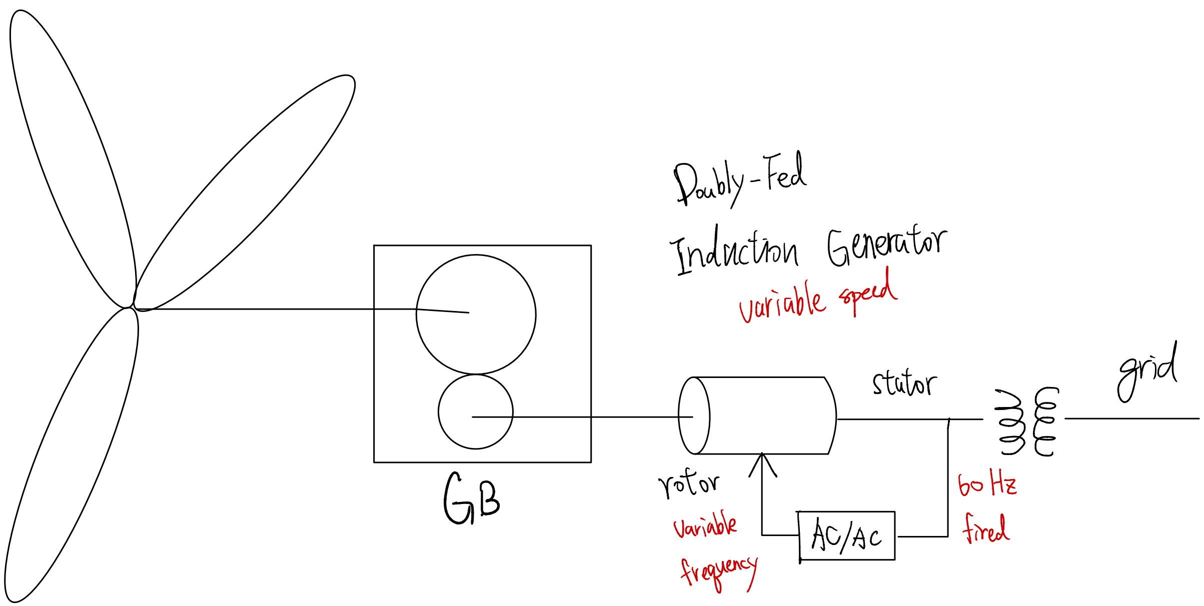



$P = IV$

$P_{loss} = I^2 R$

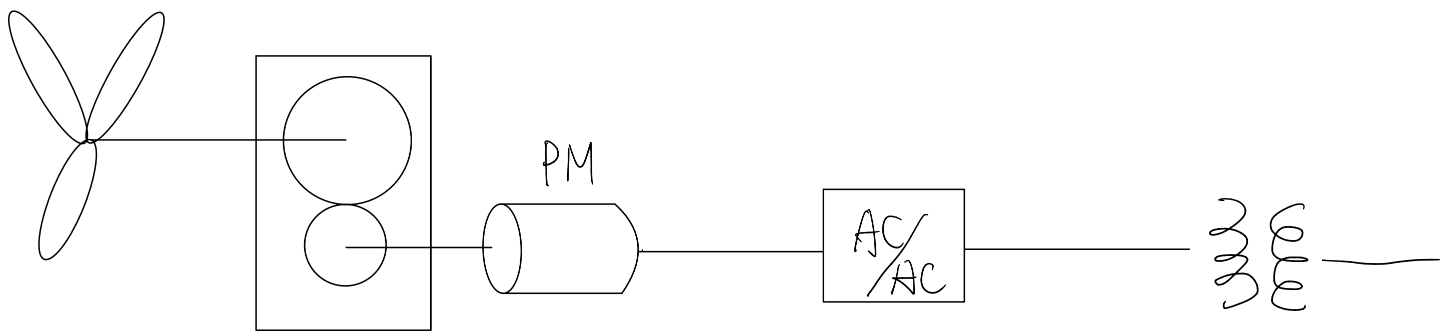
# Wind Turbine Topologies: Doubly-Fed Induction Generator

- Converter power rating is approximately 30% of total generator rating.
- Variable speed (+/- 30%)
- Reactive power control
- Slip-rings



# Wind Turbine Topologies: Permanent Magnet Synchronous

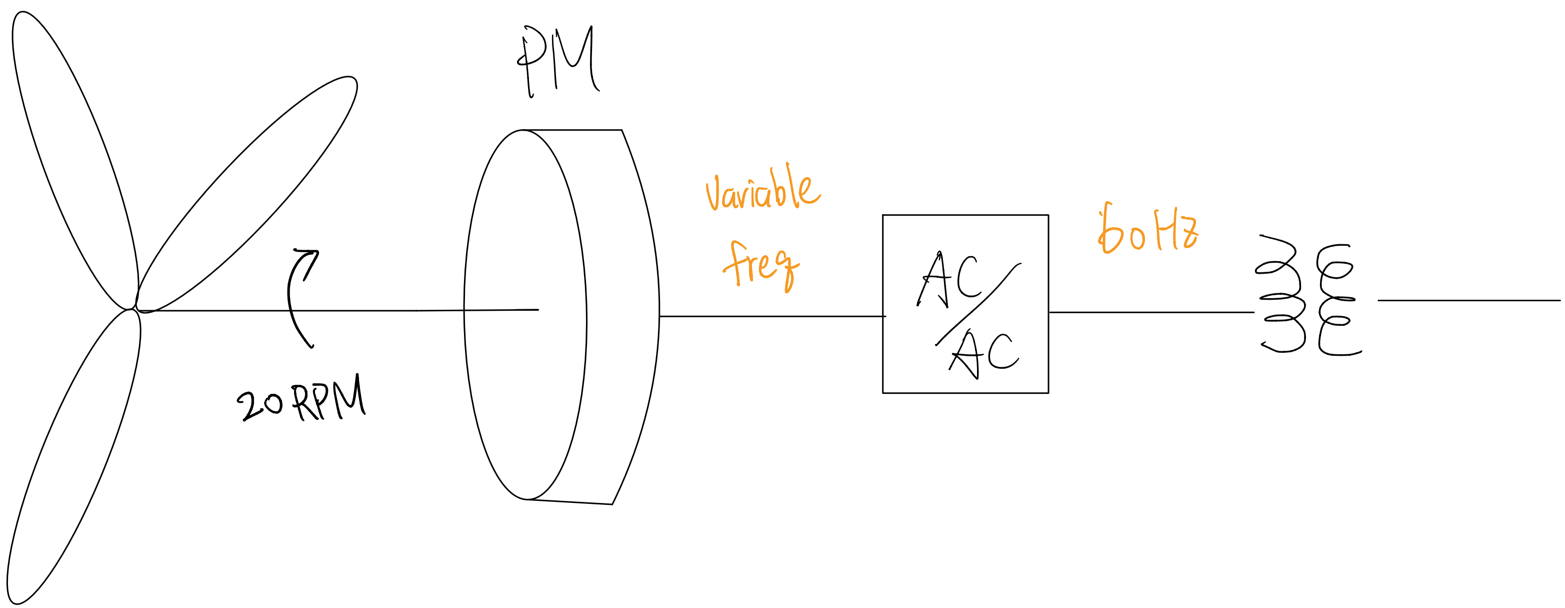
- Variable speed
- Variable VAR
- More expensive and power dense than induction.



# Wind Turbine Topologies: Direct-Drive Permanent Magnet Synchronous

- No gearbox
- Expensive, tricky generator build

No Gear Box!

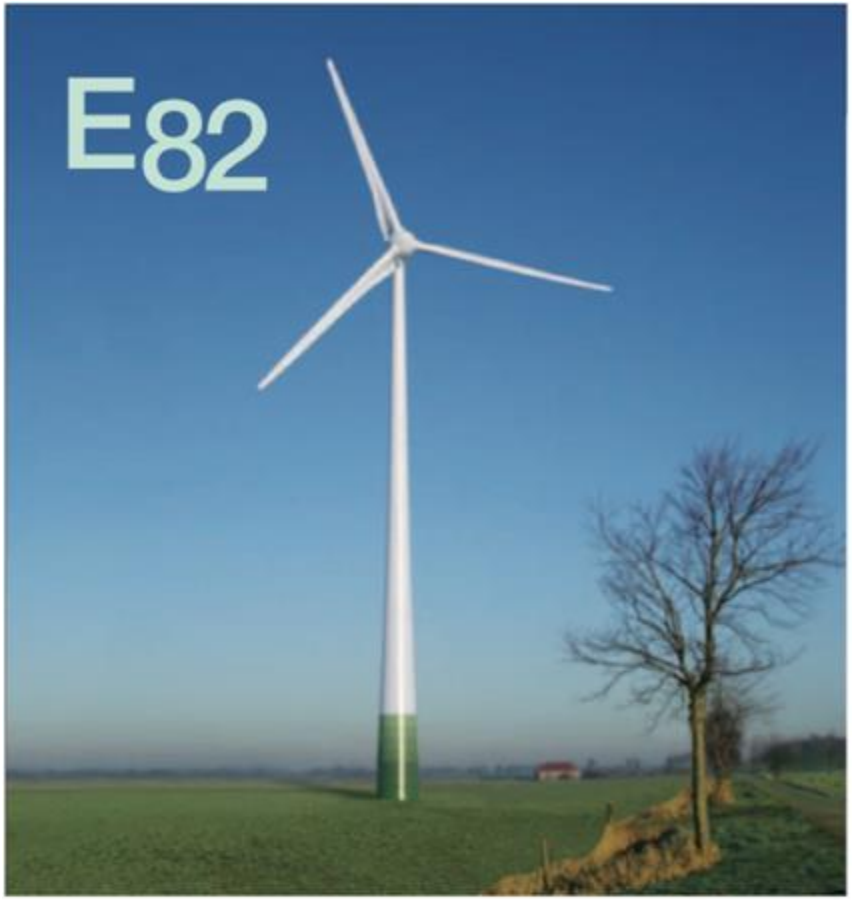


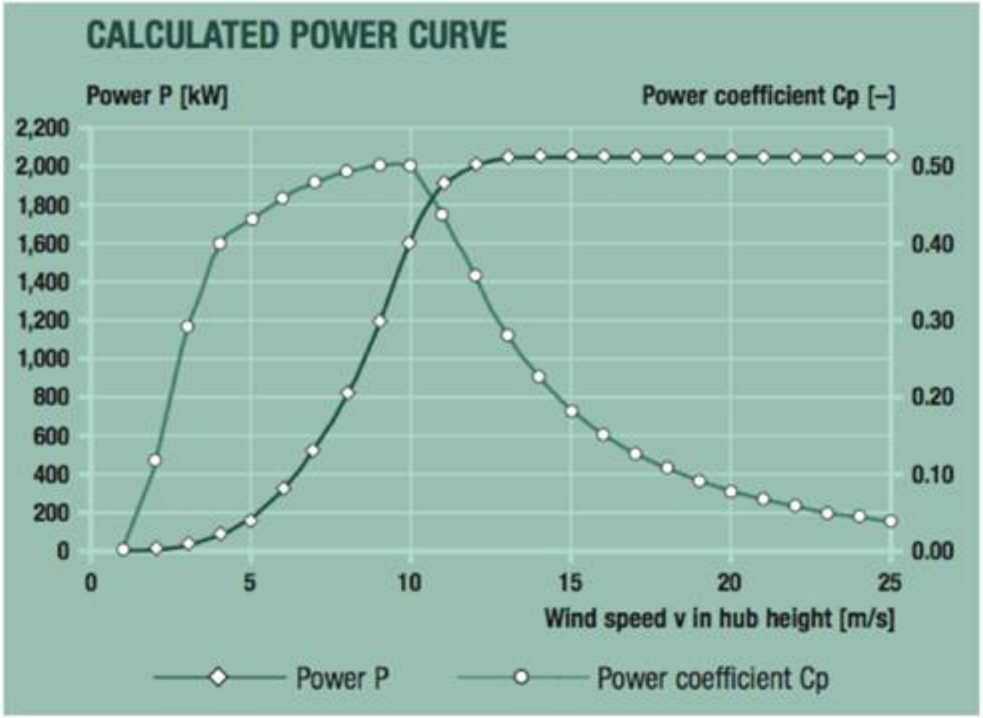

$\uparrow P = T \cdot \omega \downarrow$

# Wind Turbine Manufacturers

- Vestas (Denmark)
- Siemens Gamesa (Germany/Spain)
- Goldwind (China)
- GE (US)
- Envision (China)
- MingYang (China)
- Windey (China)
- Nordex (Germany)
- CSIC (China)
- Enercon (Germany)
- Eocycle (Canada)
- Suzlon (India)

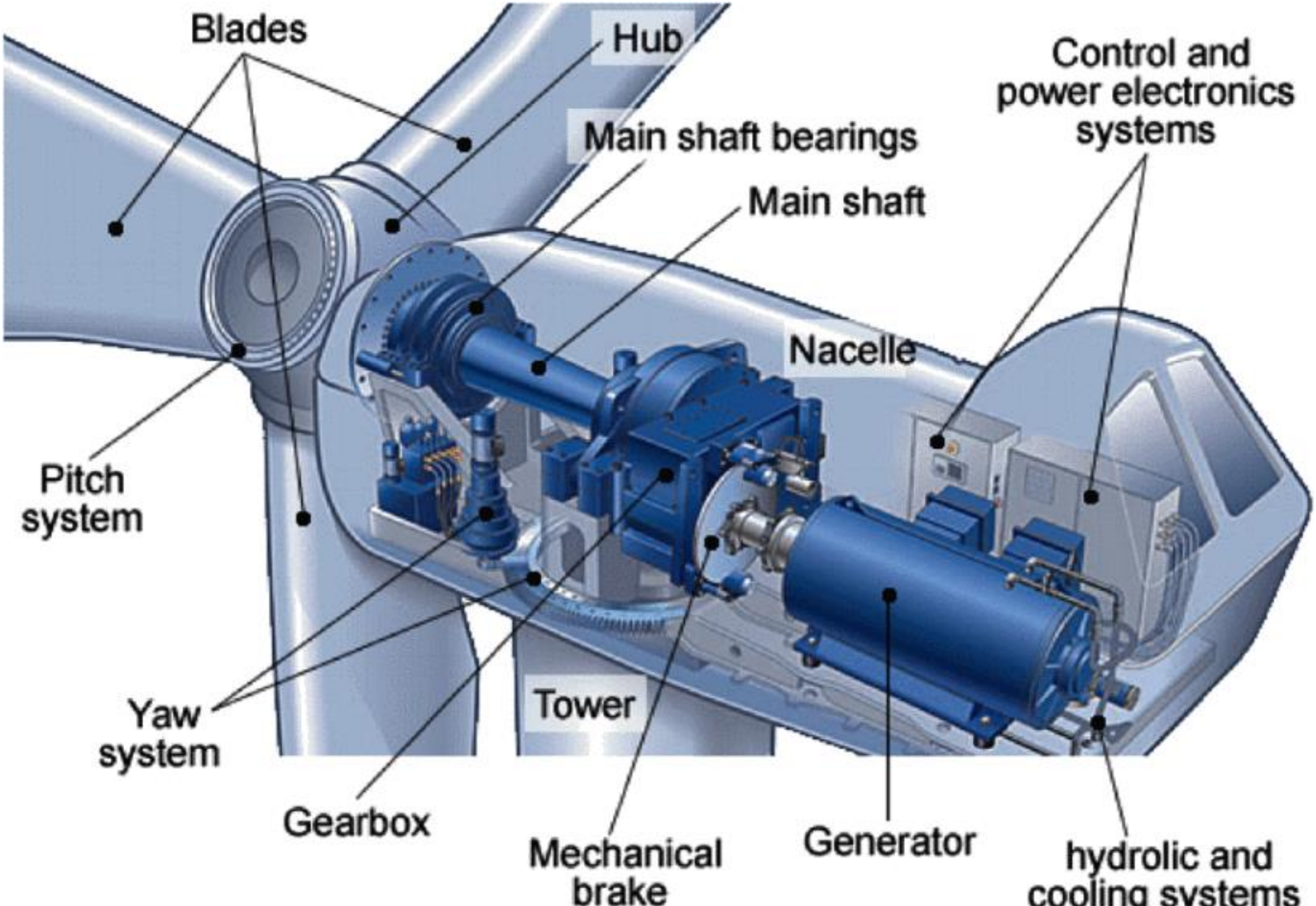
# Wind Turbine Technology



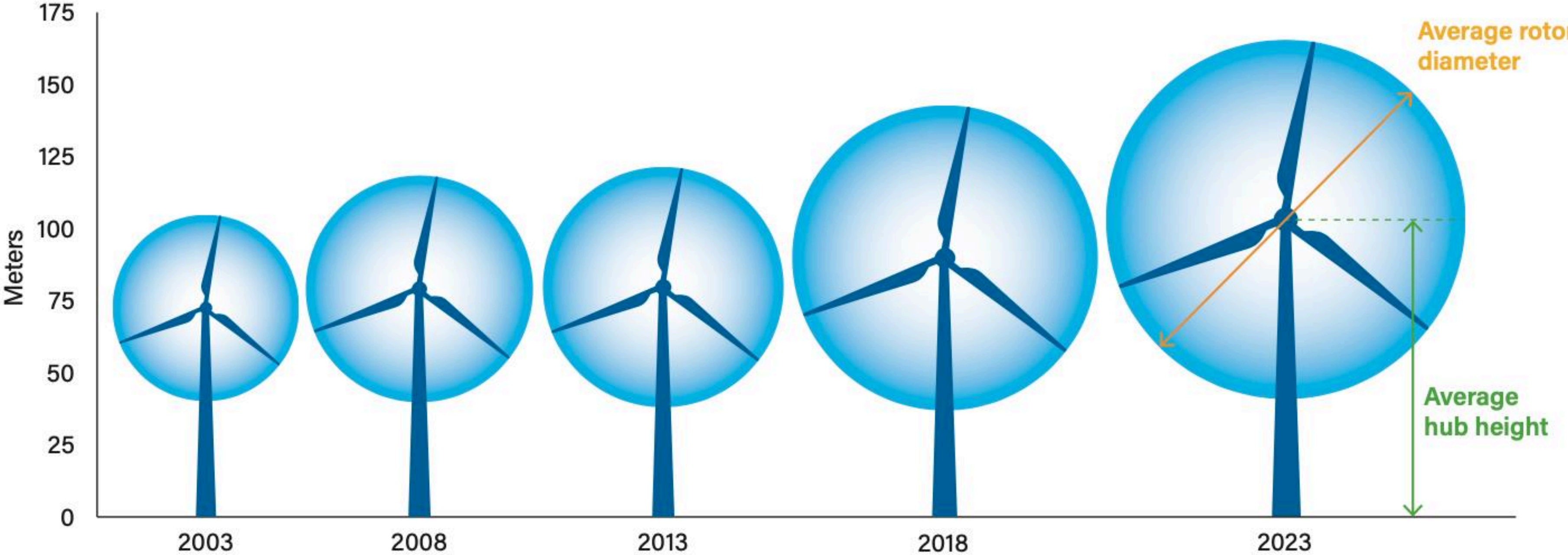

[Enercon, E82 datasheet]

# Inside a Wind Turbine



# Turbine Size

## Evolution of the "Average" Utility-Scale Turbine




| YEAR | 2003 | 2008 | 2013 | 2018 | 2023 |
|---|---|---|---|---|---|
| Average Hub Height (m) | 70 | 77 | 77 | 87 | 100 |
| Average Rotor Diameter (m) | 69 | 84 | 89 | 113 | 133 |
| Average Capacity (MW) | 1.4 | 1.7 | 1.7 | 2.4 | 3.5 |
| Homes Powered | 263 | 427 | 529 | 856 | 1,058 |

[American Clean Power Annual Report, 2023]

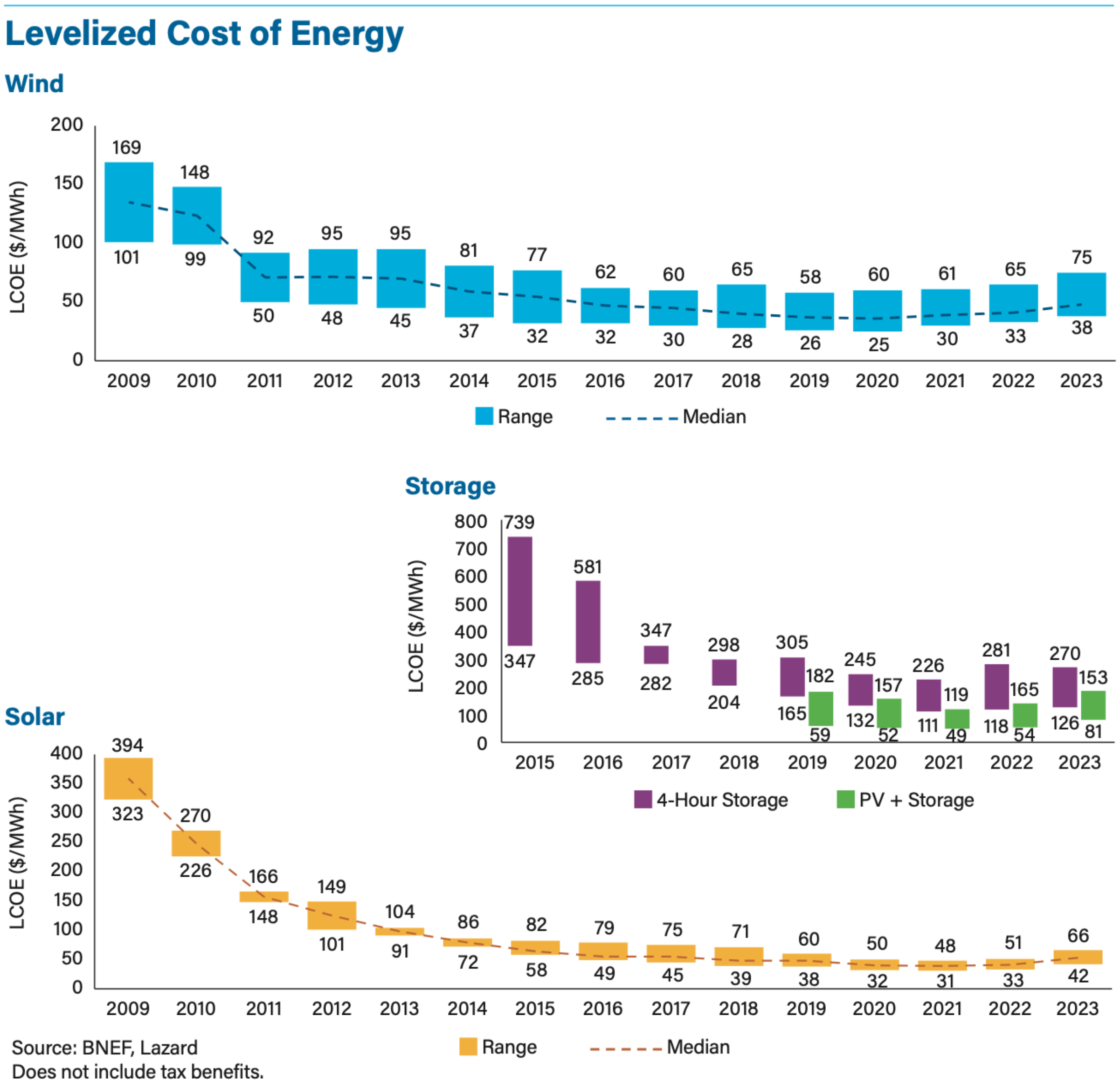
# Small Scale

- Small turbines (1 kW to 10 kW) can be useful for offgrid and residential offsetting applications.
- For large-scale energy conversion, the low height of small turbines greatly reduces their economic viability.
- Average wind speed at 10 m and 100 m could be different by a factor of 2. This is 8 times less power!
- Trees, hills, and buildings also decrease wind speed and increase turbulence.
- House or building mounted wind power is generally uneconomical due to slower, inconsistent winds.
- Xzeres
- Bergey

[Bergey]

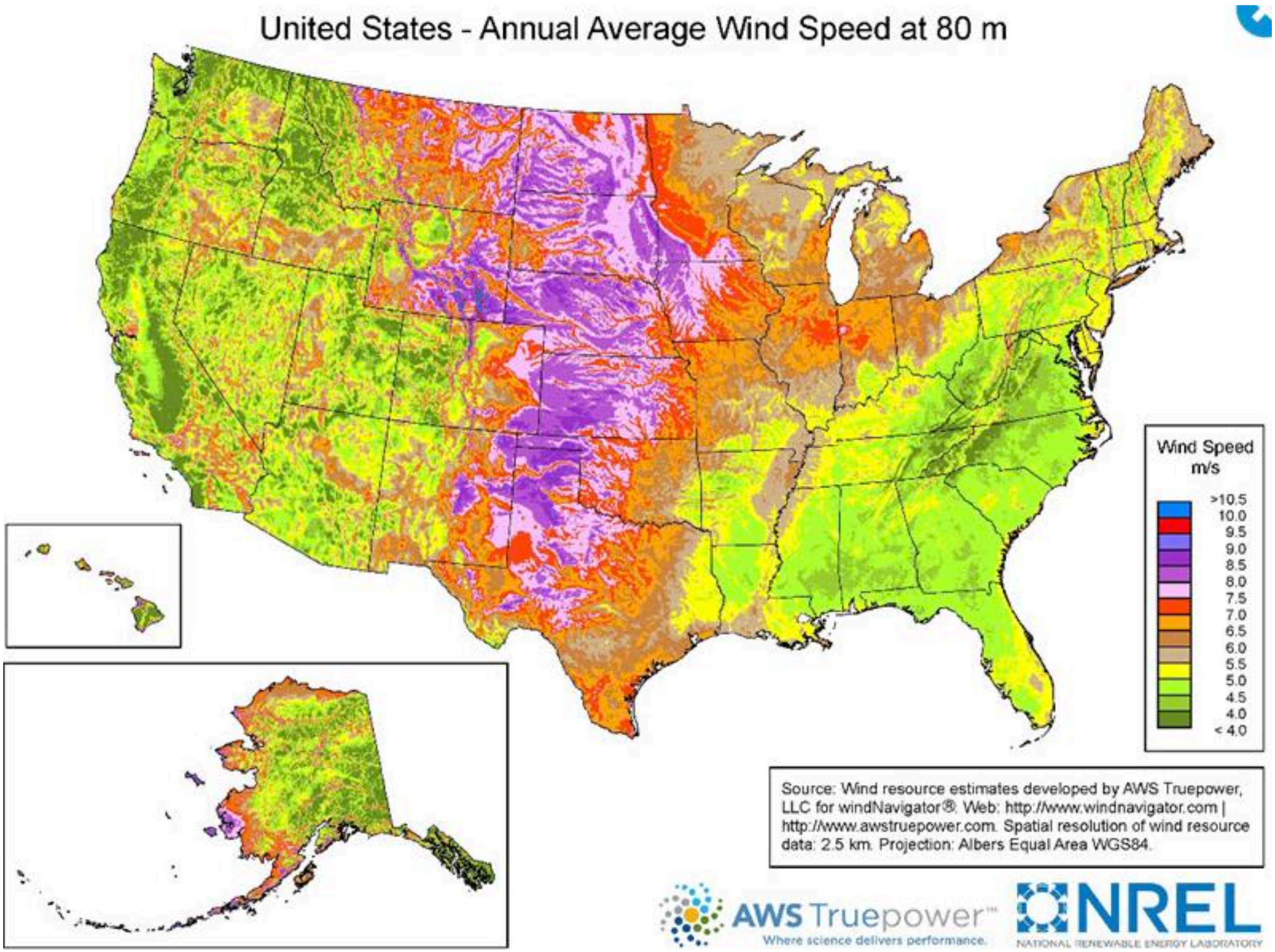
Bergey Excel 10

# Levelized Cost of Energy

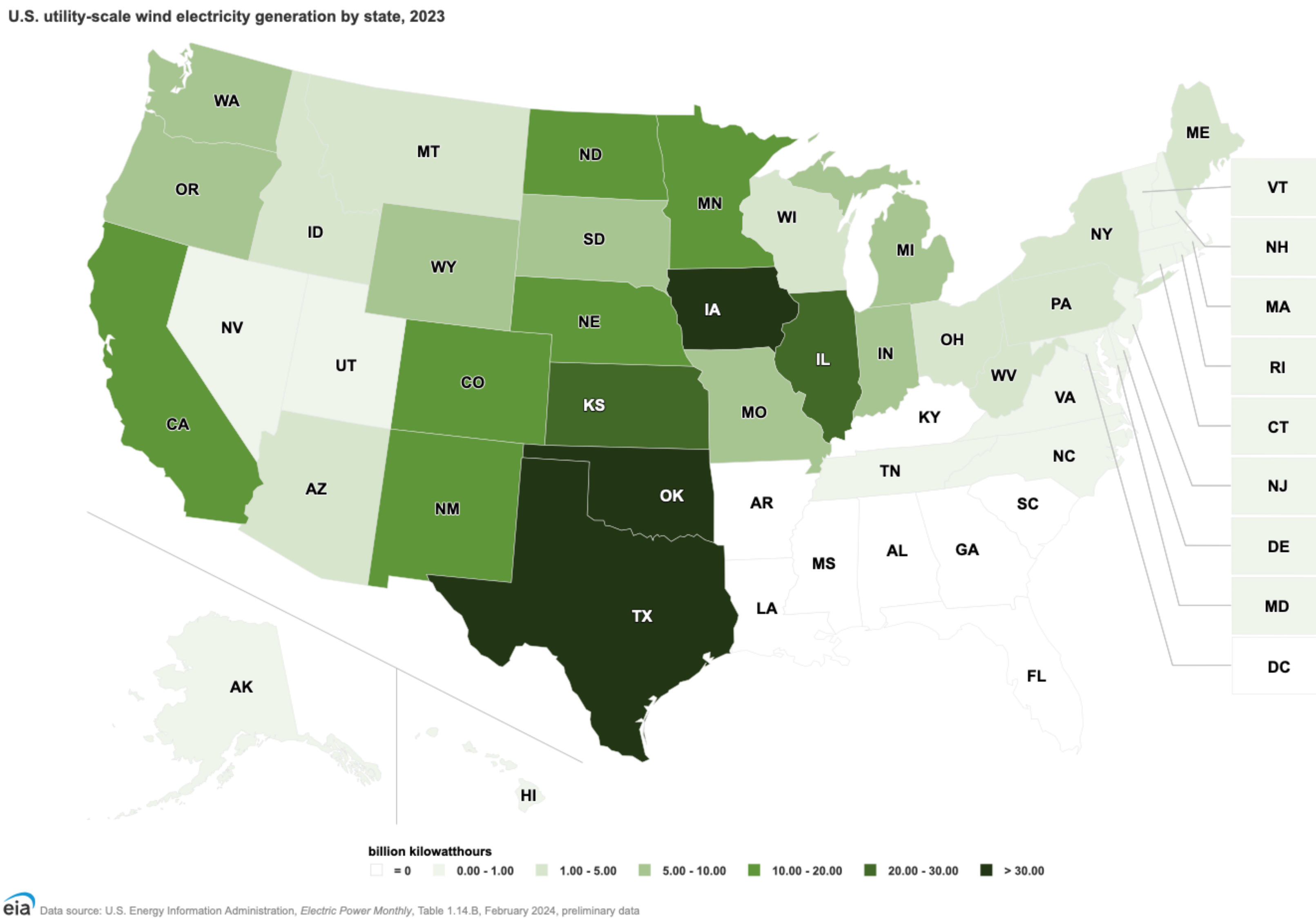



[American Clean Power Annual Report, 2023]

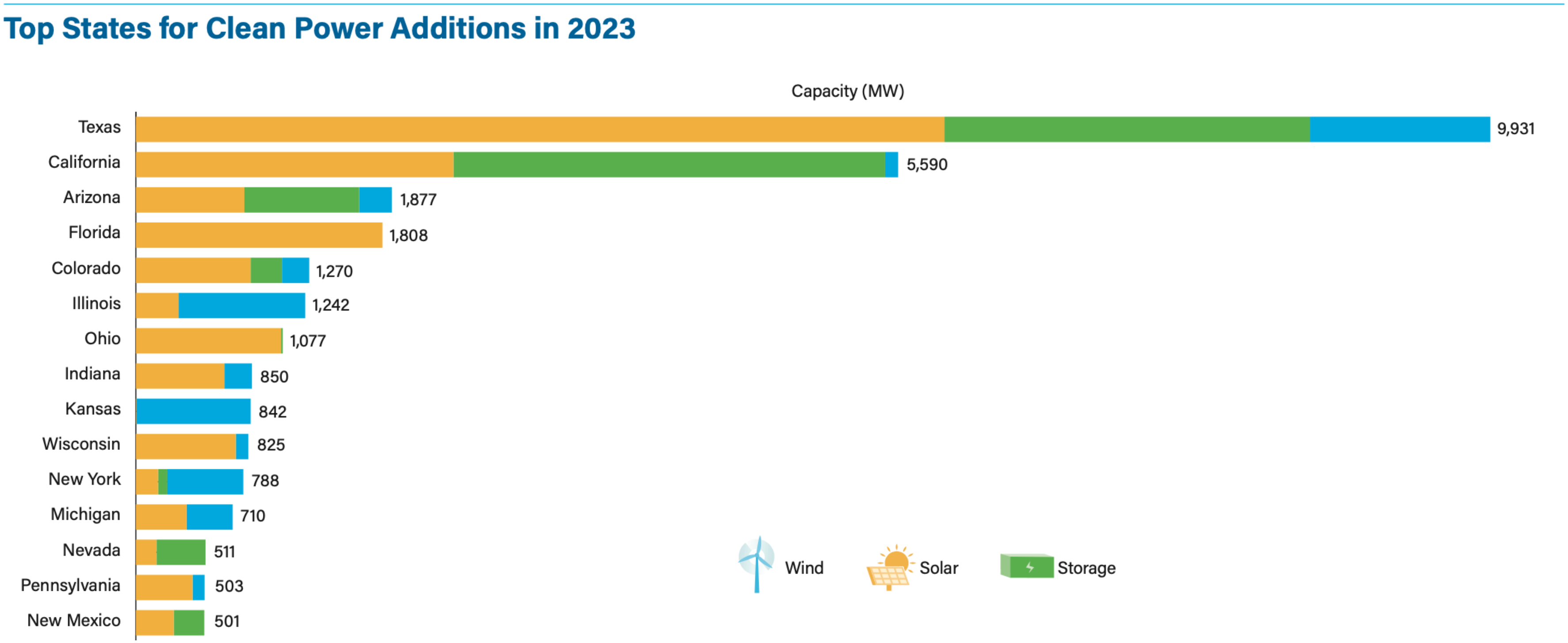
# Wind Resource



# Wind Power by State



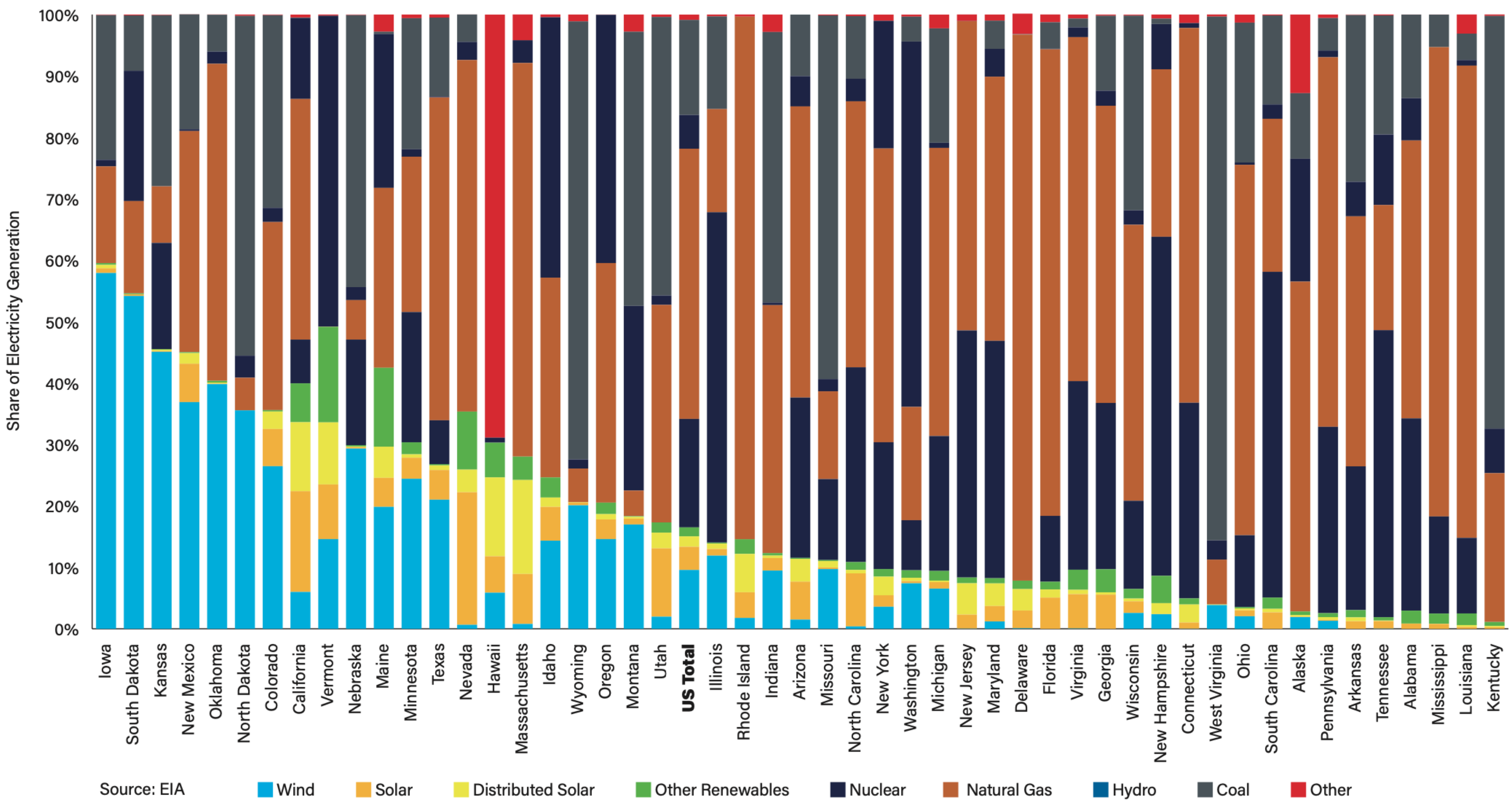
# Wind and Solar Additions




[American Clean Power Annual Report, 2023]

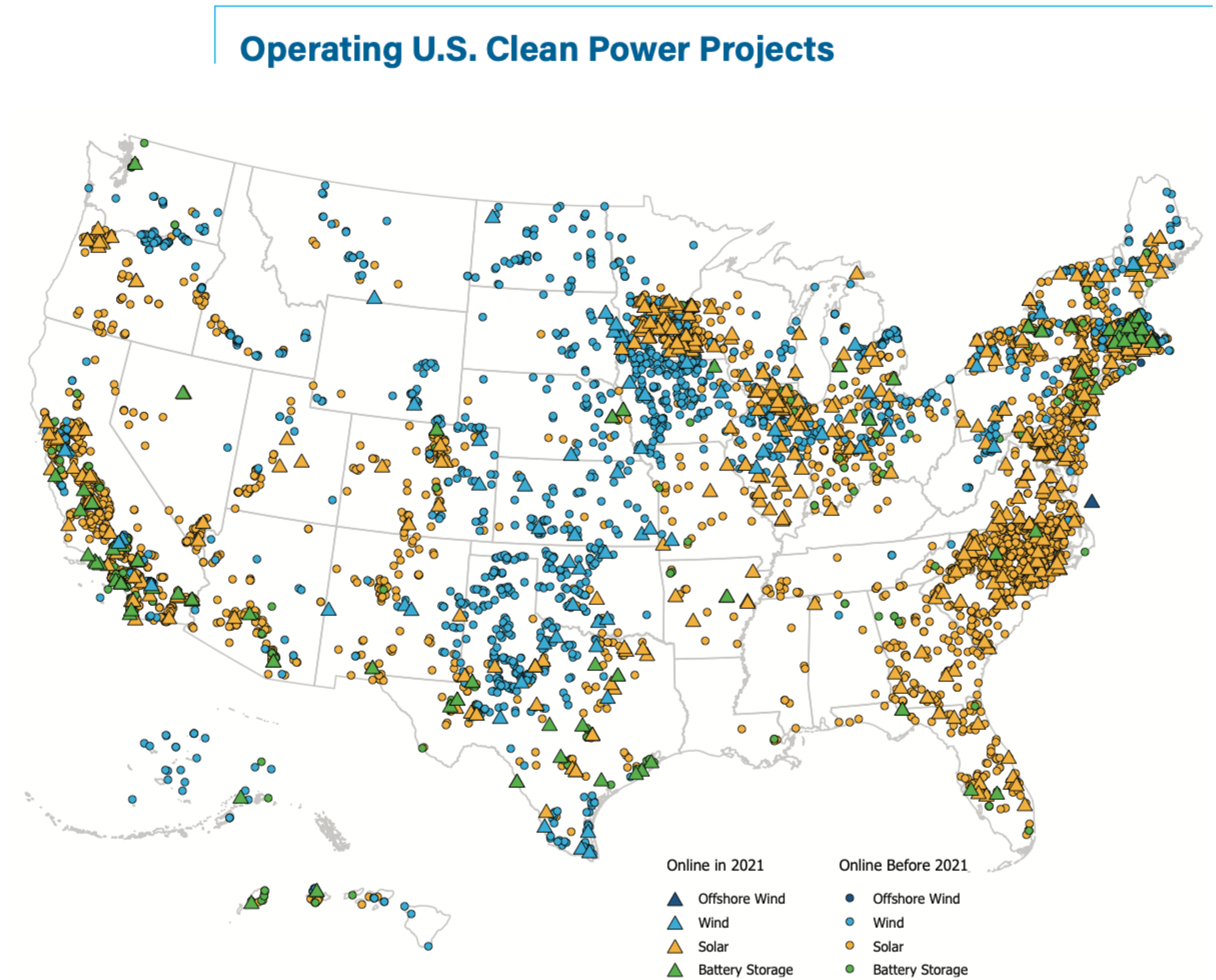
# State Mix

## Electricity Generation Mix in 2023 by State




[American Clean Power Annual Report, 2023]

# Where Are the Wind and Solar Projects?




[American Clean Power Annual Report, 2021]

# Efficiency, Coefficient of Power, and Capacity Factor

Efficiency

- Ratio of energy out to energy in
- Efficiency = $E_{out}/E_{in}$ = $(E_{in} - E_{lost})/E_{in}$
- Elost is almost always heat

$$\frac{E_{out}}{E_{in}} = \frac{E_{in} - E_{loss}}{E_{in}}$$

Coefficient of power $C_p$

- Ratio of resource available to how much is converted
- Similar in concept to efficiency, but unconverted energy isn't lost, just not captured
- Coefficient of Power = $E_{converted}/E_{in}$ = $(E_{in} - E_{unconverted})/E_{in}$

Capacity Factor CF

- Ratio of actual energy produced to the maximum theoretically possible
- Capacity Factor = $E_{out}$ / $(P_{rated}$*time) $= P_{avg} / P_{rated}$
- Very dependent on how the technology is deployed. (For example, a wind turbine in a wind tunnel will have a capacity factor near 1. The same wind turbine stored in a warehouse would have a capacity factor of 0.)

# Questions

per hour

A wind turbine is rated for 2 MW. Assume an annual capacity factor of 33 %. How many homes worth of electrical energy is supplied by the turbine over the year? (Estimate an average electrical home load as 1 kW = 24 kWh/day. Round your answer to an integer number of homes.)

$$E_{turbine} = (2\,MW)\left(\frac{1000\,kW}{MW}\right)\left(\frac{24h}{day}\right)\left(\frac{365\,\cancel{day}}{year}\right) \times \frac{1}{3} = 5{,}840{,}000\ kWh/year$$

$$E_{home} = \frac{24\,kWh}{day \cdot home} \times \frac{365\,\cancel{day}}{year} = 8{,}760\ \frac{kWh}{year \cdot home}$$

$$\#\ home = \frac{E_{turbine}}{E_{home}} = 666\ homes$$

$$\begin{array}{r} 945.5\ GW \\ 75.2\ GW \\ \hline 1020.7\ GW \end{array}$$

$$\frac{1020.7 \times 10^6 \times \cancel{24} \times 0.345 \times \cancel{365}}{1 \times \cancel{24} \times \cancel{365}}$$

$$= 352.1415 \times 10^6$$

# Wind Turbine Equation of Motion

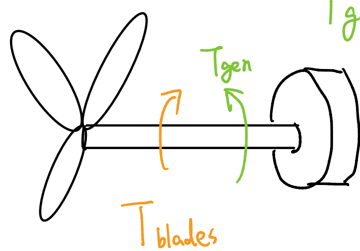
- The sum or torques (i.e., the net torque) divided by the total moment of inertia equals acceleration.
- The wind tries to accelerate the turbine, the generator tries to decelerate the turbine.
- Acceleration, and thus speed, is controlled by the generator torque.

$T_{gen}$ is completely controlled by you!

$$F = ma$$

$$\underset{\text{torque}}{T} = \underset{\text{inertia}}{J} \cdot \frac{\partial W}{\partial t}$$

is accerleration, not speed!




opposite torque

$$T_{blades} - T_{gen} = T_{net} = J \cdot \frac{\partial W}{\partial t}$$

e.g. $1\,MNm - 1\,MNm = 0 = \underset{\text{constant}}{\underline{\underline{J}}} \cdot \frac{\partial W}{\partial t}$ $\quad$ W is constant

$$T_{blades} - T_{gen} - \underset{C_{fric} \times W}{T_{friction}} = J \cdot \frac{\partial W}{\partial t}$$