Lecture 20: Wind Energy

Course: MECH-422 – Power Plants

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Term: Fall 2021

BUITEMS – DEPARTMENT OF MECHANICAL ENGINEERING

What is Wind Energy?

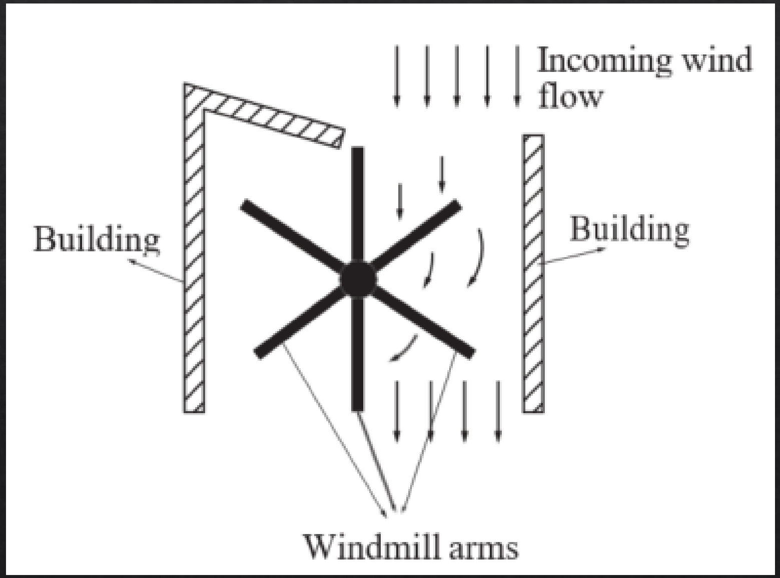
- Wind power or wind energy is the use of wind turbines to generate electricity.
- Wind power is a popular, sustainable, renewable energy source

History

- The use of wind energy dates to ancient times when it was used to propel sailboats.

History

Extensive use of wind turbines seems to have been originated in Persia, where it was used for grinding wheat.



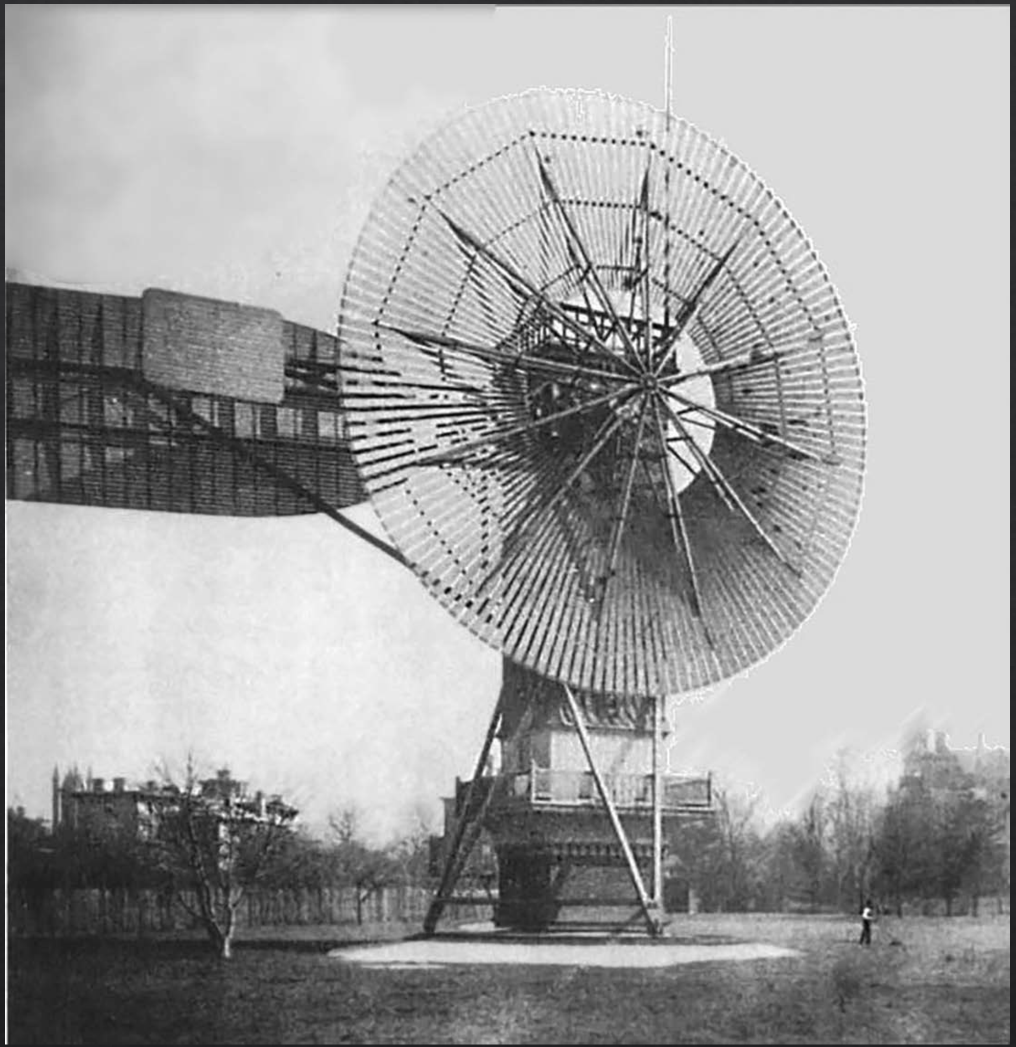
History

- In Europe wind mills appeared in the 11th centrury, and around the 13th century they became and important tool in Holland

Grafelijke Korenmolen van Zeddam (Countships grainmill of Zeddam) ~1441

Windmills in Kinderdijk in the southern Netherlands (built in the 1730s for water drainage). (Image by Ellen26 from Pixabay (https://pixabay.com/photos/mills-kinderdijk-holland- 3888276/))

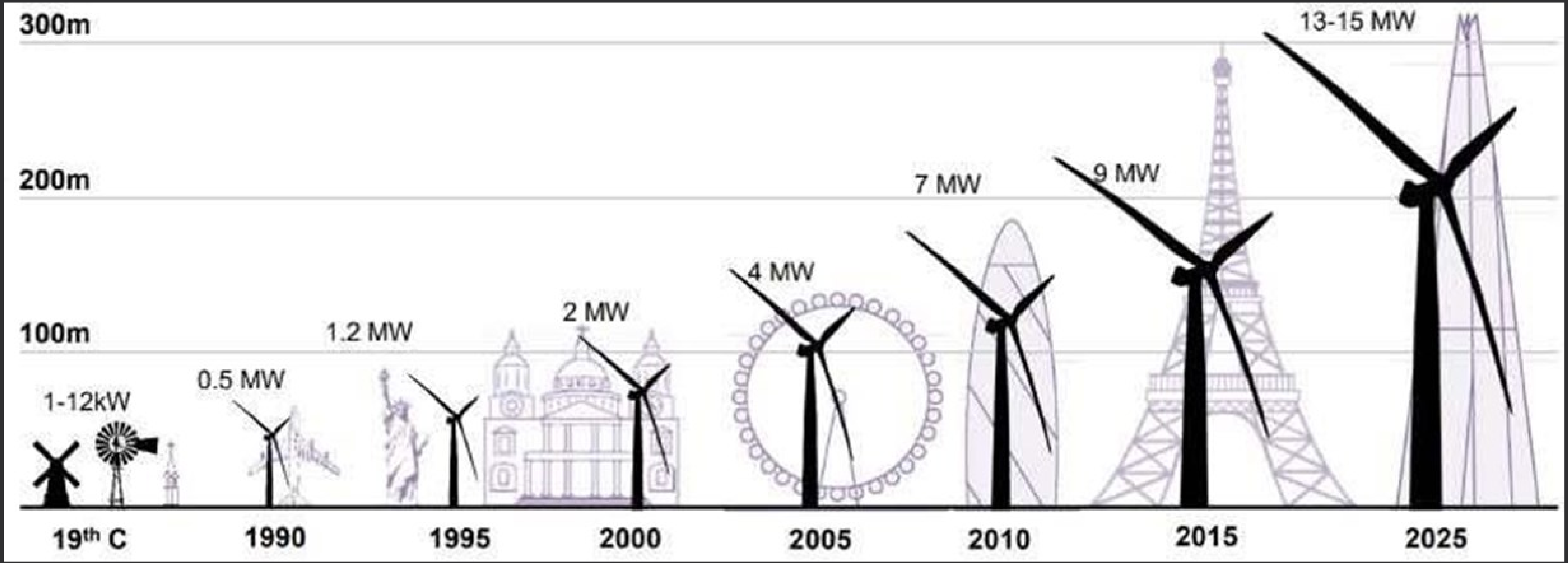
A windmill to pump water. (Image by Lisa Johnson from Pixabay, https://pixabay.com/photos/ windmill-turbine-wind-water-pump-1110079/)



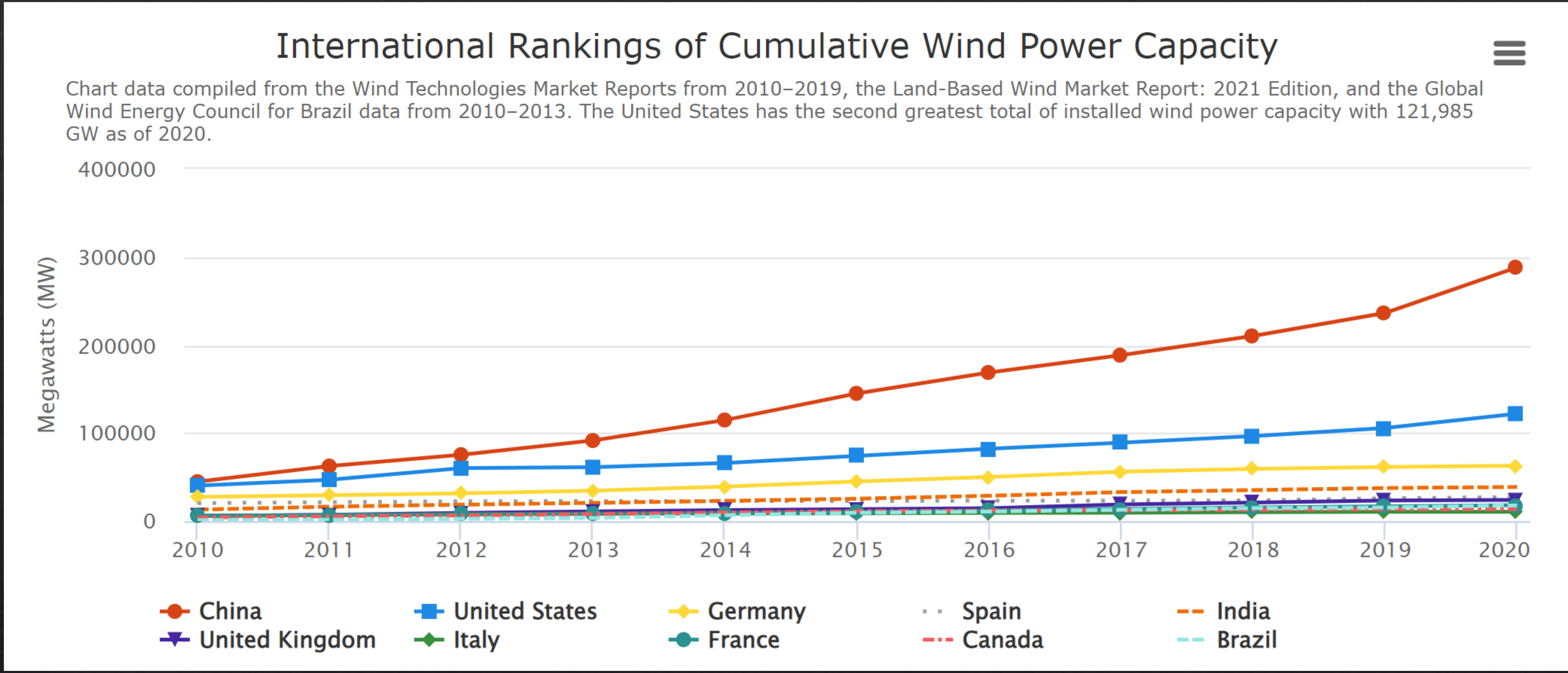
The first significant wind turbine designed specifically for electric power generation

Charles Brush's wind turbine in Cleveland, Ohio (Note the large tail and 144 blades. Compare the size of the unit with the size of the person standing on the ground on the right side of the unit.)

(By Unknown author – Robert W. Righter (1996) Wind Energy in America: A History, University of Oklahoma Press, p. page44 Retrieved on 27 December 2008. ISBN: 0806128127, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5599364)



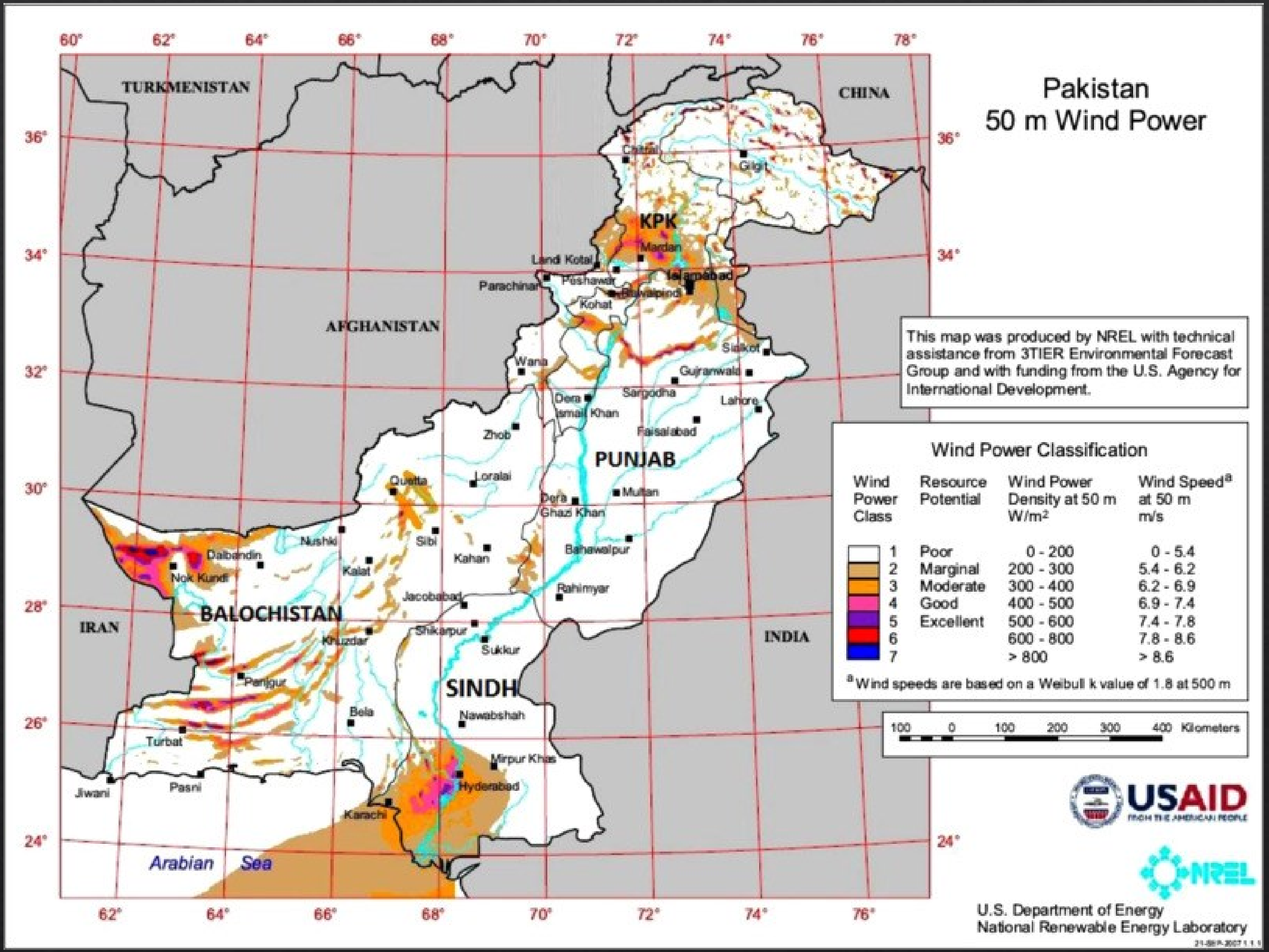
300m
200m
100m
13-15 MW
9 MW
7 MW
4 MW
2 MW
1.2 MW
0.5 MW
1-12kW
19th C
1990
1995
2000
2005
2010
2015
2025


International Rankings of Cumulative Wind Power Capacity
Chart data compiled from the Wind Technologies Market Reports from 2010–2019, the Land-Based Wind Market Report: 2021 Edition, and the Global Wind Energy Council for Brazil data from 2010–2013. The United States has the second greatest total of installed wind power capacity with 121,985 GW as of 2020.
Megawatts (MW)
400000
300000
200000
100000
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
China
United States
Germany
Spain
India
United Kingdom
Italy
France
Canada
Brazil

Pakistan – Wind Potential

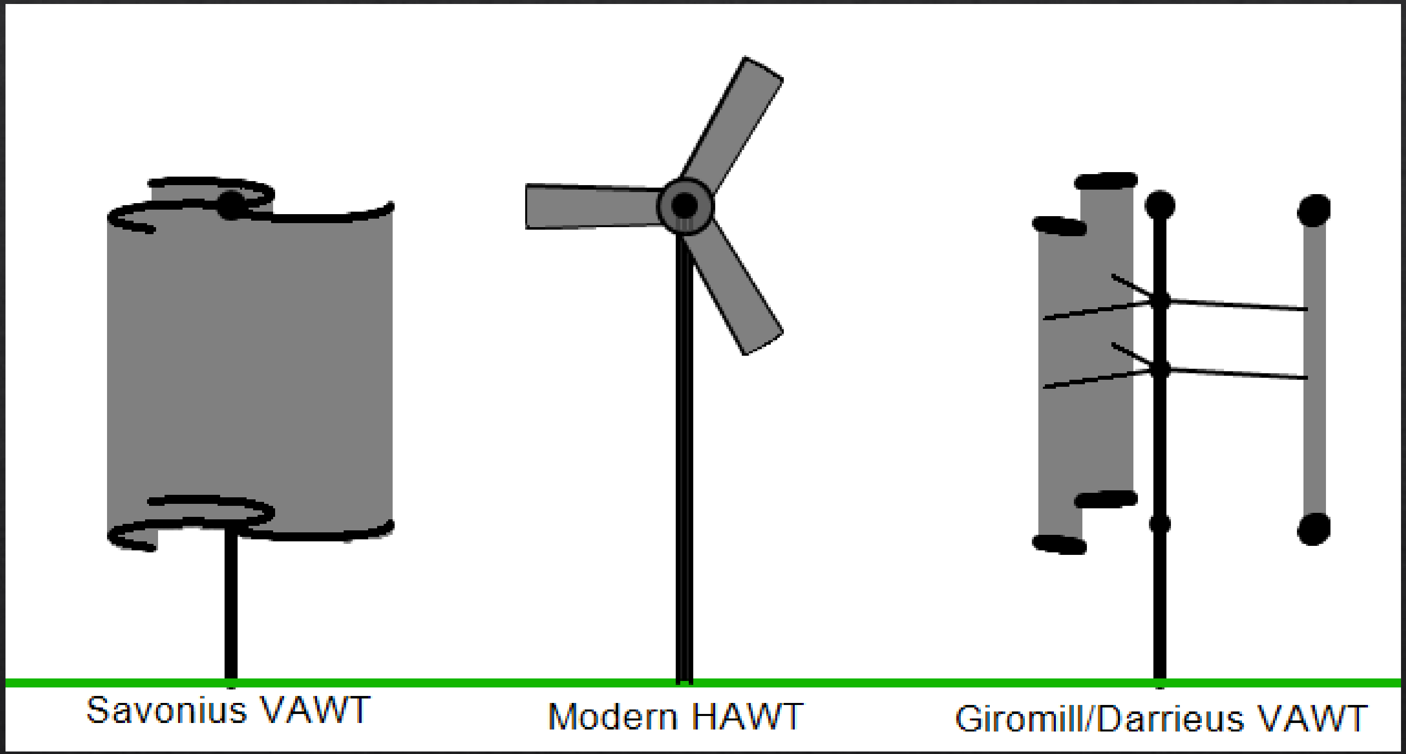
- Among alternative and renewable resources, wind power has been identified as a significant potential source of renewable energy for Pakistan.

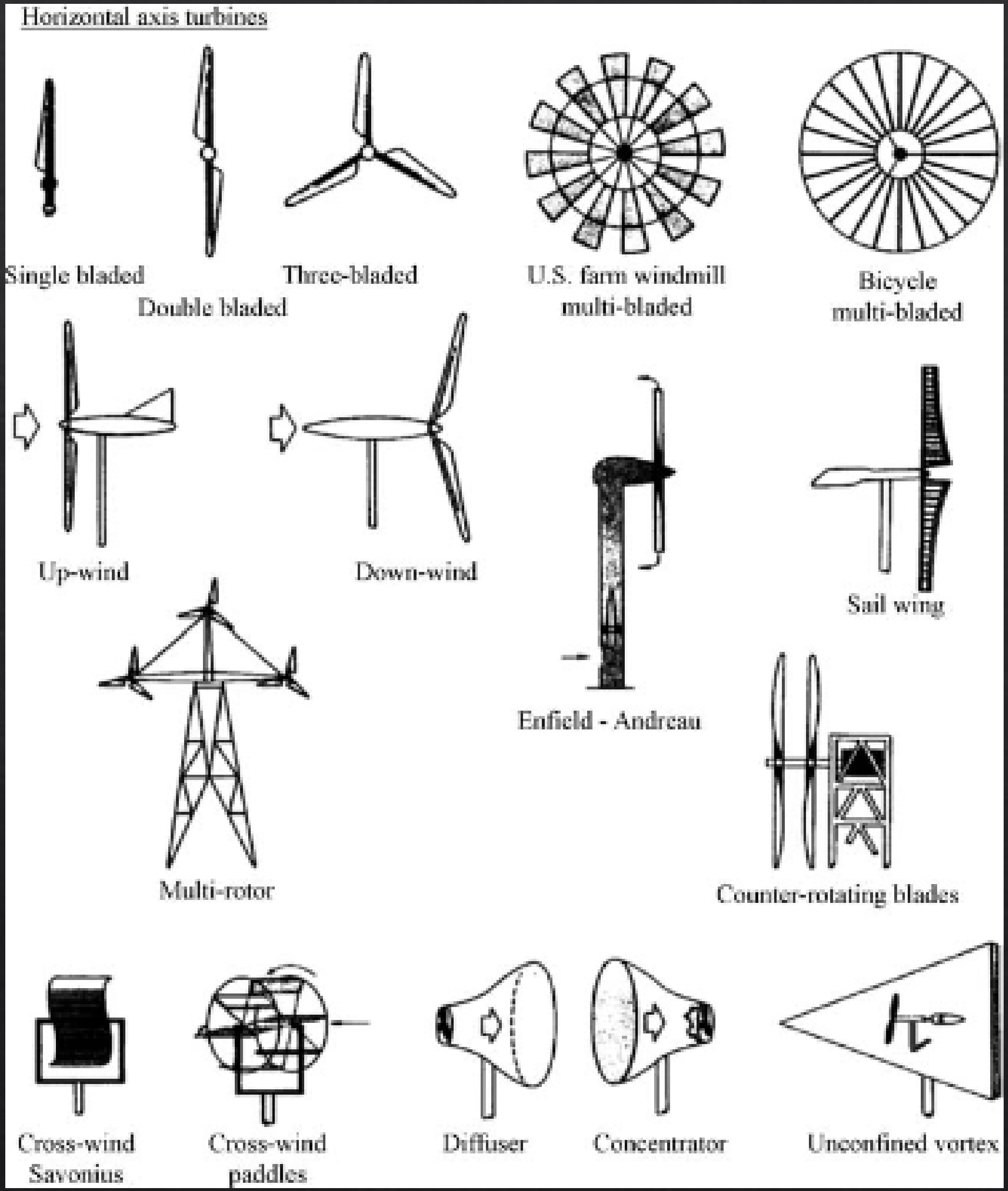
- The country has a total estimated gross wind power potential installable capacity of around **346,000 MW**



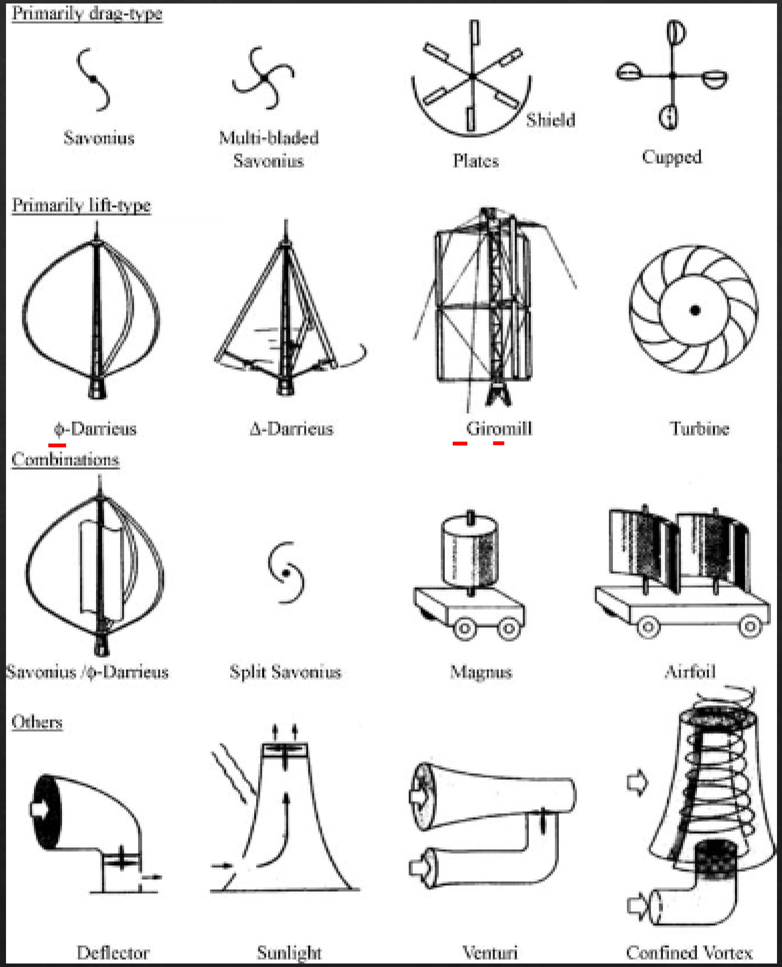
HAWT vs VAWT

- HAWT (Horizontal axis wind turbine)
  - The blades spin on an axis parallel to the ground, and the entire machine pivots (yaws) around to face the wind.
- VAWT (Vertical axis wind turbine)
  - The blades spin on an axis perpendicular to the ground; VAWT's don't need to yaw into the wind.



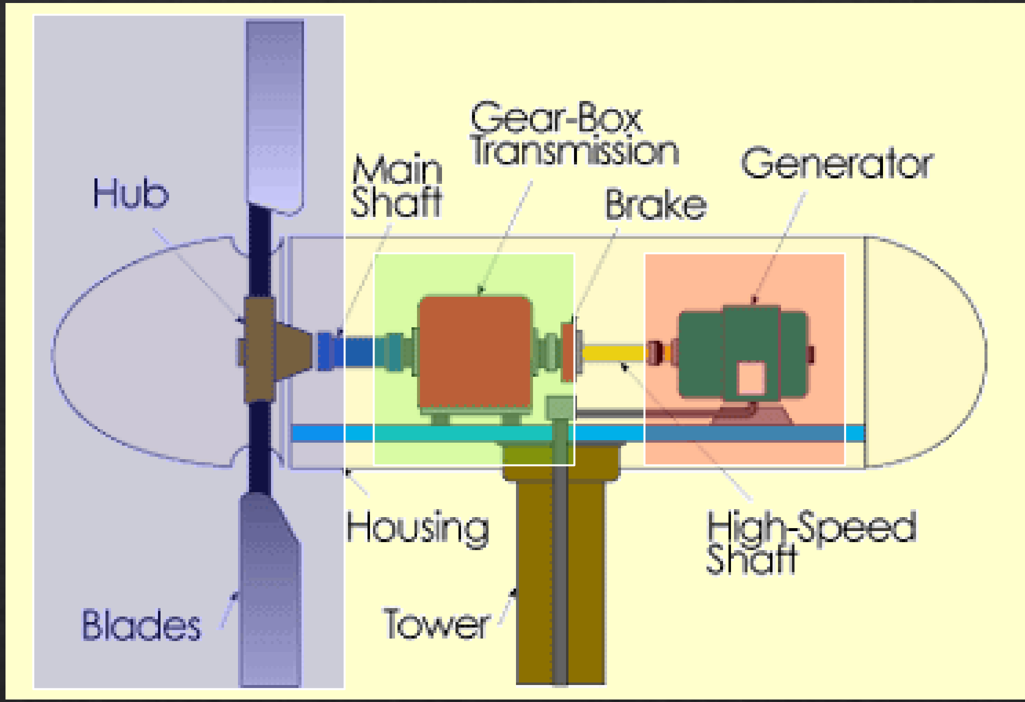


Vertical Axis



Modern Wind Turbines

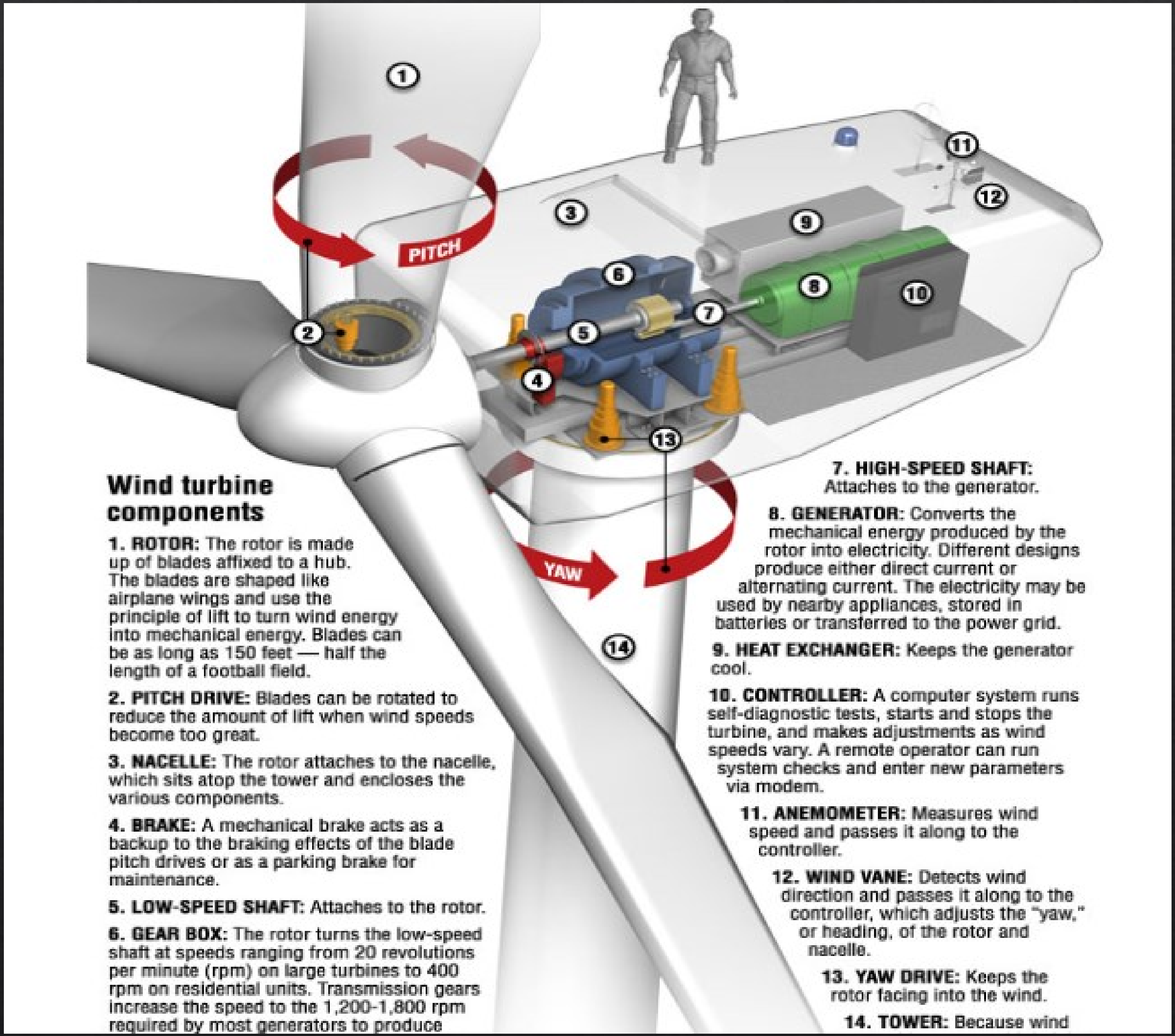
Main components of a Horizontal Axis Wind Turbine

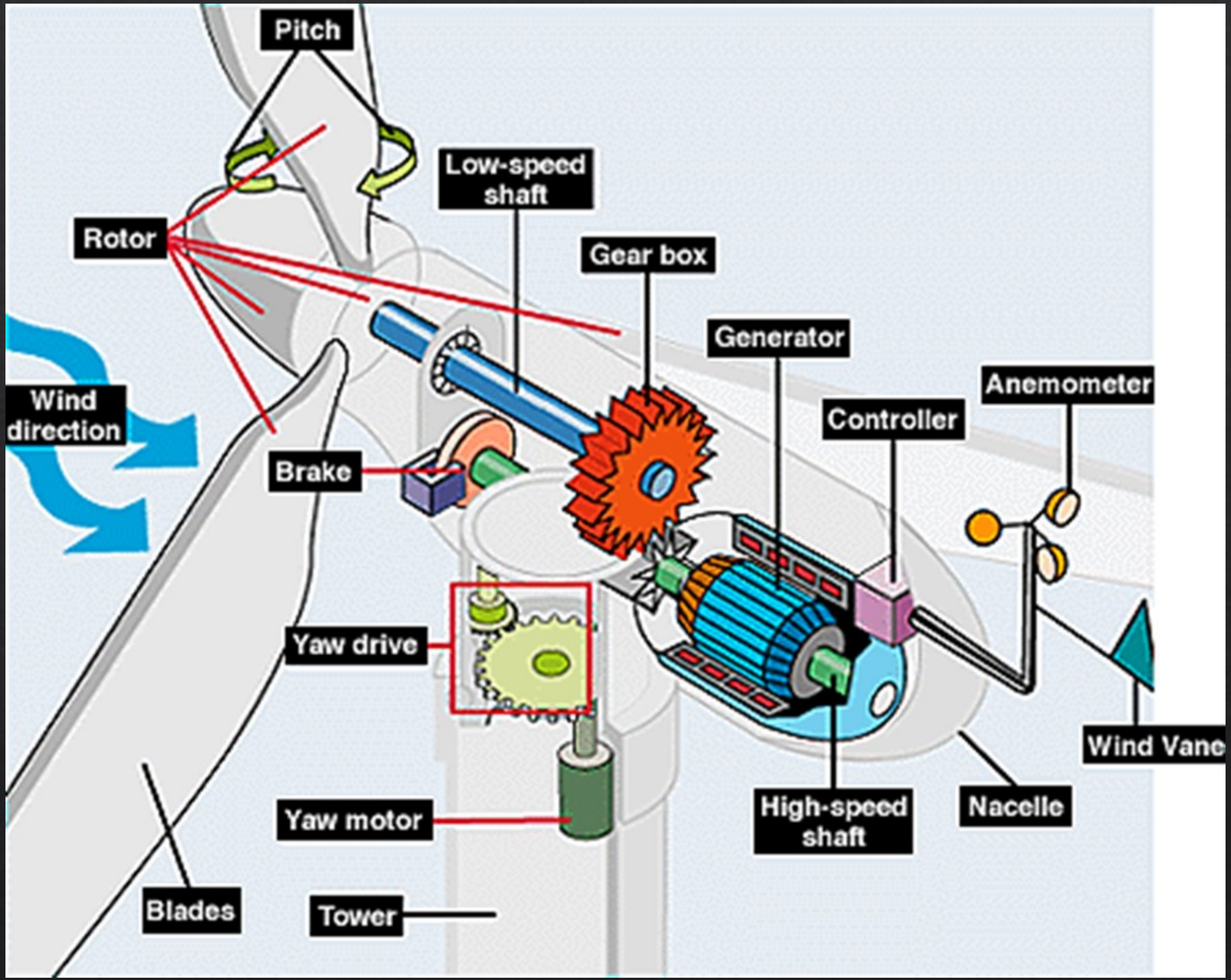


Rotor: Converts the wind power to a rotational mechanical power.

Generator: Converts the rotational mechanical power to electrical power.

Gear box: Wind turbines rotate typically between 20 rpm and 400 rpm. Generators typically rotates at 1,200 to 1,800 rpm. Most wind turbines require a step-up gear-box for efficient generator operation (electricity production).


1
PITCH
2
3
9
11
12
6
8
10
7
5
4
13
YAW
14
Wind turbine components
1. ROTOR: The rotor is made up of blades affixed to a hub. The blades are shaped like airplane wings and use the principle of lift to turn wind energy into mechanical energy. Blades can be as long as 150 feet — half the length of a football field.
2. PITCH DRIVE: Blades can be rotated to reduce the amount of lift when wind speeds become too great.
3. NACELLE: The rotor attaches to the nacelle, which sits atop the tower and encloses the various components.
4. BRAKE: A mechanical brake acts as a backup to the braking effects of the blade pitch drives or as a parking brake for maintenance.
5. LOW-SPEED SHAFT: Attaches to the rotor.
6. GEAR BOX: The rotor turns the low-speed shaft at speeds ranging from 20 revolutions per minute (rpm) on large turbines to 400 rpm on residential units. Transmission gears increase the speed to the 1,200-1,800 rpm required by most generators to produce
7. HIGH-SPEED SHAFT: Attaches to the generator.
8. GENERATOR: Converts the mechanical energy produced by the rotor into electricity. Different designs produce either direct current or alternating current. The electricity may be used by nearby appliances, stored in batteries or transferred to the power grid.
9. HEAT EXCHANGER: Keeps the generator cool.
10. CONTROLLER: A computer system runs self-diagnostic tests, starts and stops the turbine, and makes adjustments as wind speeds vary. A remote operator can run system checks and enter new parameters via modem.
11. ANEMOMETER: Measures wind speed and passes it along to the controller.
12. WIND VANE: Detects wind direction and passes it along to the controller, which adjusts the "yaw," or heading, of the rotor and nacelle.
13. YAW DRIVE: Keeps the rotor facing into the wind.
14. TOWER: Because wind


Pitch
Low-speed shaft
Rotor
Gear box
Generator
Anemometer
Controller
Wind direction
Brake
Yaw drive
Wind Vane
Yaw motor
High-speed shaft
Nacelle
Blades
Tower

Power of Wind

$$
\begin{aligned}
\text{Power} &= \text{Work} / t \\
&= \text{Kinetic Energy} / t \\
&= \tfrac{1}{2} m V^2 / t \\
&= \tfrac{1}{2} (\rho A d) V^2 / t \\
&= \tfrac{1}{2} \rho A V^2 (d/t) \\
&= \tfrac{1}{2} \rho A V^3
\end{aligned}
$$

$d/t = V$

Power in the Wind $= \tfrac{1}{2} \rho A V^3$

Power of Wind

Power in the Wind $= \frac{1}{2}\rho A V^3$

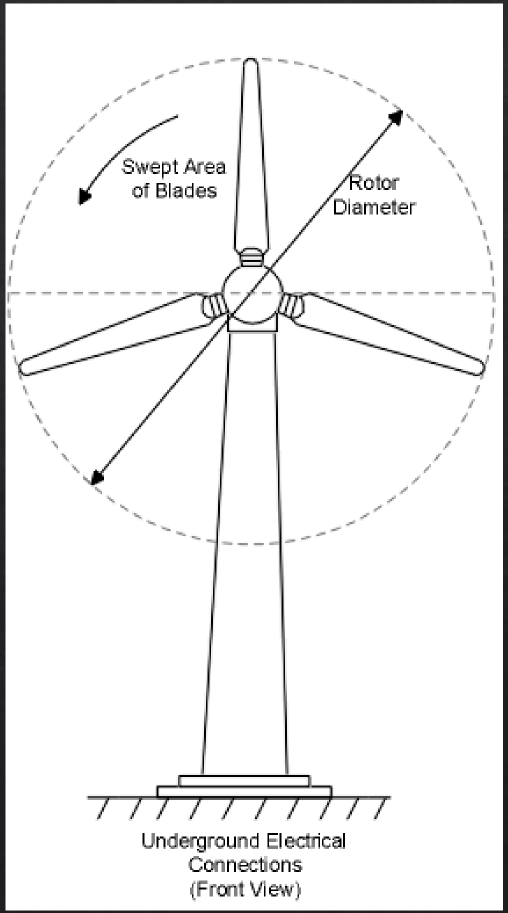
A more common parameter to express wind power is **wind power density**, which is defined as wind power per unit of area.

$$PD = \frac{P}{A} = \frac{1}{2}\rho V^3 \qquad (\mathrm{W/m^2}) \qquad (13.5)$$

Note that although the units of power density for wind energy and irradiance for solar energy are the same, the reference areas are different.
In solar energy, the area is on Earth's surface, while in wind energy, the area is perpendicular to the wind direction.

A couple things to remember…

- Swept Area – A = πR^2 (m^2) Area of the circle swept by the rotor.
- ρ = air density



Example 13.1

A horizontal-axis wind turbine with a radius of 10 m operates in a location with a uniform wind speed of 10 m/s. Determine the power of wind for an area equal to the swept area of the turbine and per unit of area.

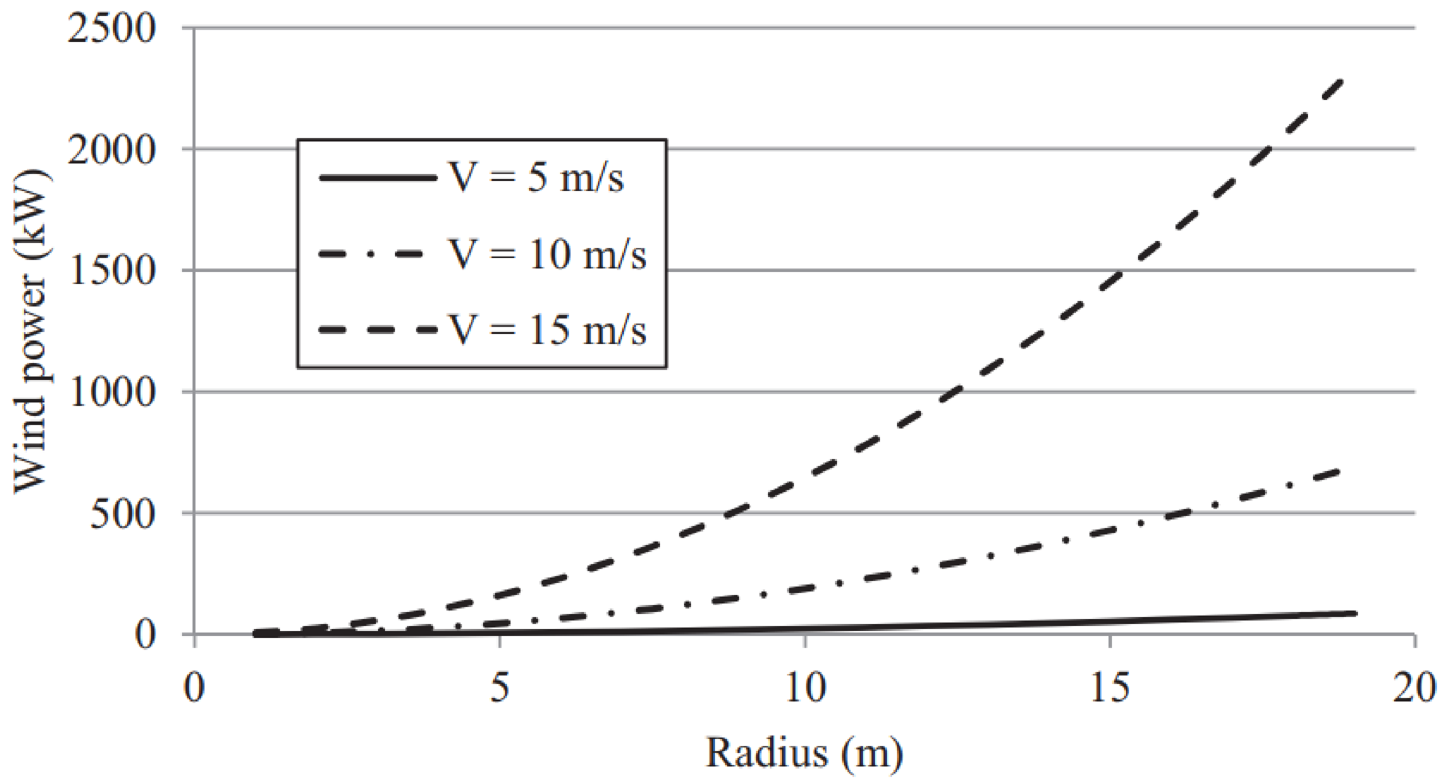


FIGURE 13.5
Diagram of wind power as a function of the radius of area perpendicular to the wind direction.

Wind Turbine Efficiency, η

Betz Limit (1919)

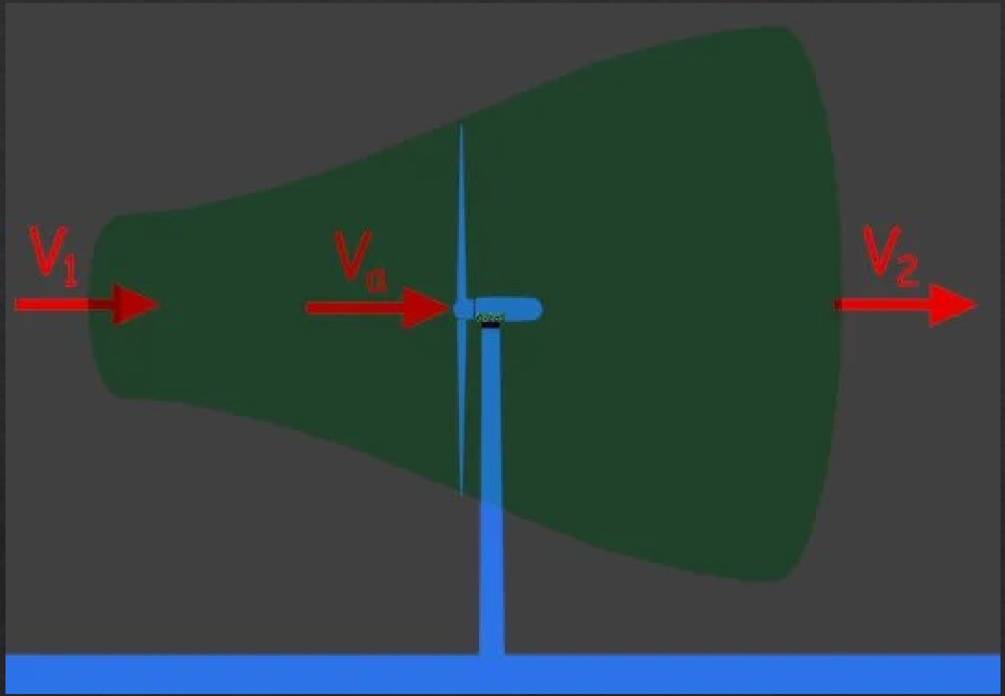
- The wind turbine extracts energy by slowing the wind down.

- The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is approximately 59.3%. This value is known as the Betz limit.

- If the blades were 100% efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop.

- In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%.

- A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will deliver between 10% and 30% of the original energy available in the wind.



Betz Limit Derivation – gives the maximum turbine output power

$$P_{\max} = \frac{8}{27}\rho A V_i^3 \qquad (13.15)$$

The efficiency, also known as the **power coefficient** (C_p) of the wind turbine can be calculated by dividing this output power of the turbine to the power of the wind in Equation 13.4, which gives

$$\eta_{\text{wind turbien}} = C_p = \frac{P_{\text{wind turbine}}}{P_{\text{wind}}} \quad \text{or} \quad P_{\text{wind turbine}} = C_p P_{\text{wind}} = \frac{1}{2} C_p \rho A_i^3 \qquad (13.16)$$

The maximum power coefficient of the ideal wind turbine can be calculated as follows:

$$\eta_{\max} = C_{p,\max} = \frac{P_{\max}}{P_{\text{wind}}} = \frac{\frac{8}{27}\rho A V_i^3}{\frac{1}{2}\rho A V_i^3} = \frac{16}{27} \sim 0.593 \qquad (13.17)$$

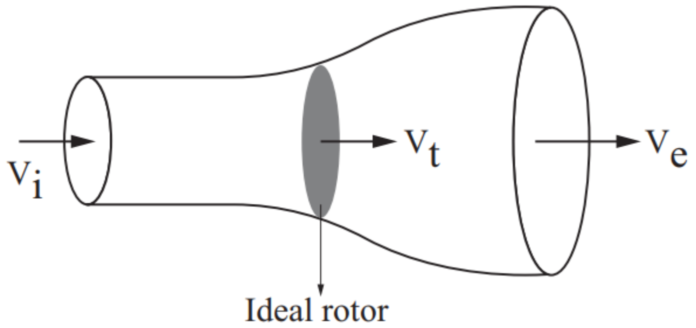


FIGURE 13.6
Schematic for the derivation of Betz's law.

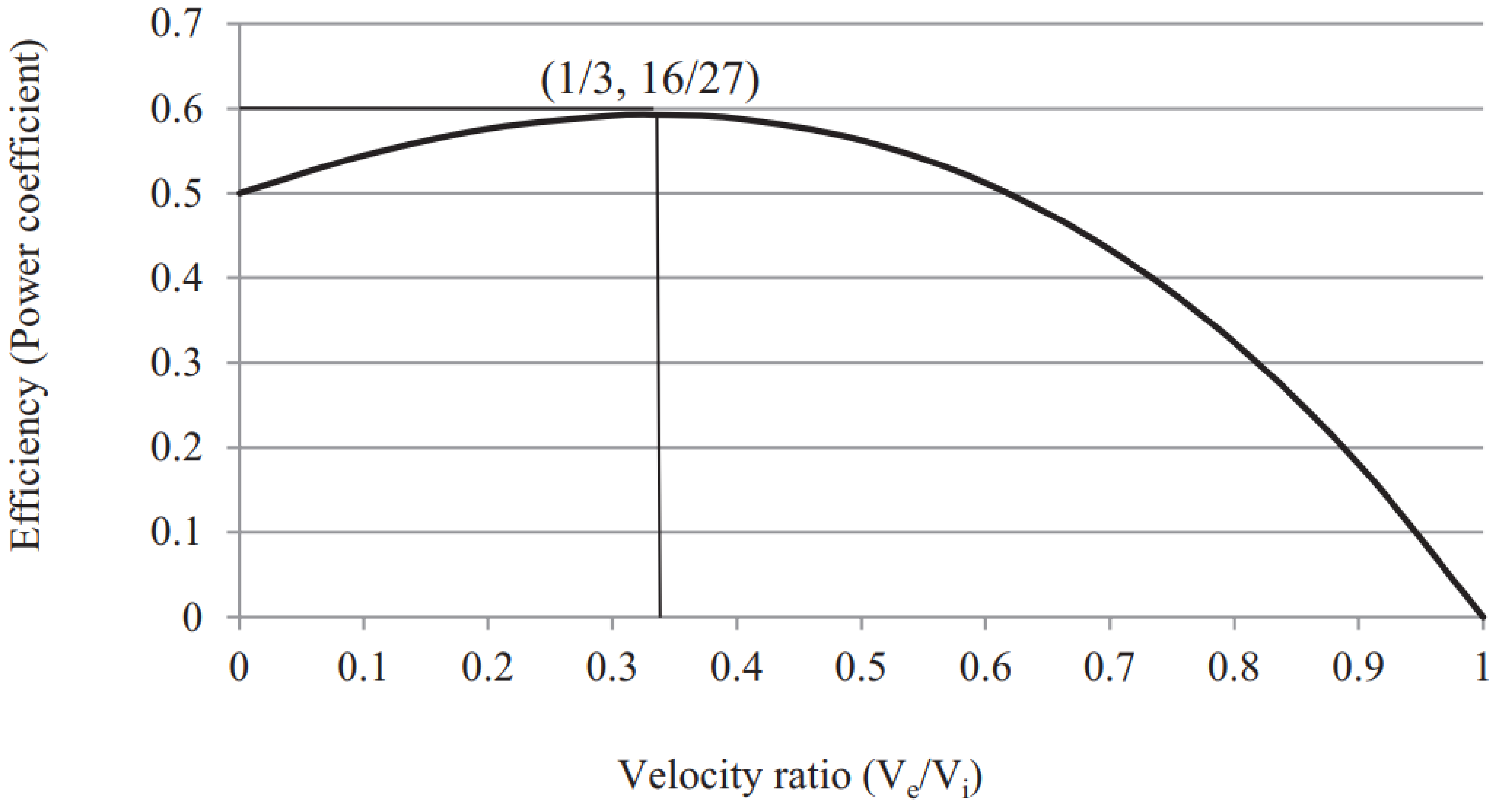


FIGURE 13.7
Efficiency (power coefficient) of an ideal wind turbine as a function of the ratio of upstream wind velocity to downstream wind velocity.

Example 13.2

Determine the blade diameter of a turbine with the rated (design) output power of 7.5 MW when the rated (design) wind speed is 12 m/s. The power coefficient of the turbine is 0.55. Repeat your calculation for the power coefficient equal to the Betz limit and 0.45.

Classification of Wind Speed at the height of 10 m and 50 m

Wind Power Category	Wind Speed at Height of 10 m (33 ft) in m/s (mph)	Wind Speed at Height of 50 m (164 ft) in m/s (mph)
poor	0–4.5 (0–10)	0–5.5 (0–12.3)
Moderate	4.5–5.5 (10–12.3)	5.5–7.0 (12.3–15.7)
Good	5.5–6 (12.3–13.4)	7–7.5 (15.7–16.8)
Excellent	>6 (>13.4)	>7.5 (>16.8)

A meteorological tower. (Image by Hans Braxmeier from Pixabay, https://pixabay.com/photos/ weather-station-anemometer-5580/)

A cup anemometer. (Image by Dragan Stanojevic from Pixabay, https://pixabay.com/photos/ anemometer-apparatus-wind-5532291/)

A handhold propeller anemometer. (Image by Bernabe Colohua from Pixabay, https://pixabay. com/photos/anemometer-kelner-temperature-wind-5160777/)

Wind Turbine

Cut-in Speed

Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7 and 15 mph.

Rated Speed

- The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power.
- For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 25 mph.
- Rated speed for most machines is in the range of 25 to 35 mph.
- Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

Wind Turbine

Cut-out Speed

- At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down.
- The wind speed at which shut down occurs is called the cut-out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage.
- Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor.

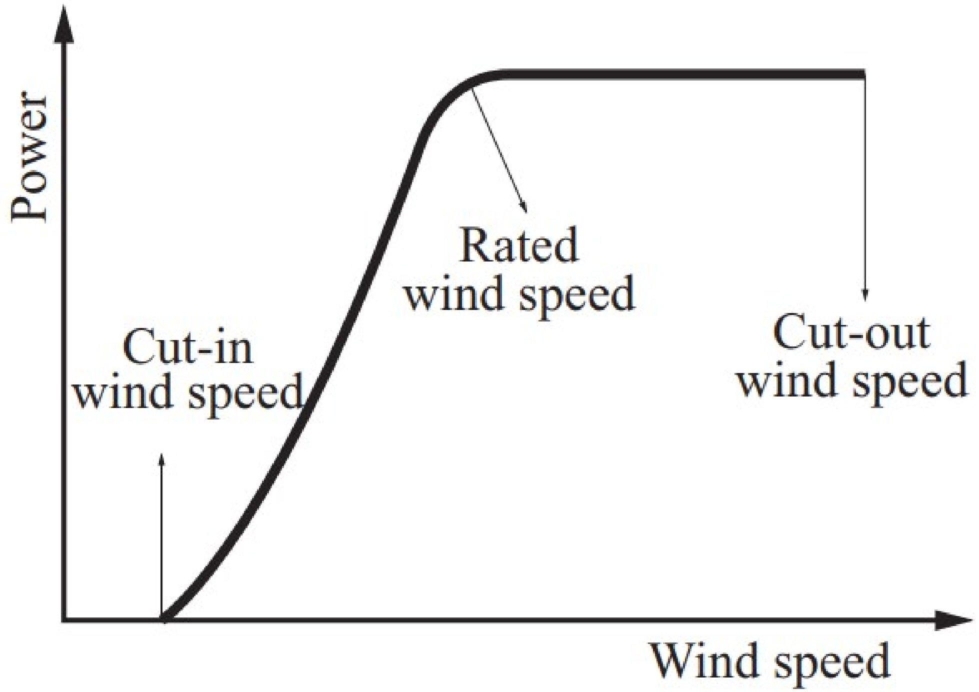
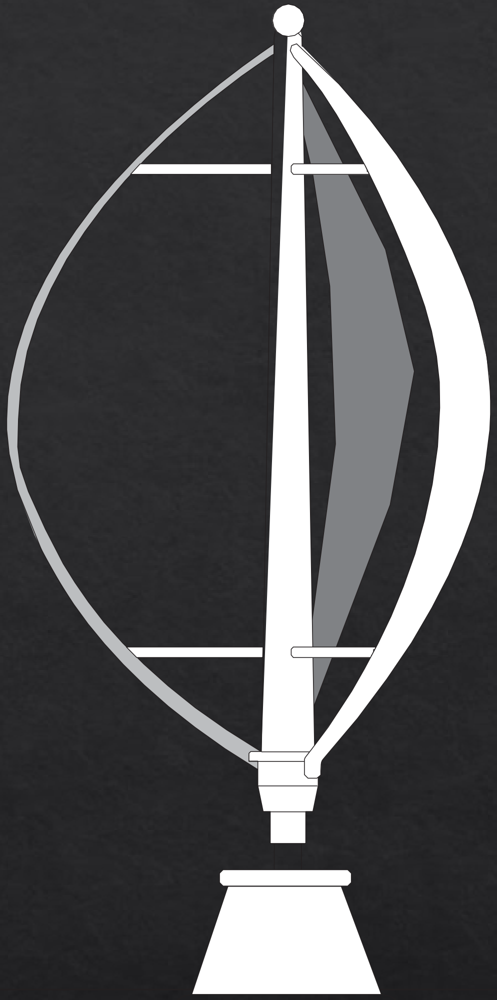


FIGURE 13.25
A typical power curve of a wind turbine.



Schematic of a Darrieus VAWT and an actual unit. (By guillom – Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=466915)

Horizontal-axis wind turbines with two blades. (Image by skeeze from Pixabay, https://pixabay.com/photos/windmills-farm-technology-energy-705282/)

A horizontal-axis wind turbine with six blades. (Image by Shutterbug75 from Pixabay, https:// pixabay.com/photos/air-battery-blade-breeze-charge-1238449/)

A residential wind turbine. (By Tobi Kellner – Own work, CC BY-SA 3.0, https://commons. wikimedia.org/w/index.php?curid=25275689)

A wind turbine blade at construction stage. (Image by Bishnu Sarangi from Pixabay, https:// pixabay.com/photos/wind-mill-turbine-rolling-stock-3674248/)

Connection of blades to the hub before (a) and after installation (b). (a: Image by Hans Linde from Pixabay, https://pixabay.com/photos/windr%C3%A4der-pinwheel-site-2759645/. b: Image by Steppinstars from Pixabay, https://pixabay.com/photos/windmill-wind-wind- turbine-electric-62257/)

Environmental Impacts of Wind Turbines

- The most important impact of wind turbines on wildlife is their effects on flying animals, such as birds and bats.
- Noise
- Land
  - The installation of wind turbines in agricultural lands, where the space between turbines can be effectively used.

Statistical Analysis of Wind Data

- Wind velocity is stochastic – Take Average?

Statistical Analysis of Wind Data

- Wind velocity is stochastic – Take Average?

$$\left(V_{\text{avg}}\right)^3 \neq \left(V^3\right)_{\text{avg}} \tag{13.18}$$

If we use the average wind velocity to estimate wind energy, it can be very misleading. If we have n readings for the velocity of wind, the average wind velocity is

$$\bar{V} = \frac{\sum_1^n V_i}{n} \tag{13.19}$$

But the mean velocity that correctly represents wind energy (known as the **mean energy velocity**, $\bar{V}_E$) can be estimated from the following equations:

$$\bar{V}_E = \left(\frac{\sum_1^n V_i^3}{n}\right)^{1/3} \tag{13.20}$$

Example 13.3

In a region for points *A* to *E*, wind velocity is measured ten times. The wind velocity data in the region are listed in Table 13.2. For each set of data determine the average wind velocity and the mean energy velocity.

TABLE 13.2

Wind Velocity Data for Example 13.3

Wind Velocity	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}
A	0	2	4	6	8	10	12	14	16	18
B	0	0	0	0	0	18	18	18	18	18
C	0	0	0	0	0	0	0	0	0	18
D	0	18	18	18	18	18	18	18	18	18
E	6	4	10	8	2	4	18	12	12	10

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Wind Velocity	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	$\bar{V}$	$\bar{V}_E$
A	0	2	4	6	8	10	12	14	16	18	9.0	11.7
B	0	0	0	0	0	18	18	18	18	18	9.0	14.3
C	0	0	0	0	0	0	0	0	0	18	1.8	8.4
D	0	18	18	18	18	18	18	18	18	18	16.2	17.4
E	6	4	10	8	2	4	18	12	12	10	8.6	10.7

As the table illustrates in all cases using average wind velocity will underestimate the wind energy sometimes with significant errors.

End of Lecture!