TSTE26 Powergrid and technology for renewable production

Lecture 5
Wind turbines

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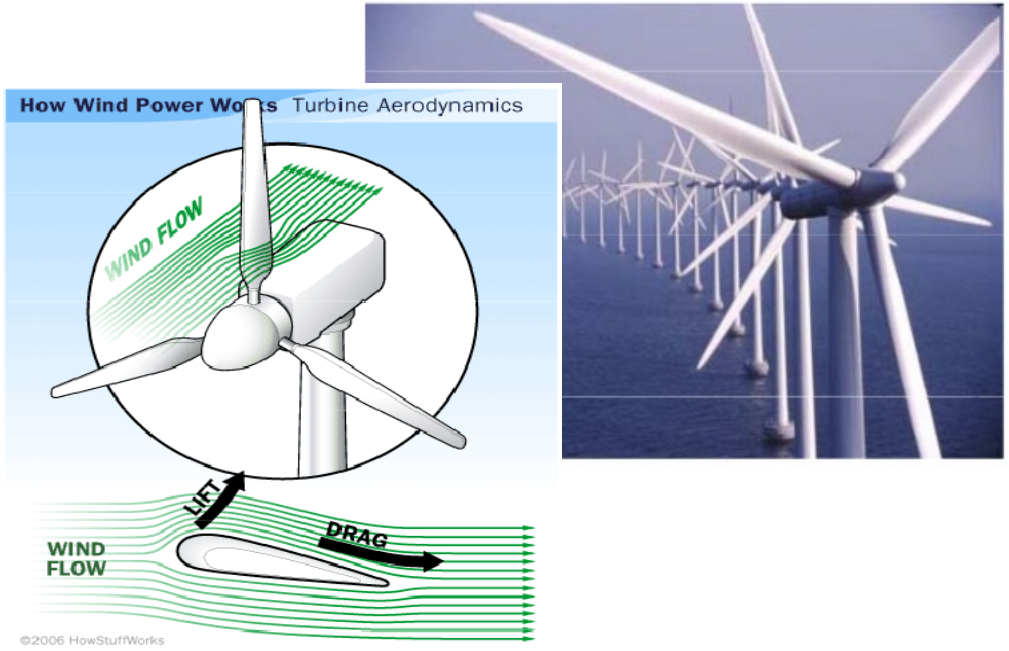
Understanding wind power

- Wind fundamentals
  - Power vs wind equations
  - Basic turbine aerodynamics
- Power control: Pitch, Yaw, Break
- Basic equipment
  - Generator
  - Gear-box
  - Transformer



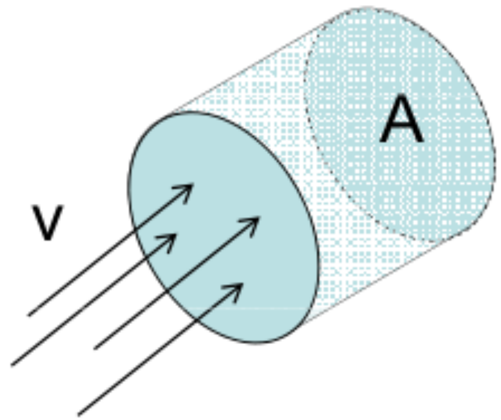
Literature (Available as eBooks at Liu library)

1. Wind Power Integration: Connection and System Operational Aspects 2nd ed, Brendan Fox et al, IET 2014 **(Chapter 3)**
2. Grid Integration of Wind Energy: Onshore and Offshore Conversion Systems, Third Edition, Siegfried Heier, John Wiley & Sons © 2014 **(Chapter 2, more details)**

Fundamental Equation of Wind Power

- Wind Power depends on:
  - amount of air (volume)
  - speed of air (velocity)
  - mass of air (density)

  flowing through the area of interest (flux)



- **Kinetic Energy** definition:
  - KE = ½ * m * v ^{2}

$$\dot{m} = \frac{dm}{dt}$$ mass flux

- Power is KE per unit time:
  - $P = {}^1/_2 \cdot \frac{dm}{dt} \cdot v^2$
- Fluid mechanics gives **mass flow rate** (density * volume flux):

$$\frac{dm}{dt} = \rho \cdot A \cdot v$$

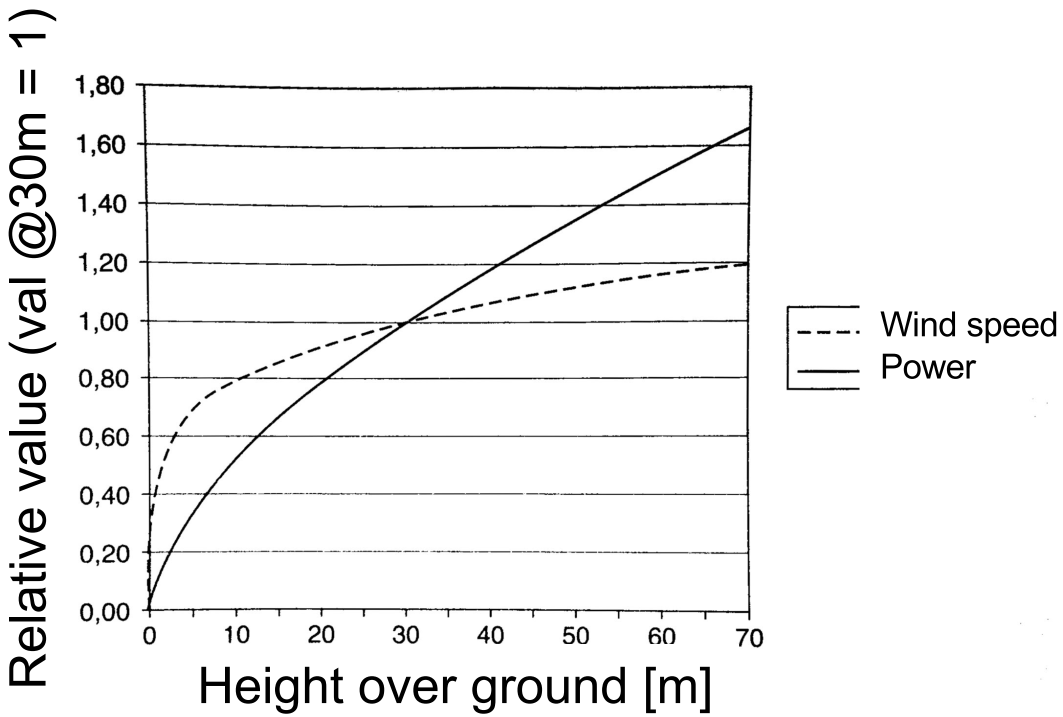
- Thus:

$$P_w = {}^1/_2 \cdot \rho \cdot A \cdot v^3$$

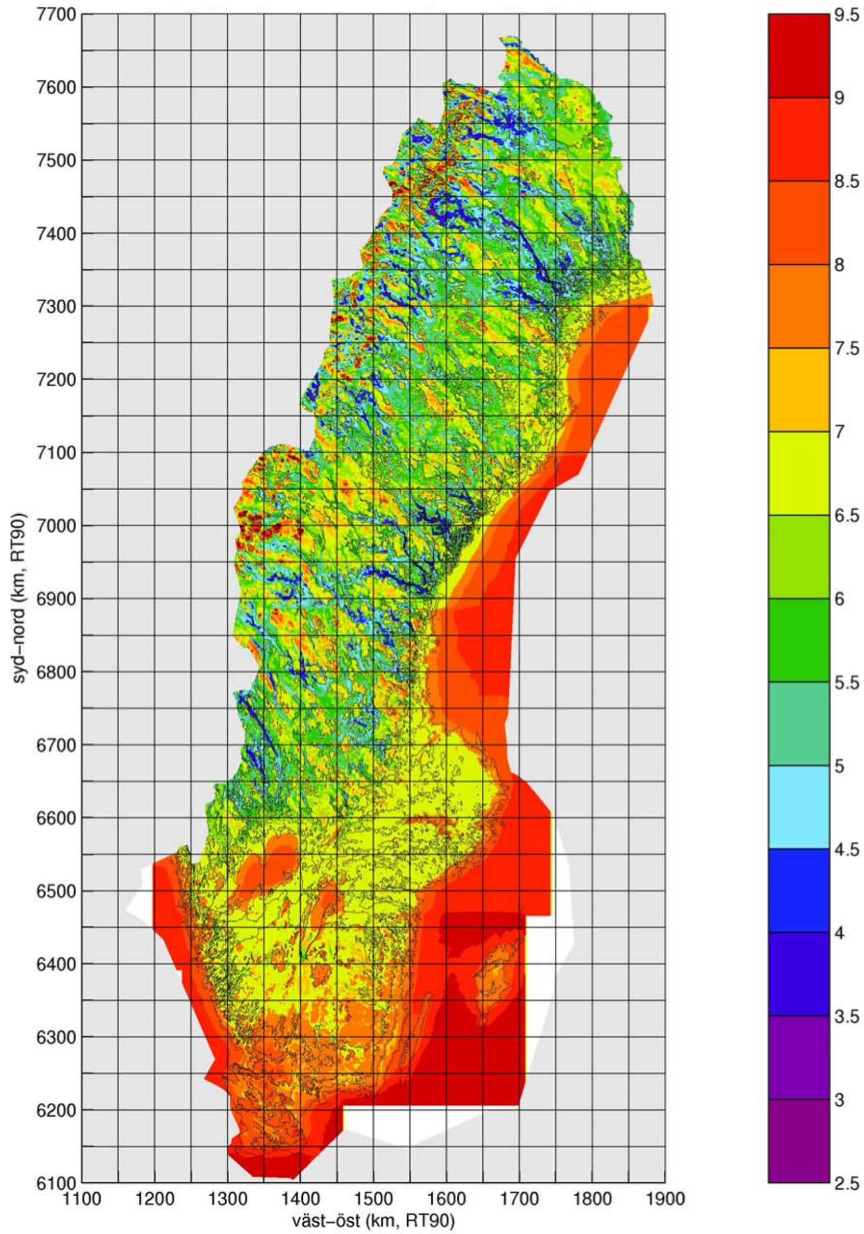
⇒

- Power ~ cube of velocity
- Power ~ air density
- Power ~ rotor swept area A= πr^2

Wind power



Average wind power for one year



Large wind power plants at sea/coast efficient

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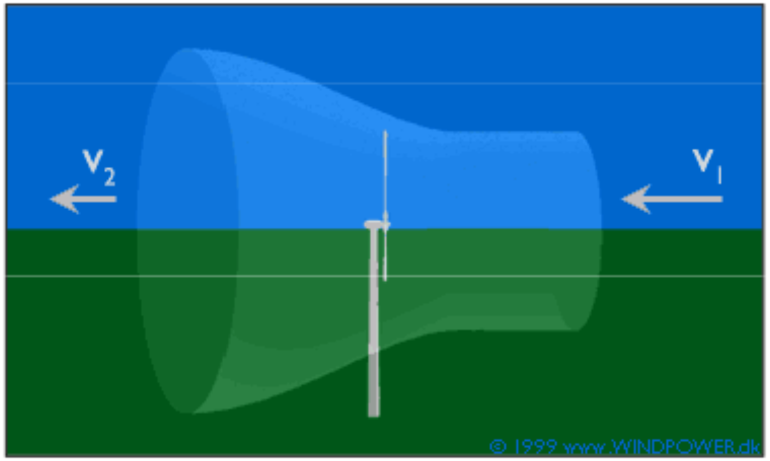
Efficiency in Extracting Wind Power

Betz Limit & Power Coefficient:

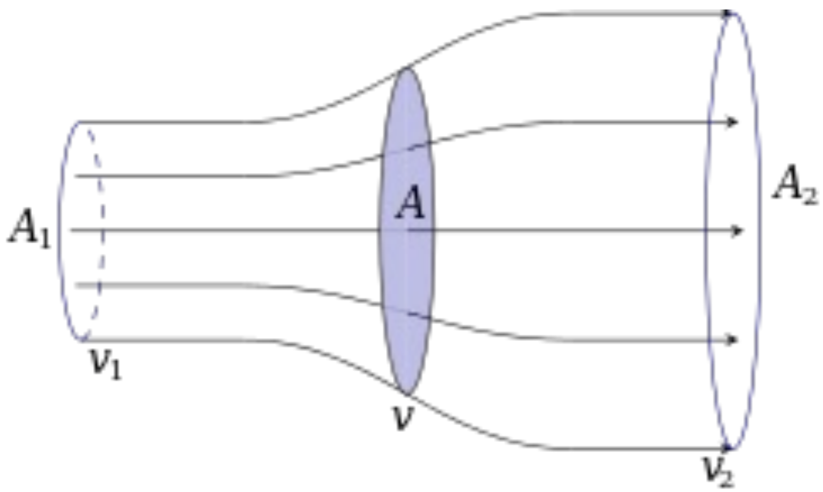
- Power Coefficient, **Cp**, is the ratio of power extracted by the turbine to the total contained in the wind resource Cp = P_T/P_W
- Turbine power output

$$P_T = \frac{1}{2} * \rho * A * v^3 * Cp$$

- The **Betz Limit** is the maximal possible Cp = 16/27
- **59%** efficiency is the **BEST** a conventional wind turbine can do in extracting power from the wind



The Betz limit



Continuity of volume flow [kg/s]:

$$\dot{m} = \rho A_1 v_1 = \rho A v = \rho A_2 v_2$$

Captured power from air flow:

$$P_{\text{turbine}} = P_{\text{air}(v_1)} - P_{\text{air}(v_2)} = C_p \cdot P_{\text{air}}$$

$$P_{\text{air}(v_1)} = \frac{1}{2}\rho A_1 v_1 \cdot v_1^2 \qquad P_{\text{air}(v_2)} = \frac{1}{2}\rho A_2 v_2 \cdot v_2^2$$

Max turbine power when wind slowed down to a third of the free wind speed

Max C_p at: $v_2 = \frac{v_1}{3}$

$$\Rightarrow C_{pmax} = \frac{16}{27} = 0.59$$

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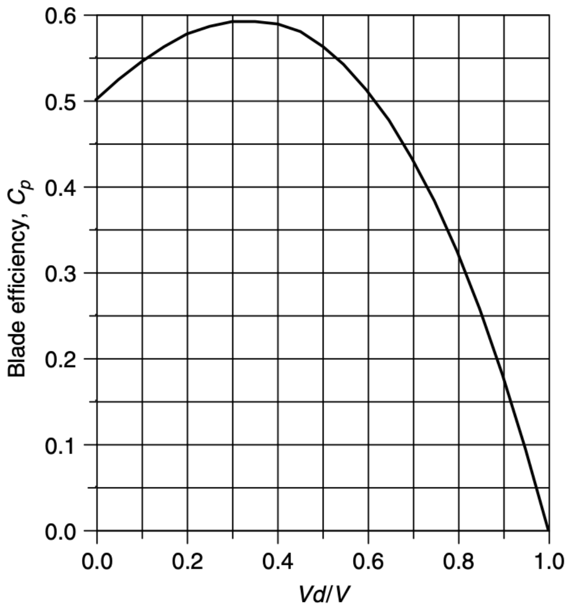
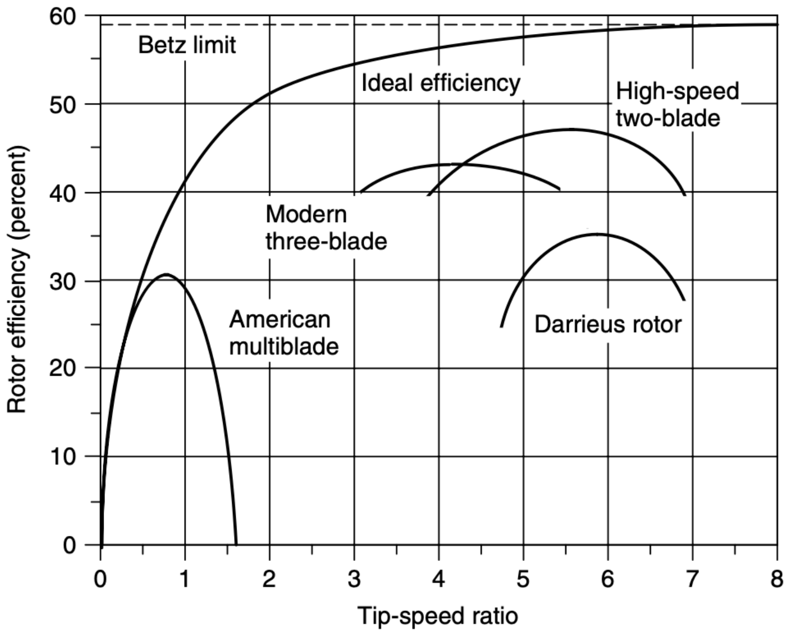
Maximum efficiency in windturbines

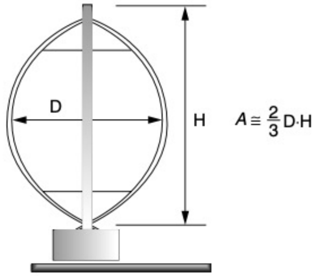
In practice:

Modern wind turbines reach about 80% of the Betz limit.

Betz theoretic curve







Darrieus

Tip speed ratio

Rotational speed of blades

- Revolutions per minute: n [rpm]
- Angular speed: $\omega = 2\pi \frac{n}{60}$ $[{}^{rad}/_{s}]$

Tip speed increases with the radius

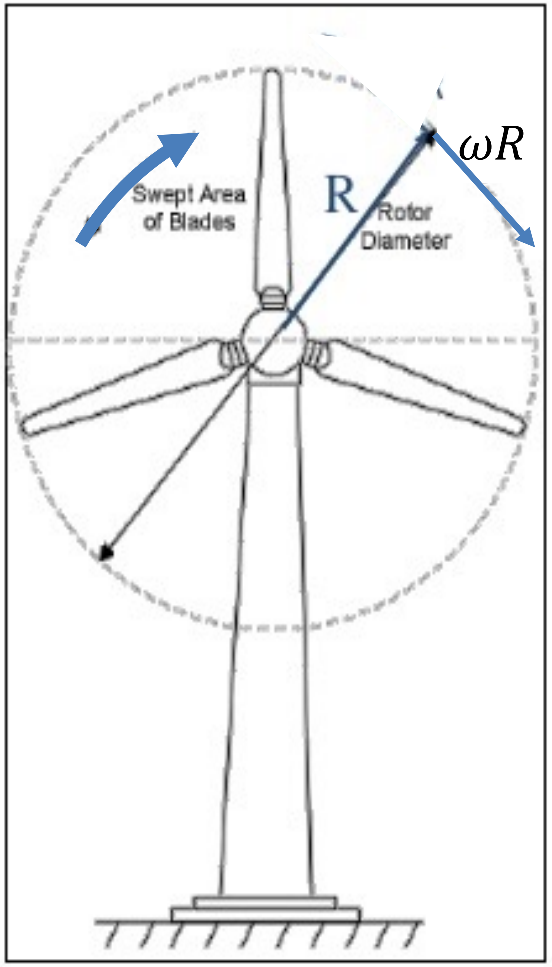
$$v_{tip} = \omega R \text{ [m/s]}$$

Wind speed, v_w [m/s]

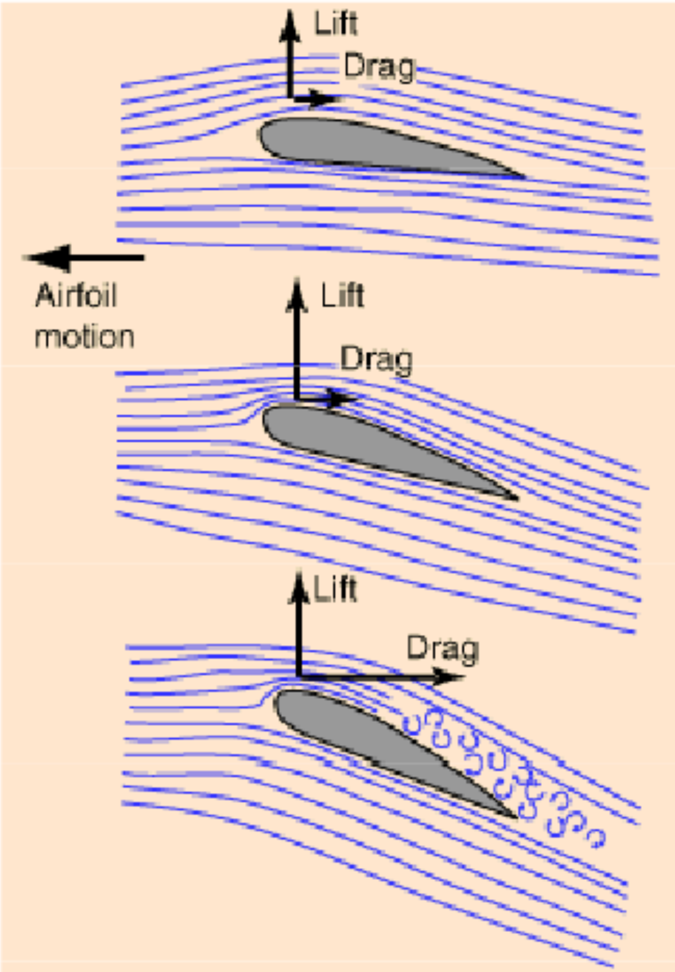
Tip speed ratio

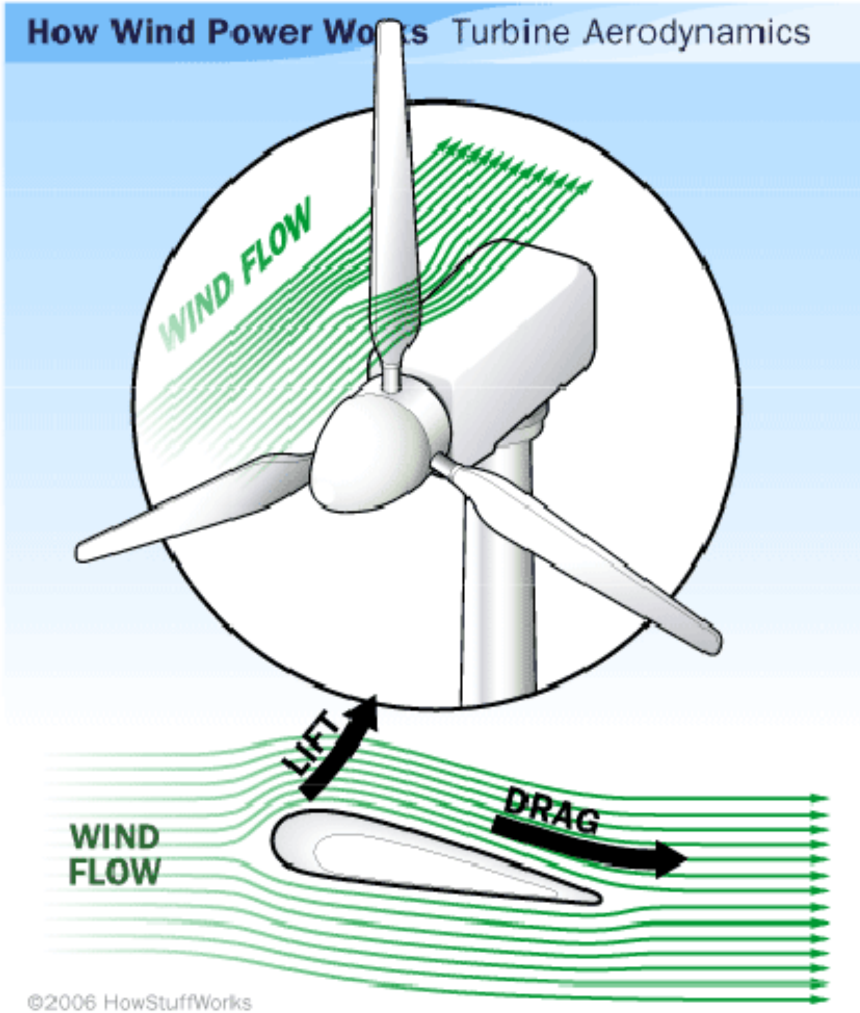
- Tip speed to wind speed ratio

$$TSR = \lambda = \frac{v_{tip}}{v_w} = \frac{\omega R}{v_w}$$



Lift and Drag Forces



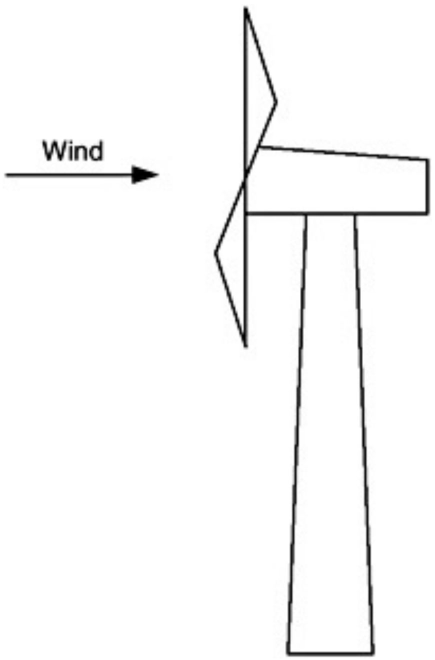


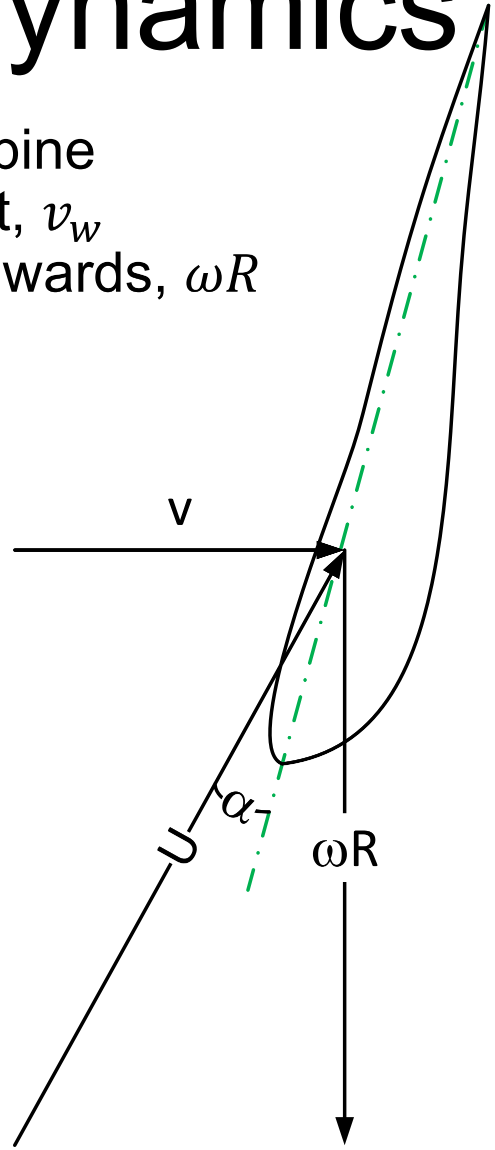
Youtube film illustrating aerodynamics

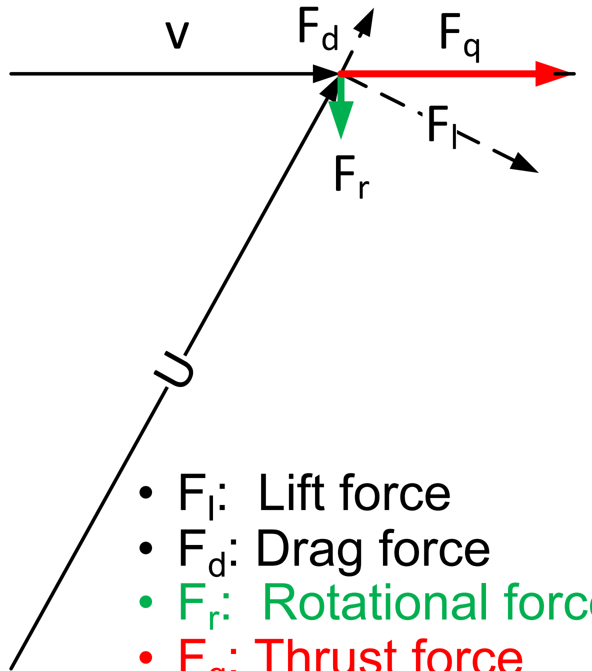
Blade aerodynamics

- Side view of the turbine
- Wind in from the left, v_w
- Blade moving downwards, ωR
- Apparent wind, U
- Angle of attack, α

$$U = \sqrt{{v_w}^2 + (\omega R)^2} =$$
$$= v_w \sqrt{1 + \left(\frac{\omega R}{v_w}\right)^2}$$







- F_l: Lift force
- F_d: Drag force
- F_r: Rotational force
- F_q: Thrust force

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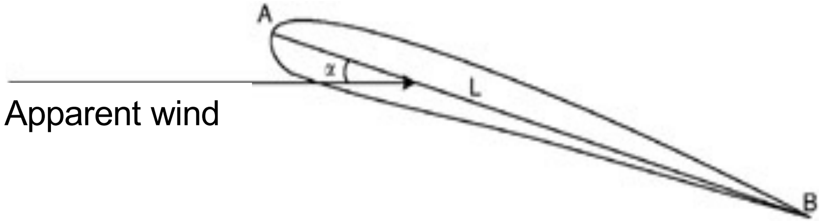
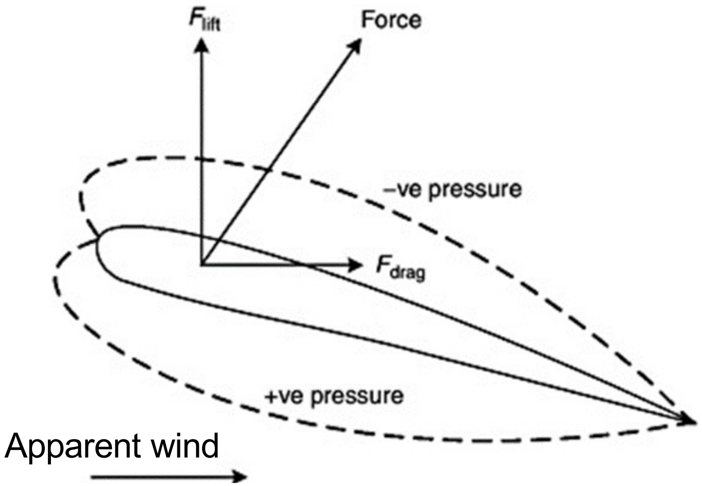
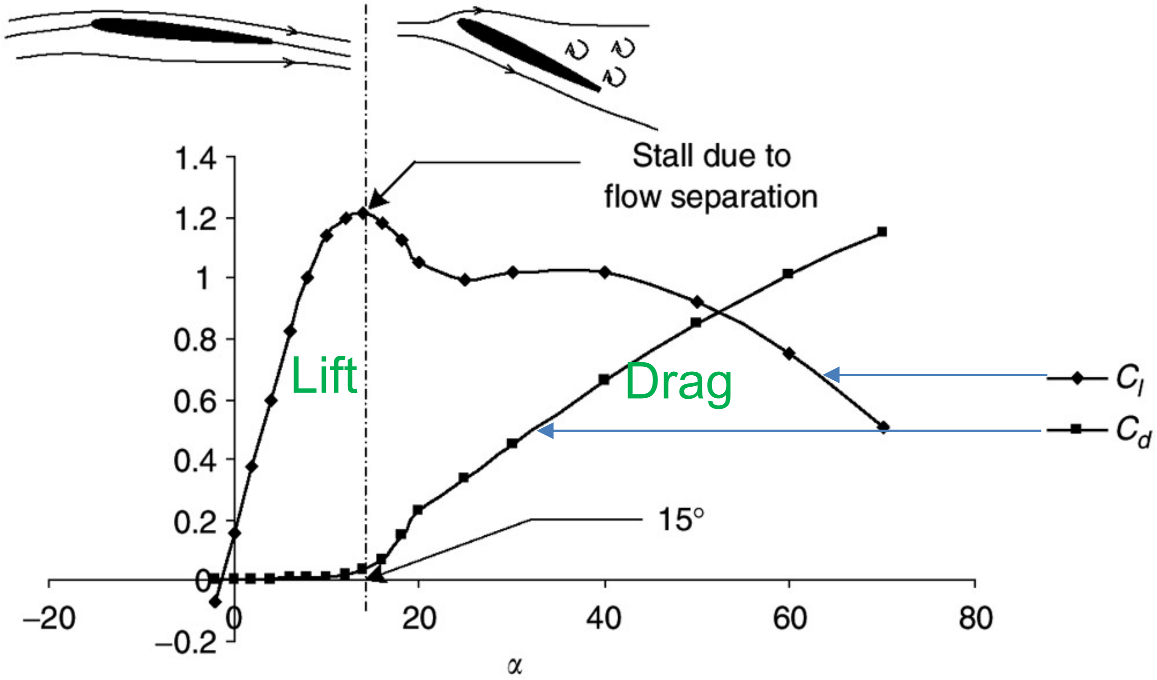
Angle of attack



The lift force is proportional to C_l and the drag force to C_d

A: leading edge
B: trailing edge
L: chord line (a straight line between the leading and trailing edges)
α: the angle of attack between the apparent wind and the chord line.

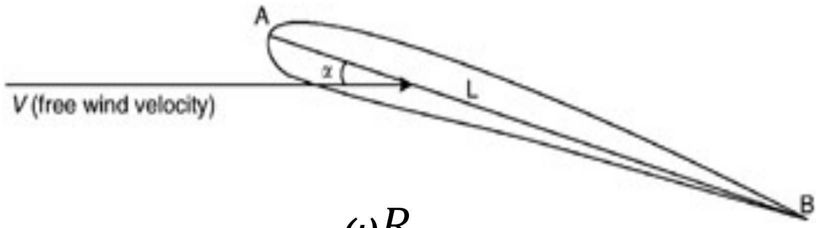




Maximum power point

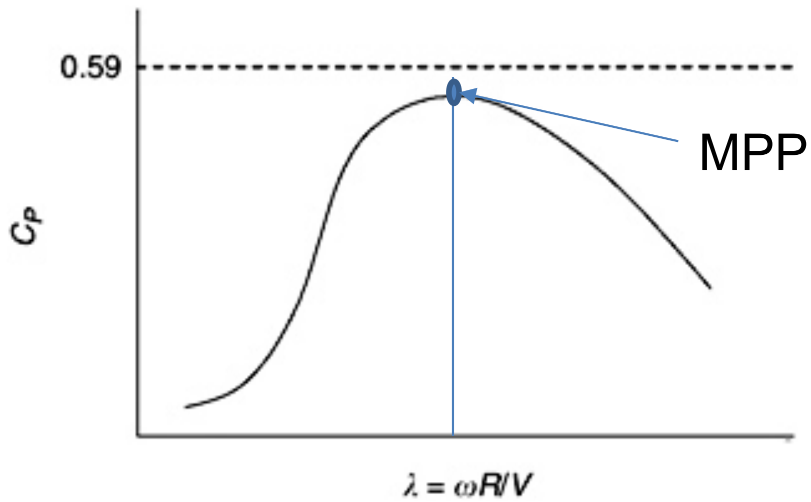
1. Captured power depends on lift force
2. Lift force depends on angle of attack
3. Angle of attack depends on tip-speed ratio

MPP given by C_P vs Lambda curve, $C_P(\lambda)$



$$\lambda = \frac{\omega R}{v_w}$$

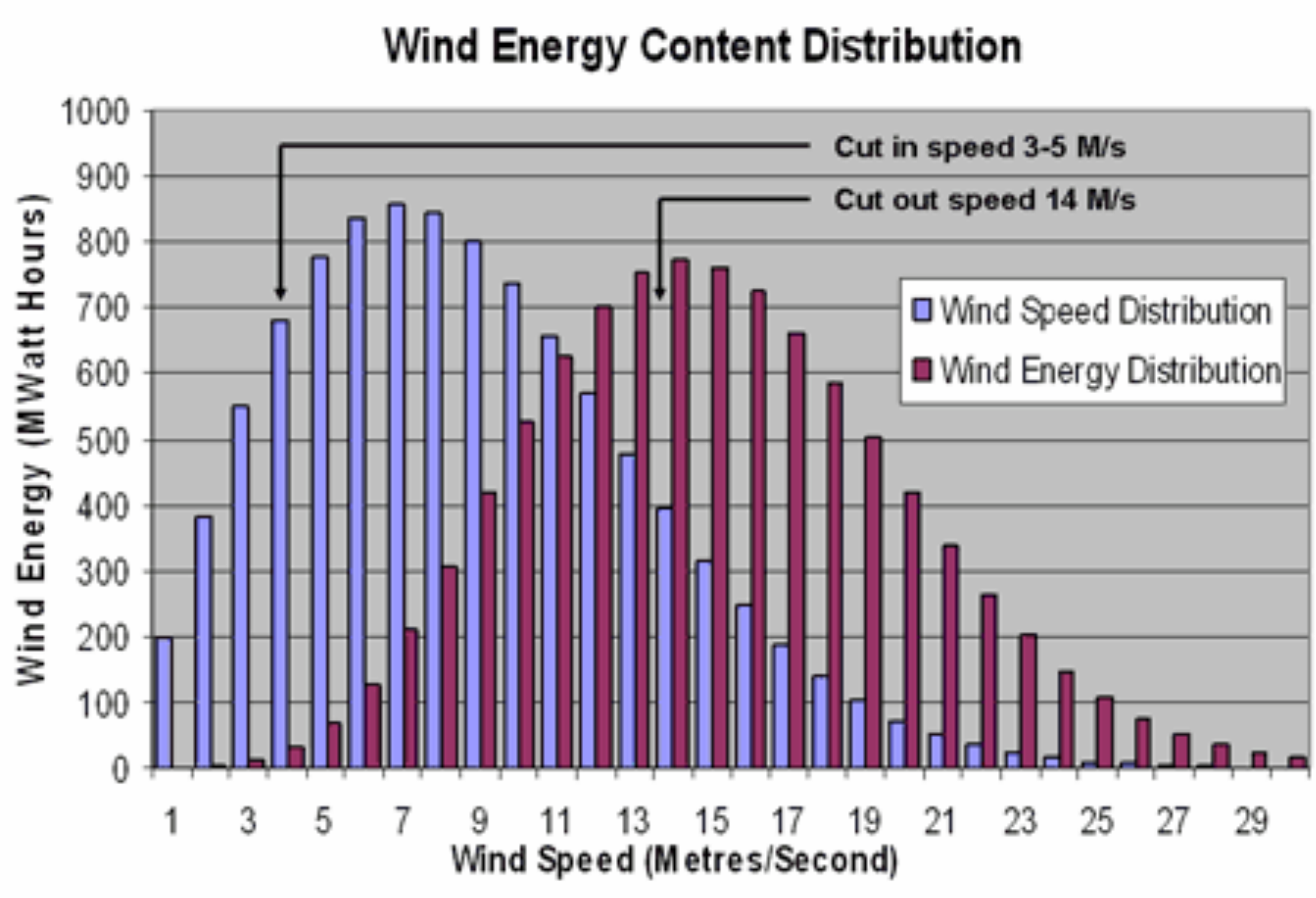
$$P_{\text{turbine}} = C_P(\lambda) \cdot P_{\text{air}} = C_P(\lambda) \cdot \frac{1}{2}\rho A V^3$$



Keep λ constant to maximize power!

Wind energy distribution

- Available energy depends strongly on site conditions
- Higher mean wind in off-shore locations
- Land, forests and mountains have a braking impact on wind

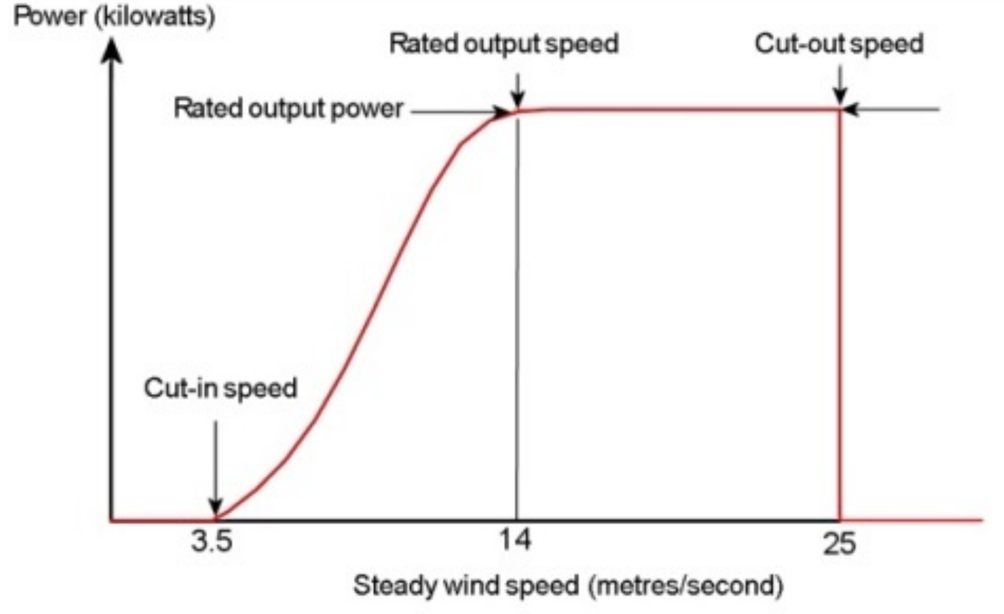


Wind energy distribution shifts to higher wind speed since $P \sim v^3$

Power control

The electrical and mechanical system has an economical **rating limit** related to wind energy distribution

- Above this point, power is limited
- Below this point, power is maximized



Typical wind turbine power output with steady wind speed.

Typical numbers

- Mean annual site wind speed
  v_m = 8 m/s
- cut-in wind speed
  5 m/s = 0.6 v_m
- rated wind speed
  12–14 m/s = 1.5–1.75 v_m
- shut-down wind speed
  25 m/s = 3 v_m

Power Curve of Wind Turbine

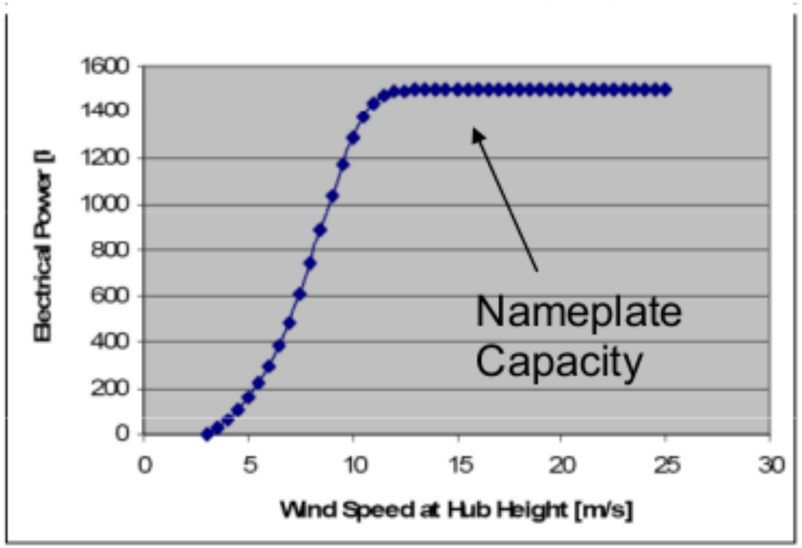
Capacity Factor (CF):

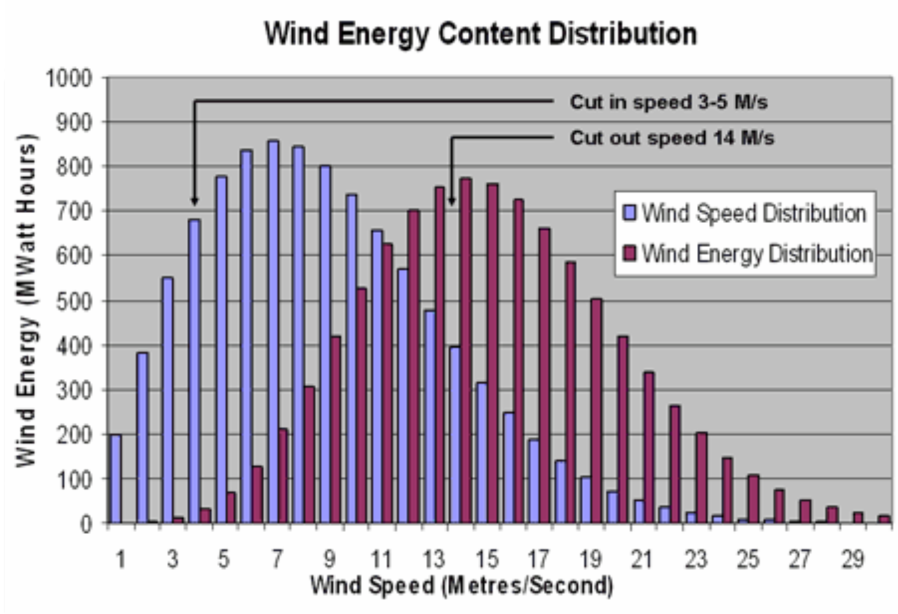
- The fraction of the year the turbine generator is operating at rated (peak) power

  Capacity Factor = Average Output / Peak Output ≈ 30%

- CF is based on both the characteristics of the turbine and the site characteristics (typically 0.3 or above for a good site)

Power Curve of 1500 kW Turbine



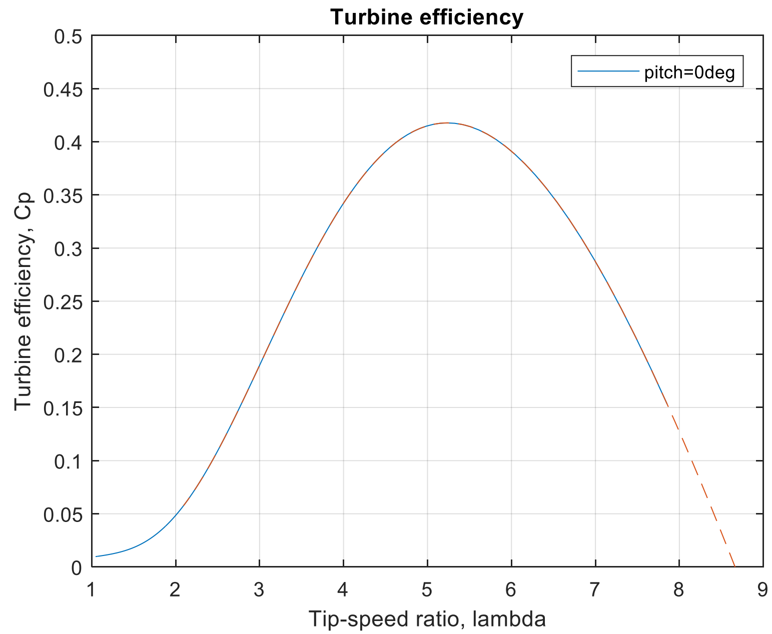


Example: Maximum power tracking through variable speed

A wind turbine is rated P=5 MW, A=11300 m2 (R=60 m), ρ=1.225 kg/m^3

a) Compute the tip speed ratio, power coefficient and generated power when v_1=12 m/s and n=10 rpm.

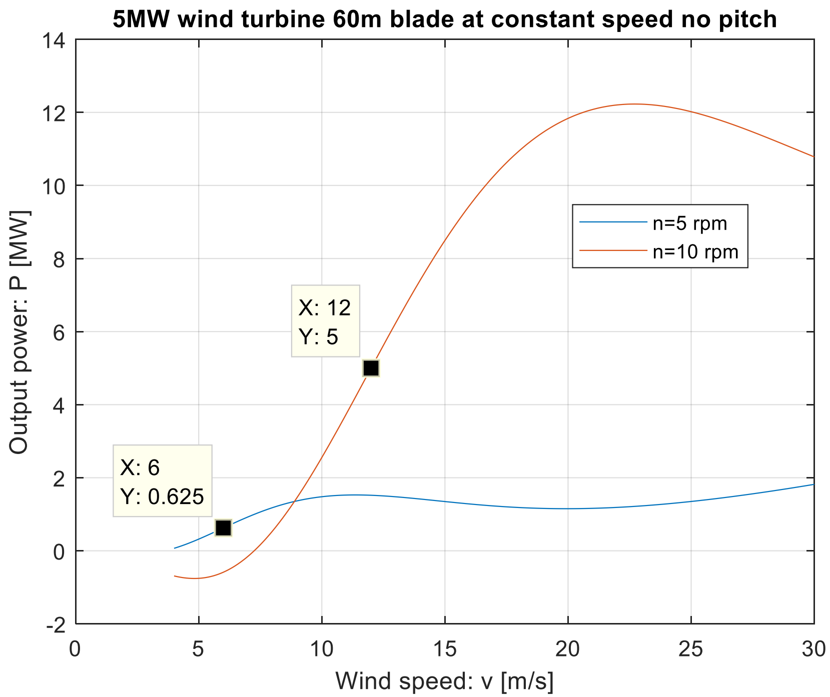
b) The wind speed has decreased to v_2 =6 m/s. Find the tip speed ratio that maximizes the generated power and compute the speed in rpm that results in this optimal tip speed ratio. Compute the generated power at this operating point.



Example: Maximum power tracking through variable speed

a)
$$A = piR^2 = \pi \cdot 60 = 11310m^2$$
$$\omega_1 = \frac{2\pi n_1}{60} = 1.05rad/s$$
$$\lambda_1 = \frac{\omega_1 R}{v_1} = 5.24$$
$$C_{p1} = 0.42$$
$$P_1 = 0.5\rho A v_1^3 C_{p1} = 5MW$$

b)
$$v_2 = 6m/s$$
$$\lambda_1 = \lambda_1$$
$$\omega_2 = \frac{\lambda_2 v_2}{R} = 0.52$$
$$n_2 = \omega_2 \cdot \frac{60}{2\pi} = 5rpm$$
$$C_{p2} = C_{P1} = 0.42$$
$$P_2 = 0.5\rho A v_2^3 C_{p2} = 0.63MW$$



Aerodynamic power control

Pitch regulation: The blades are physically rotated about their longitudinal axis.

Stall regulation: The angle of the blades is fixed but the aerodynamic performance is designed so that they stall at high wind speeds.

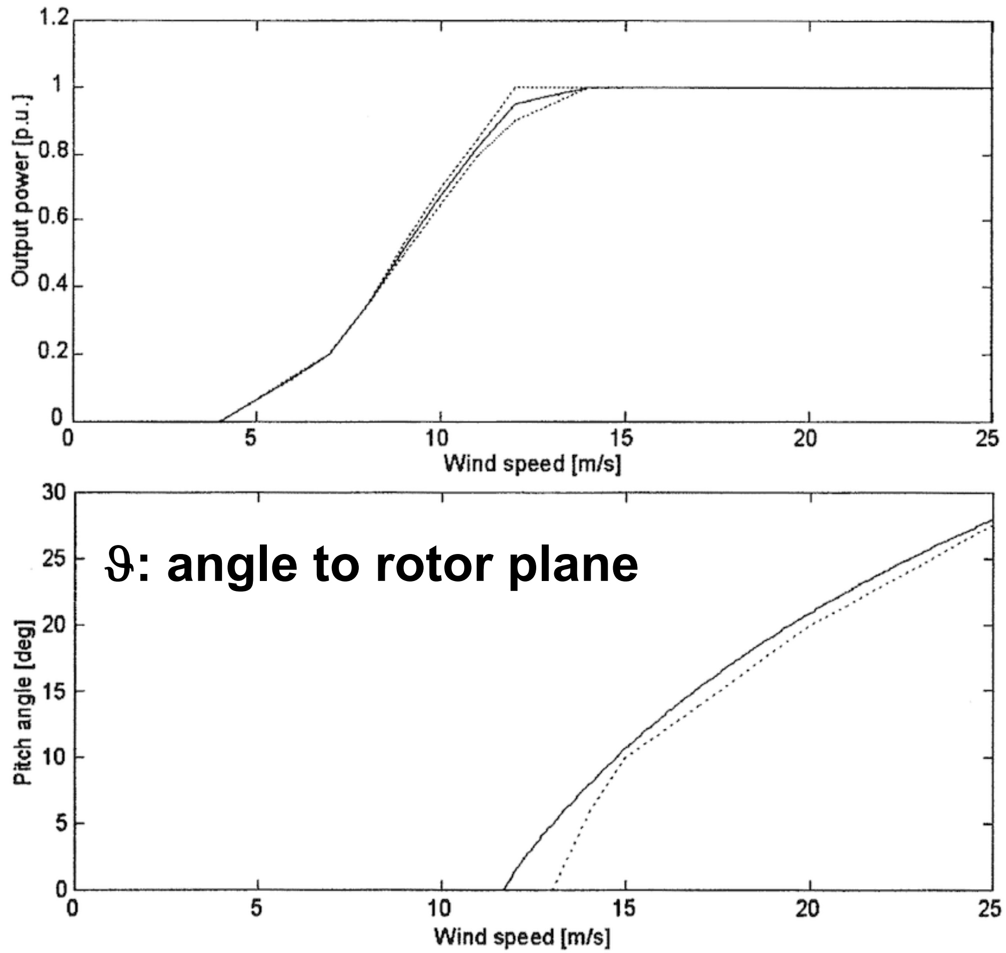
Assisted-stall regulation: The blades are rotated slowly about their longitudinal axis but the main control mechanism is stall.

Yaw control: The nacelle is rotated about the tower to yaw the rotor out of the wind. This technique is not commonly used.

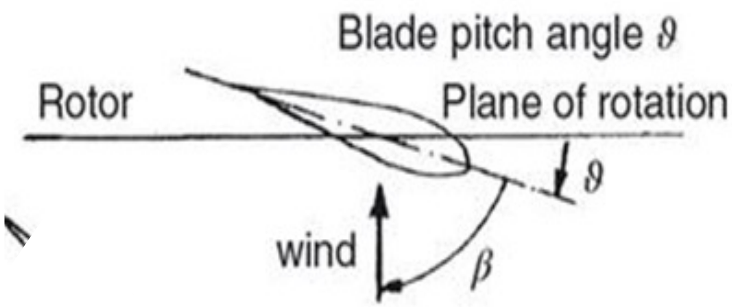
Pitch regulation

Power is reduced by turning blades into the wind (Furling)

- **ϑ: angle to rotor plane**
- β: angle to the wind

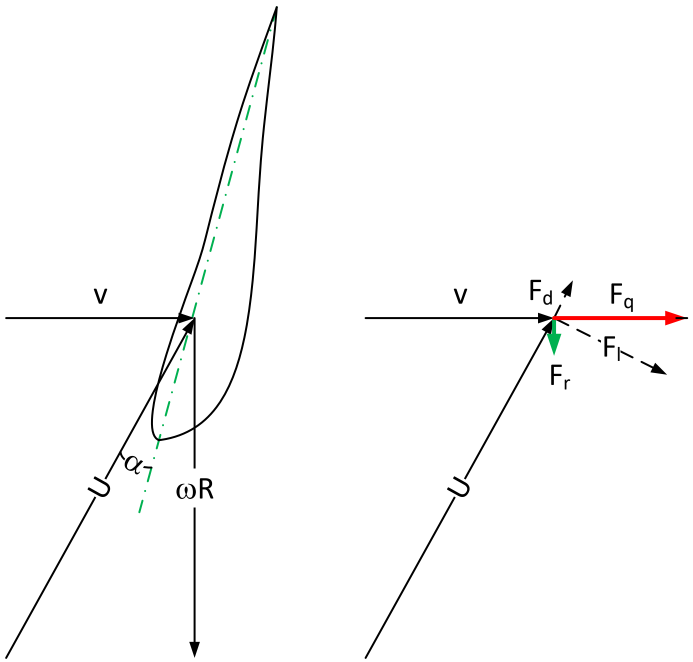


ϑ: angle to rotor plane

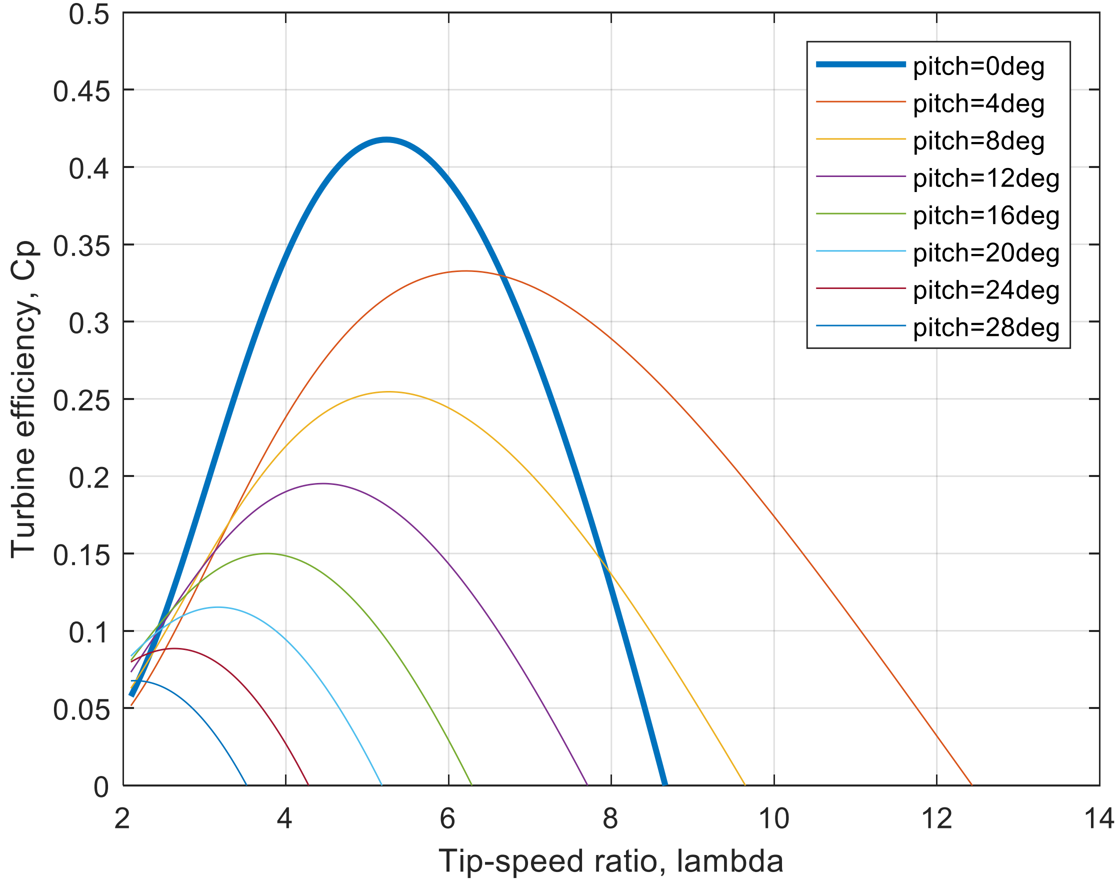


Turbine characteristics

$$TSR = \lambda = \frac{\omega R}{v_w}$$



ϑ: angle to rotor plane



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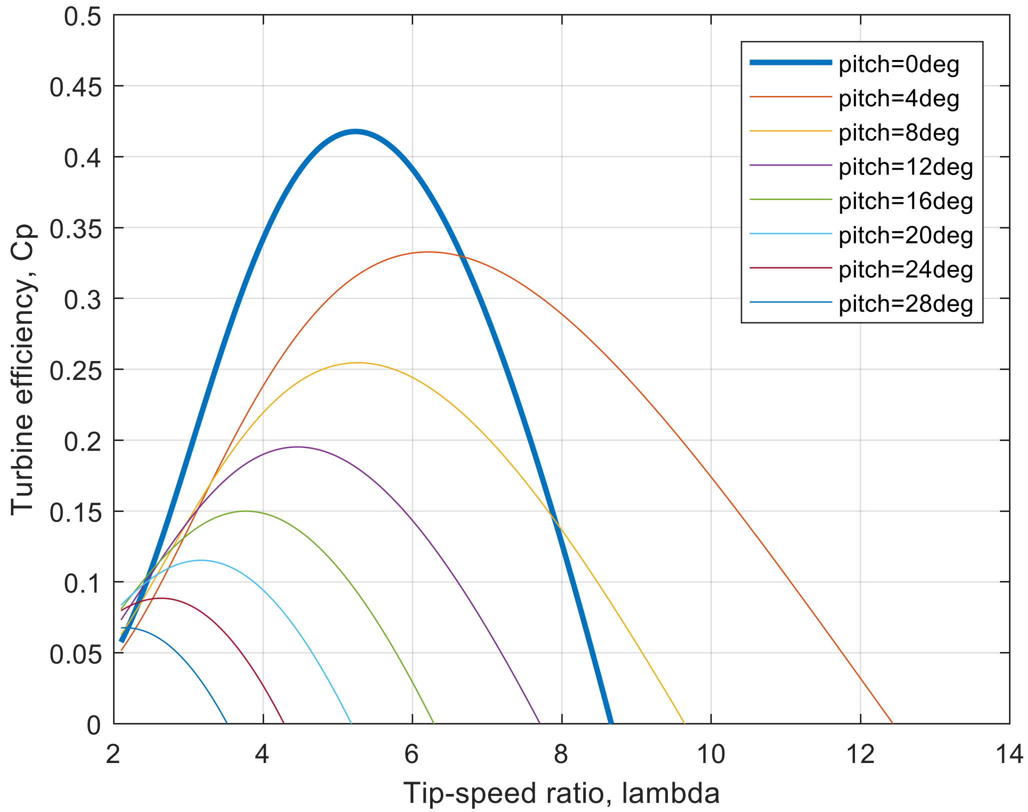
Example: Pitch regulation for power limitation

Continuation of the previous example where R=60 m and the produced power at v_1=12 m/s, n=10 rpm, λ = 5.2 and cp_{max}=0.42 is P=5 MW.

Compute the required pitch angle to produce 5MW at v_3=24 m/s and n=10 rpm.

Example: Pitch regulation for power limitation

$$v_3 = 24m/s$$
$$n_3 = 10rpm$$
$$\omega_3 = \frac{2\pi n_3}{60} = 1.05rad/s$$
$$\lambda_3 = \frac{\omega_3 R}{v_3} = 2.6$$
$$C_{p3} = \frac{P_3}{0.5\rho A v_3^3} = 0.052$$



Pitch angle of 28 degrees required to fulfill both tip speed ratio = 2.6 and power coefficient to 0.052.

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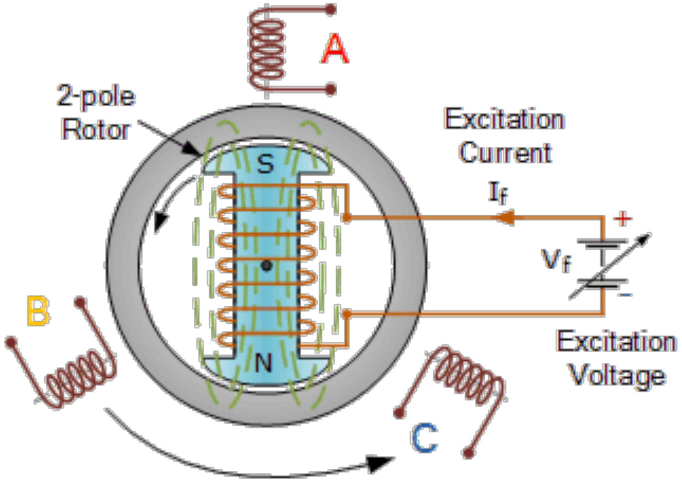
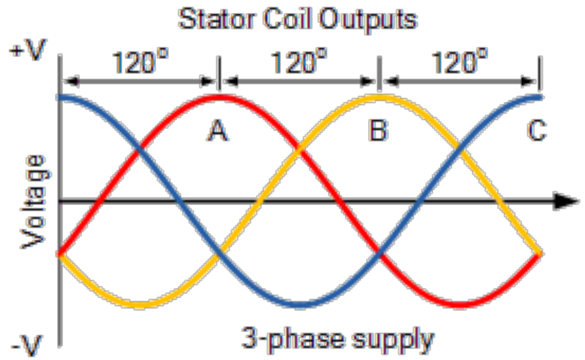
The synchronous generator





$$f_s = \frac{p}{2}\frac{n_s}{60}$$

Frequency [Hz]	50							
No of poles	2	4	6	8	12	24	36	48
Rotational speed [rpm]	3000	1500	1000	750	500	250	167	125

Rotational speed [rpm]	10							
No of poles	2	12	24	36	48	96	192	384
Frequency [Hz]	0.2	1.0	2.0	3	4	8	16	32

Wind turbine generator

Generator output

- 50 Hz 3-phase
- 600-900 V
- 6-pole synchronous generator rotor speed:
- $n_s = \frac{60 f_s}{p/2} = \frac{60 \cdot 50}{3} = 1000\ rpm$
- Wind turbine rotor speed: 10 rpm
- Gearbox ratio: 100
- Planetary 2-stage
- Transformer: 600-900 V:10-36 kV

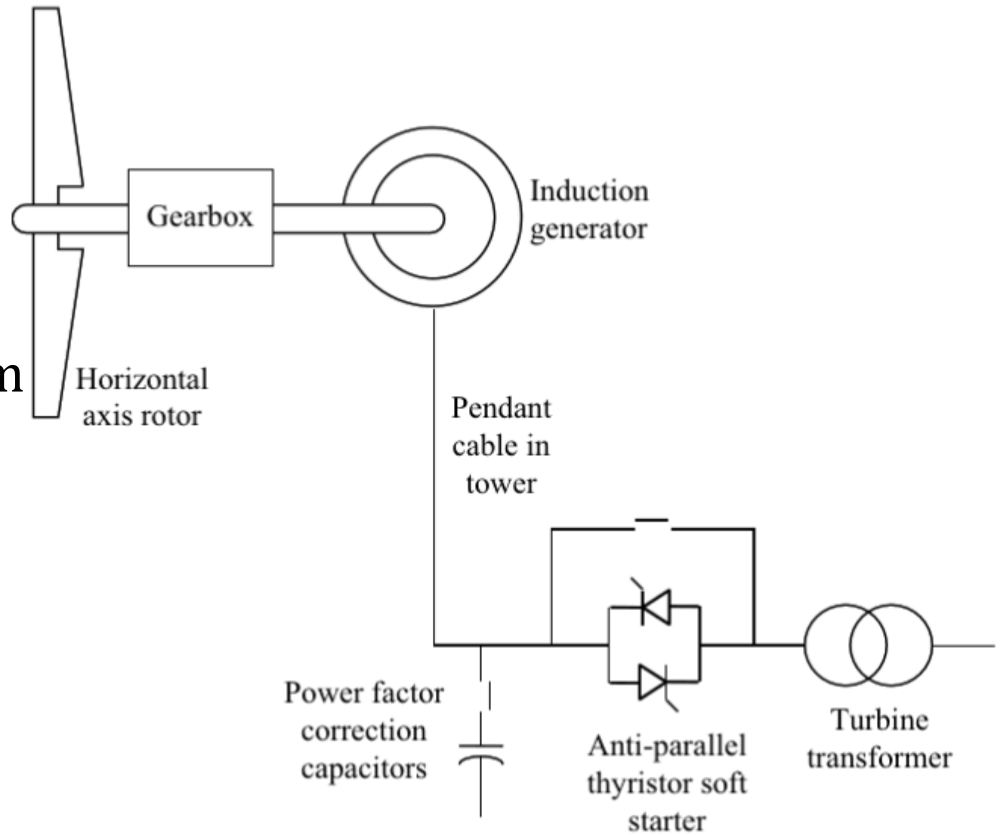


Figure 3.16 Schematic of fixed speed wind turbine

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Technical specifications

OPERATING DATA
Wind Turbine:
Class I-B IEC-61400-1 / IEC-61400-3
Rated power 6.0 MW (net after transformer)
Cut-in wind speed 3 m/s
Cut-out wind speed:
(10 minutes average) 25 m/s
Grid frequency 50 / 60 Hz

ROTOR
Rotor diameter 150.95 m
Blade length 73.5 m
Rotor swept area 17,860 m²
Rotor speed range 4 - 11.5 rpm
Tip speed 90.8 m/s

GENERATOR
Type Direct Drive Permanent Magnet
Rated voltage 900 V per phase
Number of phases 3 x 3
Protection class IPP55

CONVERTER
Type Back to back 3-phase AC/AC
Output voltage 900 V

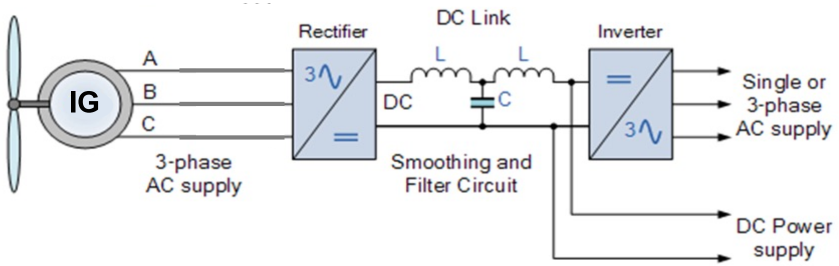
TOWER
Type Tubular steel
Hub height 100 m (or site-specific)
Standard color RAL 7035

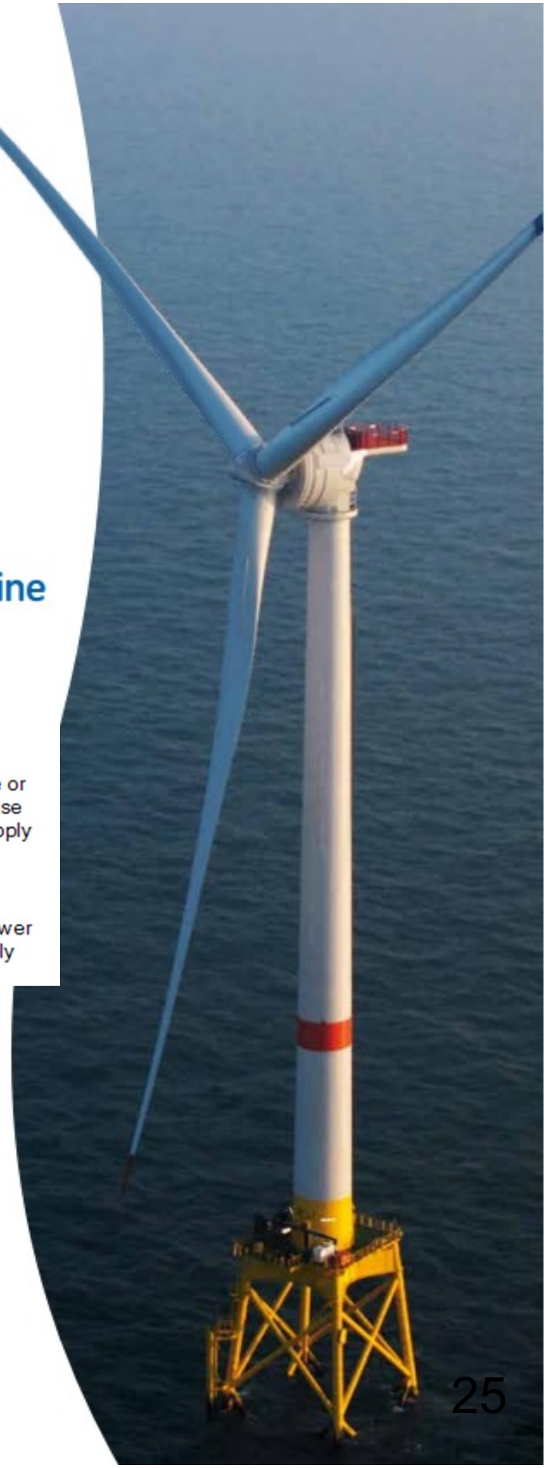
POWER CONTROL SYSTEM
Type Variable speed and independent pitch control by blade

GE Renewable Energy

GE's Haliade* 150-6MW

High yield offshore wind turbine





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The V150-4.2 MW™ IEC IIIB/IEC S

V150-4.2 MW™

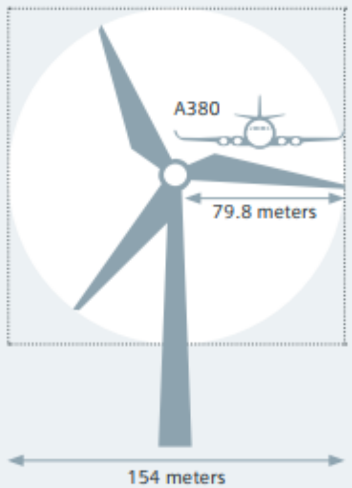
V150-4.2 MW™ is the industry's highest producing onshore low wind turbine

View the 4 MW Brochure ›

Technical Specifications

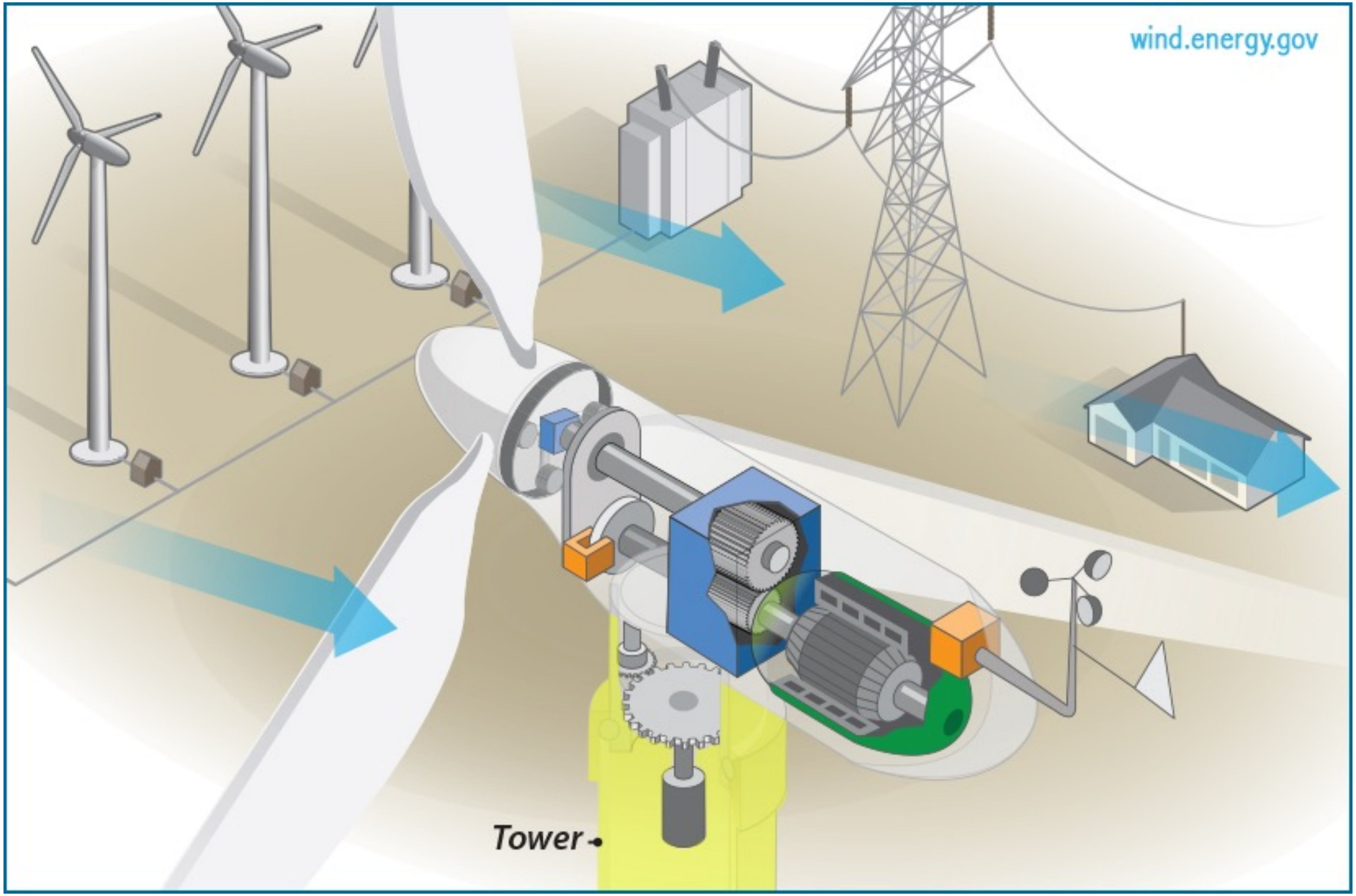
OPERATIONAL DATA	
Rated power	4,000 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	22.5 m/s
Re cut-in wind speed	20 m/s
Wind class	IEC IIIB
Standard operating temperature range	from -20°C* to +45°C with de-rating above 30°C
SOUND POWER	
Maximum	104.9 dB Sound Optimised modes dependent on site and country
ROTOR	
Rotor diameter	150 m
Swept area	17,671 m^2
Air brake	full blade feathering with 3 pitch cylinders
ELECTRICAL	
Frequency	50/60 Hz
Converter	full scale

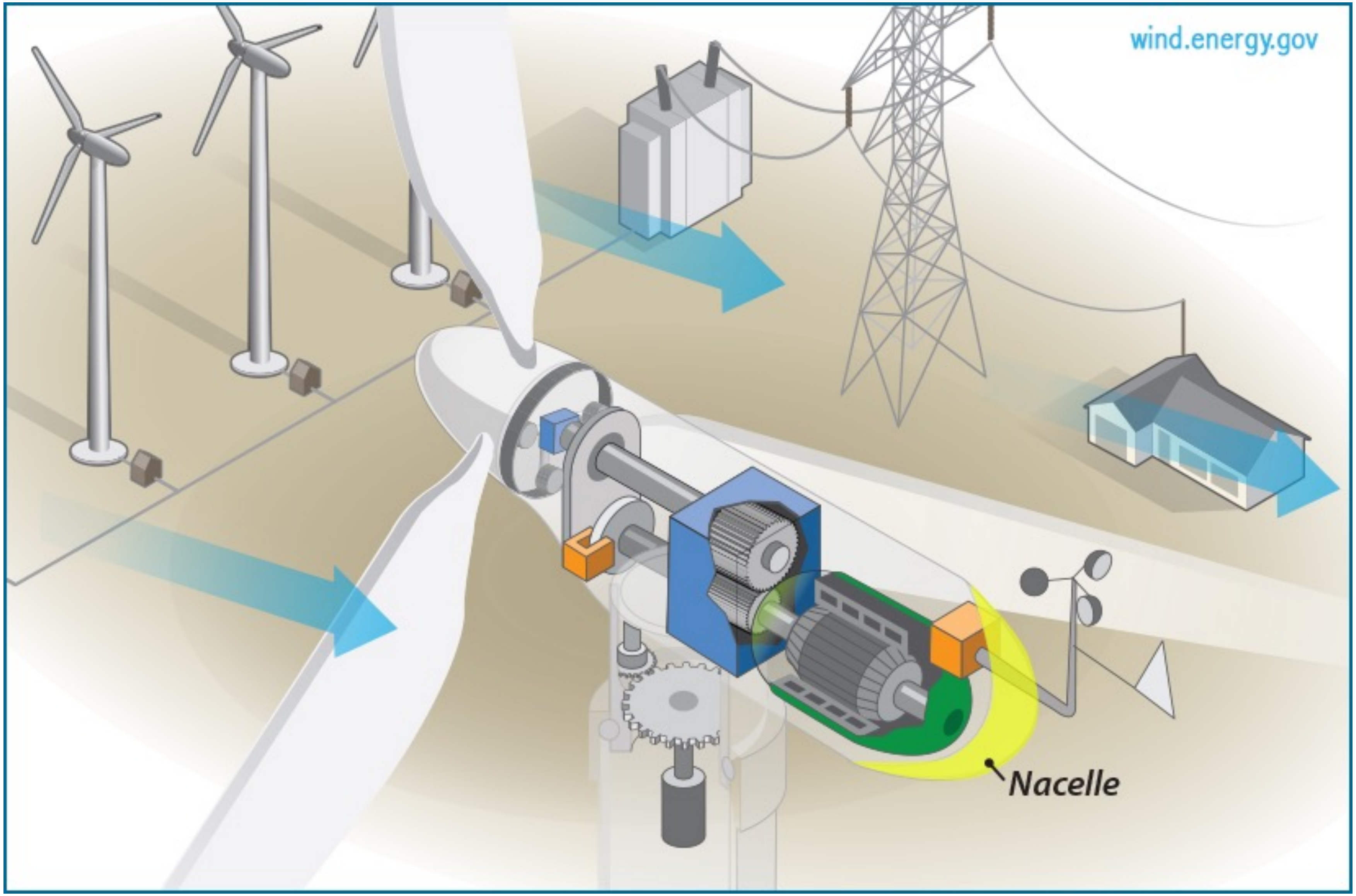
GEARBOX	
Type	two planetary stages and one helical stage
TOWER	
Hub heights	Site and country specific
NACELLE DIMENSIONS	
Height for transport	3.4 m
Height installed (incl. CoolerTop®)	6.9 m
Length	12.8 m
Width	4.2 m
HUB DIMENSIONS	
Max. transport height	3.8 m
Max. transport width	3.8 m
Max. transport length	5.5 m
BLADE DIMENSIONS	
Length	73.7 m
Max. chord	4.2 m
Max. weight per unit for transportation	70 metric tonnes



	SWT-6.0-154	SWT-7.0-154	SWT-8.0-154
IEC Class	IA	IB	IB
Nominal power	6,000 kW	7,000 kW	8,000 kW
Rotor diameter	154 m		
Blade length	75 m		
Swept area	18,600 m²		
Hub height	Site specific		
Power regulation	Pitch regulated, variable speed		

Gearless, direct drive
Permanent magnet synchronous generator


wind.energy.gov
Tower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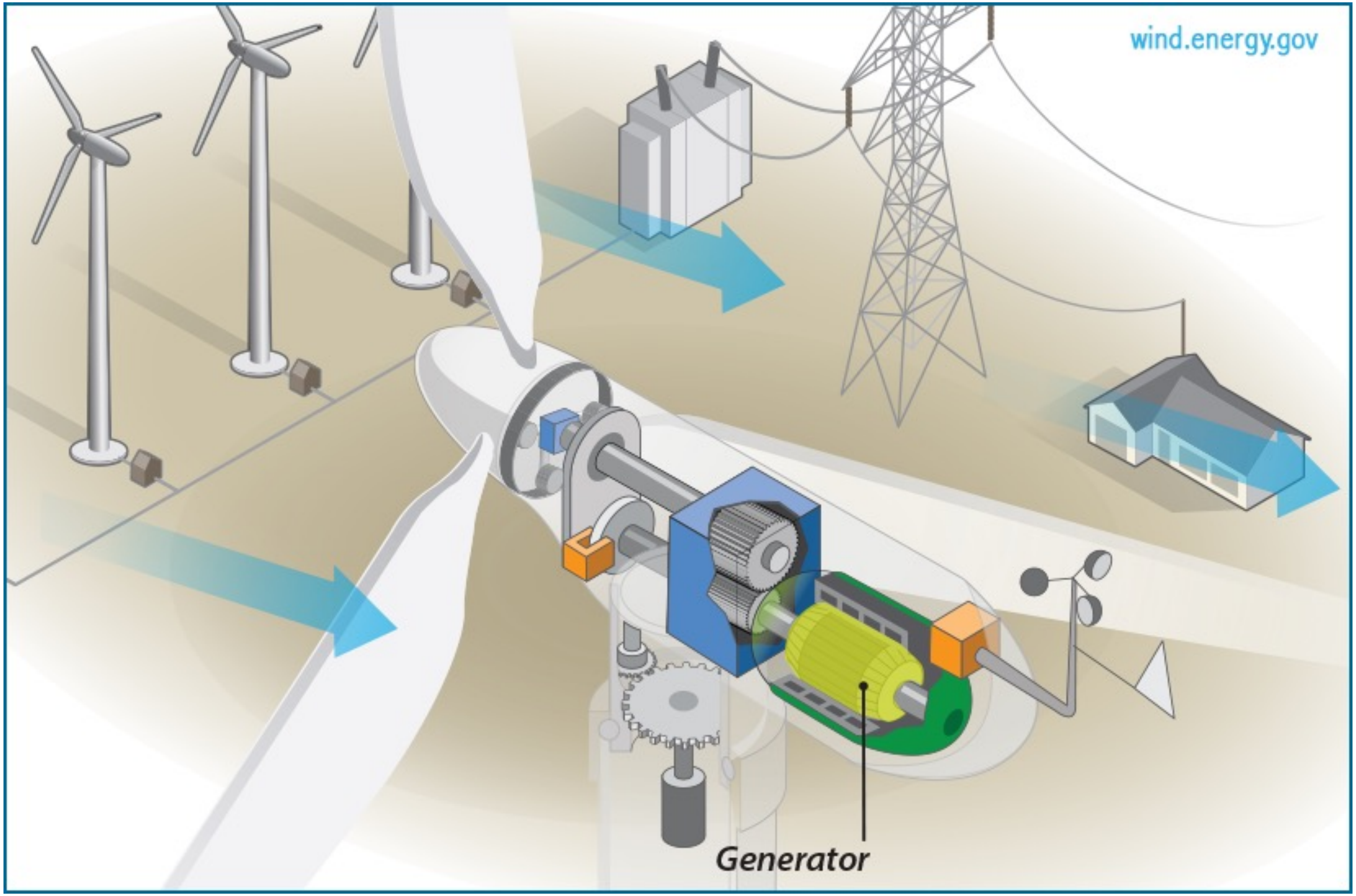
Nacelle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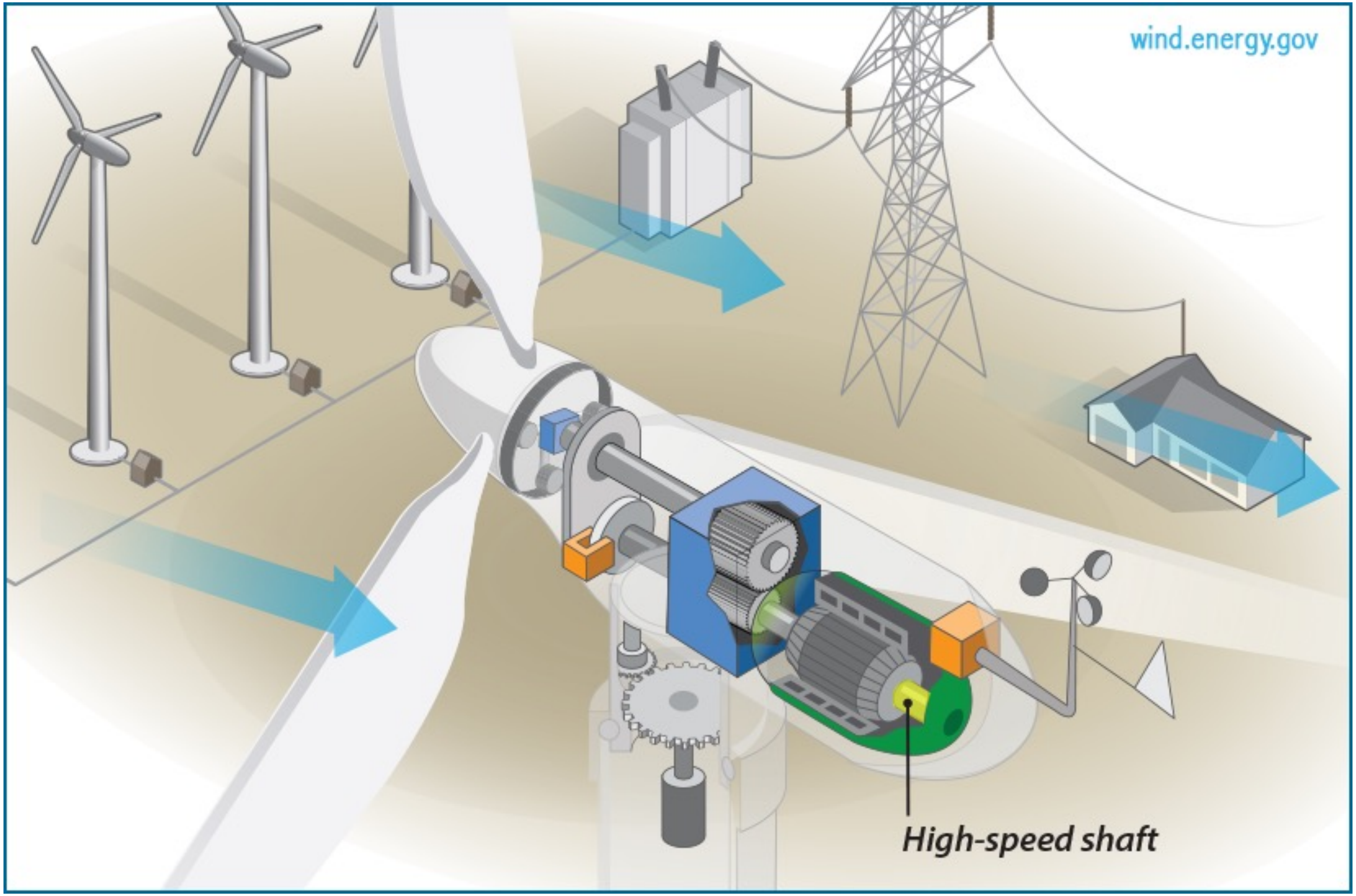
Generator



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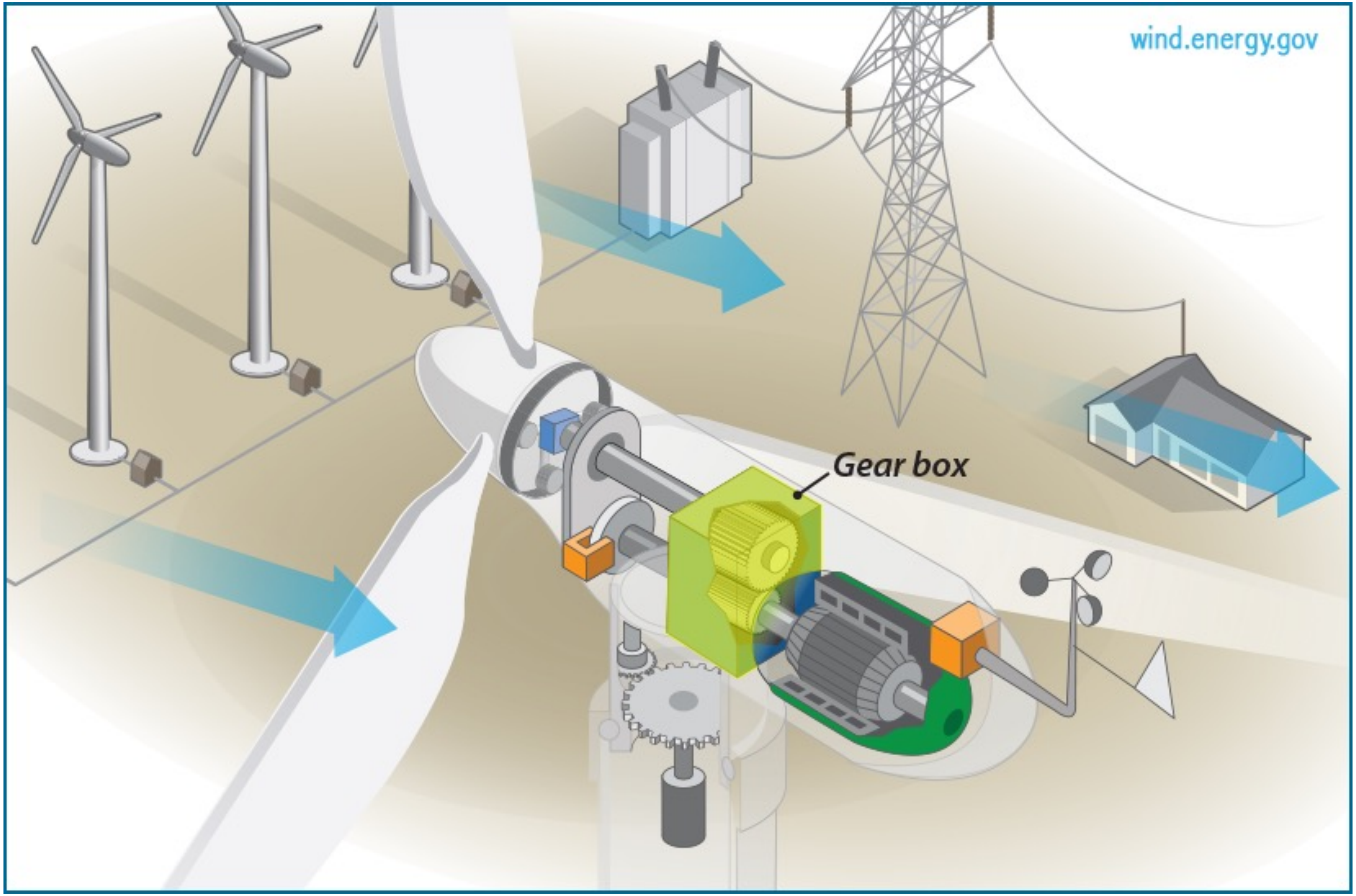
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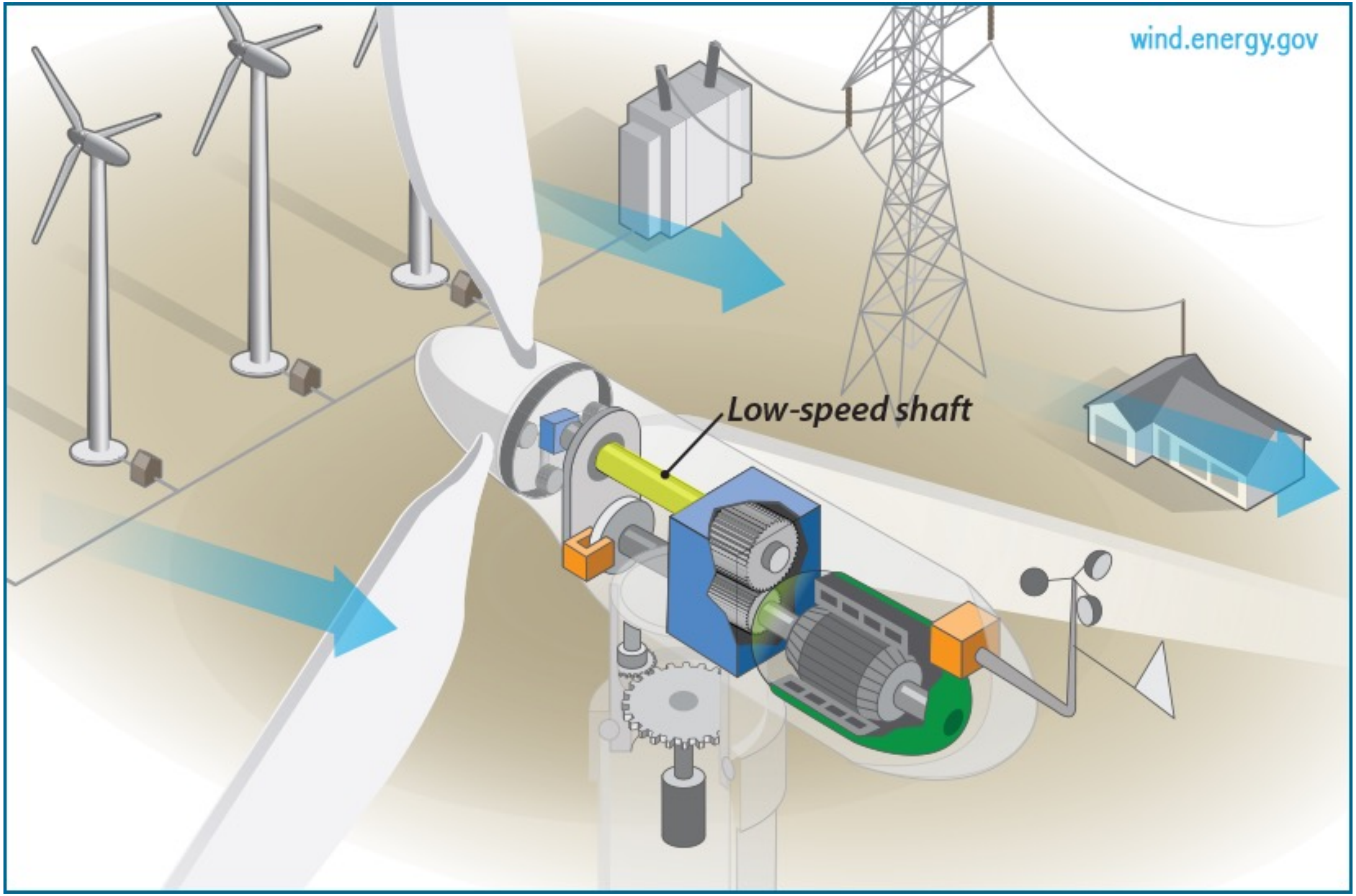
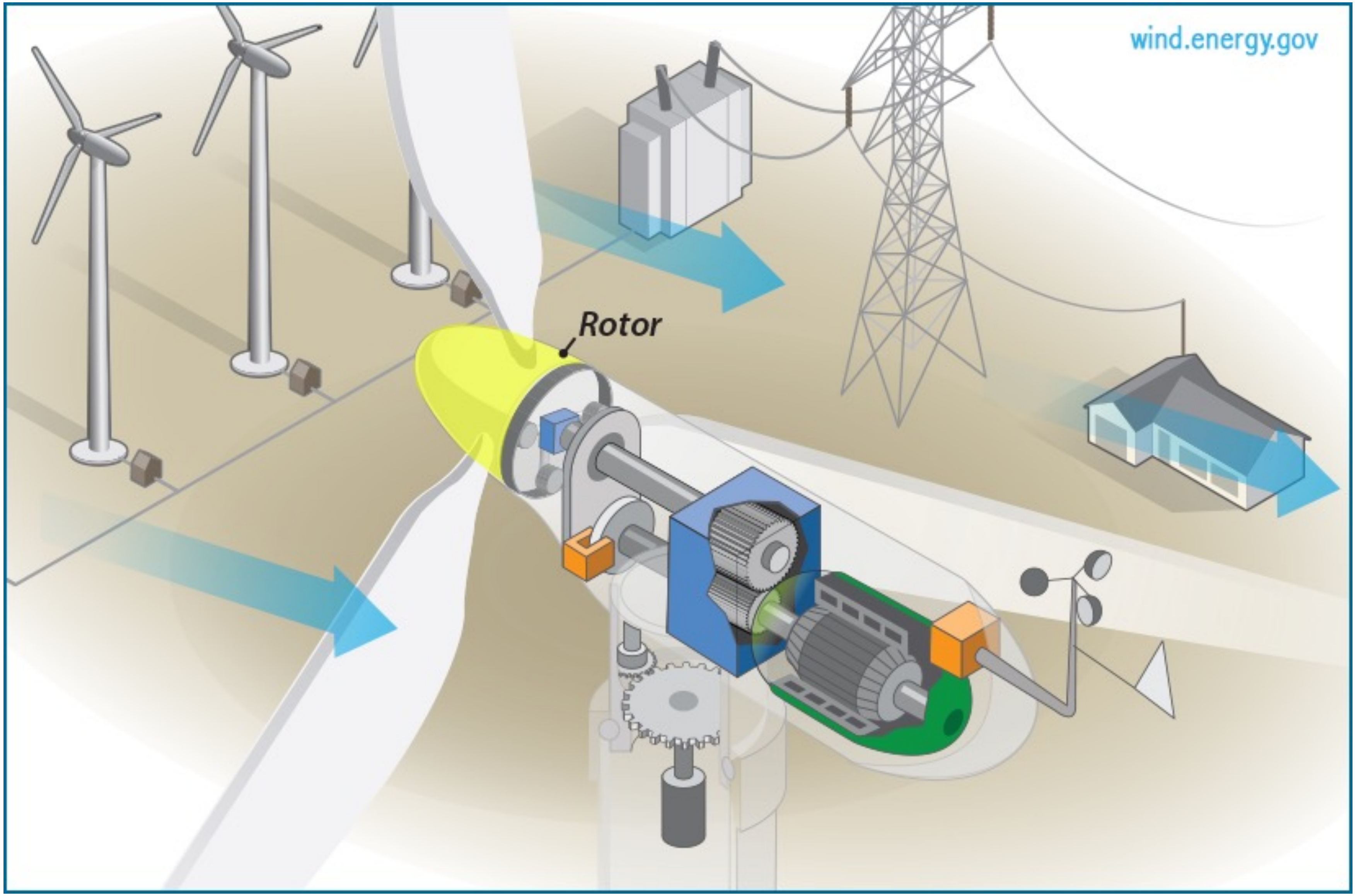
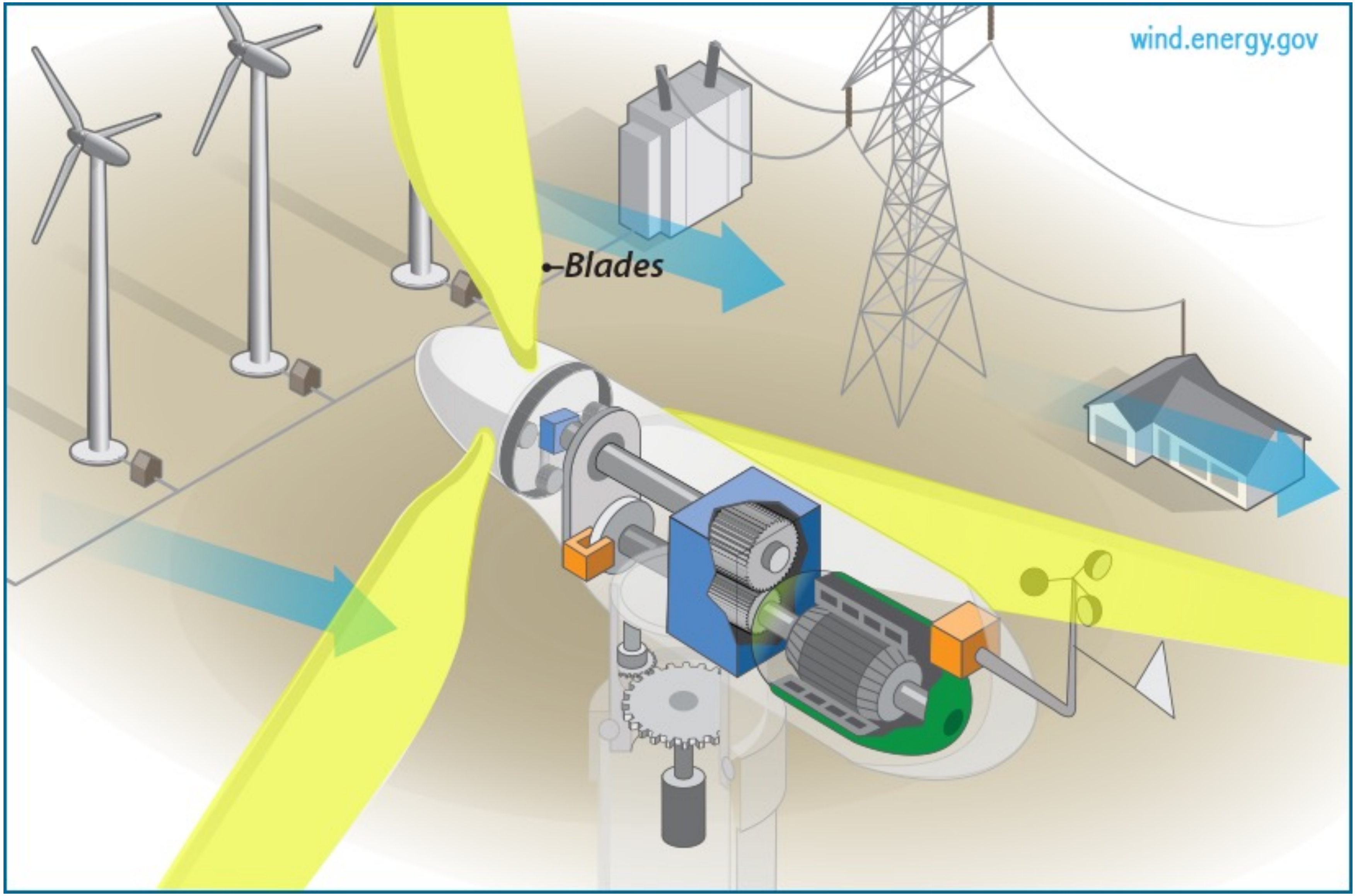
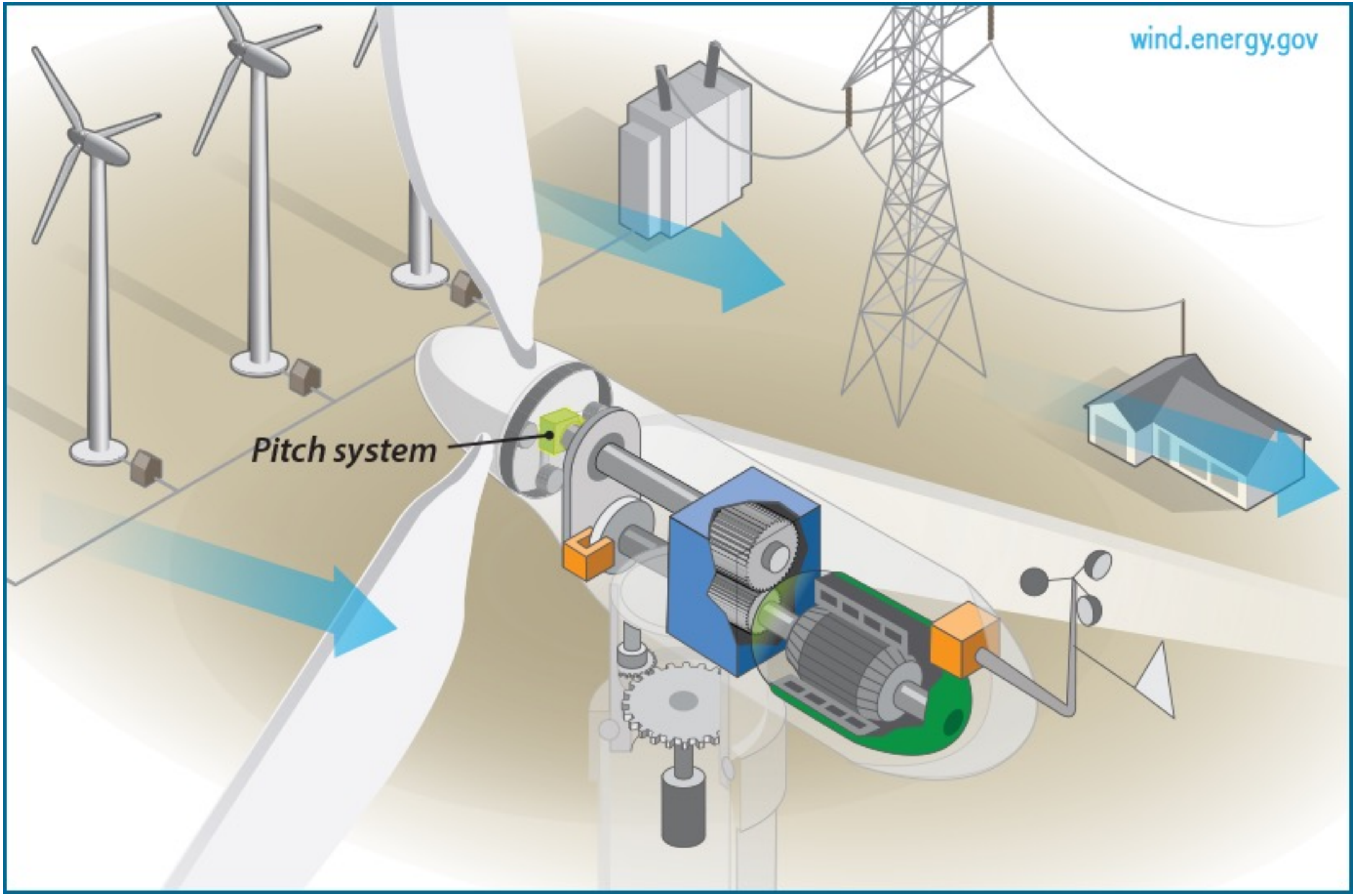
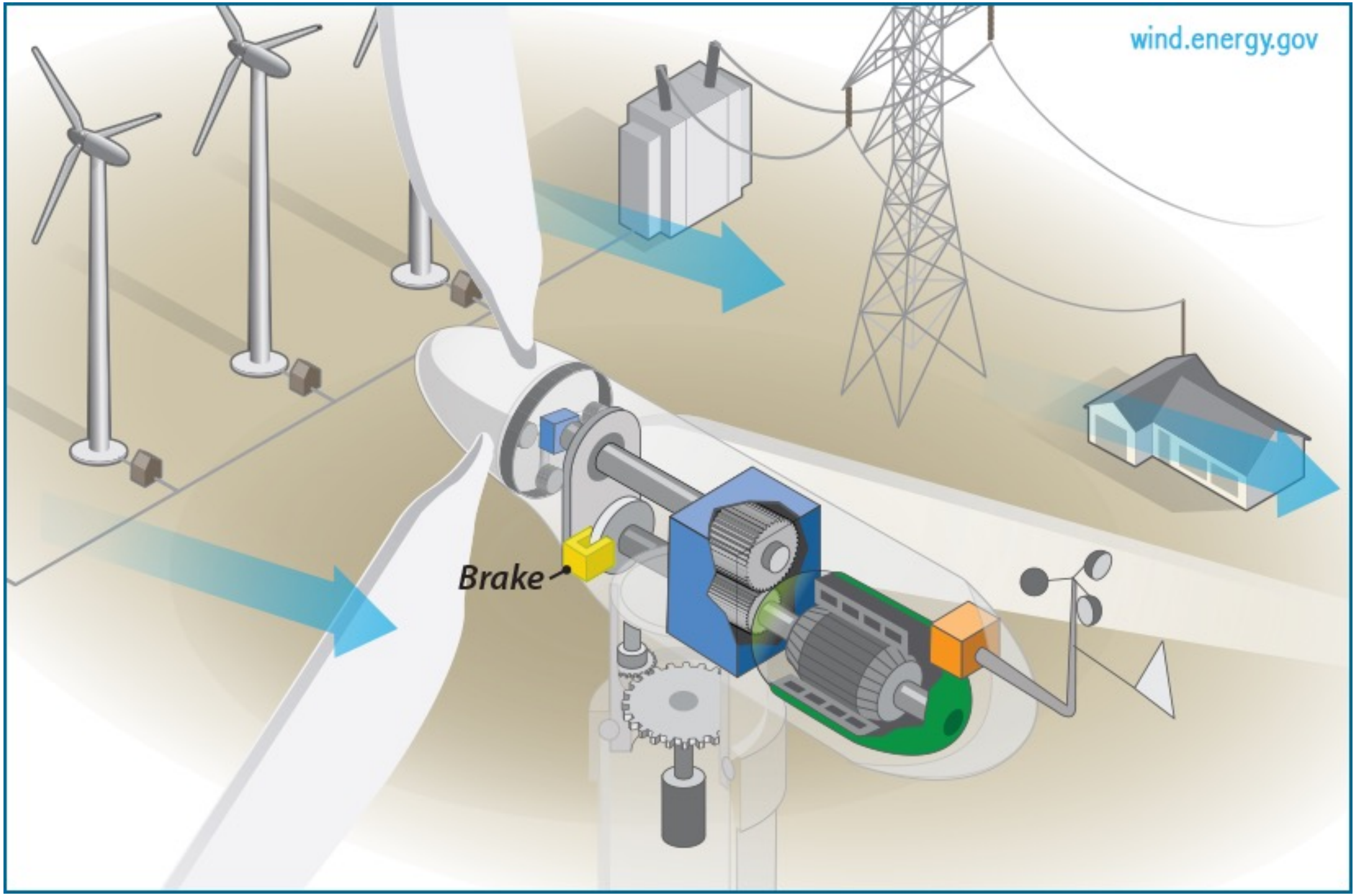
Gear box


wind.energy.gov
Low-speed shaft


wind.energy.gov
Rotor


wind.energy.gov
Blades


wind.energy.gov
Pitch system



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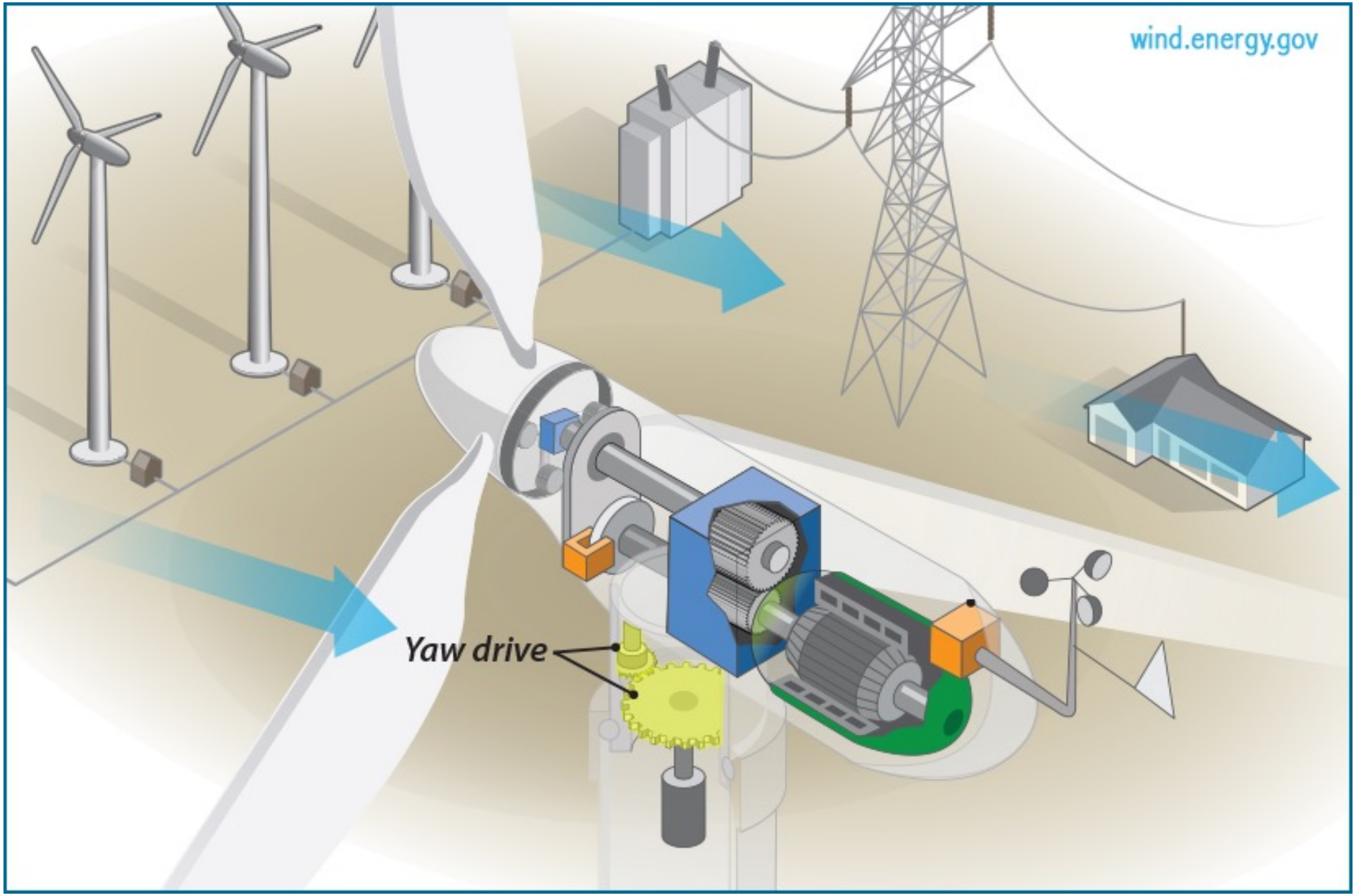
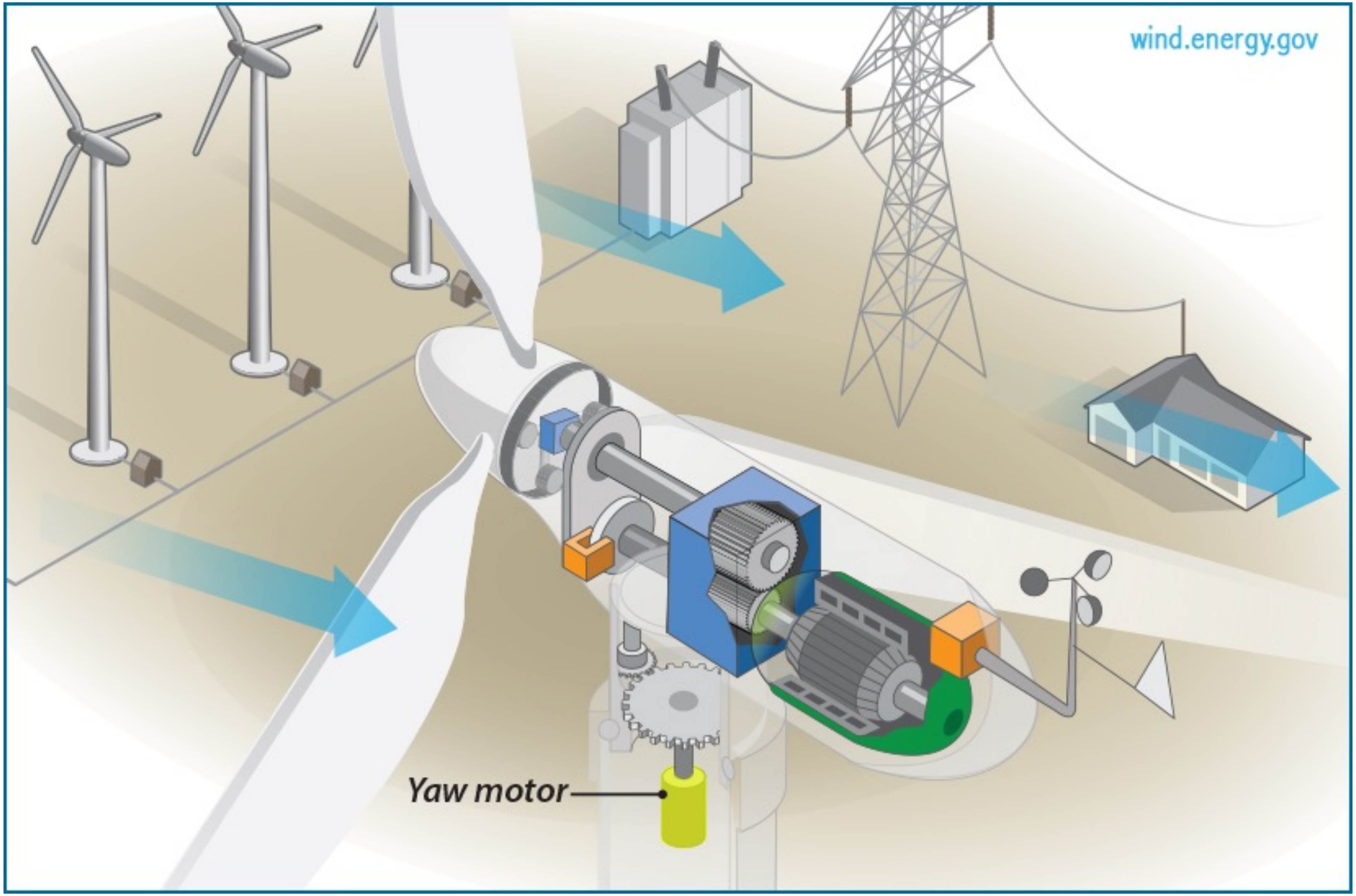
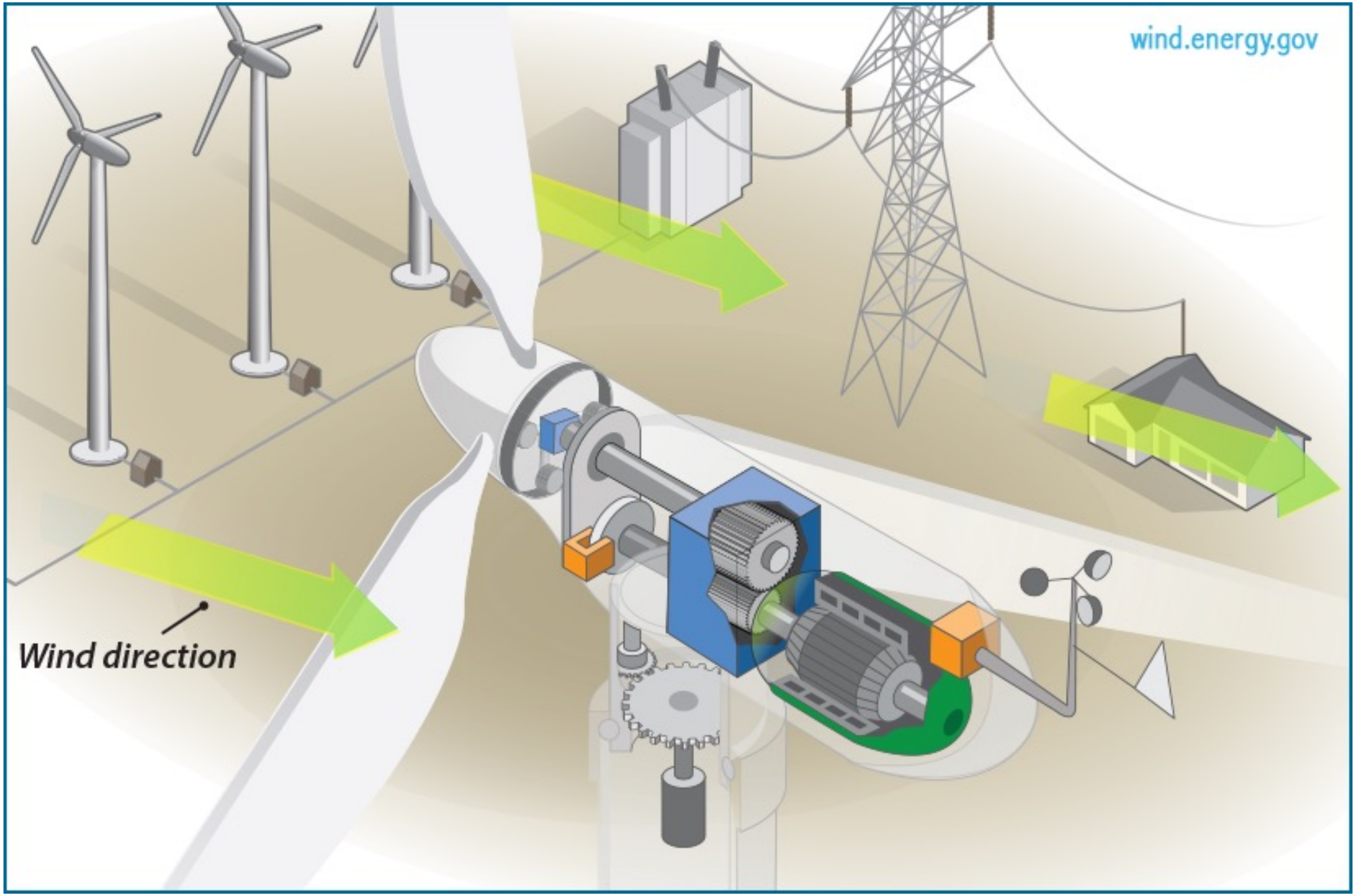
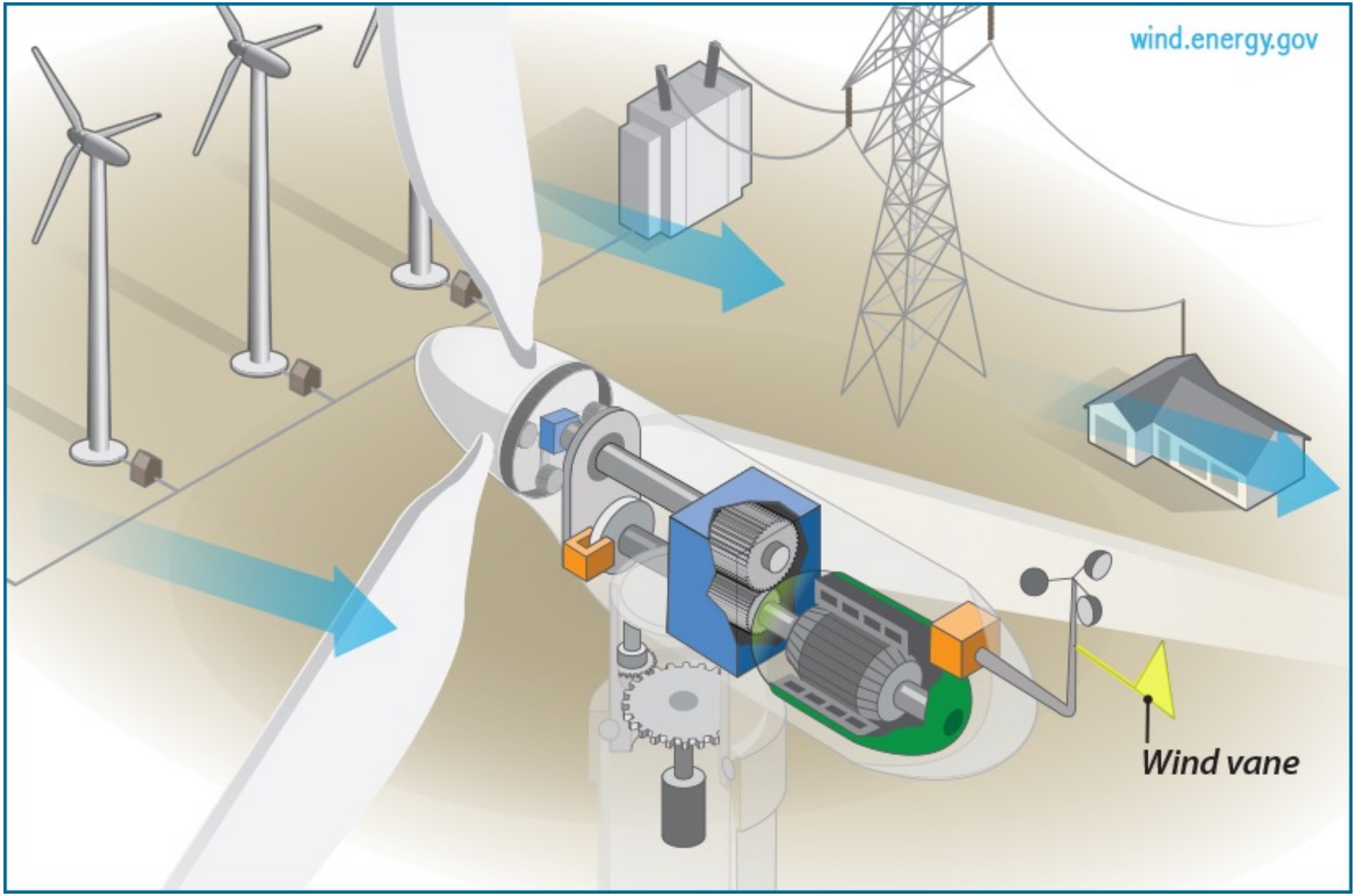
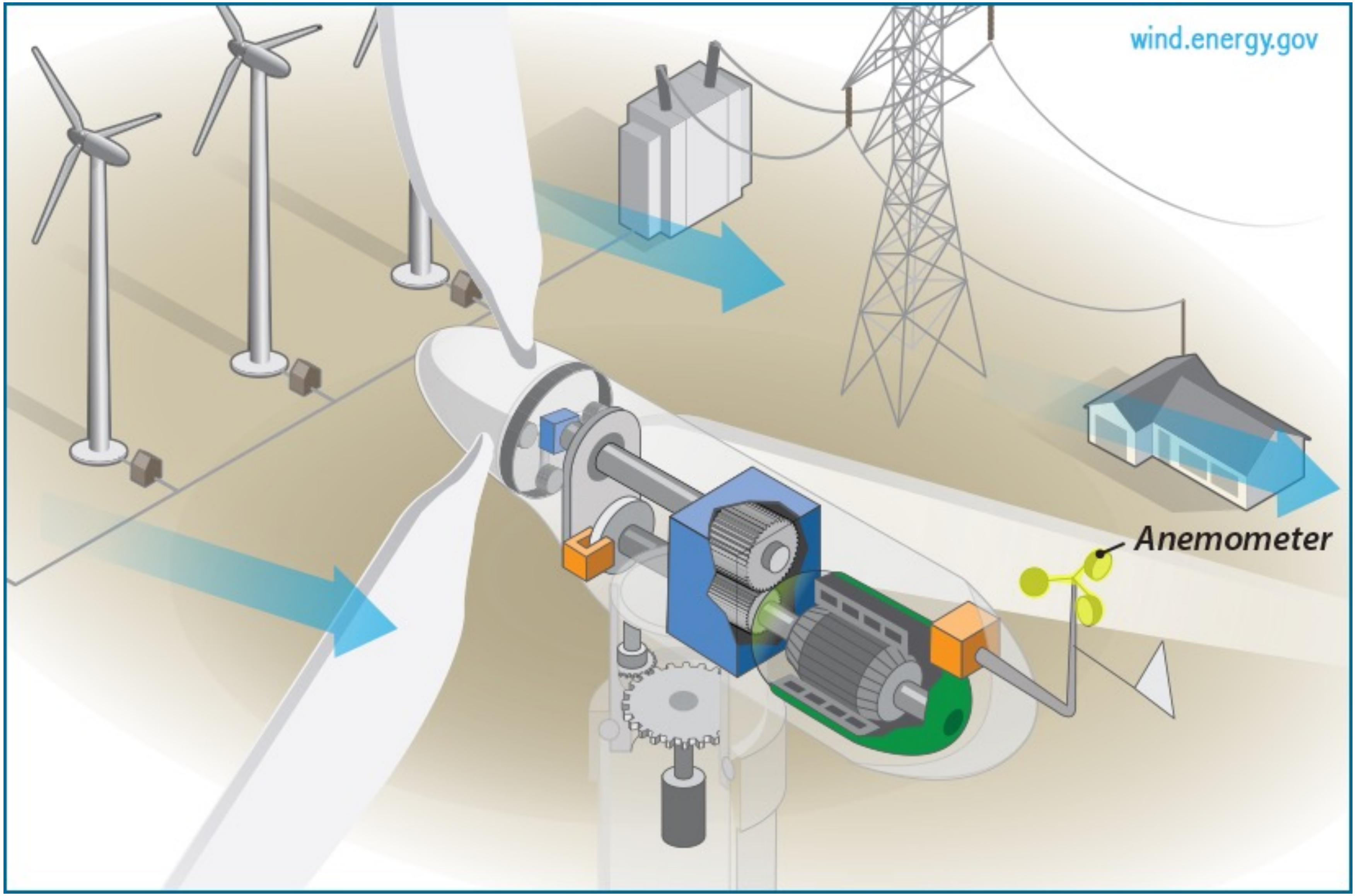
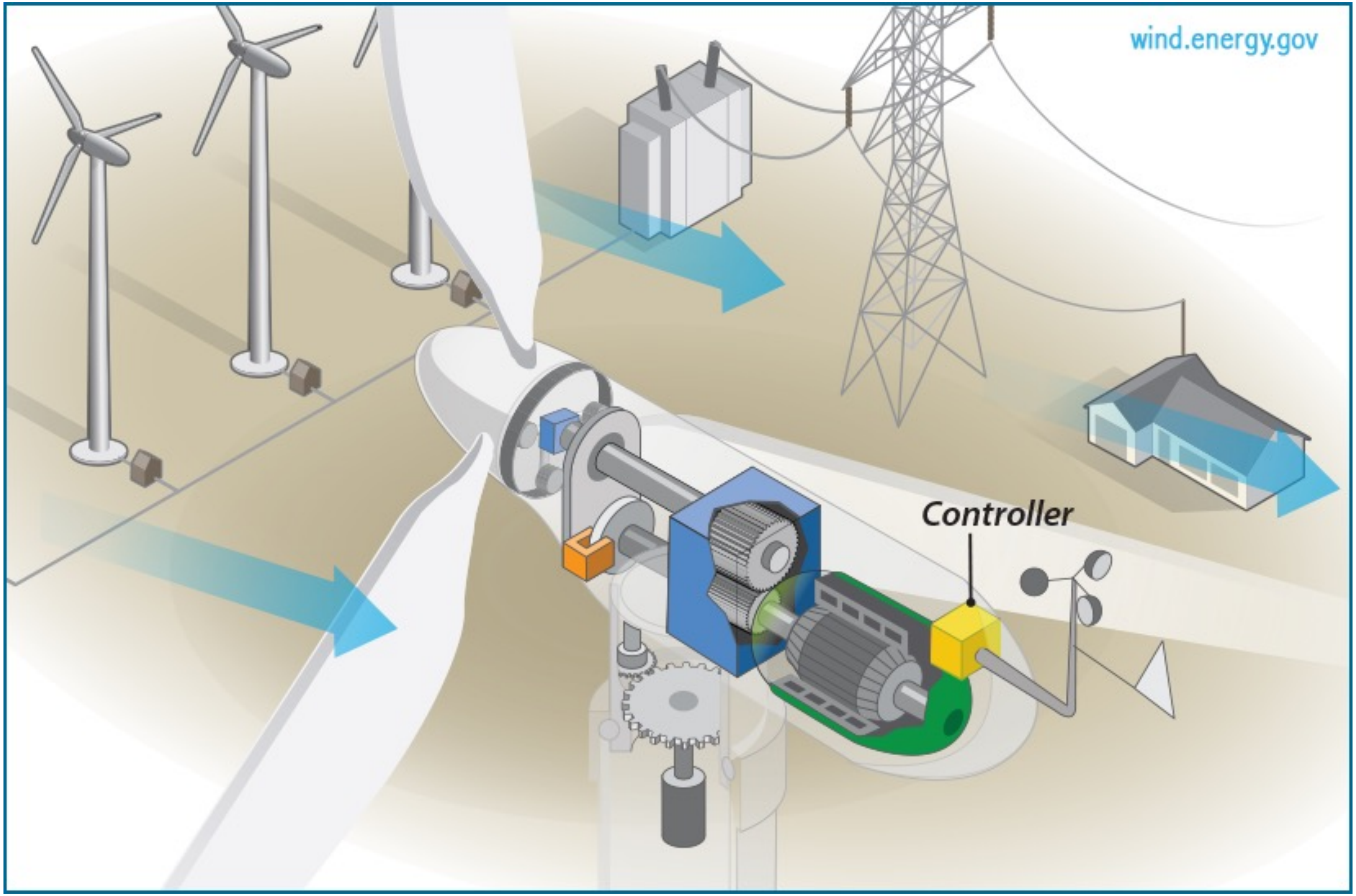

wind.energy.gov
Yaw drive


wind.energy.gov
Yaw motor


wind.energy.gov
Wind direction


wind.energy.gov
Wind vane


wind.energy.gov
Anemometer



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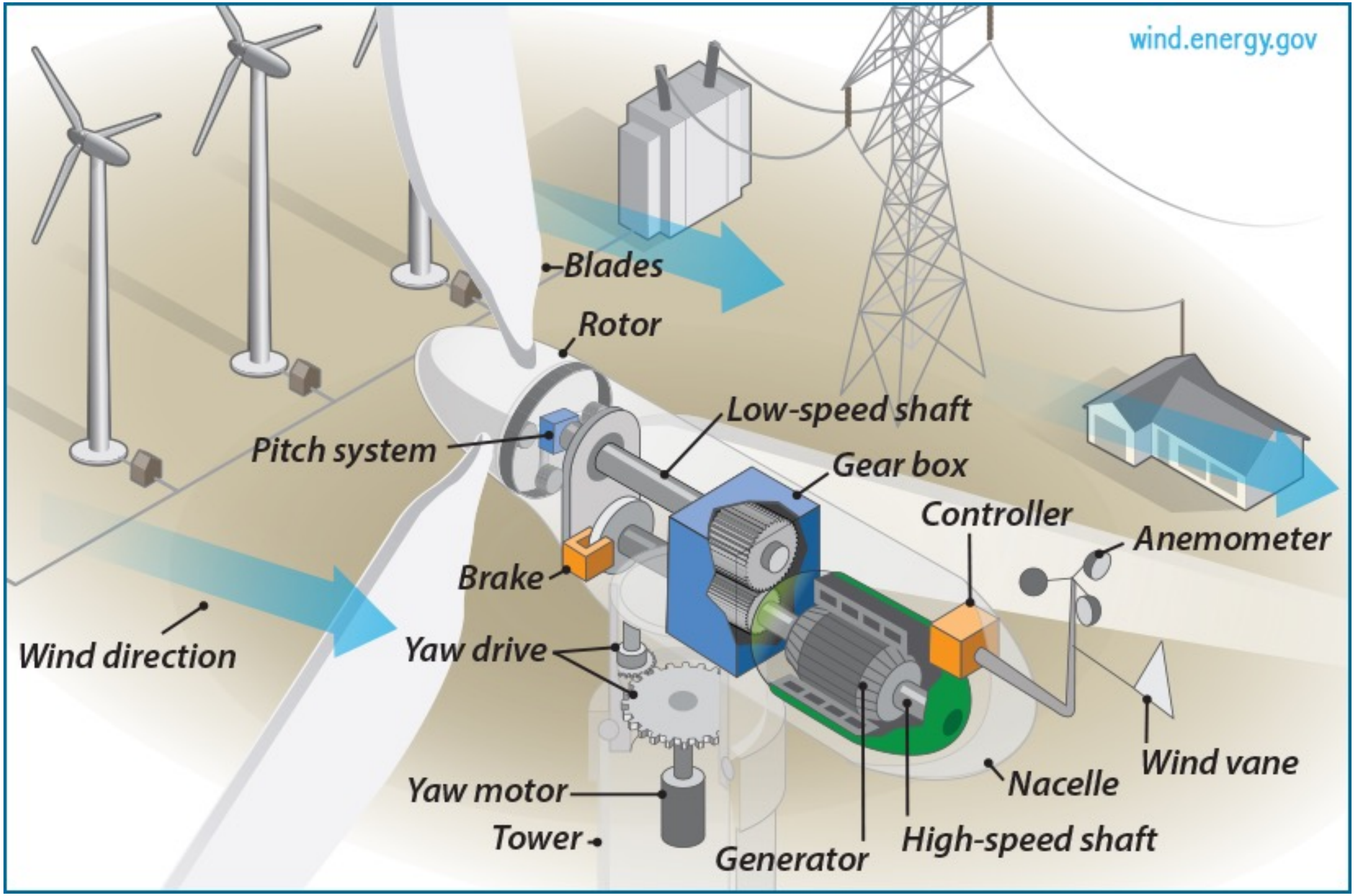

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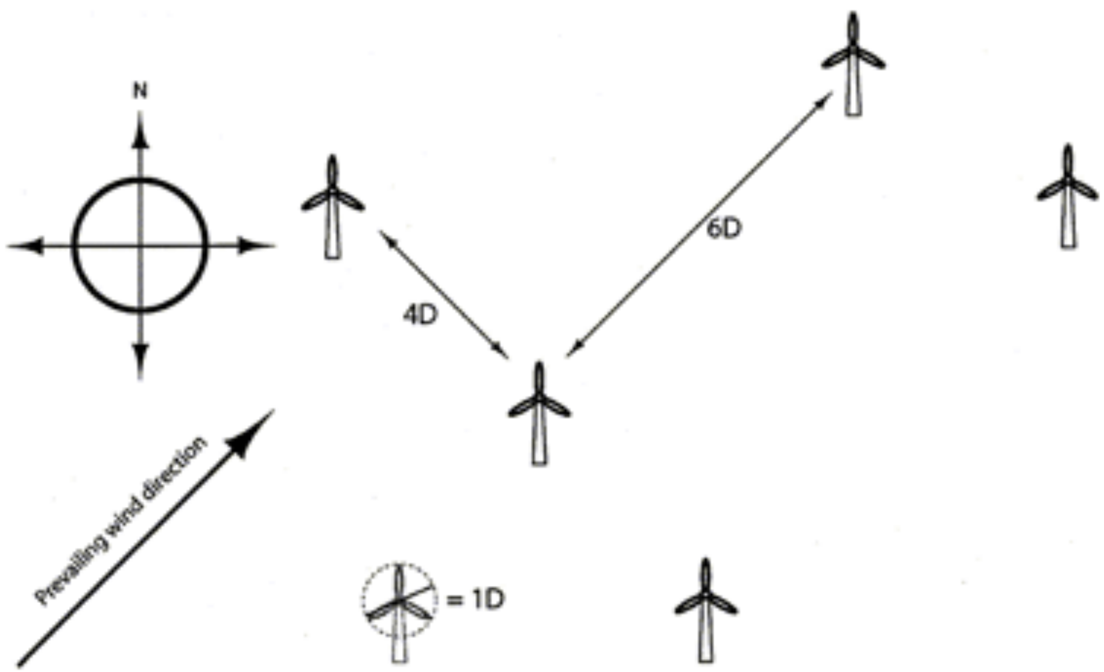
Blades
Rotor
Low-speed shaft
Pitch system
Gear box
Controller
Anemometer
Brake
Wind direction
Yaw drive
Wind vane
Nacelle
Yaw motor
Tower
Generator
High-speed shaft

Wind farm

To avoid aerodynamic interference between turbines sufficient spacing is required

Example turbine spacing in a wind farm with a South Westerly prevailing wind direction



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