Lecture 13 – Wind Energy III

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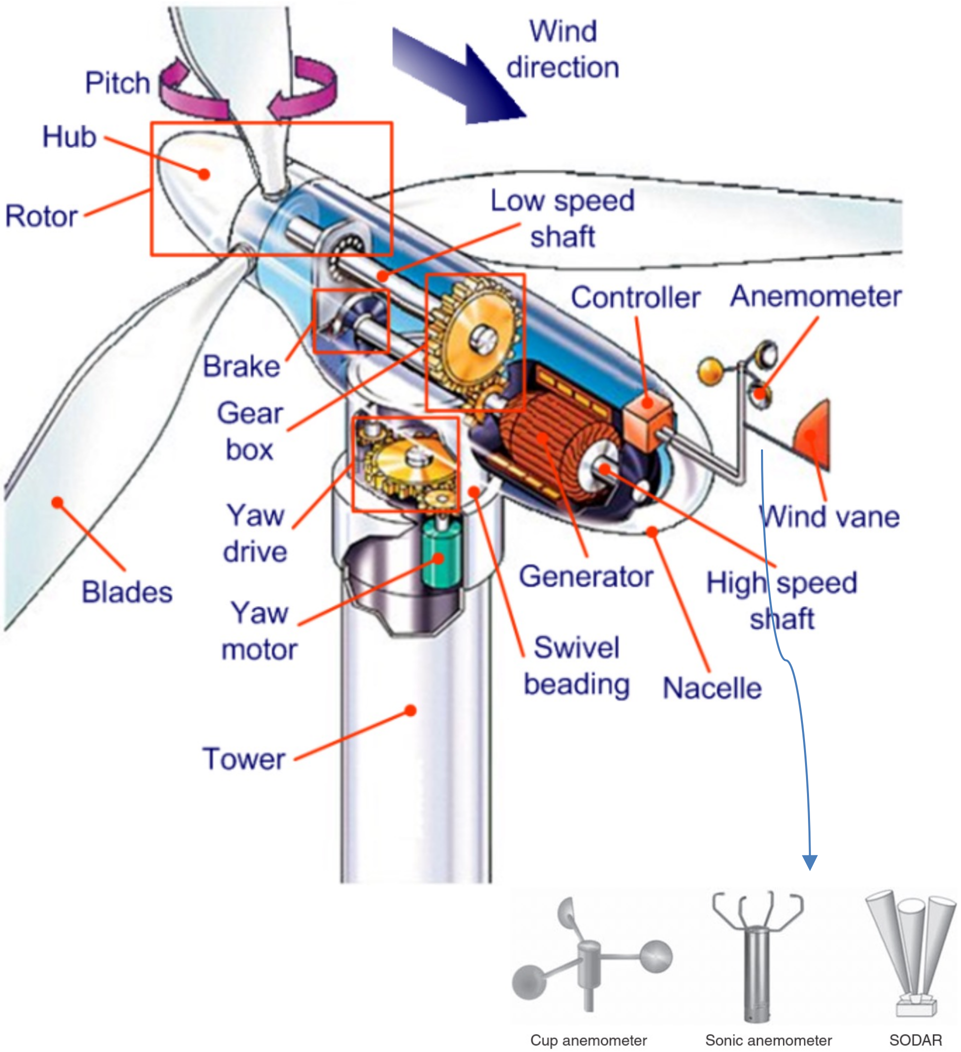
ECE180J

Outline

- Wind Turbine Structure and Types
- Harnessing Aerodynamic Forces
- Onshore and Offshore Turbines
- Wind Turbine Costs
- Environmental Impact

- B3 Chap 8
- B1 Chap 7

Wind Turbine Structure



- Blades are used to convert kinetic energy in the wind into rotating shaft power to spin a generator that produces electric power.
- A gearbox transfers power from the low speed shaft to a high speed shaft that spins the generator.
- Yaw motor keeps the blades facing into the wind.
- Brake engages to lock the blades in place when winds are too strong.

Figure source: http://www.loce.nl/our-business/renewable-energy/

Yaw, Pitch and Roll Directions

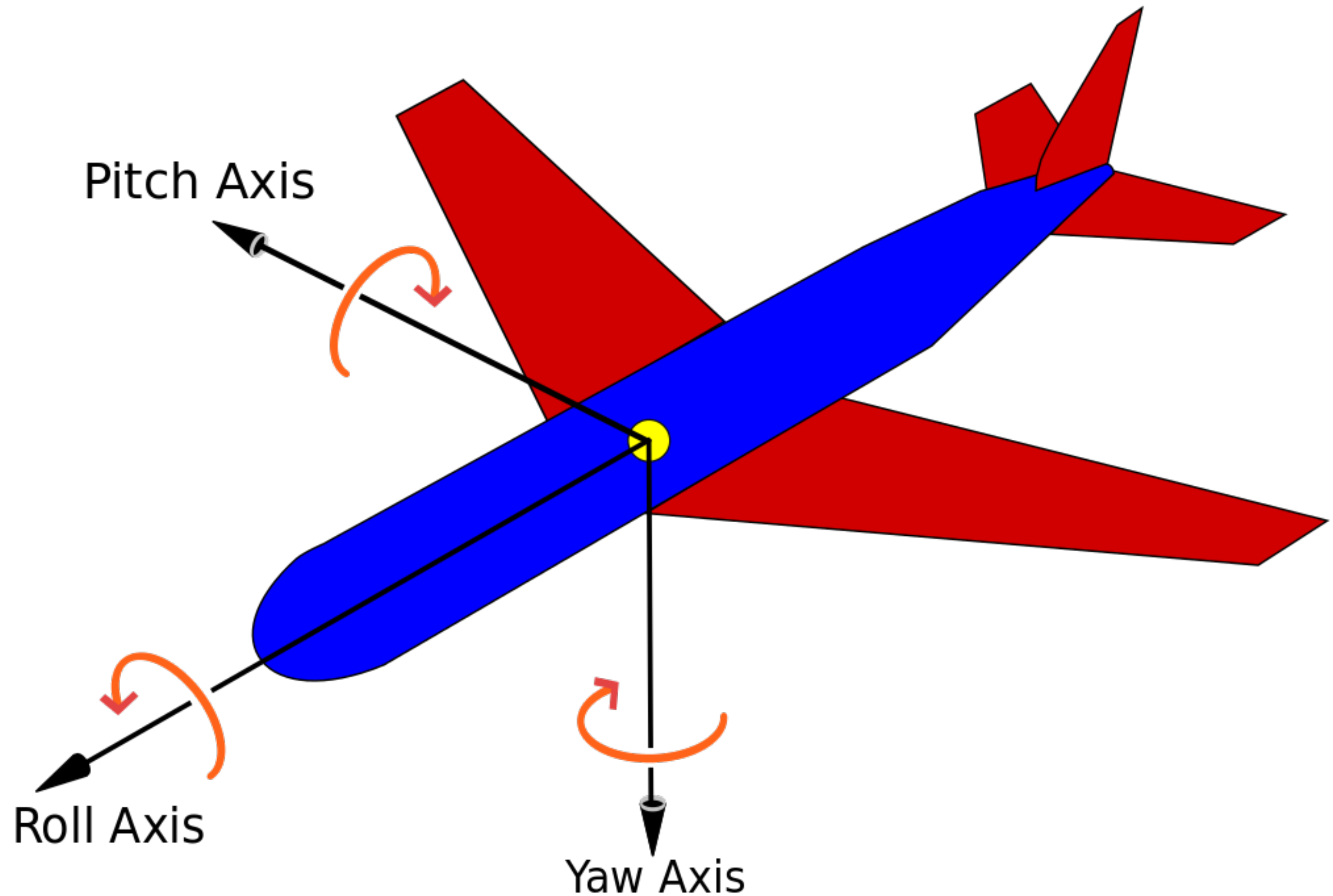


Figure source: https://commons.wikimedia.org/wiki/File:Yaw_Axis_Corrected.svg

Why Three Blades?

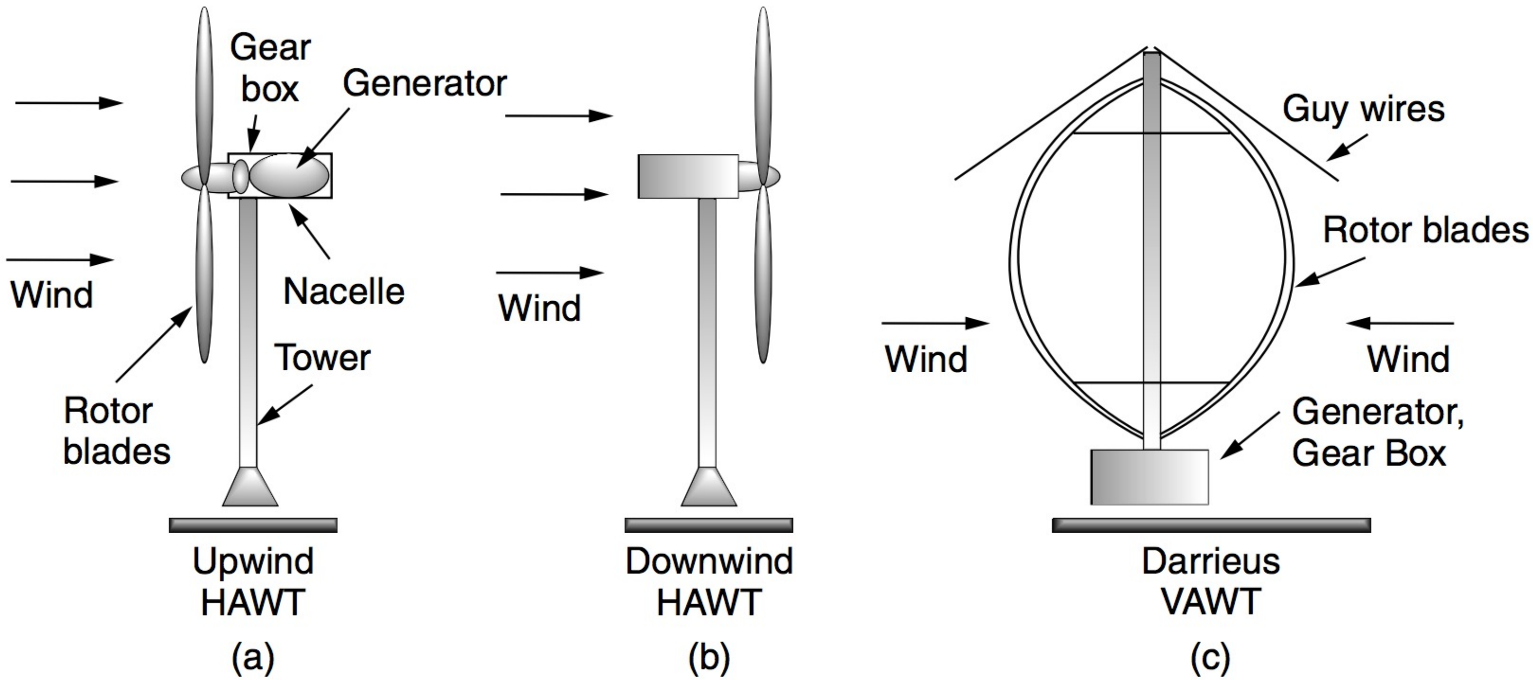
The three-blades design is an ideal compromise between high energy yield and greater stability and durability of the turbine itself.

1) Because of the decreased drag, one blade would be the optimum number for energy yield. However, it can cause the turbine to become unbalanced.

2) Similarly, two blades would offer greater energy yield than three. Two-bladed wind turbines are more prone to a phenomenon known as gyroscopic precession, resulting in a wobbling that would create further stability issues.

3) Any number of blades greater than three would create greater wind resistance, slowing the generation of electricity and thus becoming less efficient than a three-blade turbine.

Wind Turbine Types



- All large wind turbines are horizontal axis wind turbines (HAWT) are either upwind machines (a) or downwind machines (b).
- Downwind HAWT naturally let wind control the yaw, but have the flexing issue leading to blade failure, increased noise, and reduced power output
- Vertical axis wind turbines (VAWT) accept the wind from any direction (c). Heavy generator and gear box are located down on the ground.

Wind Turbine Types

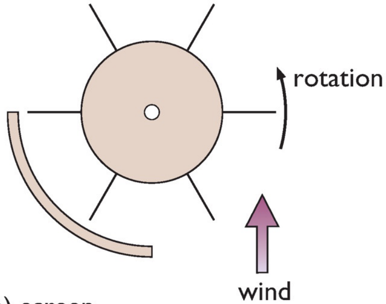
- **Horizontal axis wind turbines (HAWTs):** *'Axial flow'* type, i.e. the rotation axis is in line with the wind direction. They produce a few tens or hundreds of watts to 7.5 MW or more.

Wind Turbine Types (Cont'd)

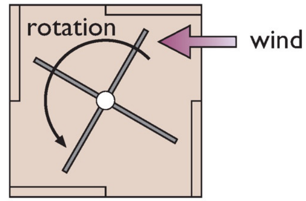
- **Vertical axis wind turbines (VAWTs):** *'Cross flow'* type, i.e. the rotation axis is perpendicular to the wind direction. They can harness winds from any direction without repositioning the rotor. VAWTs have little commercial success, due to issues with power quality, cyclic loads and the lower efficiency designs.

Traditional Vertical-Axis Windmills

Screen wind machines



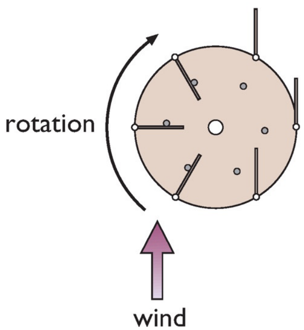
(a) screen



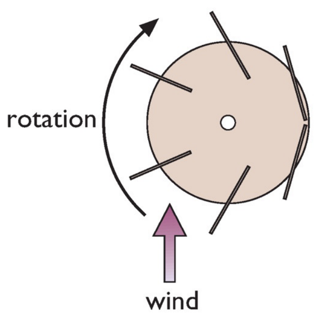
(b) vertical axis windmill screened by walls

- Employ walls that are positioned to screen windmill sails from the wind during the ‘backward’ cycle.

Clapper-type wind machines

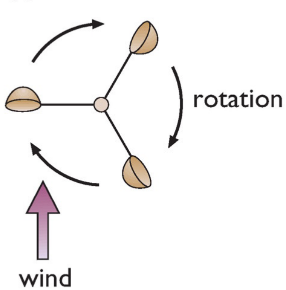


Wind machine with cyclic pitch variation

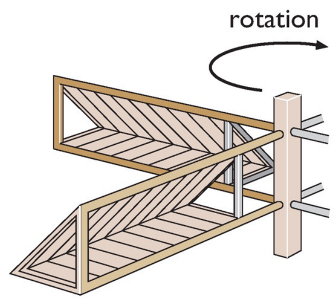


- Moveable sails ‘clap’ against stops when the rotor turns with the wind forwards.

Cup-type wind machines



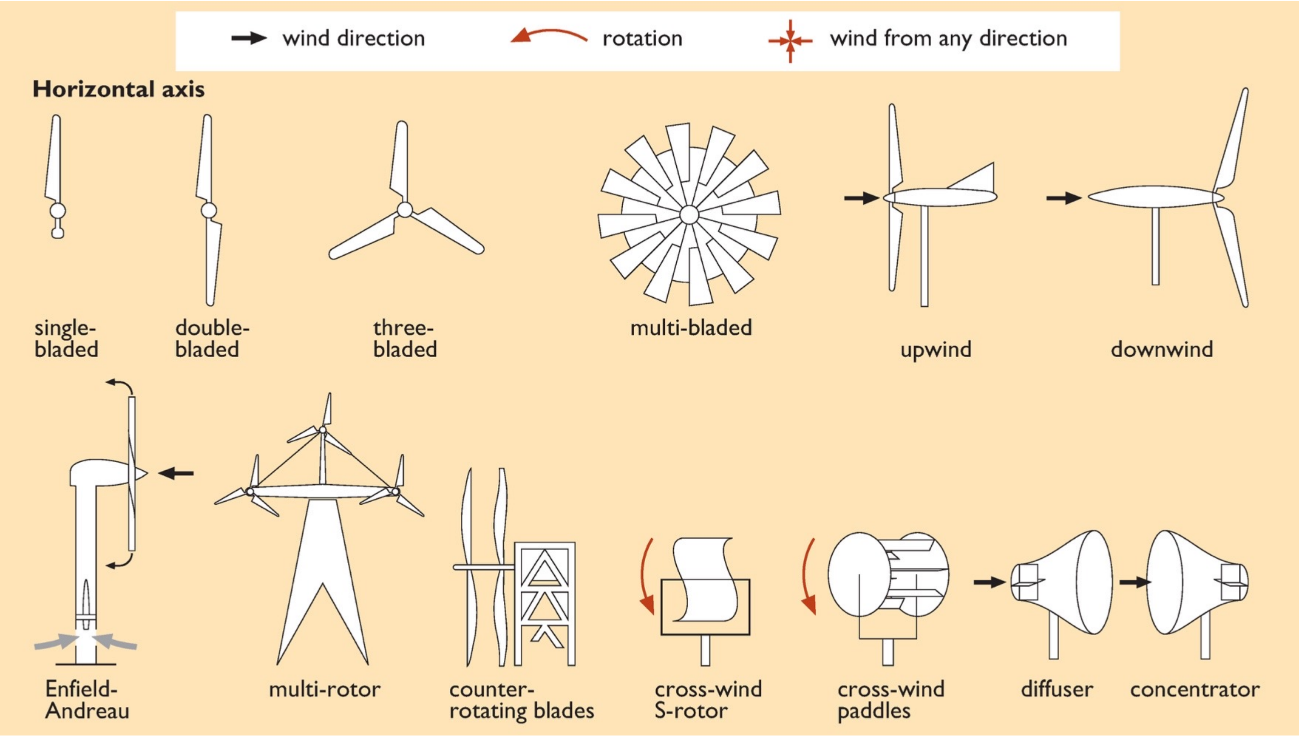
(a) cup anemometer

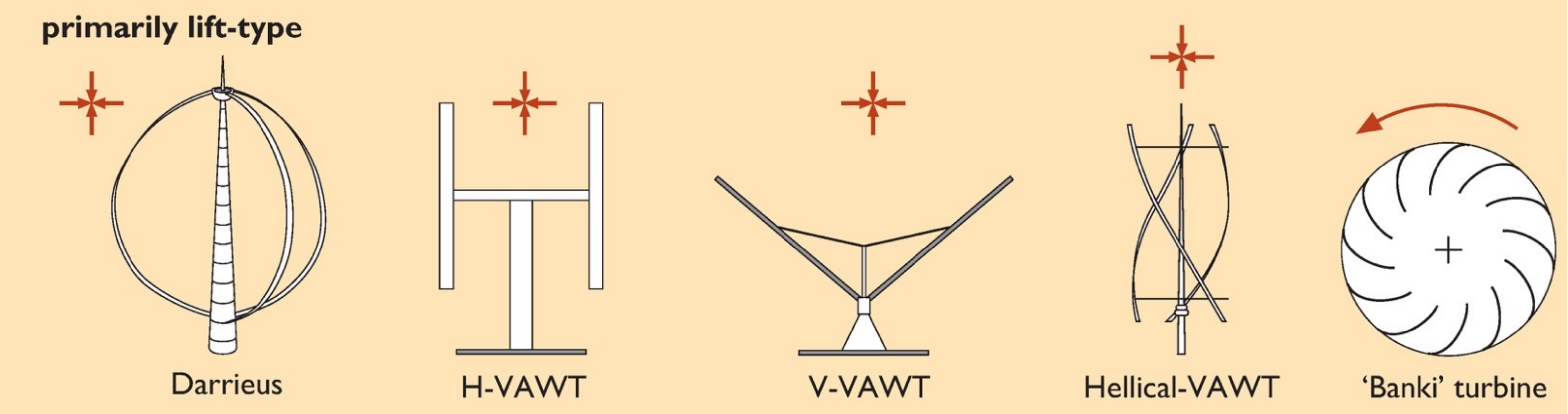


(b) ‘streamlined anemometer sail windmill’ invented by Faustus Verantius, a seventeenth century bishop and engineer (Needham, 1965)

- Cup/streamlined windmills: blades are shaped to offer greater resistance to the wind on one surface compared with the other.

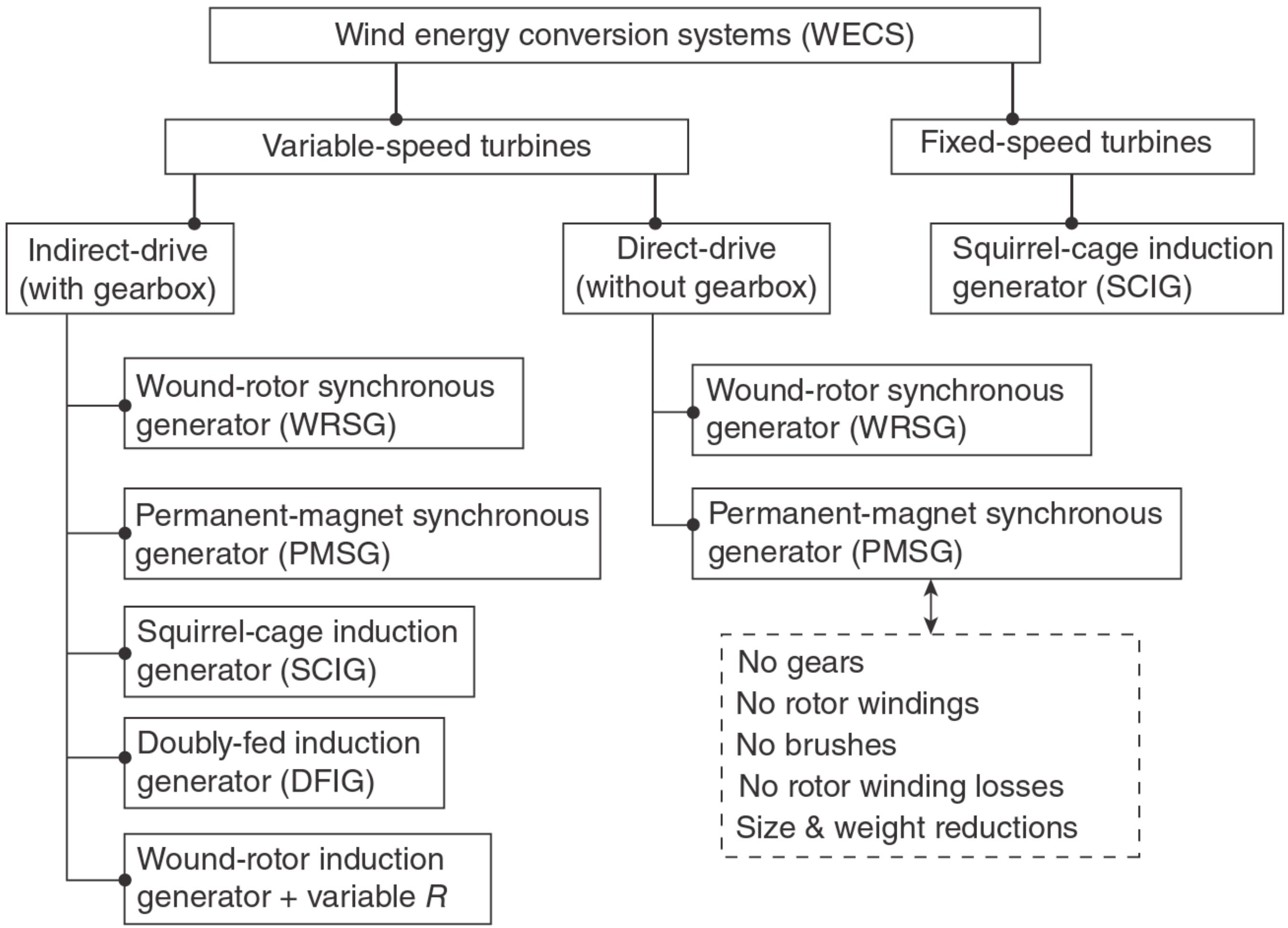
Wind Energy Conversion Systems (WECS)





Wind Energy Conversion Systems (WECS)

- Variable-speed or fixed-speed rotor (here means rotor speed)
- Synchronous generator or induction generator
- With or without gearbox



Synchronous Generator

Synchronous generators (great majority in power systems)

- Can generate reactive power (control the output voltage level).
- Have their own magnetic field: A permanent magnet or have a field winding where a magnetizing current establishes the necessary magnetic field.
- Frequency of the generated voltage and the mechanical speed are synchronized by the magnetic field.
- The generated frequency f is an integer multiple of the rotational speed N, which also depends on number of poles p:

$$N(\text{rpm}) = \frac{120f}{p}$$

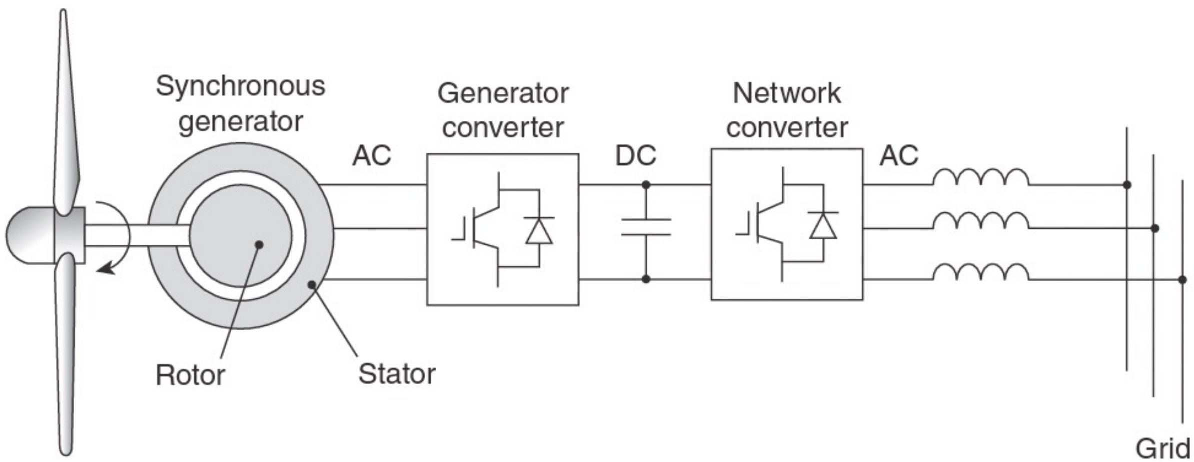


FIGURE 7.13 A gearless, variable-speed synchronous generator with full-capacity converters.

Induction Generator

Induction generators (used by most of the world's wind turbines)

- Can't generate their own magnetic field, need to be magnetized via the grid.
- They consume reactive power (e.g., from a capacitor bank).
- Their rotors run with negative slip (rotor runs ahead of the rotating field) that is mandatory to transfer the power from the rotor to the stator.
- Do not turn at a fixed speed, aka asynchronous generators.

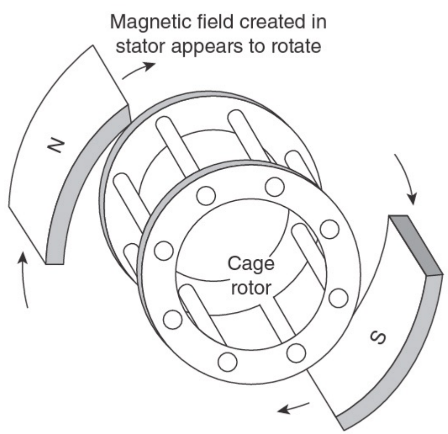


FIGURE 7.10 A cage rotor consists of thick, conducting bars shorted at their ends, around which circulates a rotating magnetic field.

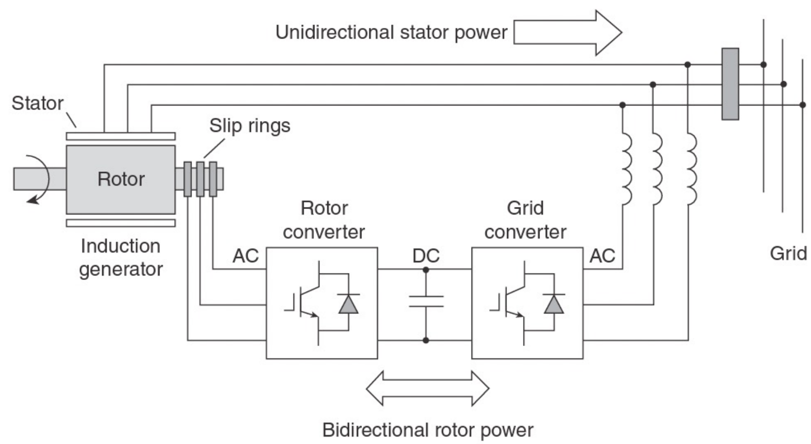


FIGURE 7.12 A wound-rotor, doubly-fed induction generator (DFIG).

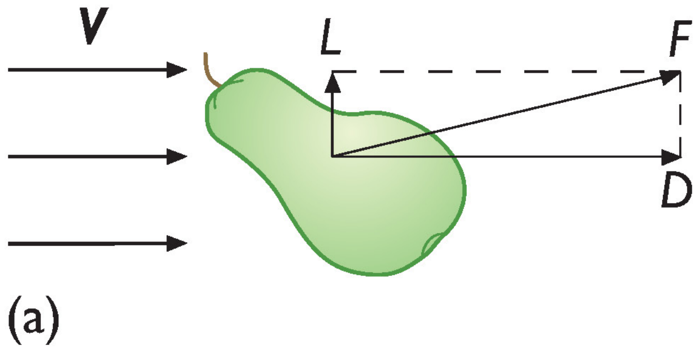
- Squirrel-cage rotor: no need of exciter, brushes, and slip rings (simple & robust)
- Pole switching: remotely switch the number of poles by clever wiring of the stator windings.
- Slip speed: see details on page 421 of B1.

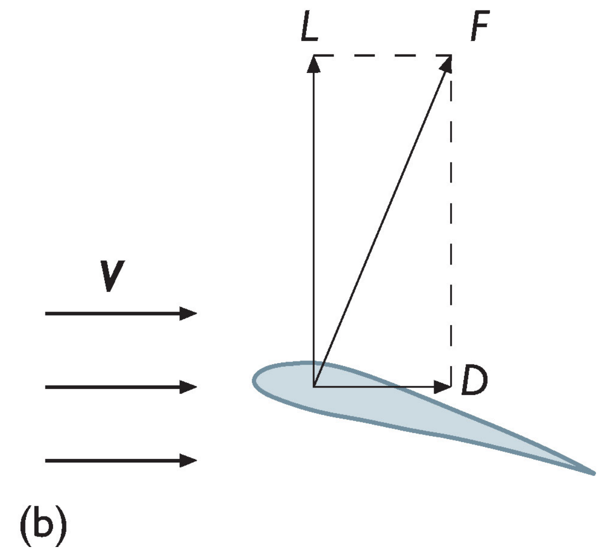
- Wound rotor: the grid creates the stator's rotating magnetic field.
- Slip rings are used to energize the rotor.
- Bidirectional rotor power: power always flows from high freq side to low freq side.

Speed-Power Curve Factors

- Rotor swept area
- Choice of aerofoil (cross-sectional shape of a wing)
- Number of blades
- Blade shape
- Speed of rotation
- Cut-in/rated/cut-out wind speed
- Aerodynamic efficiency
- Gearing and generator efficiency

Aerodynamic Forces



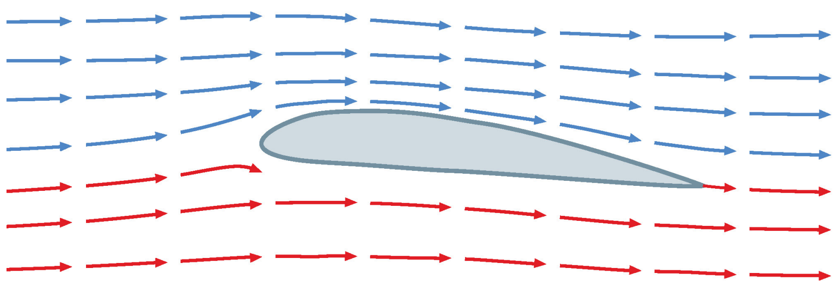


An object in an air stream is subjected to a force F, from the air stream.

Two component forces:

- Drag force D: acting in line with the direction of air flow.
- Lift force L: acting at 90° to the direction of air flow.

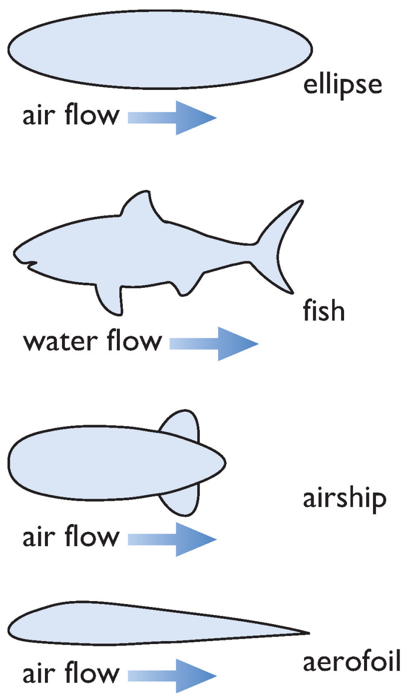
Aerodynamic Forces (cont'd)

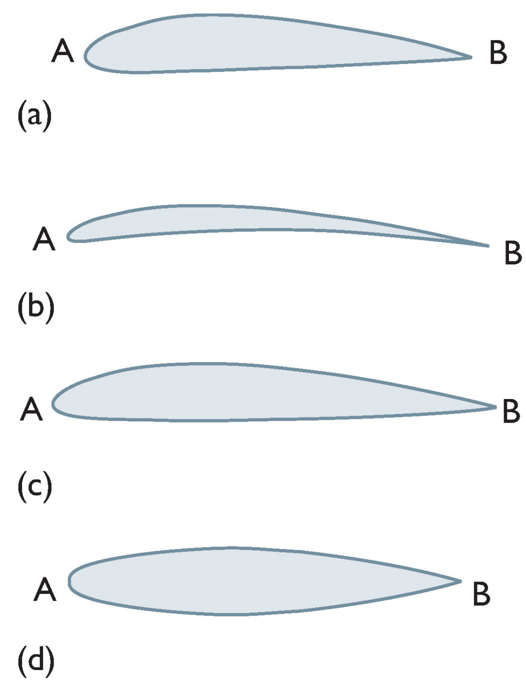


The magnitude of these forces depends on

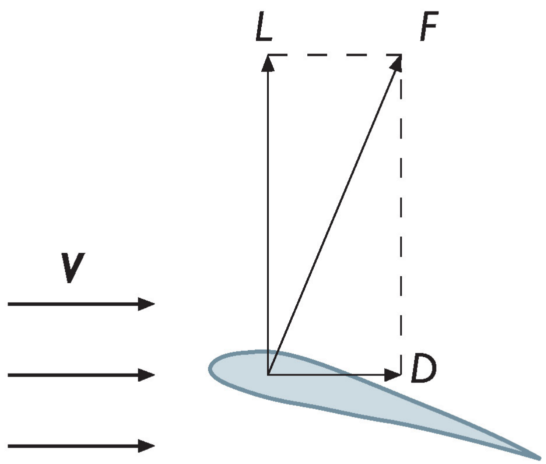
- shape of the object
- its orientation to the air stream
- air stream velocity.

Objects designed to minimize drag forces – 'streamlined'





Lift and Drag Coefficients

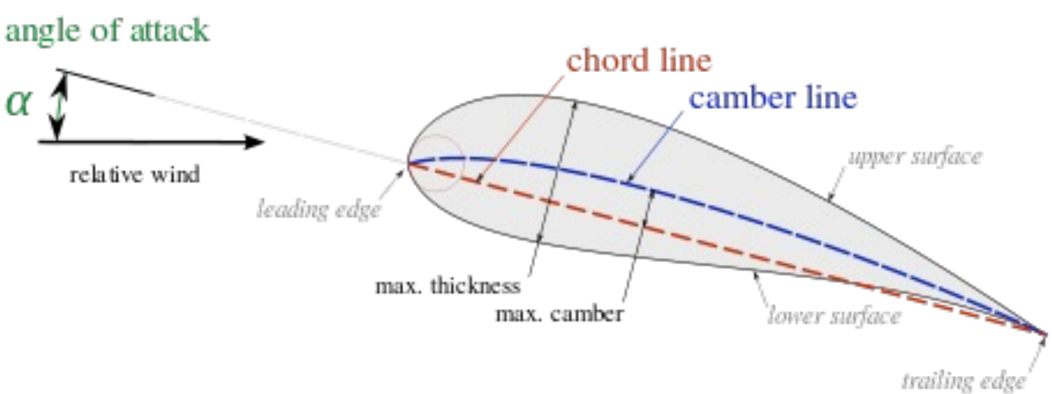


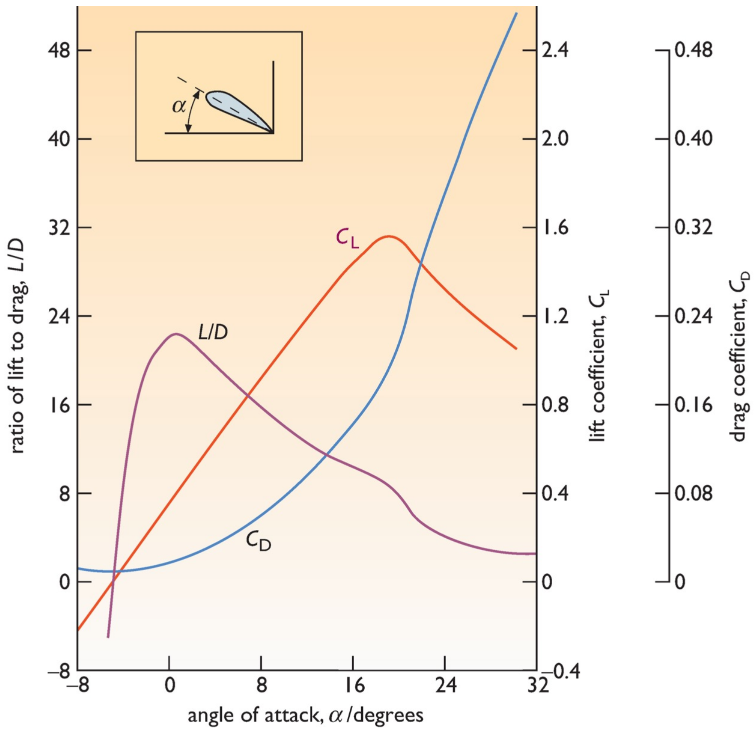
$$\text{Drag coefficient}: \quad C_\mathrm{D} = \frac{D}{0.5\rho V^2 A_b}$$

$$\text{Lift coefficient}: \quad C_\mathrm{L} = \frac{L}{0.5\rho V^2 A_b}$$

ρ – air density, V – velocity of the air, A_b – blade area

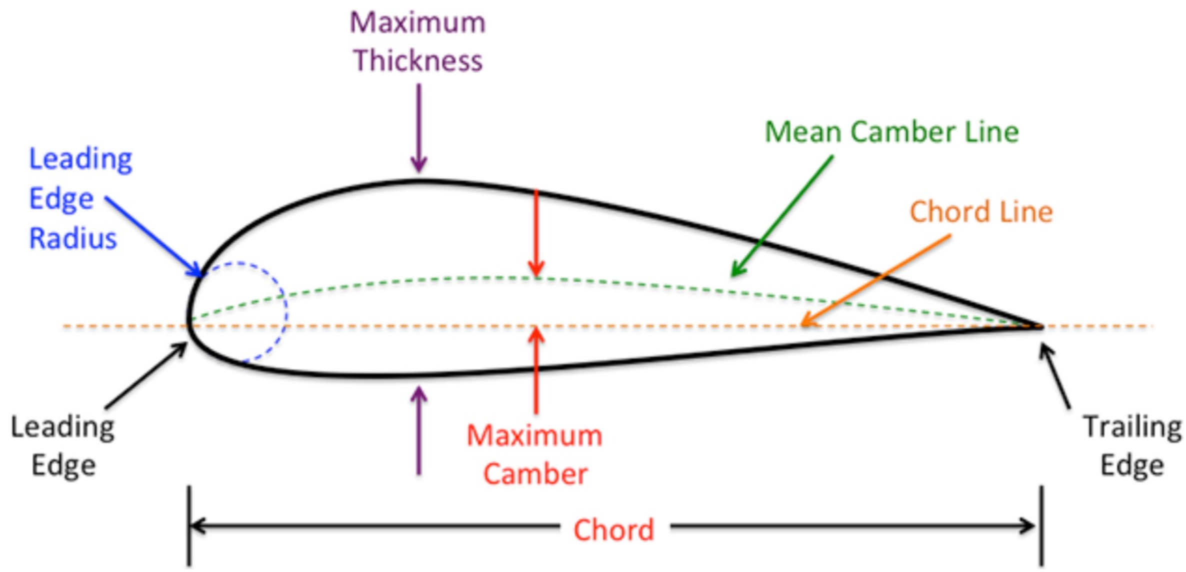
When airflow is directed towards the underside, α is positive





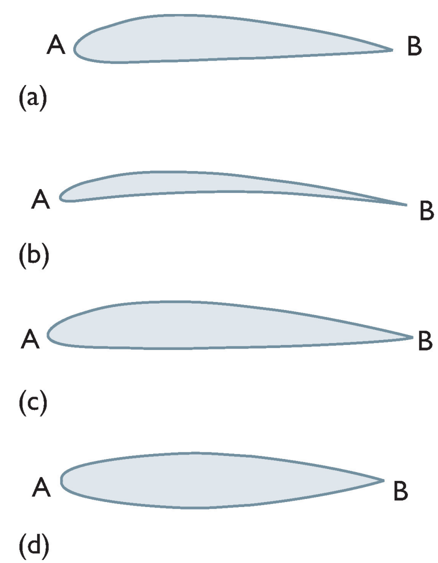
Airfoil Shape

Airfoil Terminology



- **Asymmetrical airfoils (a) – (c):** Optimized to produce most lift when the underside of the airfoil is closest to the direction from which the air is flowing.

- **Symmetrical airfoils (d):** Able to induce lift equally well when the air flow is approaching from either side of the 'chord line'.



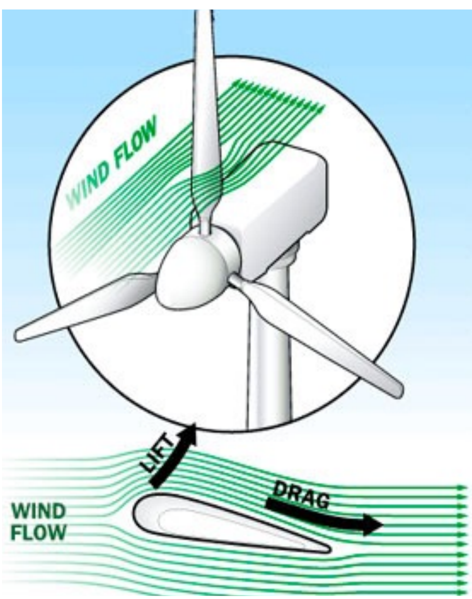
From Aircraft to Wind Turbine

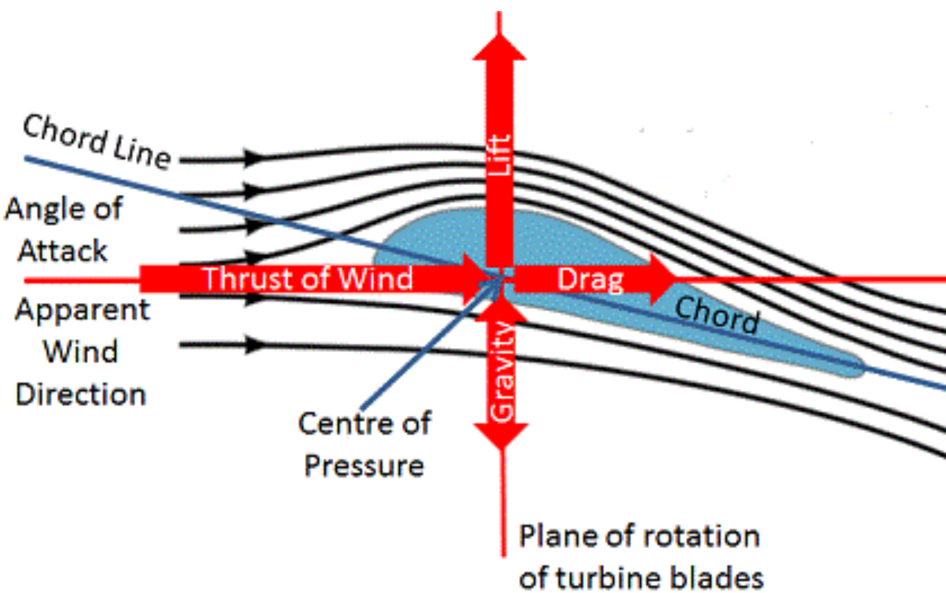
Aerodynamic

Turbine blade ⟷ Wing of airplane

Bernoulli's principle

The faster the airflow, the lower the pressure
(the greater the 'suction effect')





Harnessing Aerodynamic Forces

HAWT & VAWT harness aerodynamic forces in a different way:

- HAWT with fixed-pitch blades, with its rotor axis in constant alignment with the wind direction, for a given wind speed and constant rotation speed the angle of attack at a given position on the rotor blade **stays constant** throughout its rotation cycle.

- VAWT with fixed-pitch blades, under the same conditions the angle of attack at a given position on the rotor blade **constantly varies** throughout its rotation cycle. This means that the 'suction' side reverses during each cycle, so a symmetrical airfoil has to be employed to ensure that power can be produced irrespective of whether the angle of attack is positive or negative.

Harnessing Aerodynamic Forces (HAWT)

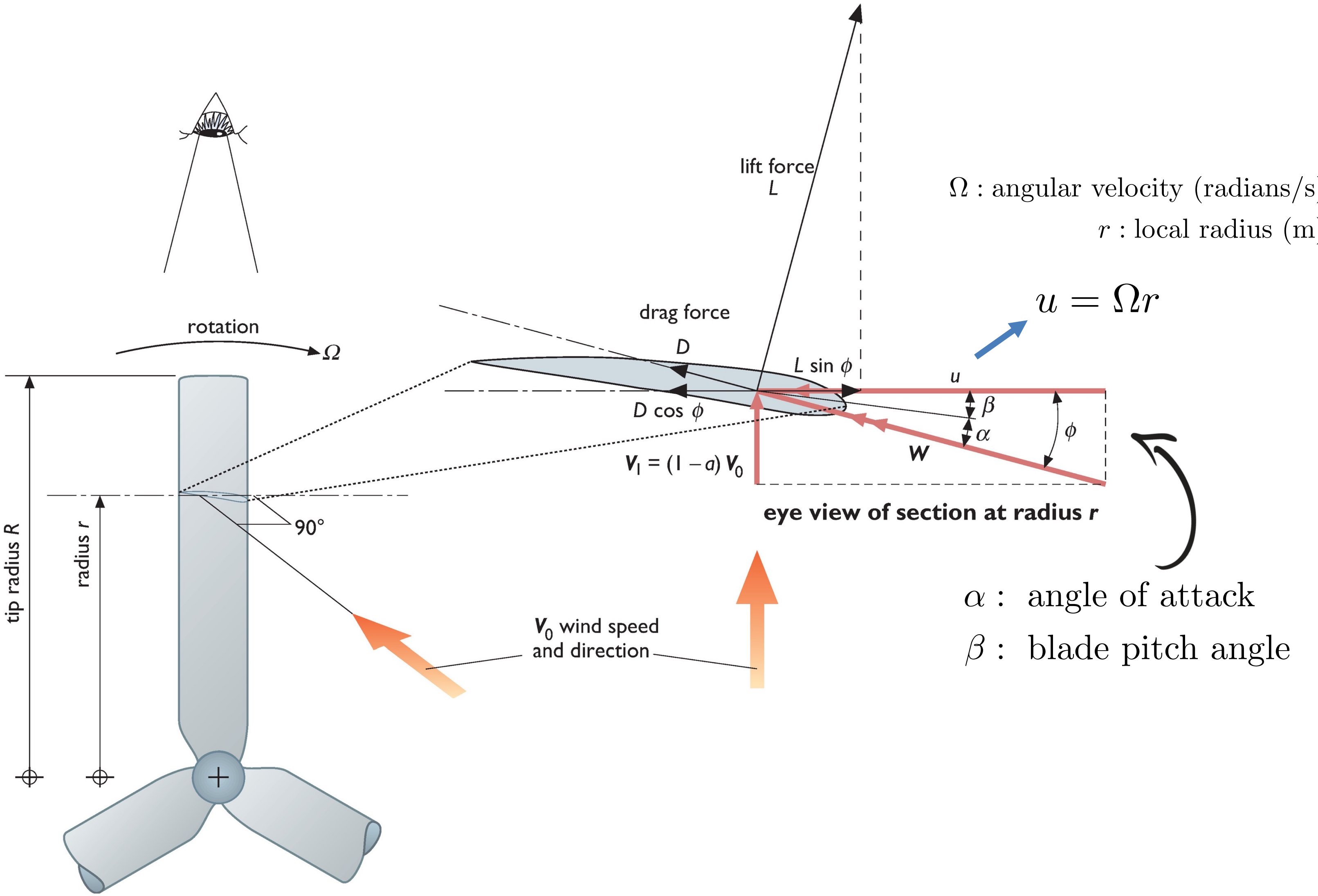


Fig: Vector diagram showing a section thru a moving HAWT rotor blade

HAWT Rotor Blade Design

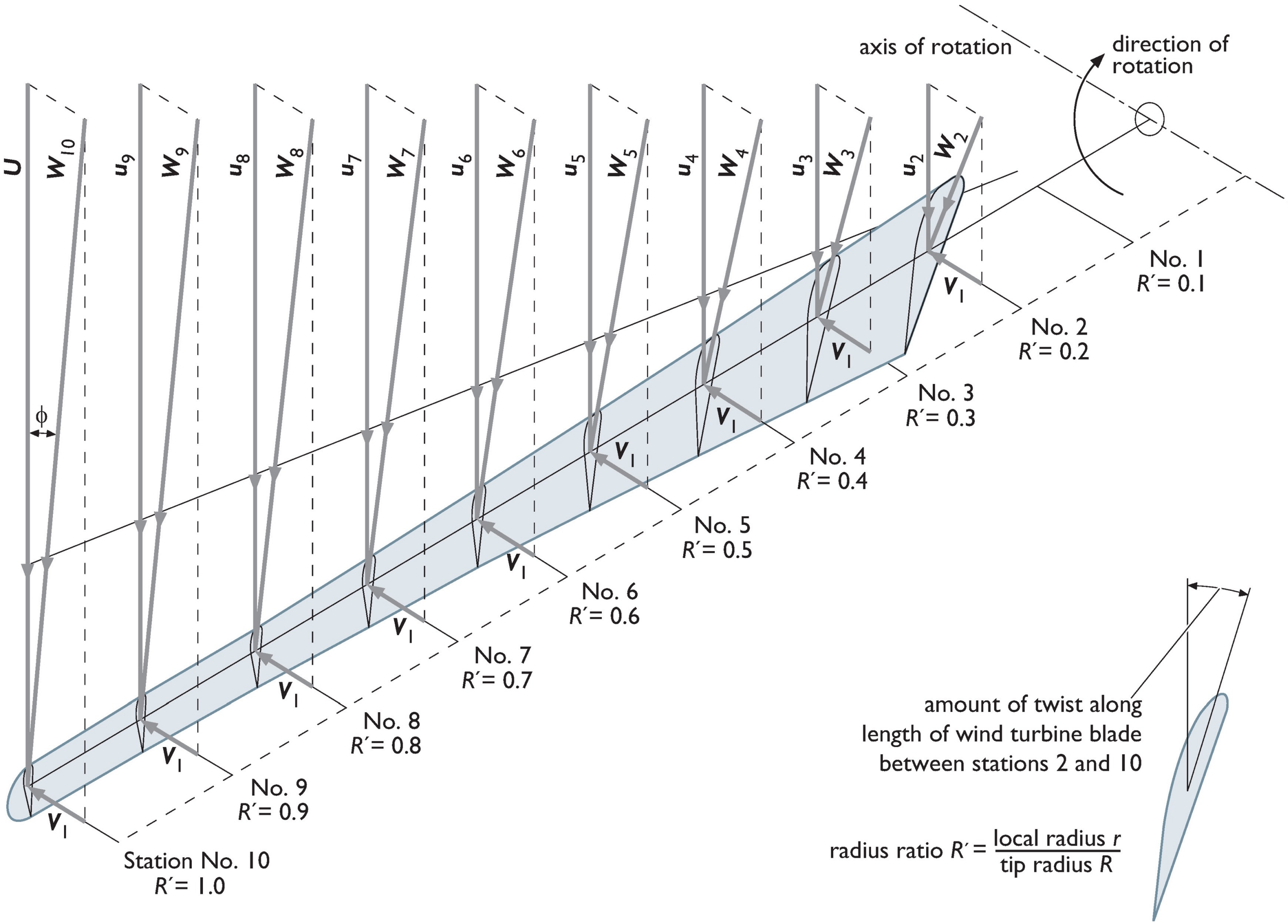
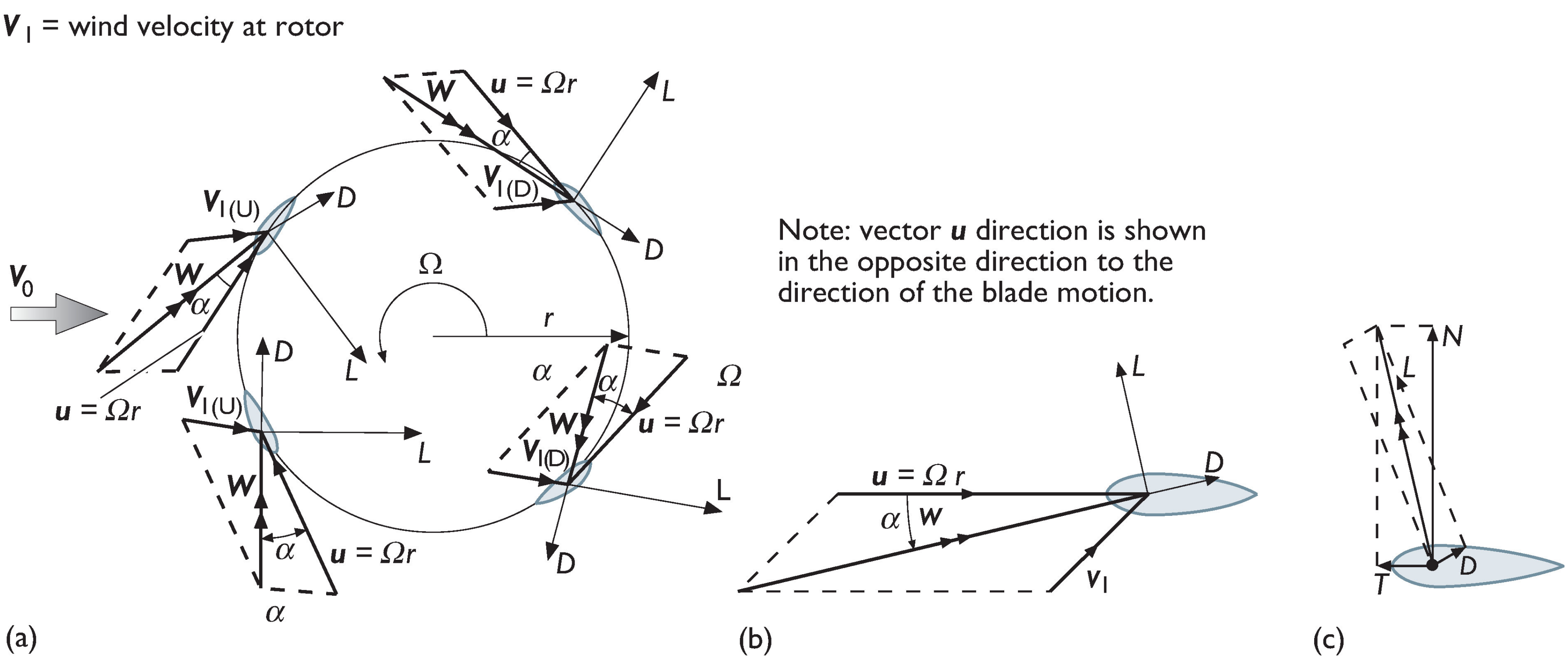


Fig: 3D view of an optimally tapered and twisted HAWT rotor blade design

VAWT Harnessing Aerodynamic Forces



Figures:
(a) angles of attack at different positions
(b) detail of aerodynamic forces
(c) normal (radial) & tangential (chord-wise) components of lift force

Onshore or Offshore?

Pros:

- An offshore turbine can last around 25-30 years
- Produce about 50% more energy (3-5MW per hour w/ strong wind)
- Higher and more constant wind speed

Cons:

- More expensive to built
- More difficult to maintain & access

Onshore wind turbines

Offshore wind turbines

Foundation Tech

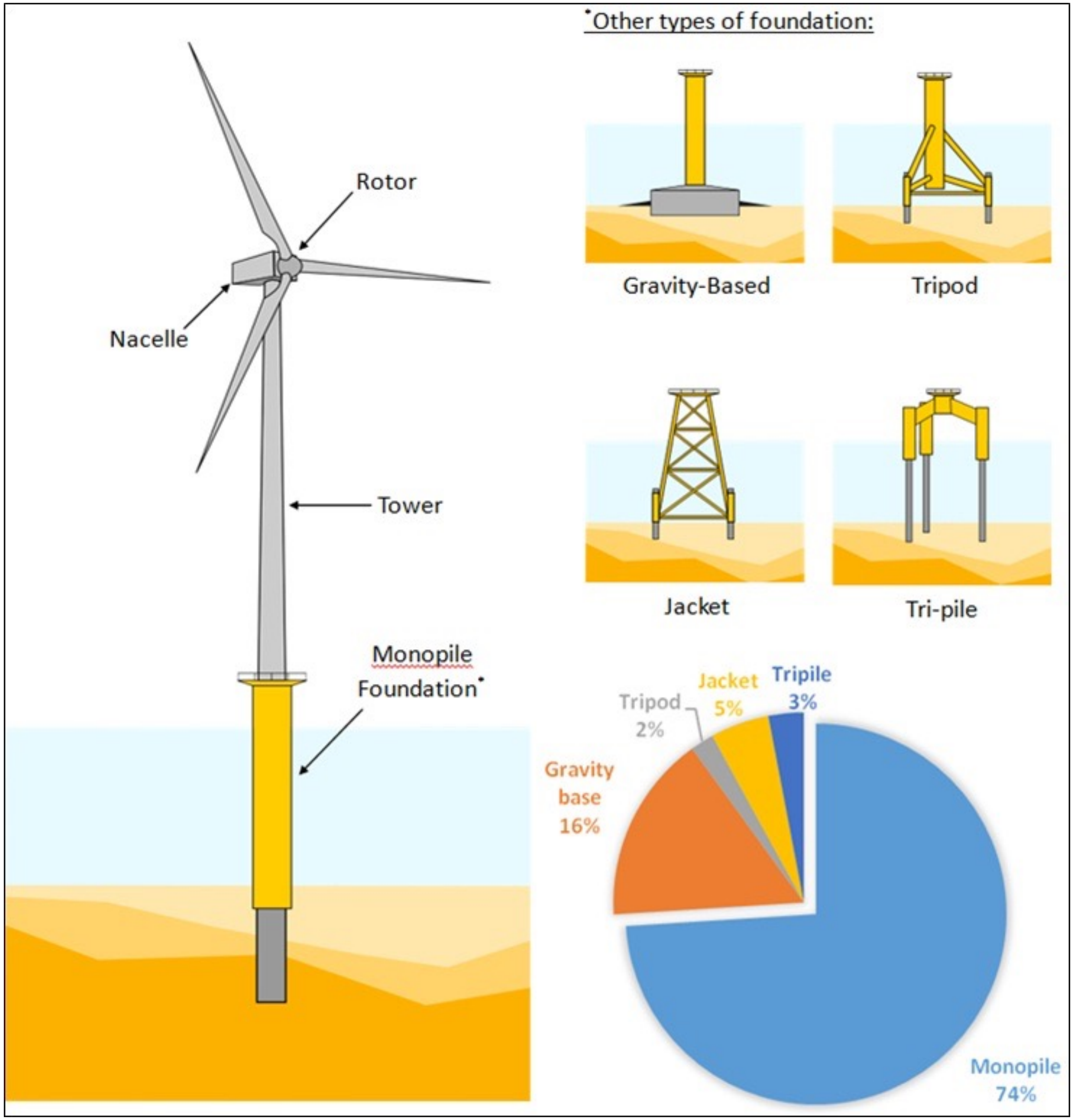


Figure source: VJ Tech

Transitional Depth Foundations (30-60m)

- Transitional waves are waves traveling in water where depth is less than half the wavelength but greater than one-twentieth the wavelength (1/20 L < D < 1/2 L).
- Transitional waves are often wind-generated waves that have moved into shallower water.

Figure source: DOE EERE office

Floating Foundations (50-200m)

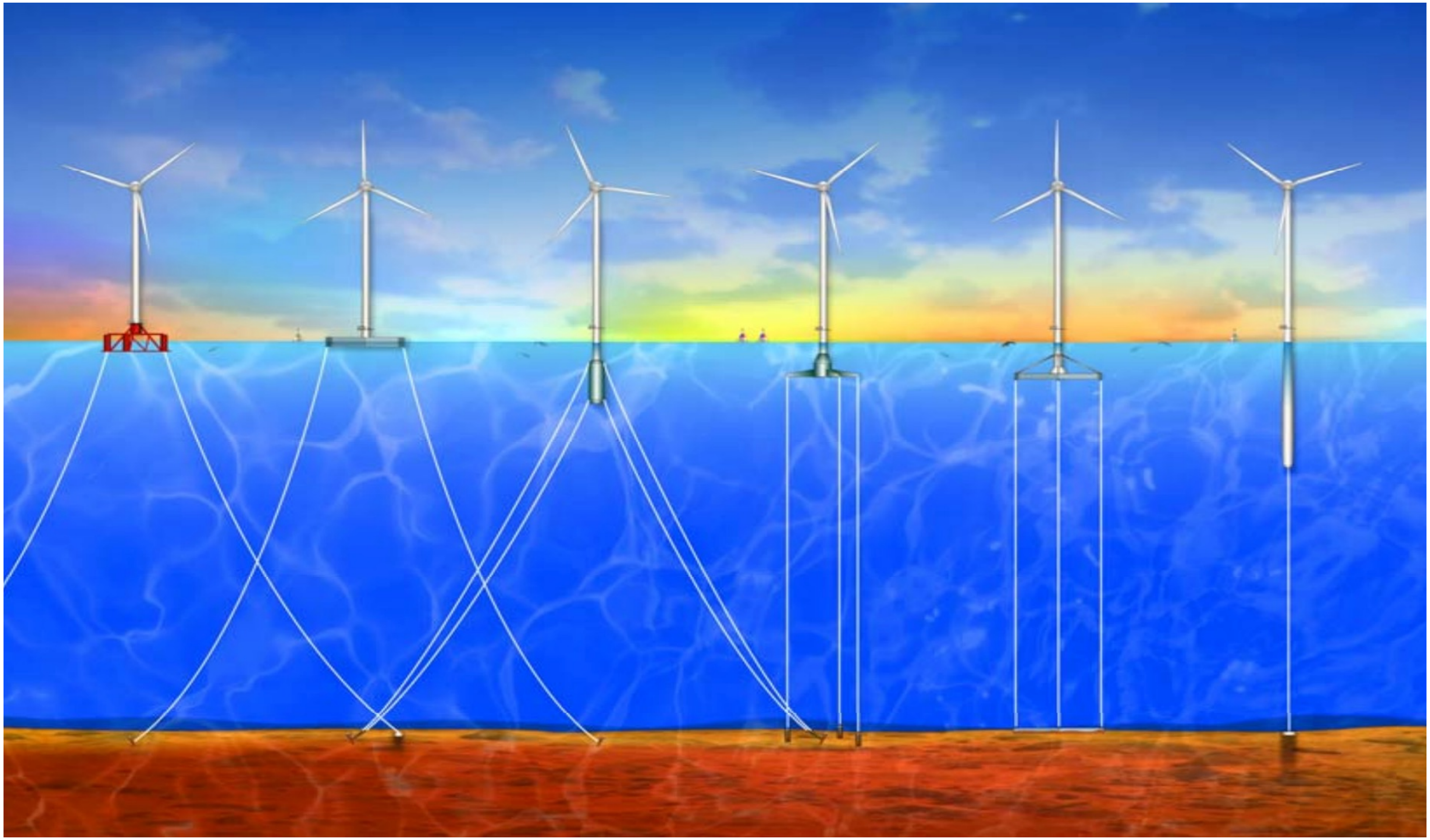
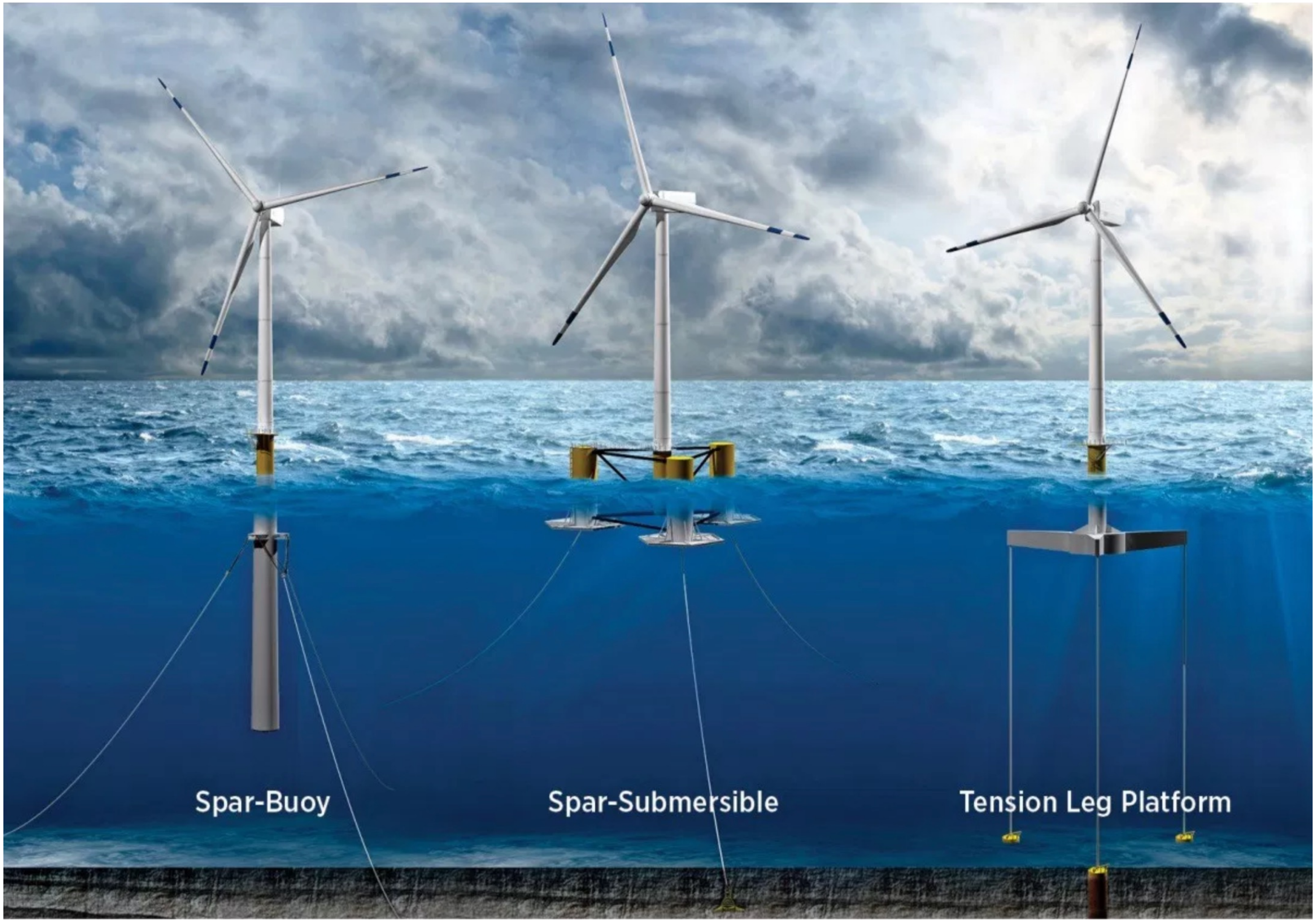


Figure source: DOE EERE office

Floating Foundations



By Joshua Bauer, NREL

Floating Wind Turbine Concepts


(a)


(b)


(c)


(d)


(e)


(f)

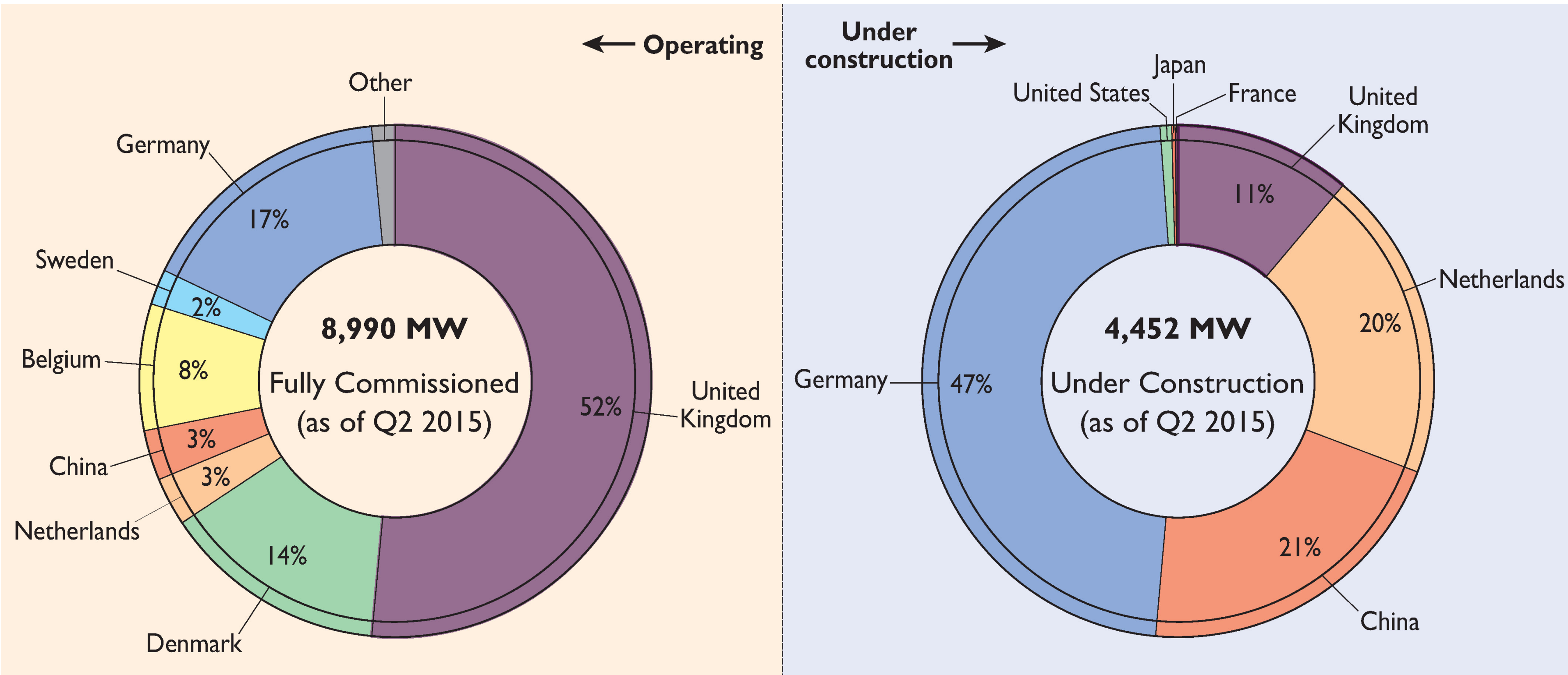

(g)


(h)

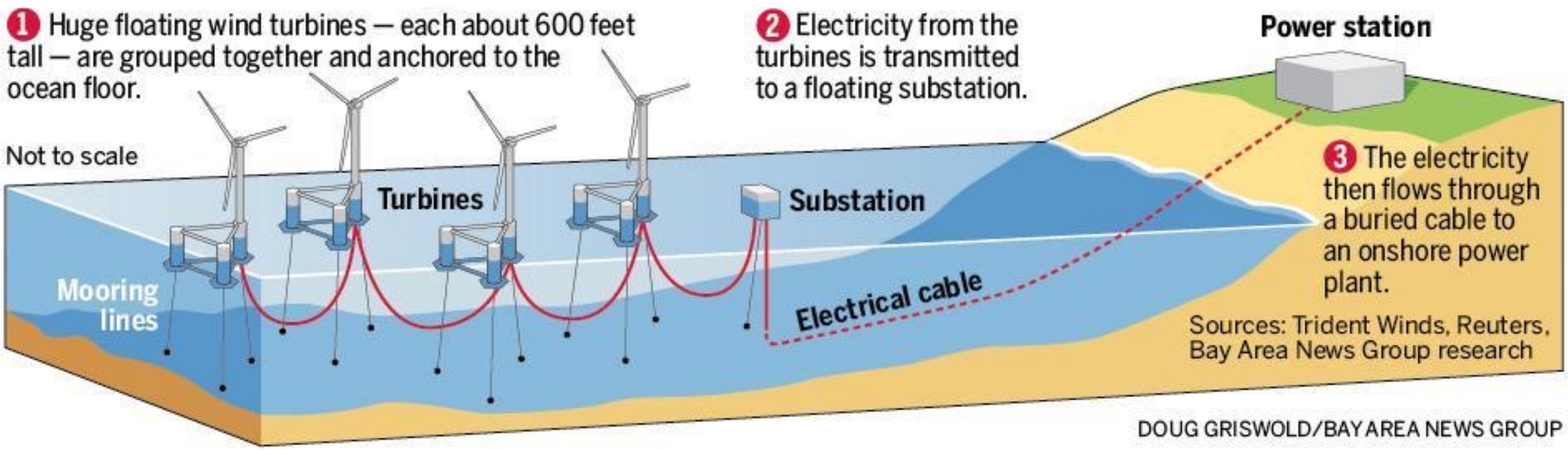

(i)


(j)

Global Offshore Wind Power Capacity



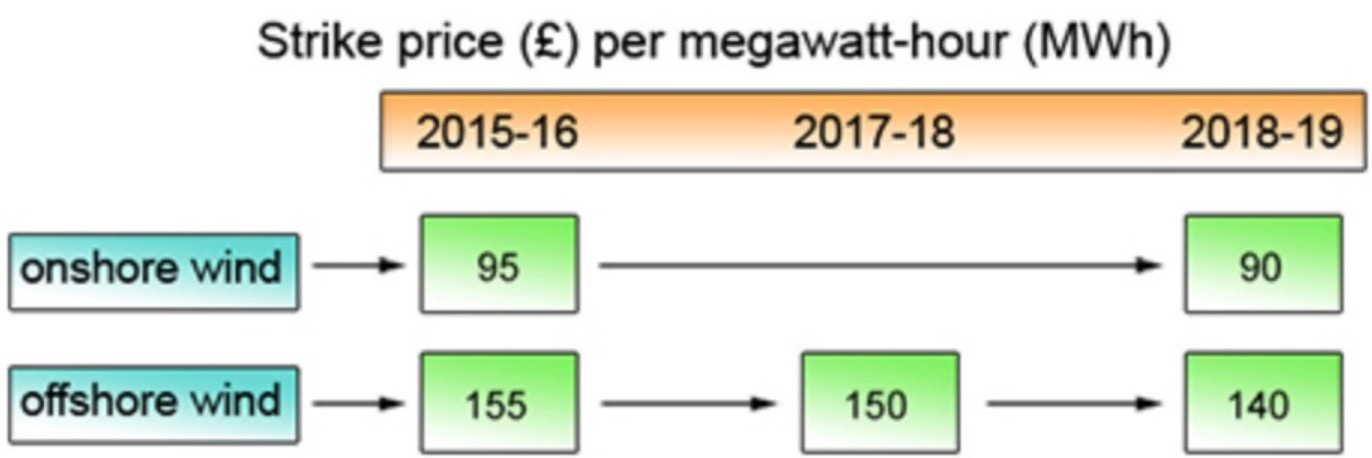
How Offshore Wind Farms Work



Electricity Cost from Wind

The costs of electricity from wind depend on:

- Annual energy production from the wind turbine installation
- Capital cost of the installation
- Discount rate being applied to the project
- Length of the contract with the purchaser
- Loan repaid
- O&M costs



Capital Cost Breakdown

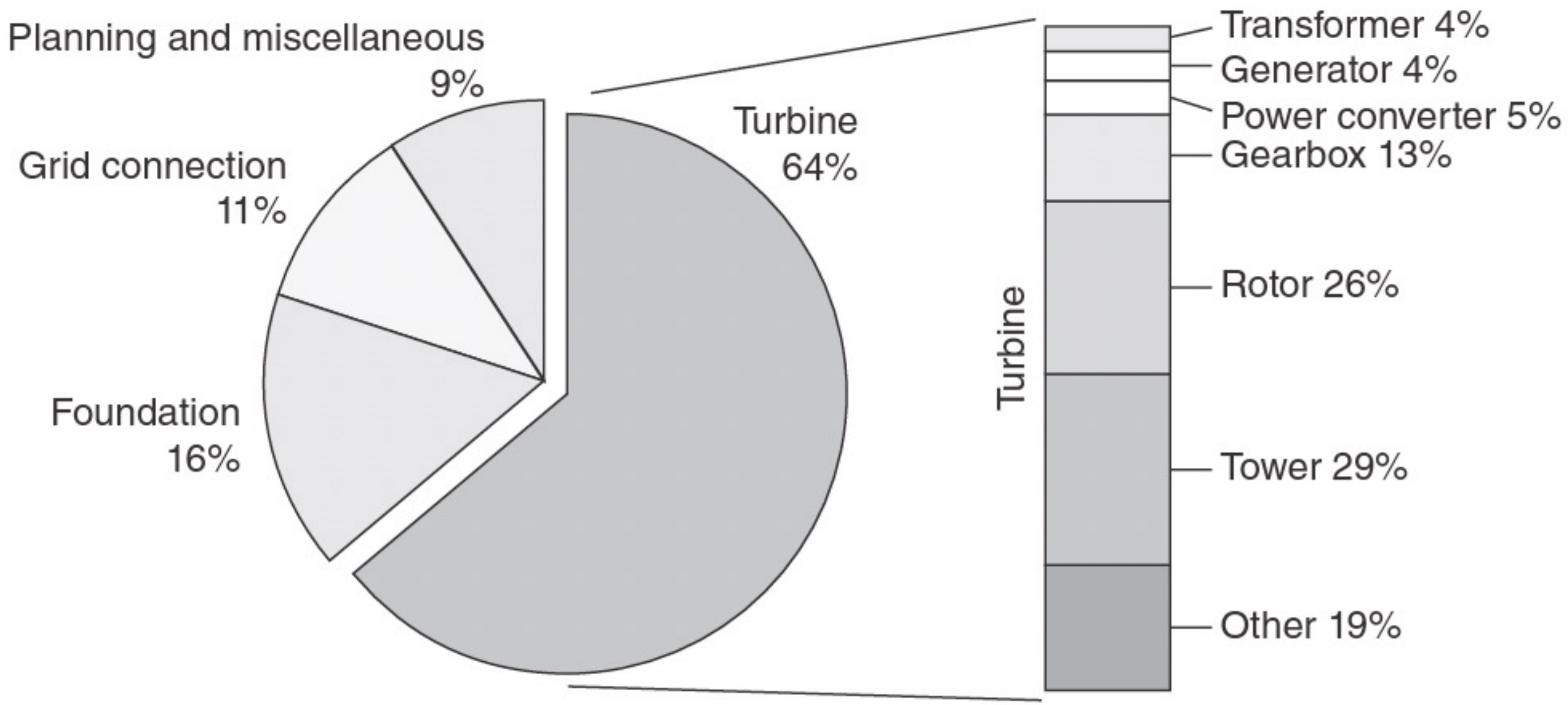


FIGURE 7.47 A breakdown of the capital costs of a wind system. Based on Blanco (2009) and EWEA (2007).

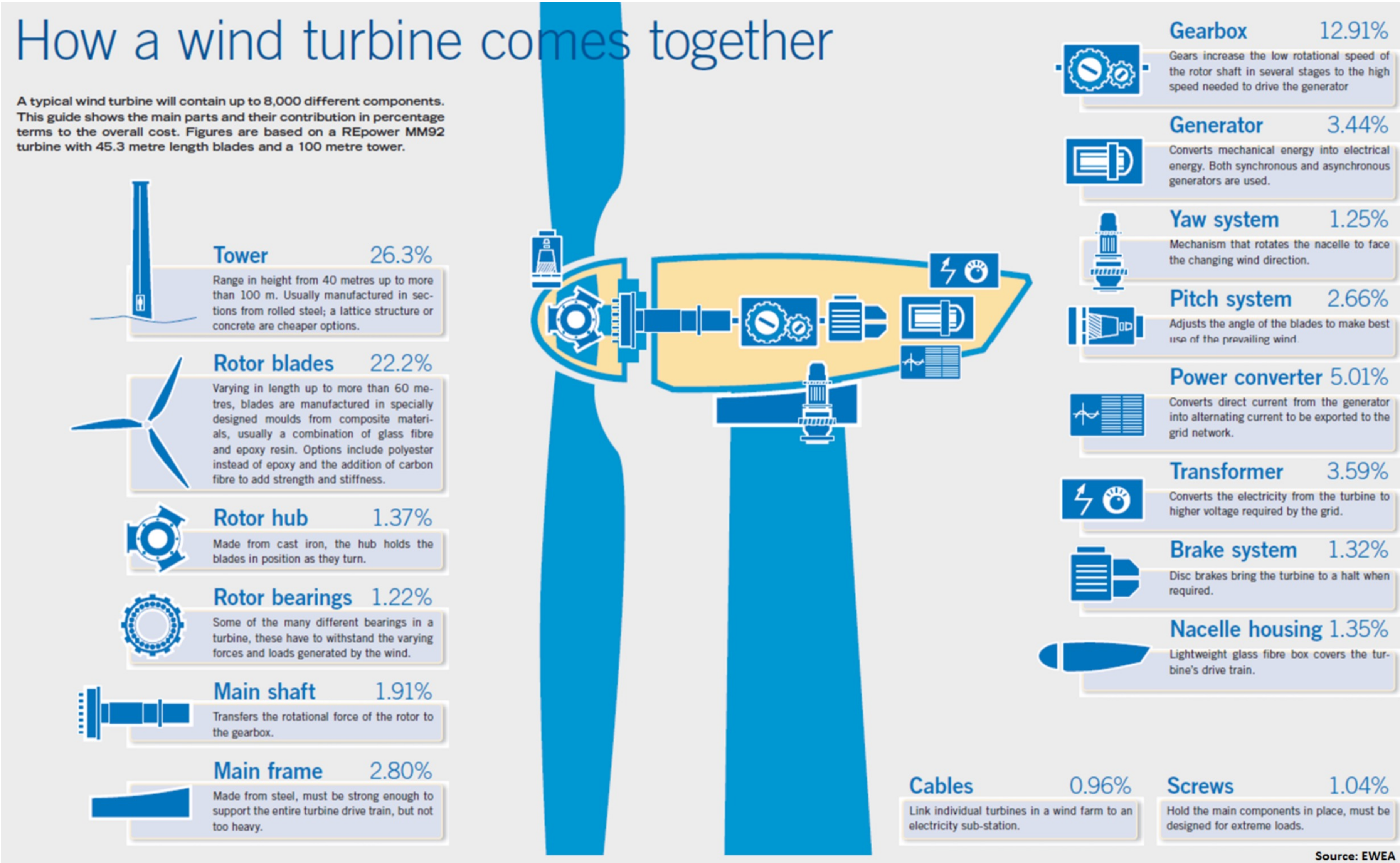
Capital Cost and Annual Cost

Table: An Example Cost Analysis for a 60-MW Wind Park

Capital Costs	Amount ($)	Percentage
40 1.5-MW turbines @ $1.1 M, spare parts	46,640,000	76.6
Site prep, grid connections	9,148,000	15.0
Interest during construction, contingencies	3,514,000	5.8
Project development, feasibility study	965,000	1.6
Engineering	611,000	1.0
Total Capital Cost	60,878,000	100.0
Annual Costs	**Amount ($/yr)**	**Percentage**
Parts and labor	1,381,000	70.3
Insurance	135,000	6.9
Contingencies	100,000	5.1
Land lease	90,000	4.6
Property taxes	68,000	3.5
Transmission line maintenance	80,000	4.1
General and miscellaneous	111,000	5.6
Total Annual Costs	1,965,000	100.0

Source: Ministry of Natural Resources, Canada.

Cost Structure



Decreasing Costs

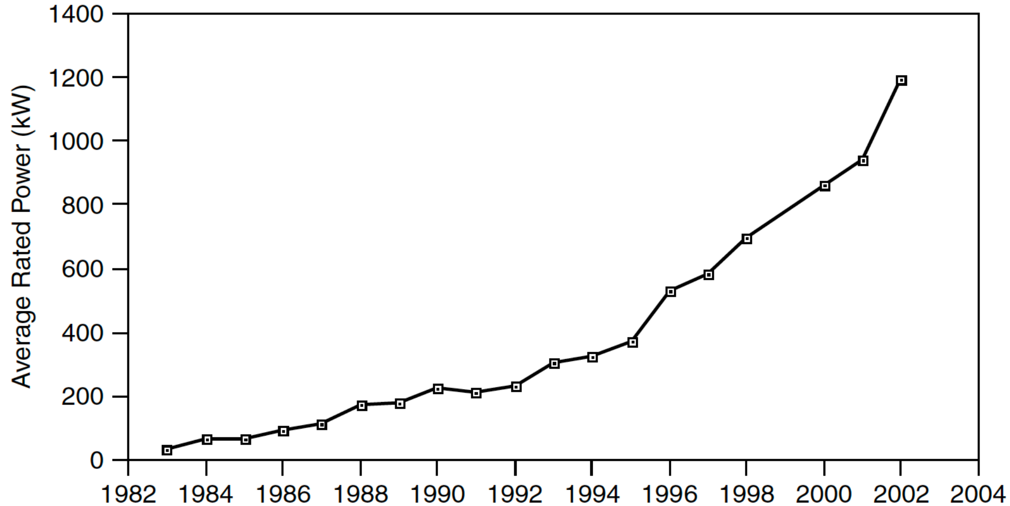


Fig a: Average rated power of new wind turbines manufactured in Denmark.

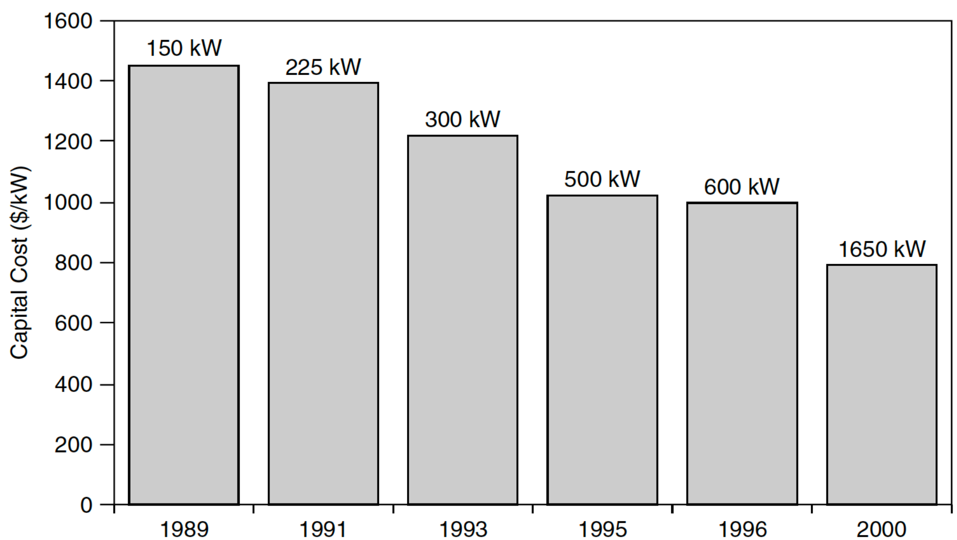


Fig b: Capital costs of wind systems including turbine, tower, grid connection, site preparation, controls, and land.

Environmental Impact

Pros

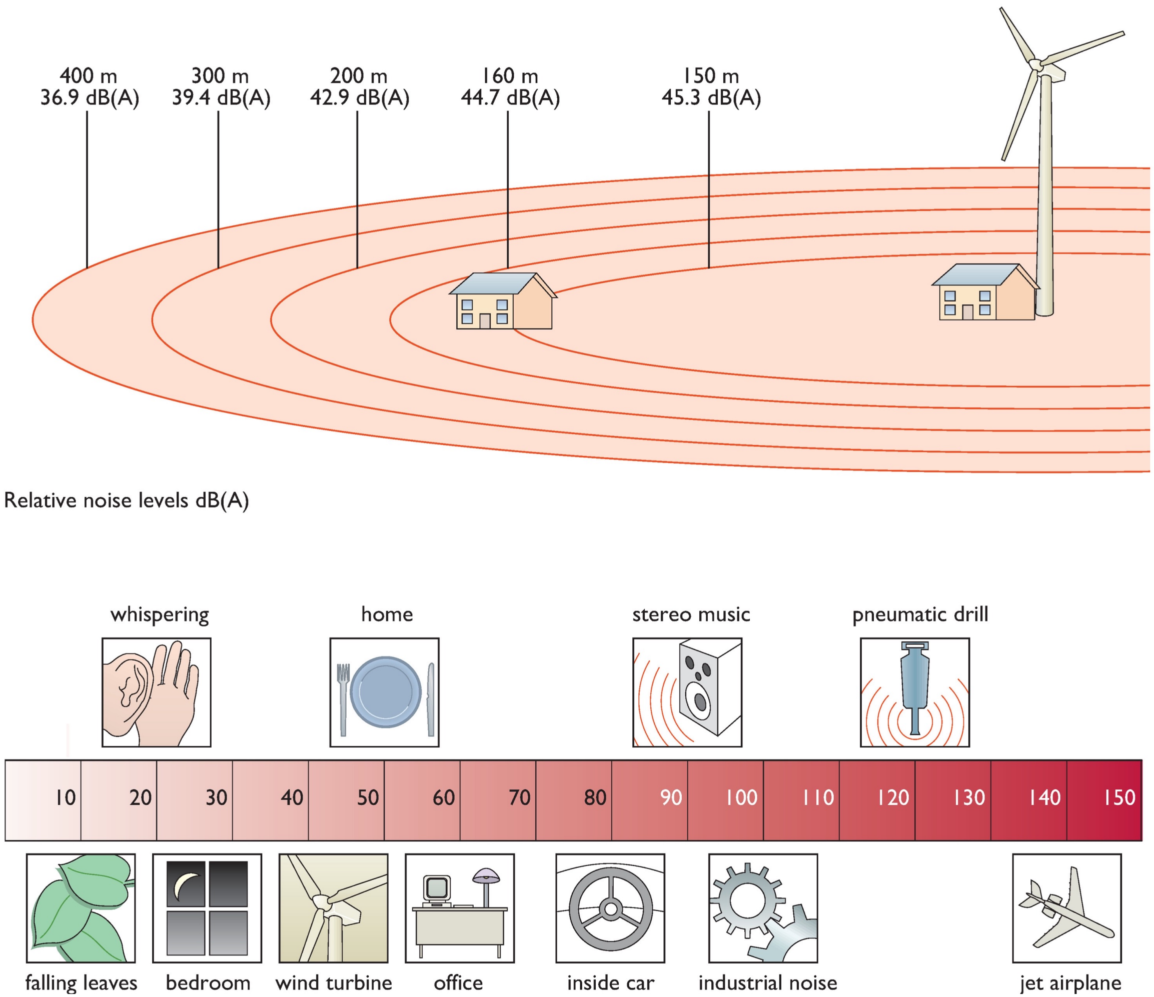
Generation of electricity by wind turbines does NOT involve:

- release of CO_2 or other greenhouse gases
- pollutants leading to acid rain or smog causing diseases
- radioactivity
- contamination of land, sea or water courses
- the consumption of water

Cons

- noise
- electromagnetic interference
- aviation-related issues
- wildlife
- public attitudes and planning

Noise

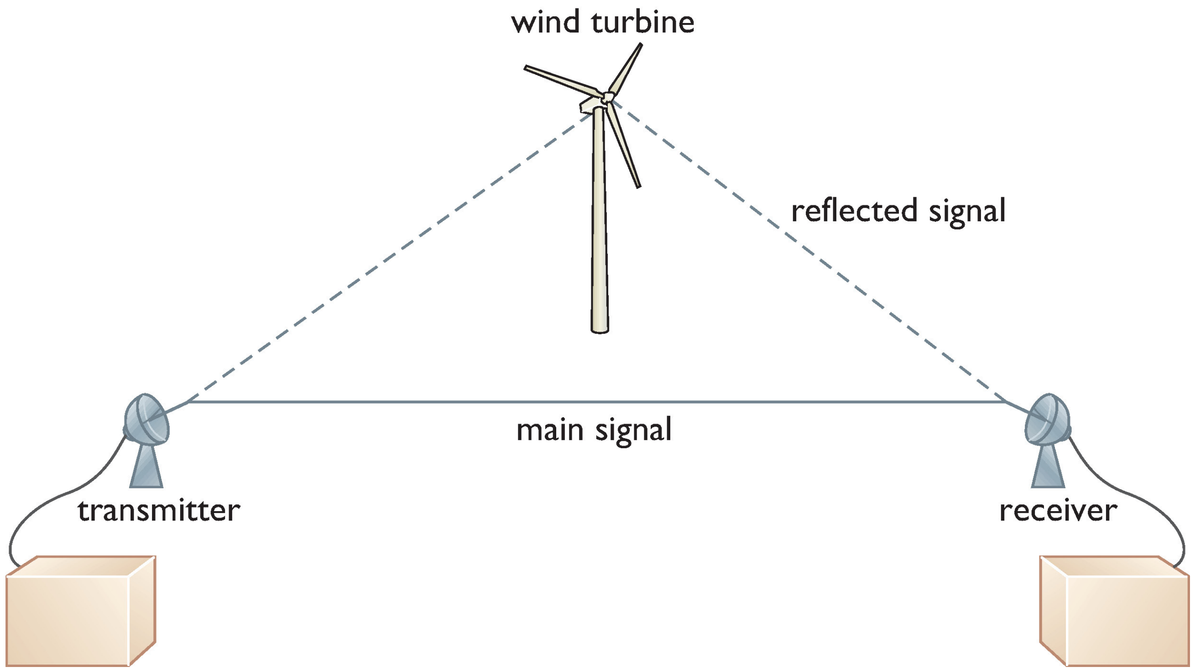


Mechanical noise

produced by equipment such as the gearbox

Aerodynamic noise due to the interaction of the airflow with the rotor

Electromagnetic Interference



Wind turbines can reflect some of the electromagnetic radiation: cause the received signal to be distorted significantly.

The extent of electromagnetic interference depends mainly on
1) the materials used to make the blades
2) the surface shape of the tower

Wind Turbines and Aviation

Solutions:

1) adapting the design of wind turbine blades to include radar absorbing materials.

2) development of systems that can filter out; e.g., BAE's advanced digital tracking system (Butler, 2007).

Impact on Wildlife

American Bird Conservancy, 2011

Obstruction	Collisions per year
wind turbines	100,000–440,000
towers	4–50 million
power lines	10–154 million
roads/vehicles	10.7–380 million
urban lights	31 million
glass on buildings	100 million–1 billion

Impact on Wildlife (Cont'd)

- Install radar systems that automatically detect approaching birds/bats.
- If there is a likelihood of collisions, bird deterrent devices can be activated or the turbines shut down until after the birds have passed.
- Help planners and wind farm operators take account of potential impacts on wildlife when developing and assessing wind turbines.

[Video: Meet the Dog Protecting Planes From Bird Strikes]

Public Attitudes and Planning Considerations

The visual perception of a wind farm is determined by

- turbine size/design/color
- number of blades/ turbines
- layout of the wind farm
- extent to which moving rotor blades attract attention.