Sustainable Technologies (2C)
Wind Energy

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What we have discussed so far?

- Introduction to sustainability
- Sustainable Development Goals: A Brief Introduction
- The Blue-Green Economic Policy: The Creator of New Prospects in the Economy
- What is green technology?
- Importance of green technology
- Evolution of green technology
- Emerging green technologies
- Why is Green Technology Necessary?
- Principles of Green Engineering and principles of green chemistry
- Introduction to the concept of energy, Types and forms of energy, Energy sources, flow, Power, Energy losses and efficiency, Energy demand, Rising of renewables
- Introduction to renewable energy
- **Solar energy**

Today's Outline

- Introduction
- Energy from wind
- History of wind
- Advantages & drawbacks
- **Technological aspects of wind energy**
    - **Applications and efficiency of wind energy**
    - **Wind Turbine Types**
    - **Considerations in Wind Power Applications**
- **Future of wind**

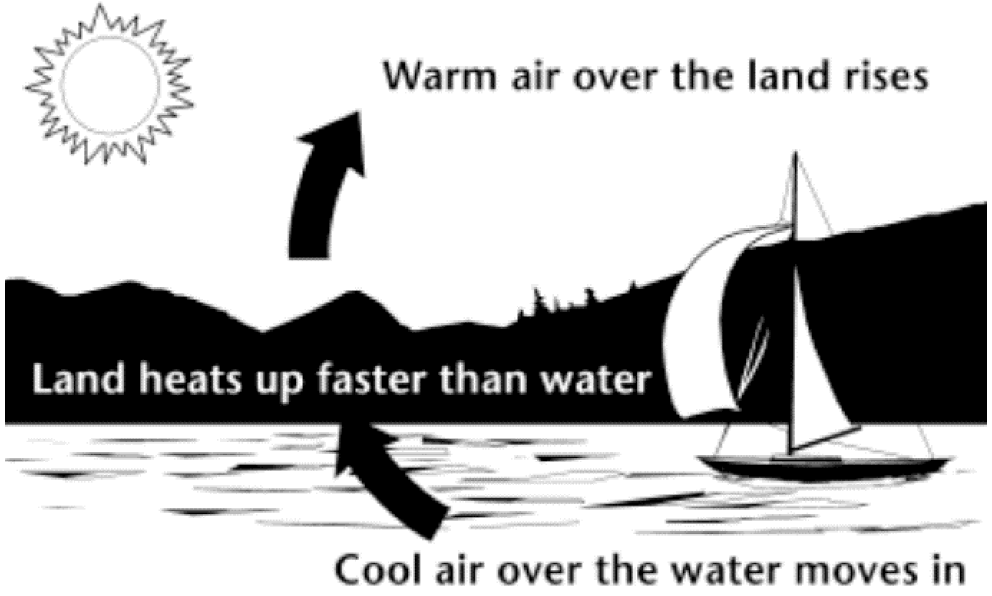
Introduction

- Winds result from the large scale movements of air masses in the atmosphere.
- These movements of air are created on a global scale primarily by differential solar heating of the earth 's atmosphere.
- Therefore, wind energy, like hydro, is also an indirect form of solar energy.
- Air in the equatorial regions is heated more strongly than at other latitudes, causing it to become lighter and less dense.
- This warm air rises to high altitudes and then flows northward and southward towards the poles where the air near the surface is cooler.
- This movement ceases at about 30 °N and 30 °S, where the air begins to cool and sink and a return flow of this cooler air takes place in the lowest layers of the atmosphere.

- The areas of the globe where air is descending are zones of high pressure.
- Conversely where air is ascending, low pressure zones are formed.
- This horizontal pressure gradient drives the flow of air from high to low pressure, which determines the speed and initial direction of wind motion.
- The greater the pressure gradient, the greater is the force on the air and the higher is the wind speed.
- Since the direction of the force is from higher to lower pressure, the initial tendency of the wind is to flow perpendicular to the isobars (lines of equal pressure).
- However, as soon as wind motion is established, a deflective force is produced due to the rotation of the earth, which alters the direction of motion.
- This force is known as the Coriolis force.
- It is important in many of the world ’ s windy areas, but plays little role near to the equator.

Energy from Wind

- Wind is simple air in motion.
- It is caused by the uneven heating of the earth's surface by the sun.
- Since the earth's surface is made of very different types of land and water, it absorbs the sun's heat at different rates.
- During the day, the air above the land heats up more quickly than the air over water.
- The warm air over the land expands and rises, and the heavier, cooler air rushes in to take its place, creating winds.
- At night, the winds are reversed because the air cools more rapidly over land than over water.



- In the same way, the large atmospheric winds that circle the earth are created because the land near the earth's equator is heated more by the sun than the land near the North and South Poles.
- Today, wind energy is mainly used to generate electricity.
- Wind is called a renewable energy source because the wind will blow as long as the sun shines.

- In addition to the main global wind systems there is also a variety of local effects.
- Differential heating of the sea and land also causes changes to the general flow.
- The nature of the terrain, ranging from mountains and valleys to more local obstacles such as buildings and trees, also has an important effect.
- The boundary layer refers to the lower region of the atmosphere where the wind speed is retarded by frictional forces on the earth's surface.
- As a result wind speed increases with height; this is true up to the height of the boundary layer, which is at approximately 1000 meters, but depends on atmospheric conditions.
- The change of wind speed with height is known as the wind shear.

The History of Wind

- Since ancient times, people have harnessed the winds energy.
- Over 5,000 years ago, the ancient Egyptians used wind to sail ships on the Nile River.
- Wind has been used by people for over 3000 years for grinding grain, sailboats, and pumping water
- Windmills were an important part of life for many communities beginning around 1200 BC.
- The earliest known windmills were in Persia (Iran).
- These early windmills looked like large paddle wheels.
- Centuries later, the people of Holland improved the basic design of the windmill.
- They gave it propeller-type blades, still made with sails.
- Holland is famous for its windmills.

The History of Wind

- Wind was first used for electricity generation in the late 19^{th} century.
- The Babylonian emperor Hammurabi planned to use wind power for his ambitious irrigation project during seventeenth century B.C.
- The wind wheel of the Greek engineer Heron of Alexandria in the 1^{st} century AD is the earliest known instance of using a wind-driven wheel to power a machine
- Wind-driven wheel was the prayer wheel, which was used in ancient Tibet and China since the 4^{th} century

- By the 13th century, grain grinding mills were popular in most of Europe
- French adopted this technology by 1105 A.D. and the English by 1191 A.D.
- The era of wind electric generators began close to 1900’s.
- The first modern wind turbine, specifically designed for electricity generation, was constructed in Denmark in 1890.
- The first utility-scale system was installed in Russia in 1931.
- A significant development in large-scale systems was the 1250 kW turbine fabricated by Palmer C. Putman.

The History of Wind

- American colonists used windmills to grind wheat and corn, to pump water, and to cut wood at sawmills.
- As late as the 1920s, Americans used small windmills to generate electricity in rural areas without electric service.
- When power lines began to transport electricity to rural areas in the 1930s, local windmills were used less and less, though they can still be seen on some Western ranches.
- The oil shortages of the 1970s changed the energy picture for the world.
- It created an interest in alternative energy sources, paving the way for the re-entry of the windmill to generate electricity.

Current status and future prospects

- Wind is the world's fastest growing energy source today
- The global wind power capacity increases at least 40% every year.
- Over 80 percent of the global installations are in Europe.
- Installed capacity may reach a level of 1.2 million MW by 2020

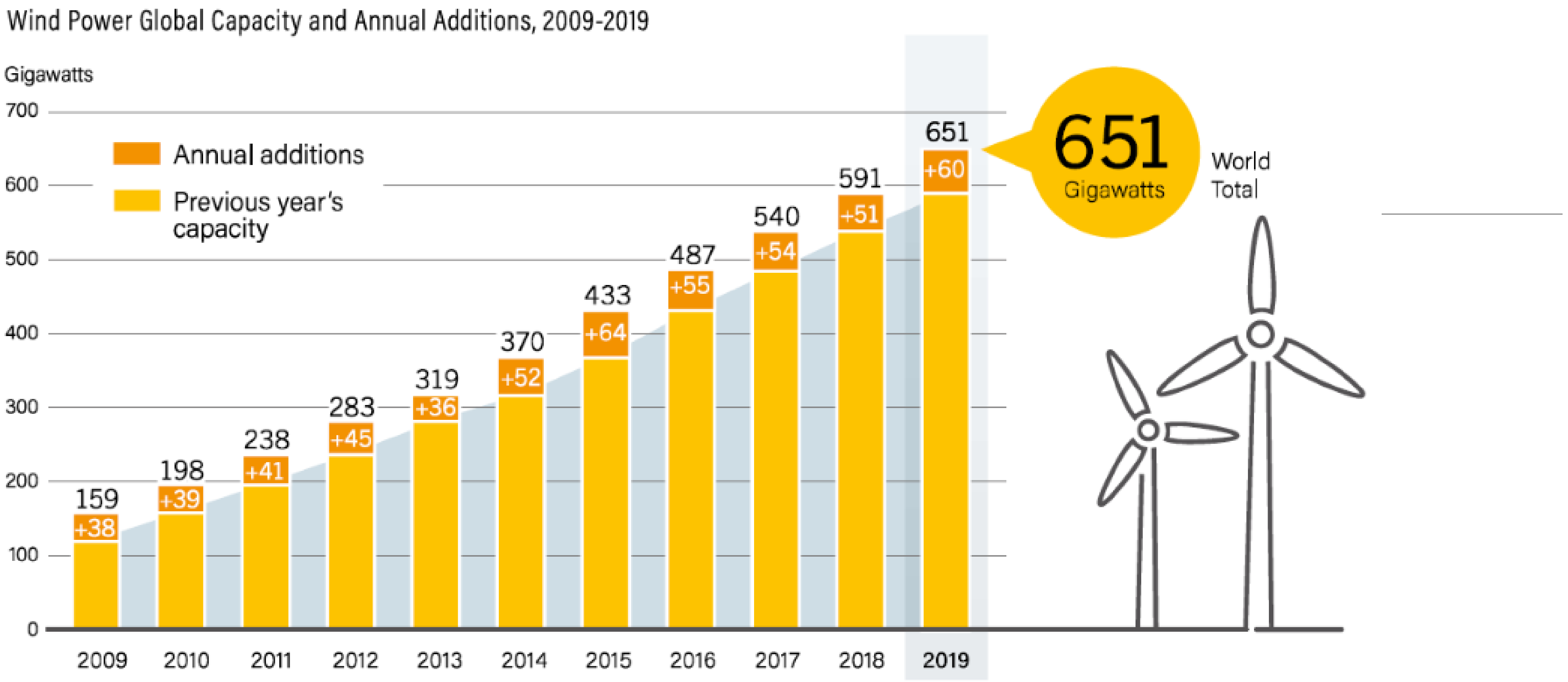
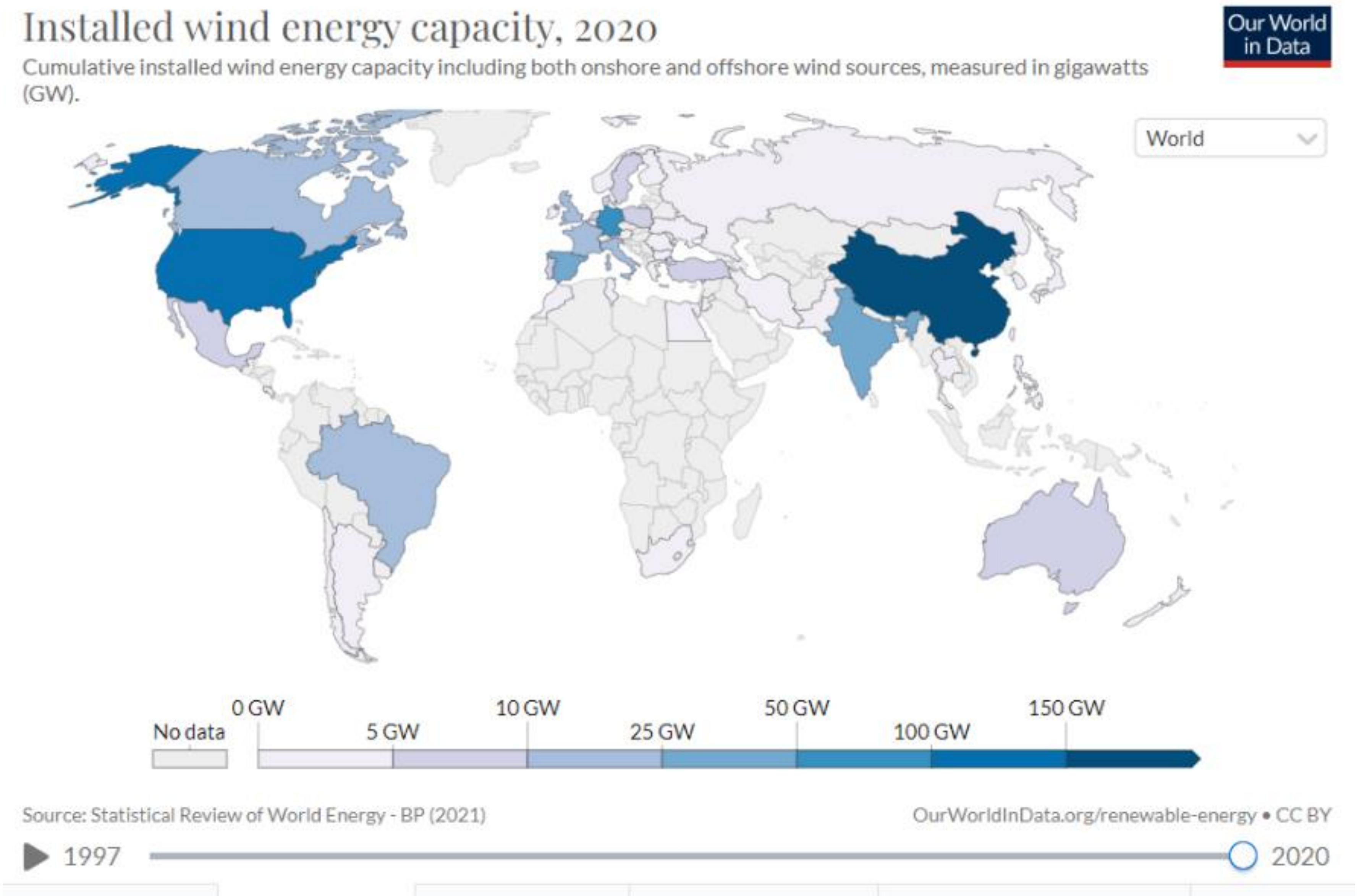


Fig. 2 Evolution of wind power capacity between 2009 and 2019. Source: REN21 (2020 Report). https://bit.ly/39IvYMz



(https://ourworldindata.org/grapher/cumulative-installed-wind-energy-capacity-gigawatts?tab=map)

KEY FACTS

- The global wind power market saw its second largest annual increase, with offshore wind accounting for a record 10% of new installations.
- Market growth reflected surges in China and the United States in advance of policy changes, and a significant increase in Europe despite continued market contraction in Germany.
- At least 102 countries had some level of commercial wind power capacity, enough to provide an estimated 5.9% of global power generation; the highest shares of generation were in Denmark (57%), Ireland (32%), Uruguay (29.5%) and Portugal (26.4%).
- Falling prices are opening new markets, but the global transition to auctions and tenders has resulted in intense price competition, reducing the number and diversity of participants and leading to further attrition among turbine manufacturers.

Fig. 6. *Key facts* for wind power according to REN21. Source: Renewables 2020 Global Status Report (REN21). https://bit.ly/39IvYMz

What advantages does wind energy offer to have experienced this evolution?

- Safe and renewable energy
- No emissions or residues (with the exception of the manufacturing process, transport and the oils used in its maintenance)
- Easily removable and recoverable installations
- Facilities compatible with other land uses (for example livestock)
- Generation adjustable according to demand
- Possibility of installing *offshore*.
  - Wind installations *offshore* are those that are located in the sea, typically a few kilometers from the
  - coast, thus avoiding the visual impact of wind farms conventional *onshore*.

Does wind power have drawbacks?

- Obviously yes.
- The first problem posed by this technology is associated with its **capacity assurance**.
- Both PV solar energy and wind energy belong to the so-called **"fluctuating renewables"**,
  - since they depend on resources (solar radiation, wind) that are intermittent, which prevents ensuring the availability of installed power at any given time.
- On the other hand, wind power installations imply a **visual impact** that sometimes generates opposition from society to carry out actions in specific locations.
- There is also a certain **impact on flora and fauna**, especially associated with birds.
- Conventional wind turbines generate **noise** that can also be considered a drawback,
  - especially in areas close to them. Manufacturers usually specify the noise generated (e.g. if
  - we talk about micro/mini-wind).

- Although the wind is “free” and renewable, modern wind turbines are expensive and suffer from one obvious disadvantage compared to most other power generation devices

Wind Energy: Levelized Cost of Energy

- The **Levelized Cost of Energy (LCOE)** is a key parameter for analyzing the performance of a given technology and which allows comparing different RE technologies in this case.

- LCOE can be defined as the lifetime costs associated with a given plant (including the manufacturing costs of the plant/infrastructure, as well as operation and maintenance costs over the entire expected lifetime) divided by energy production.

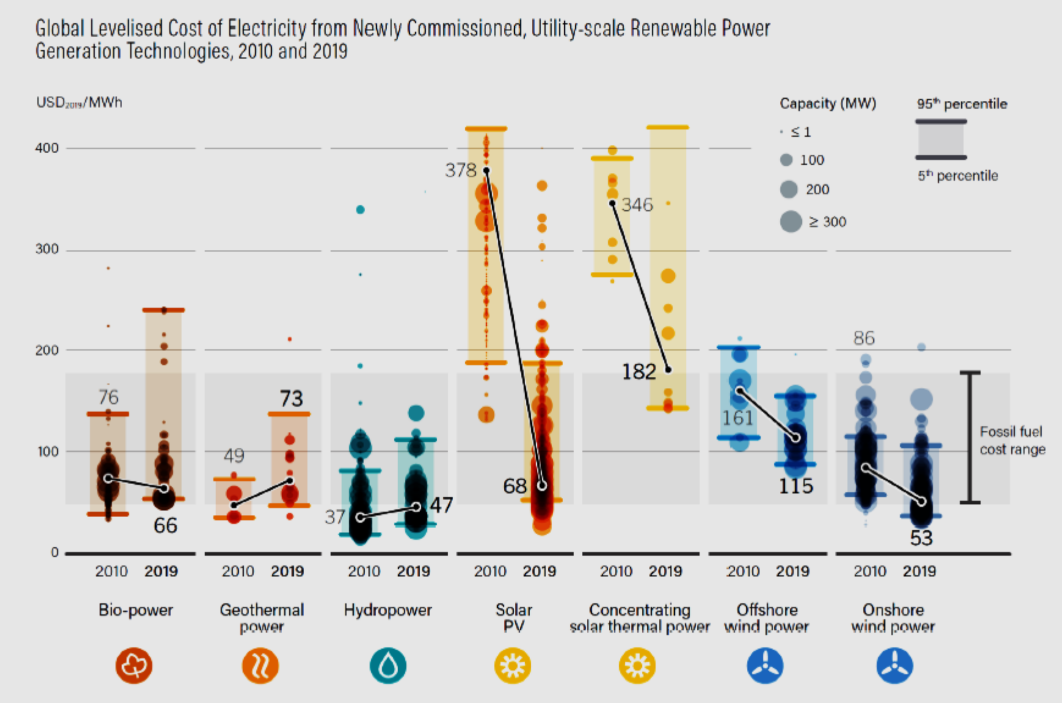


Fig. 5. LCOE for renewable technologies (2020). Source: Lazards Levelized Cost of Energy Analysis 2020. http://bit.ly/3oYyYZr

Wind variability

- The wind speed at a given location is continuously varying.
- There are changes in the annual mean wind speed from year to year (annual) changes with season (seasonal), with passing weather systems (synoptic), on a daily basis (diurnal) and from second to second (turbulence).
- All these changes, on their different timescales, can cause problems in predicting the overall energy capture from a site (annual and seasonal), and in ensuring that the variability of energy production does not adversely affect the local electricity network to which the wind turbine is connected.

Technological aspects of wind energy

Wind power is the conversion of wind energy into electricity or mechanical energy using wind turbines.

The power in the wind is extracted by allowing it to blow past moving blades that exert torque on a rotor.

The amount of power transferred is dependent on the rotor size and the wind speed.

Applications and efficiency of wind energy

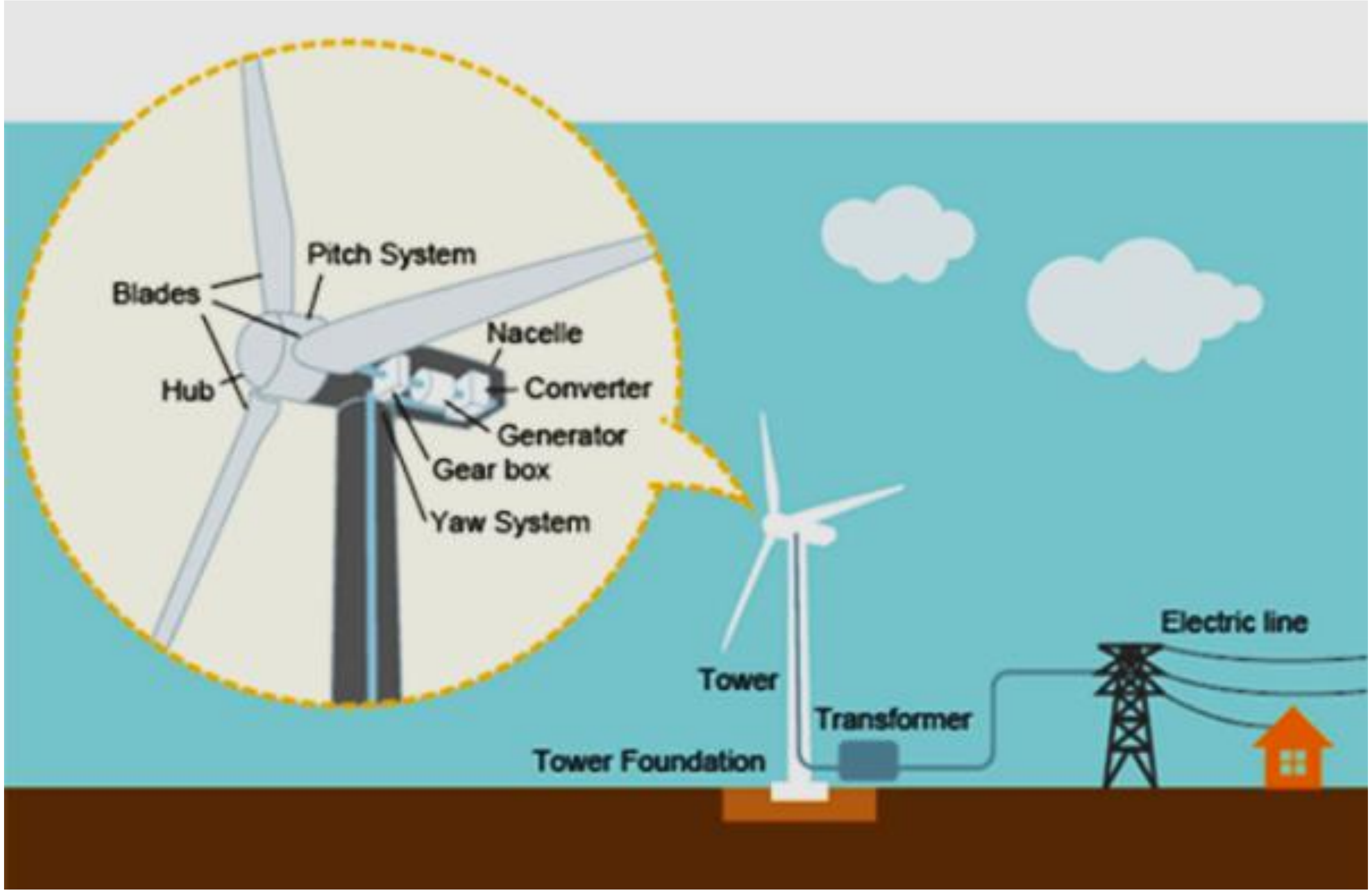
Most modern wind power is generated in the form of electricity by converting the rotation of turbine blades into electrical current by means of an electrical generator.

In windmills (a much older technology), wind energy is used to turn mechanical machinery to do physical work, such as crushing grain or pumping water.

Recently, wind energy has also been used to desalinate water.

1. Wind electric systems

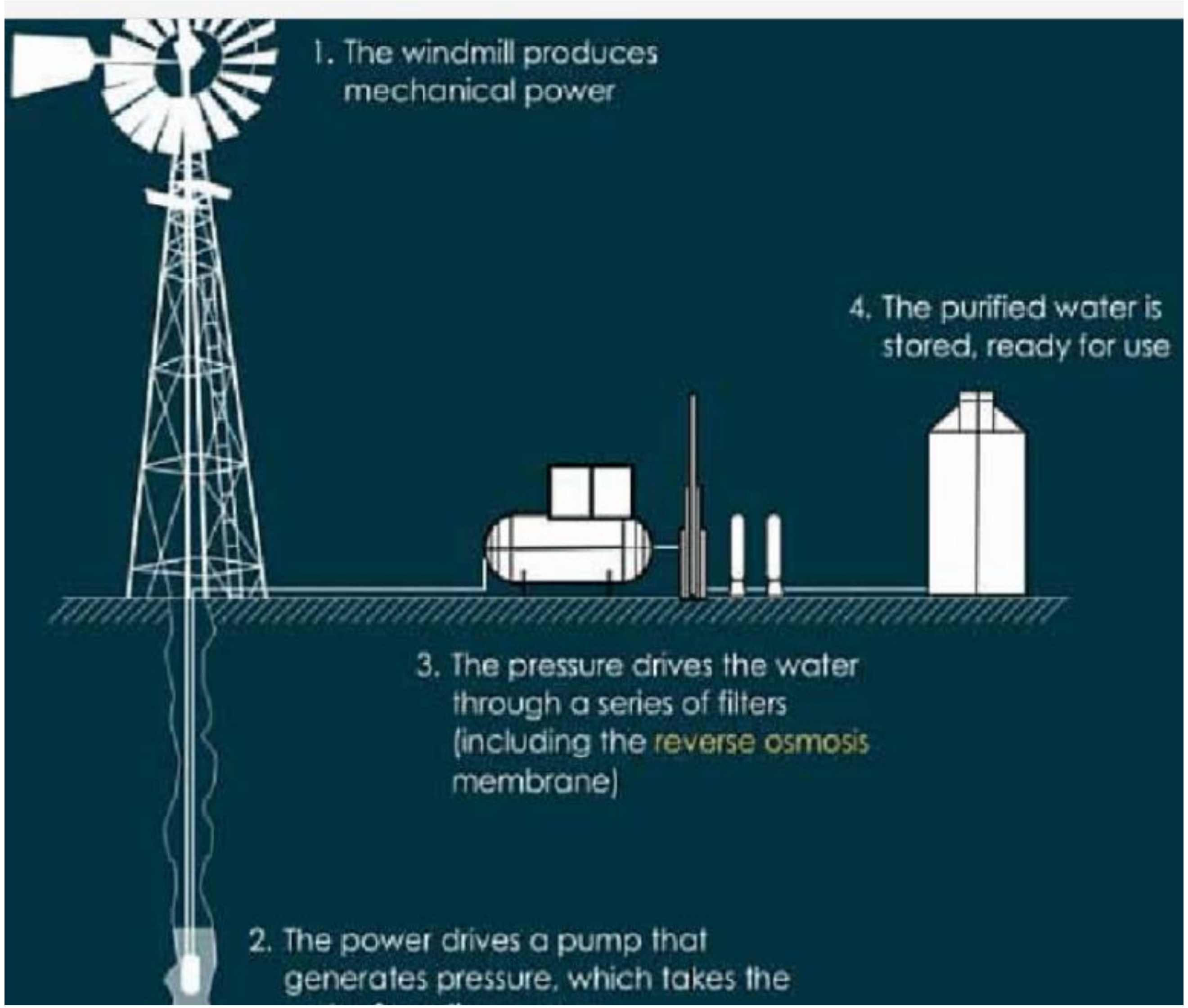
- In wind electric systems, the rotor is coupled, via., a gearing or speed control system to a generator, which produces electricity.
- Wind power is used in large-scale wind farms for national electrical grids as well as in small individual turbines for providing electricity to rural residences or grid-isolated locations.



https://www.global.toshiba/ww/products-solutions/renewable-energy/products-technical-services/wind-power.html

2. Wind energy - water desalination

- As wind energy converters supply mechanical or electrical energy, only vapour compression, reverse osmosis or electrodialysis come into consideration for wind-powered water desalination.
- Wind-powered water desalination plants can be operated in island mode (with or without an additional supply of electrical energy, for example from a diesel generator set) or in grid-parallel mode.



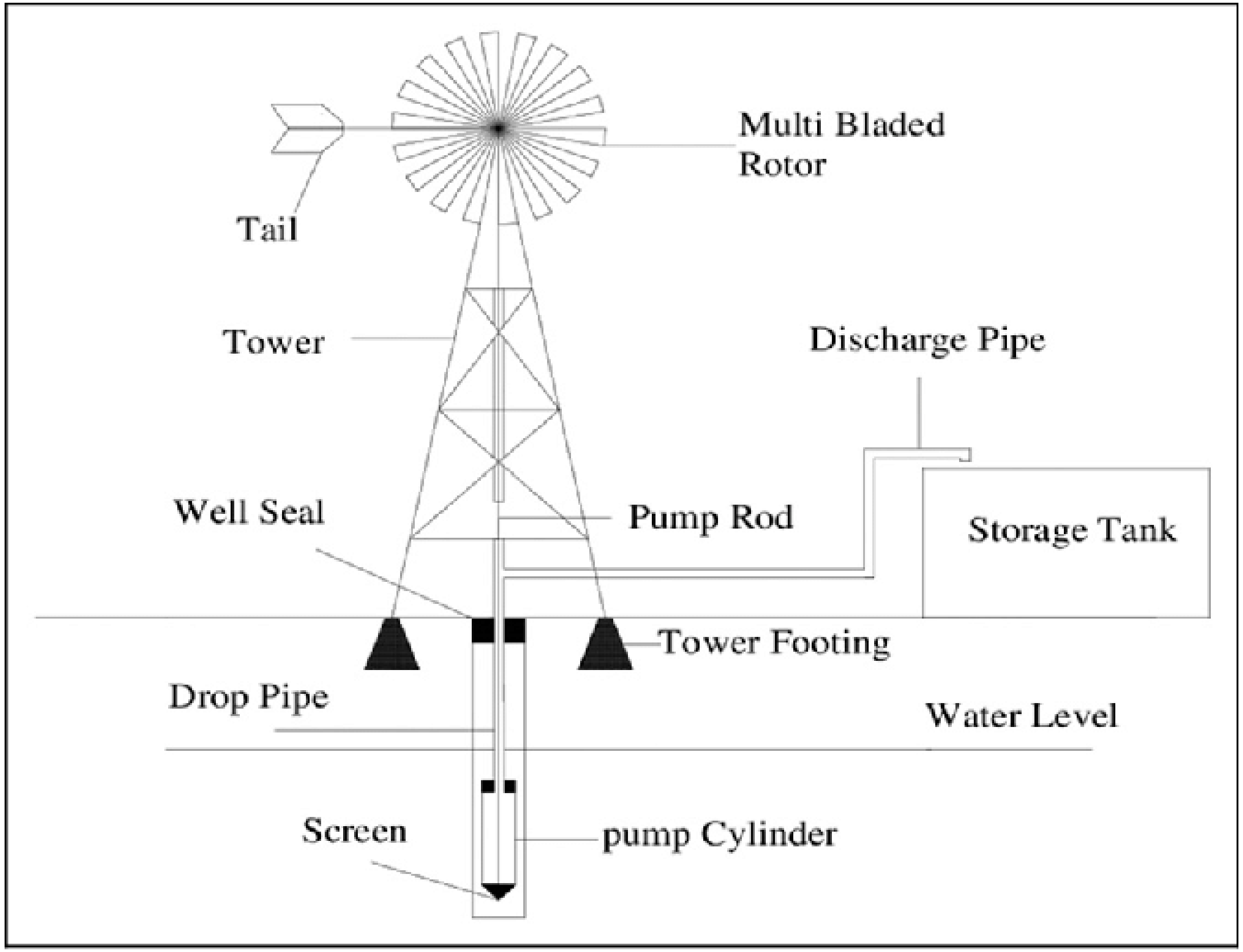
Wind powered desalination Source: www.ecofriend.com

3. Wind pumps

- With wind pumps, moving air turns a ‘rotor’ and the rotational motion of the blades is transferred to the harmonic motion of the shaft, which is used to pump water or drive other mechanical devices such as grain mills.
- Water from wells as deep as 200 m can be pumped to the surface by wind pumps.
- To select a suitable wind pump, the following information is needed: mean wind speed, total pumping head, daily water requirement, well drawdown, water quality, and storage requirements.

A Wind Water Pumping Tower

(https://www.alternative-energy-tutorials.com/wind-energy/wind-water-pumping.html)



Components and working of a wind pump

Towers

Lattice tower

Guyed Pole Tower

Concrete tower

Tubular steel towers

3. Wind turbine technology

- Wind turbine technology has developed rapidly in recent years and Europe is at the hub of this high-tech industry.
- Wind turbines are becoming more powerful, with the latest turbine models having larger blade lengths which can utilize more wind and therefore produce more electricity, bringing down the cost of renewable energy generation.

https://unsplash.com/s/photos/wind-farm

Components of wind turbines

Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Blades: Most turbines have either two or three blades. Wind blowing over the blades causes the blades to ‘lift’ and rotate.

Brake: A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Controller: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph.

- Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.

Gear box: Wind turbines rotate typically between 40 rpm and 400 rpm.

Generators typically rotate at 1200 to 1800 rpm.

Most wind turbines require a step-up gearbox for efficient generator operation (electricity production).

Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 40 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm, the rotational speed required by most generators to produce electricity.

The gearbox is a costly (and heavy) part of the wind turbine and engineers are exploring 'direct-drive' generators that operate at lower rotational speeds and don't need gearboxes.

Generator: Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.

High-speed shaft: Drives the generator.

Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

Nacelle: The nacelle sits atop the tower and contains the gear box, lowand high-speed shafts, generator, controller and brake. Some nacelles are large enough for a helicopter to land on.

Pitch: Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.

Rotor: The blades and the hub together are called the rotor.

Tower: Towers are made from tubular steel, concrete, or steel lattice.

- Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

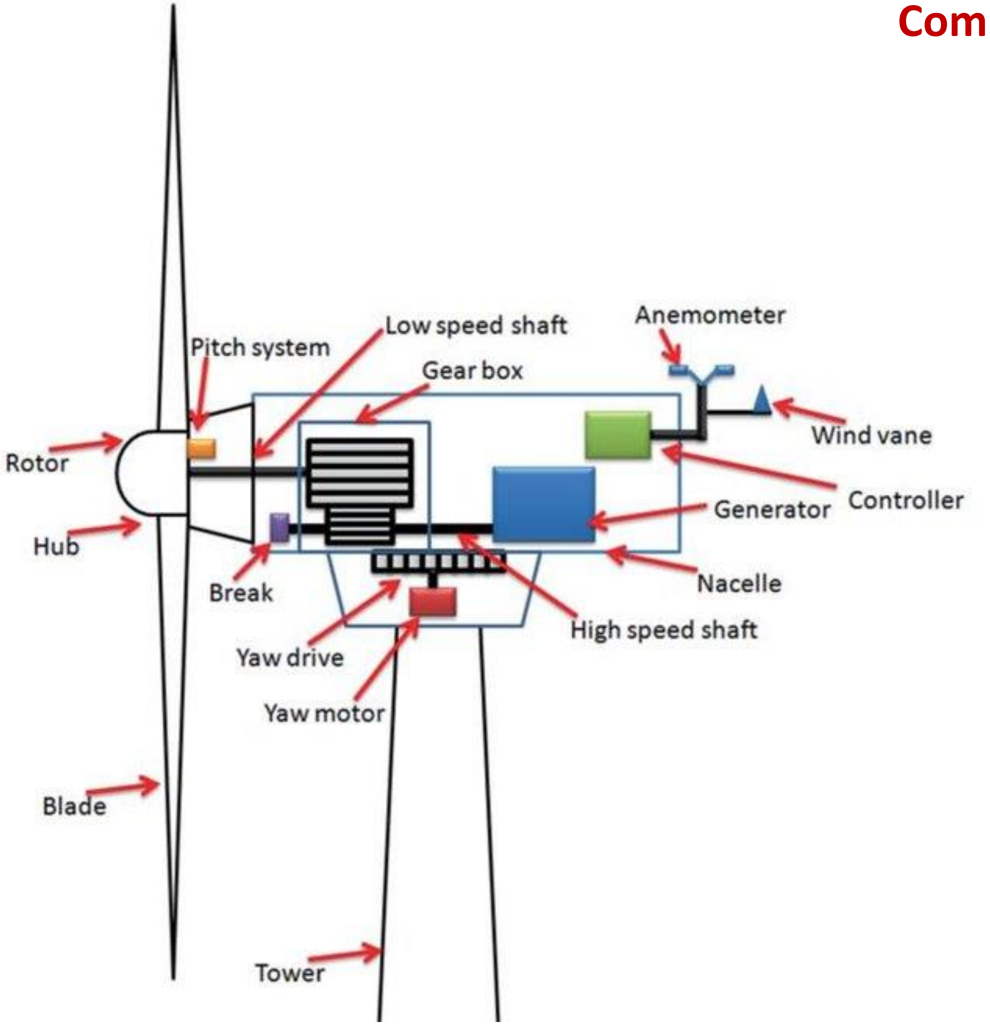
Wind direction: This is an ‘upwind’ turbine, so-called because it operates facing into the wind. Other turbines are designed to run ‘downwind,’ facing away from the wind.

Wind vane: Measures wind direction and communicate with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive: Upwind turbines face into the wind, the yaw drive is used to keep the rotor facing into the wind as the wind direction changes.

Downwind turbines don’t require a yaw drive, the wind blows the rotor downwind.

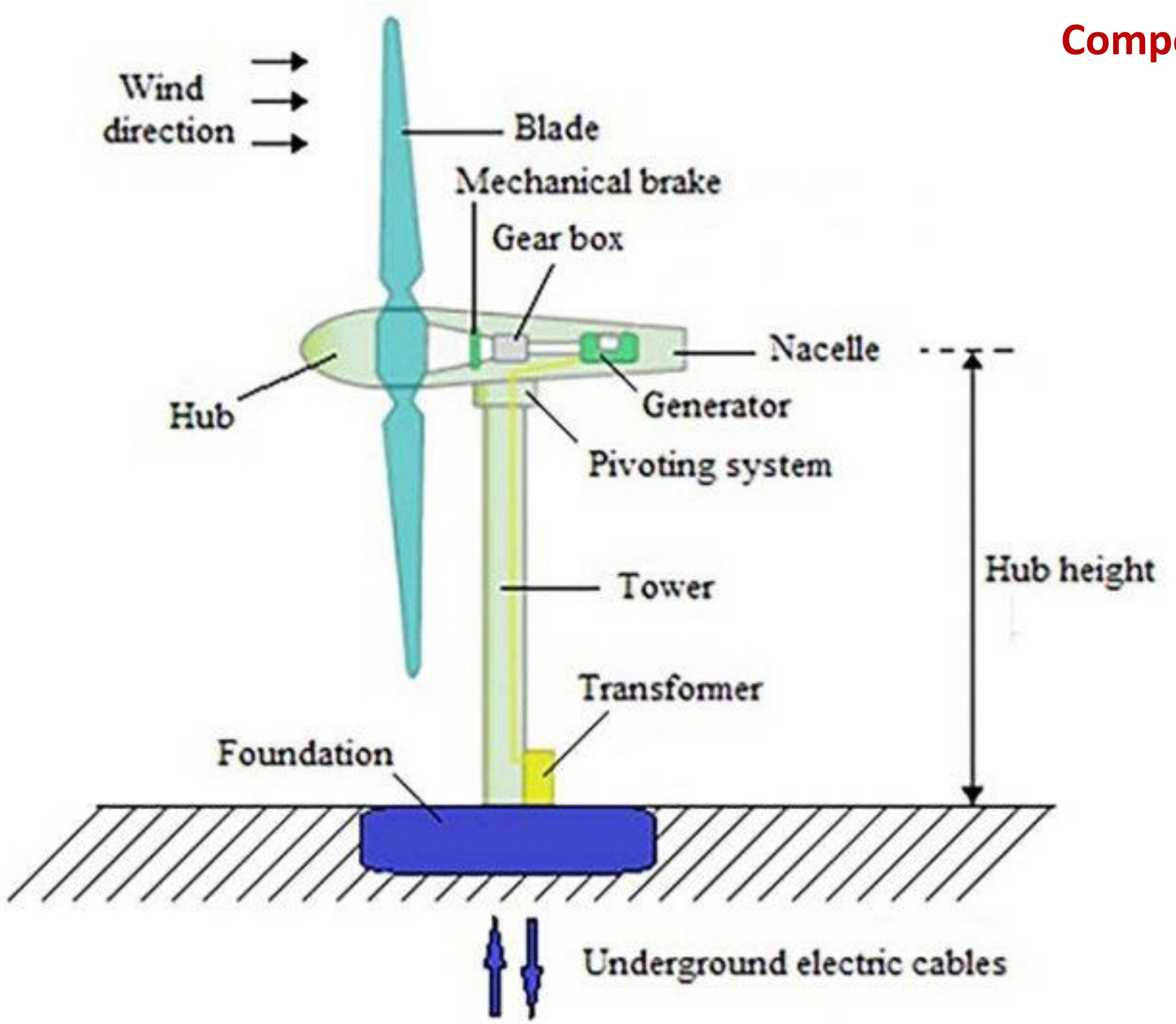
Components of wind turbines



Wind Turbine Components

(https://www.researchgate.net/publication/326111405_OPTIMAL_DESIGN_OF_JACKET_SUPPORTING_STRUCTURES_FOR_OFFSHORE_WIND_TURBINES_USING_ENHANCED_COLLIDING_BODIES_OPTIMIZATION_ALGORITHM/figures?lo=1)

Components of wind turbines

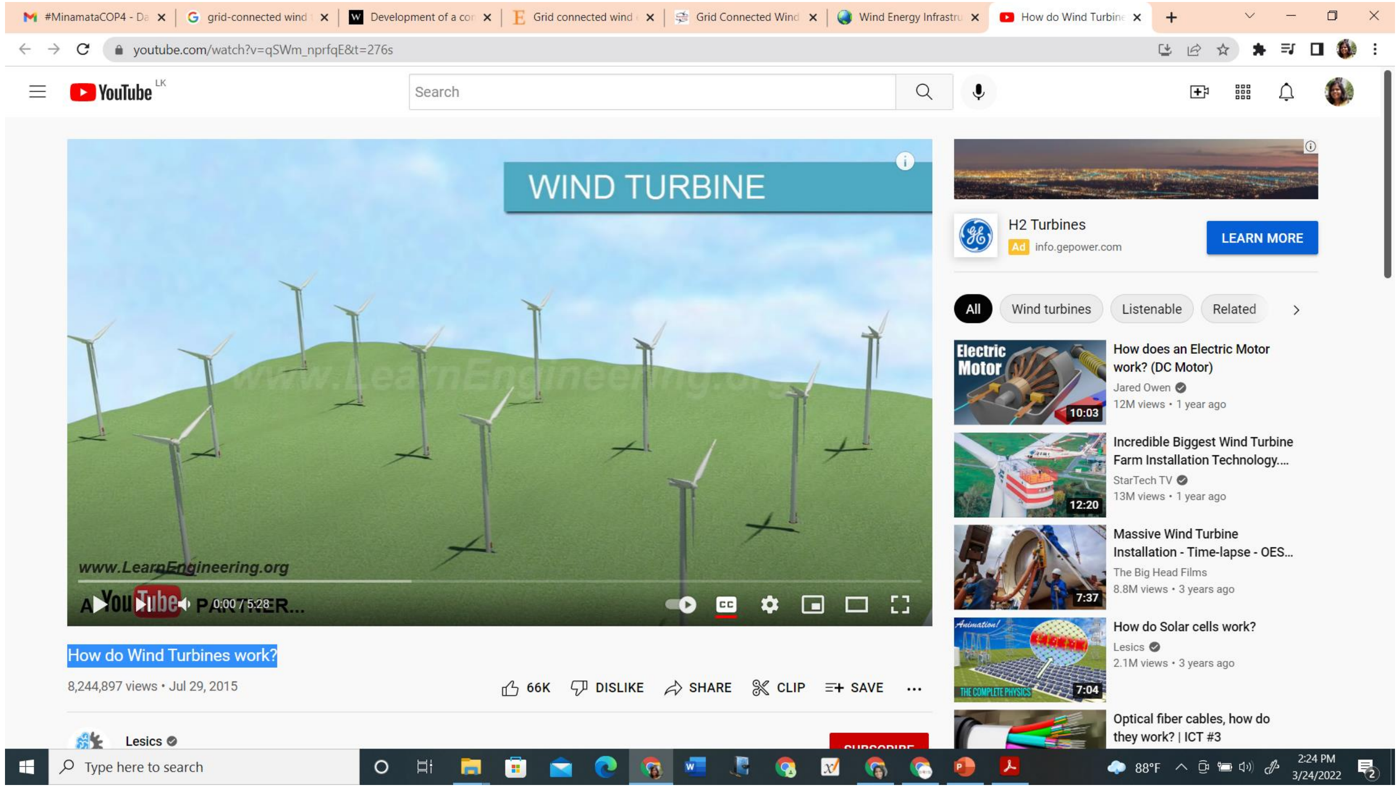


Overview of main components for a wind turbine

(https://www.researchgate.net/publication/318112329_Influence_of_the_material_used_to_build_the_blades_of_a_wind_turbine_on_their_starting_conditions/figures?lo=1)

How do Wind Turbines work?

https://www.youtube.com/watch?v=qSWm_nprfqE&t=276s



Some wind turbines are even being installed on buildings! These three turbines are on a building at the Bahrain World Trade Center. (© *Adam Jan/AFP/Getty Images*.)

Types of wind turbines

Wind turbines are classified into two general types:

(i) horizontal axis and

(ii) vertical axis

- A horizontal axis machine has its blades rotating on an axis parallel to the ground.
- A vertical axis machine has its blades rotating on an axis perpendicular to the ground.
- There are a number of available designs for both and each type has certain advantages and disadvantages.
- However, compared with the horizontal axis type, very few vertical axis machines are available commercially.

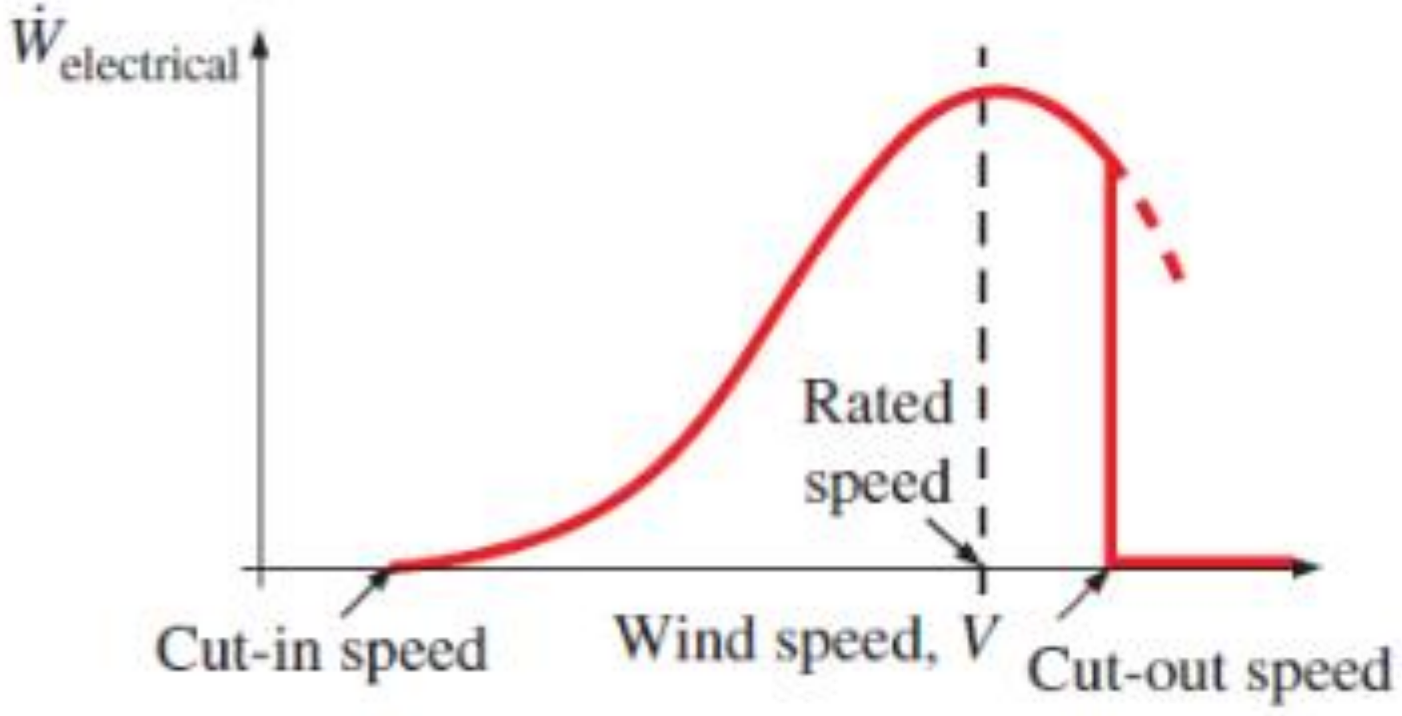
Generating electricity from the wind turbines

- Generating electricity from the wind is simple: Wind passes over the blades exerting a turning force.
- The rotating blades turn a shaft inside the nacelle, which goes into a gearbox.
- The gearbox increases the rotation speed for the generator, which uses magnetic fields to convert the rotational energy into electrical energy.
- The power output goes to a transformer, which converts the electricity from the generator at around 700 Volts (V) to the right voltage for the distribution system, typically between 11 kV and 132 kV.

Wind Turbine Types and Power Performance Curve

- Numerous innovative wind turbine designs have been proposed and tested over the centuries.
- Categorize wind turbines by the orientation of their axis of rotation:
  - *horizontal axis wind turbines* (HAWTs) and
  - *vertical axis wind turbines* (VAWTs).
- An alternative way to categorize them is by the mechanism that provides torque to the rotating shaft: lift or drag.
- So far, none of the VAWT designs or drag-type designs has achieved the efficiency or success of the lift-type HAWT.
- This is why the vast majority of wind turbines being built around the world are of this type, often in clusters affectionately called *wind farms*.

- Every wind turbine has a characteristic power performance curve, in which electrical power output is plotted as a function of wind speed *V* at the height of the turbine's axis.
- We identify three key locations on the wind-speed scale:
- *Cut-in speed* is the minimum wind speed at which useful power can be generated.
- *Rated speed* is the wind speed that delivers the rated power, usually the maximum power.
- *Cut-out speed* is the maximum wind speed at which the wind turbine is designed to produce power.
  - At wind speeds greater than the cut-out speed, the turbine blades are stopped by some type of braking mechanism to avoid damage and for safety issues.
  - The short section of dashed curve line indicates the power that *would* be produced if cut-out were not implemented.



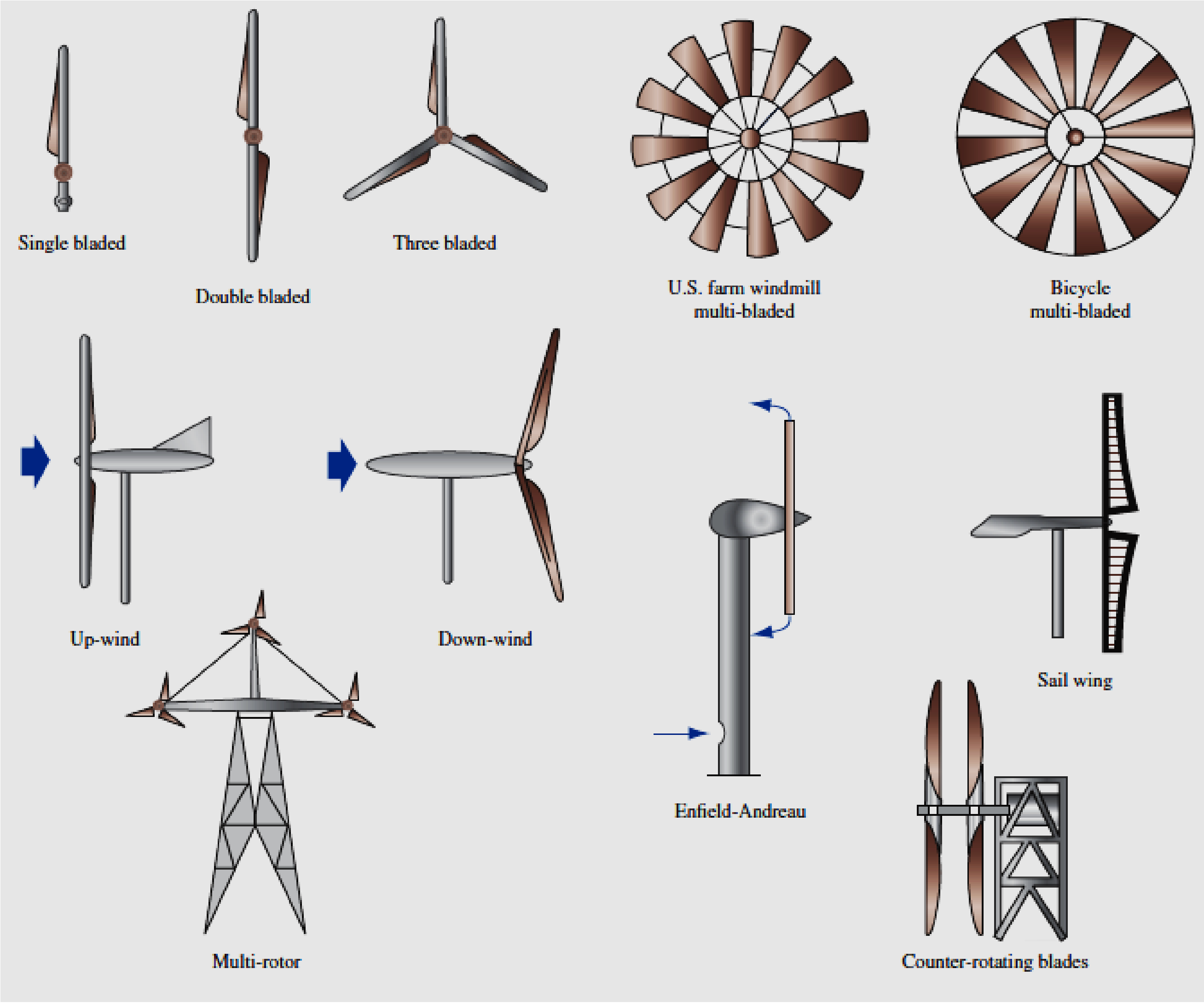
Typical qualitative wind-turbine power performance curve with definitions of cut-in, rated, and cut-out speeds

Orientation of WT

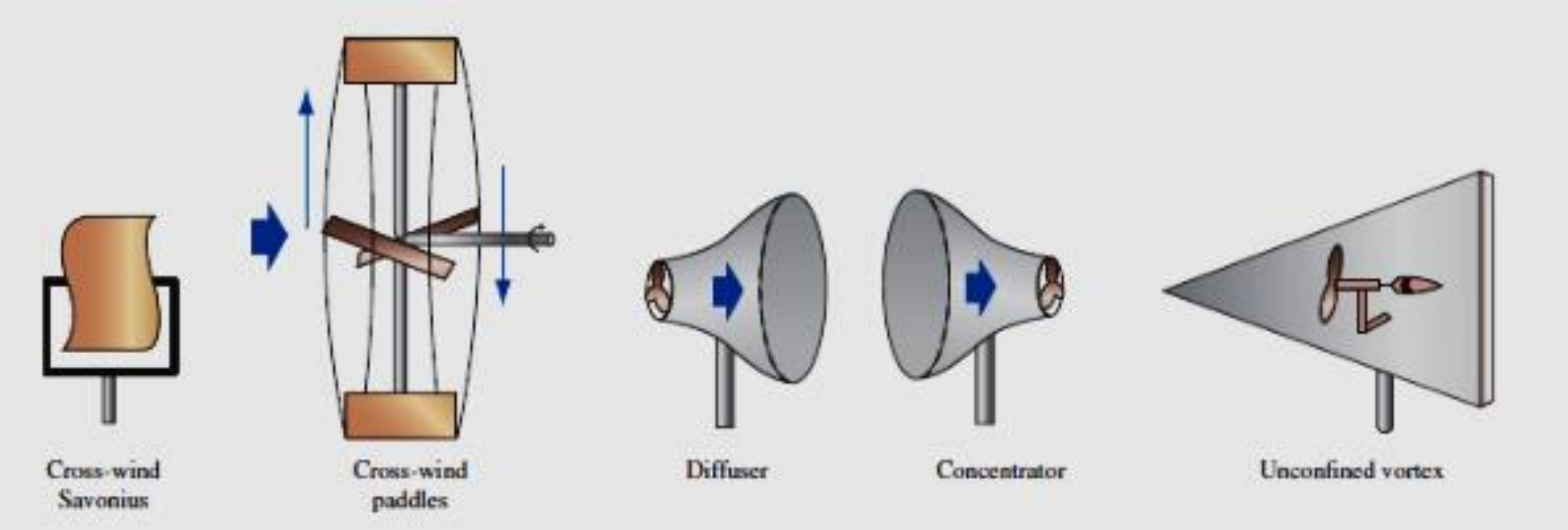
Turbines can be categorized into two overarching classes based on the orientation of the rotor

Vertical Axis

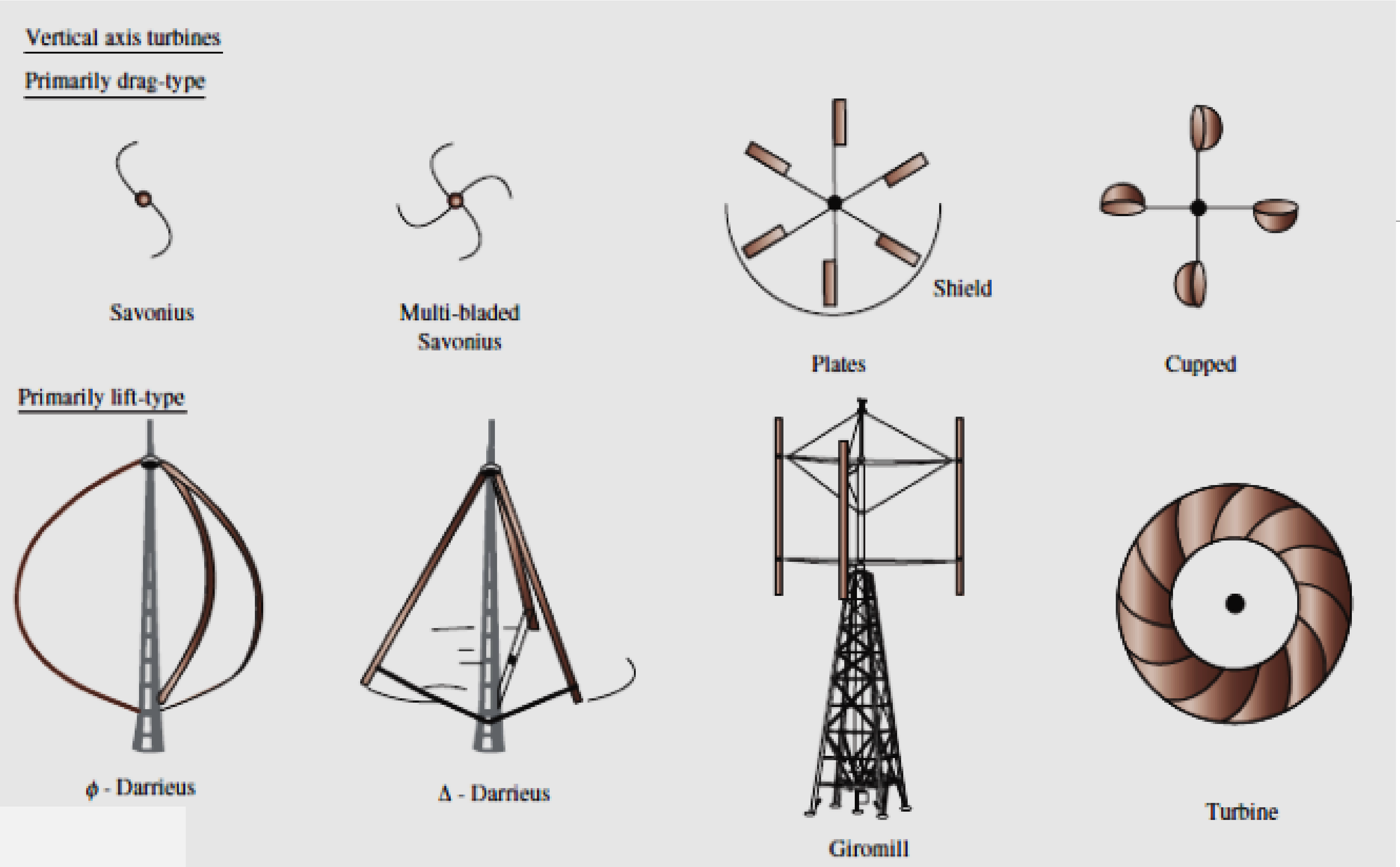
Horizontal Axis



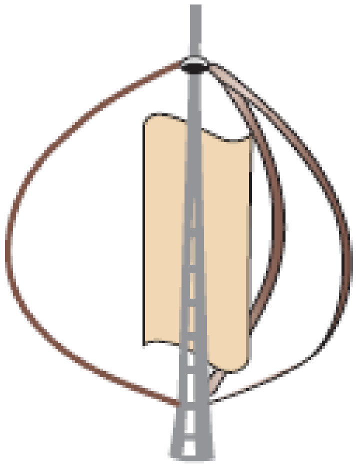
Horizontal axis turbines (*Adapted from Manwell et al., 2010*)



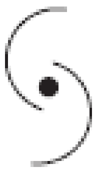
Horizontal axis turbines (*Adapted from Manwell et al., 2010*)


Vertical axis turbines
Primarily drag-type
Savonius
Multi-bladed
Savonius
Shield
Plates
Cupped
Primarily lift-type
ϕ - Darrieus
Δ - Darrieus
Giromill
Turbine

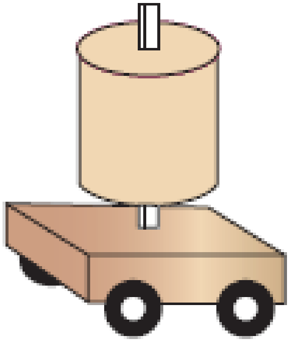
Combinations



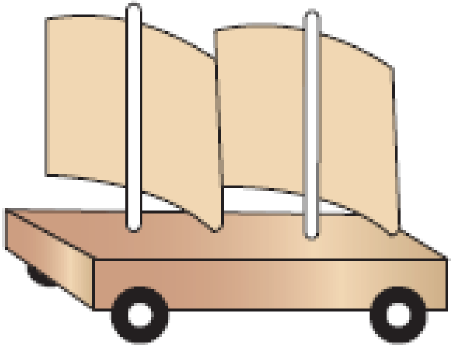
Savonius / ϕ - Darrieus



Split Savonius

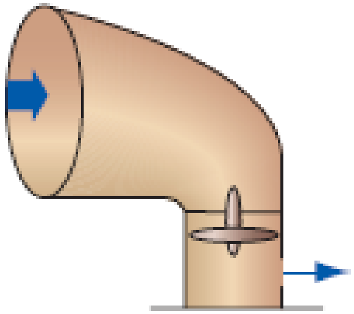


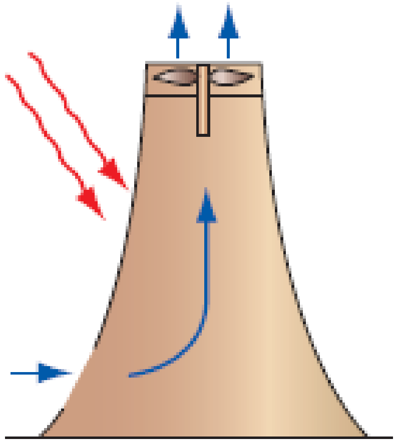
Magnus

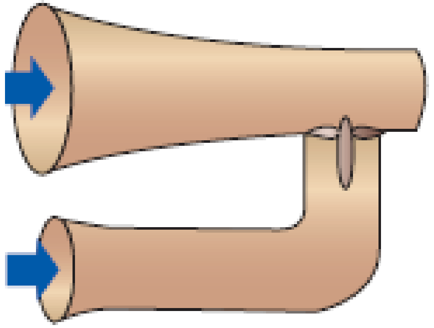


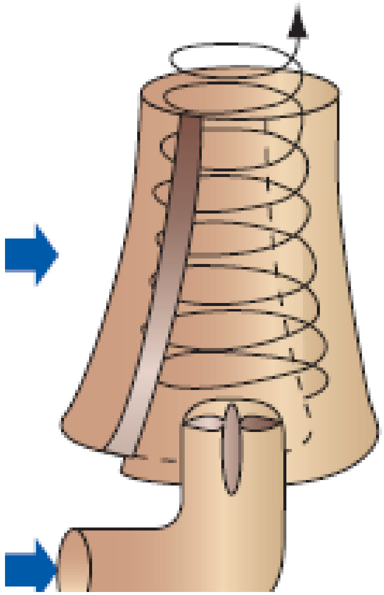
Airfoil

Others









Vertical Axis Wind Turbines

Advantages

•Omnidirectional

–Accepts wind from any angle

•Components can be mounted at ground level

–Ease of service

–Lighter weight towers

•Can theoretically use less materials to capture the same amount of wind

Disadvantages

•Rotors generally near ground where wind poorer

•Centrifugal force stresses blades & components

•Poor self-starting capabilities

•Requires support at top of turbine rotor

•Requires entire rotor to be removed to replace bearings

•Overall poor performance and reliability/less efficient

•Have never been commercially successful (large scale)

Generating electricity from the wind turbines

- Generating electricity from the wind is simple: Wind passes over the blades exerting a turning force.
- The rotating blades turn a shaft inside the nacelle, which goes into a gearbox.
- The gearbox increases the rotation speed for the generator, which uses magnetic fields to convert the rotational energy into electrical energy.

Onshore

- Onshore turbine installations in hilly or mountainous regions tend to be on ridgelines generally three kilometers or more inland from the nearest shoreline.
- This is done to exploit the so called topographic acceleration as the wind accelerates over a ridge.

Nearshore

- Nearshore turbine installations are on land within three kilometers of a shoreline or on water within ten kilometers of land.
- These areas are good sites for turbine installation, because of wind produced by convection due to differential heating of land and sea each day.
- Wind speeds in these zones share the characteristics of both onshore and offshore wind, depending on the prevailing wind direction.

Offshore

- Offshore wind development zones are generally considered to be ten kilometers or more from land.
- Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise is mitigated by distance.
- In stormy areas with extended shallow continental shelves, turbines are practical to install.
- Offshore installation is more expensive than onshore but this depends on the attributes of the site.

Offshore technology

- Offshore wind farms are an exciting new area for the industry, largely due to the fact that there are higher wind speeds available offshore and economies of scale allow for the installation of larger size wind turbines offshore.
- Offshore wind turbine technology is based on the same principles as onshore technology.
- Foundations are constructed to hold the superstructure, of which there are a number of designs, but the most common is a driven pile.

Off-shore

On-shore

Wind Power Potential

Mechanical *energy* can be defined as *the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine*.

The mechanical energy of a flowing fluid can be expressed as

$$\dot{E}_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

where $P/\ p$ is the flow energy, $V^2/2$ is the kinetic energy, and gz is the potential energy of the fluid, all per unit mass, and $m^{\bullet}$ is the mass flow rate of the fluid.

The pressures at the inlet and exit of a wind turbine are both equal to the atmospheric pressure and the elevation does not change across a wind turbine.

Therefore, flow energy and potential energy do not change across a wind turbine.

A wind turbine converts the kinetic energy of the fluid into power.

If the wind is blowing at a location at a velocity of *V*, the available wind power is expressed as

$$\dot{W}_{\text{avalable}} = \frac{1}{2}\dot{m}V^2 \qquad \text{(kW)}$$

This is the *maximum power* a wind turbine can generate for the given wind velocity *V*. The mass flow rate is given by

$$\dot{m} = \rho A V \qquad \text{(kg/s)}$$

where *p* is the density and *A* is the disk area of a wind turbine (the circular area swept out by the turbine blades as they rotate). Substituting,

Wind power potential: $$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V^3$$

The power potential of a wind turbine is proportional to the cubic power of the wind velocity.

The amount of electricity produced from a wind turbine depends on three factors

1. Wind speed: The power available from the wind is a function of the cube of the wind speed.

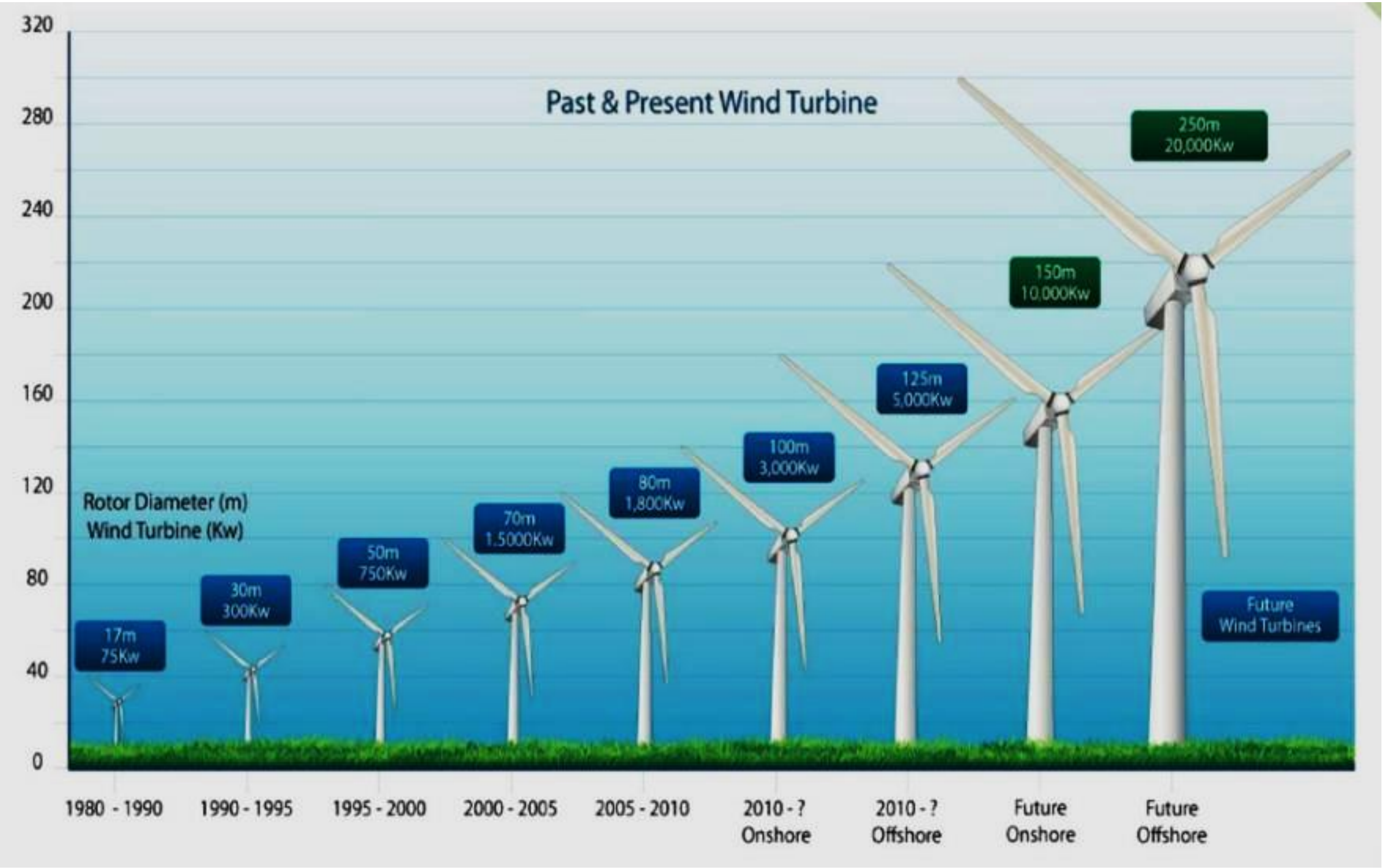
- Therefore if the wind blows at twice the speed, its energy content will increase eight-fold.
- Turbines at a site where the wind speed averages 8 m/s produce around 75–100% more electricity than those where the average wind speed is 6 m/s.

2. Wind turbine availability:

- This is the capability to operate when the wind is blowing, i.e., when the wind turbine is not undergoing maintenance.
- This is typically 98% or above for modern European machines.

3. The way wind turbines are arranged:

- Wind farms are laid out so that one turbine does not take the wind away from another.
- However other factors such as environmental considerations, visibility and grid connection requirements often take precedence over the optimum wind capture layout.


Past & Present Wind Turbine
Rotor Diameter (m)
Wind Turbine (Kw)
320
280
240
200
160
120
80
40
0
17m
75Kw
30m
300Kw
50m
750Kw
70m
1,5000Kw
80m
1,800Kw
100m
3,000Kw
125m
5,000Kw
150m
10,000Kw
250m
20,000Kw
Future
Wind Turbines
1980 - 1990
1990 - 1995
1995 - 2000
2000 - 2005
2005 - 2010
2010 - ?
Onshore
2010 - ?
Offshore
Future
Onshore
Future
Offshore

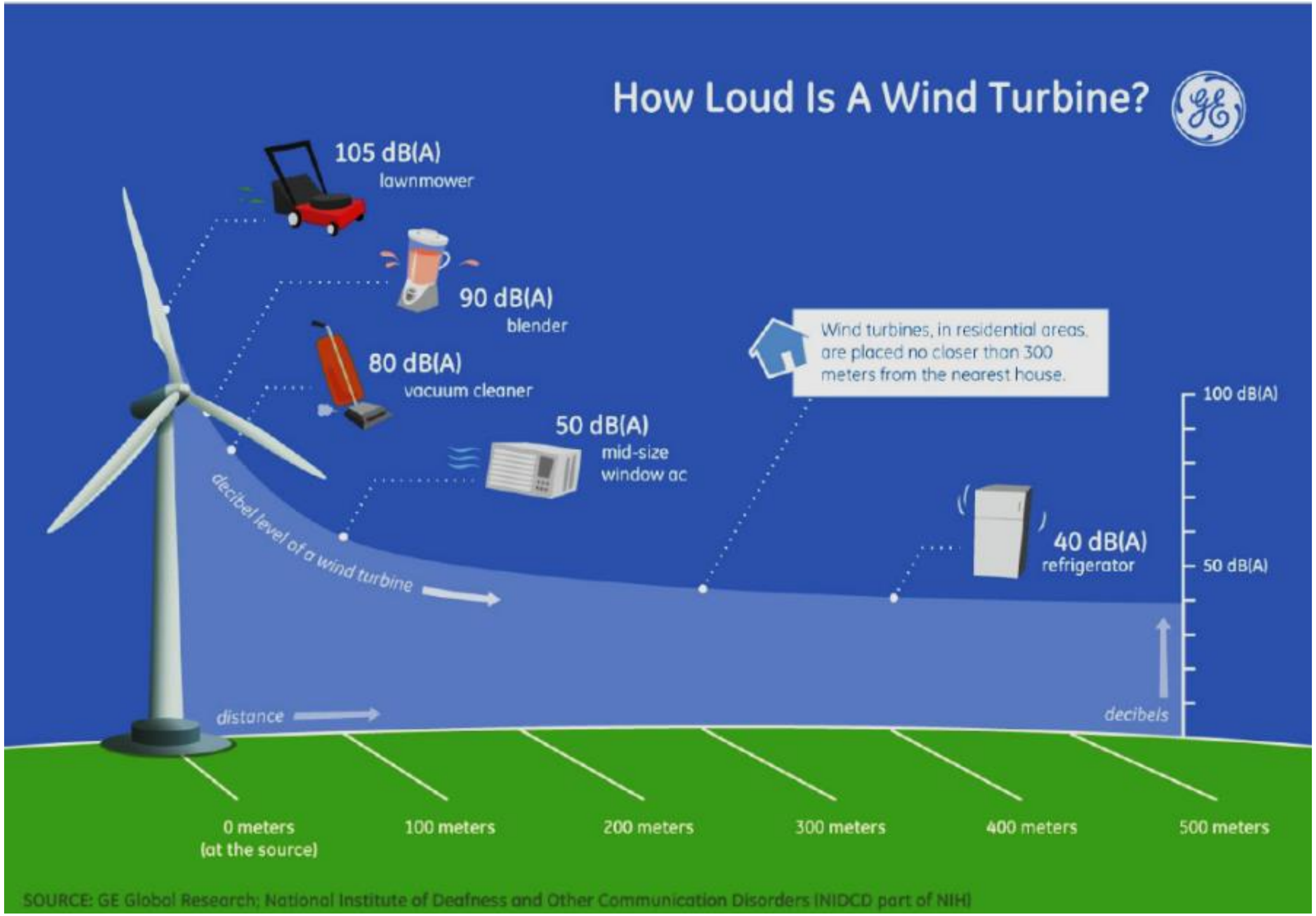


Fig. 4 Noise associated with a wind turbine. Source: GE Global Research / National Institute of Deafness and Other Communication Disorders

Wind power density

Available wind power *per unit area*, which we call the *wind power density* (WPD), typically in units of W/m^2

Betz Limit for Wind Turbine Efficiency

- A wind turbine converts the kinetic energy of air into work.
- This conversion is perfect (the wind turbine efficiency is 100 percent) under ideal conditions based on the second law of thermodynamics.
- This would be the case only when the velocity of air at the turbine exit is zero.
- This is not possible for operational reasons because air must be taken away at the turbine exit to maintain the mass flow through the turbine.
- It turns out that there is a maximum possible efficiency for a wind turbine.
- This was first calculated by Albert Betz (1885–1968) in the mid-1920s.

Considerations in Wind Power Applications

- When a wind turbine project is underway on a windy site, many turbines are installed, and such sites are properly called as a wind farm or a wind park.
- The use of a wind farm is highly desirable due to reduced site development costs, simplified transmission lines, and centralized access for operation and maintenance.
- Single-use of a wind turbine is used for off-grid homes, off-shore areas, and demonstration projects.
- The number of wind turbines in a given site depends on the spacing between the turbines.
- If the turbines are spaced too close to each other, the flow-through one turbine affects the flow through the next turbine, and this reduces the turbine performance.
- If the turbines are far from each other, this means a poor use of the site as the potential for the installation of additional turbines for greater power outputs is not realized.
- It turns out that there is an optimum spacing between the turbines, and it is estimated to be 3 to 5 blade diameters between the turbines in a row and 5 to 9 blade diameters between rows.

The wind tower should be strong enough to support the turbine weight and withstand the forces during high wind speeds and the thrust on the wind turbine.

Using tall wind towers minimizes the turbulence-induced and allows flexibility in sitting.

Factors that need to be considered when a wind farm project is planned on a particular site

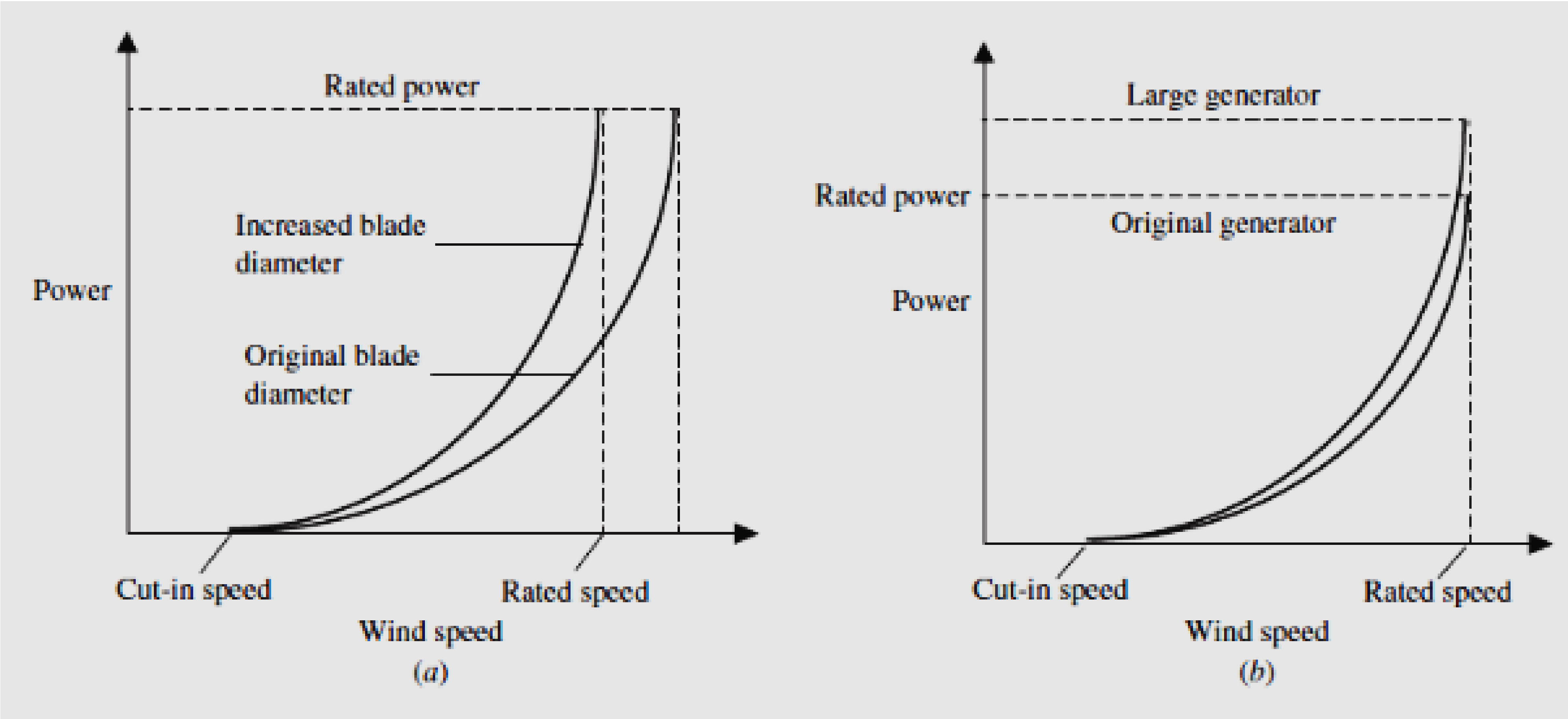
1. Ground conditions such as vegetation,
2. Topography and ground roughness.
3. Convenient access to the farm site,
4. Load capacity of the soil, and earthquake characteristics
5. Another important factor is to make sure that the planned wind farm site is not a traveling route of the birds.

6. Selection of the turbine blade diameter and the power rating or the size of the generator is important to maximize power output from the turbine.

- When the blade diameter is increased at the same generator rating, the power curve will move left.
- Then, the rated power can be realized at a lower wind speed.
- When a larger generator is used, the rated power increases.
- This is particularly advantageous at high wind speeds.
- Therefore, the generator size can be increased to maximize turbine power output if the turbine mostly operates at high wind speeds.

7. For effective wind power generation, **a reliable power grid/transmission network near the site and good grid stability** are essential.

- The wind turbine generates power at 400 V, which is stepped up to 11 to 110 kV.
- The poor grid stability may cause 10 to 20 percent power loss (Bansal et al., 2001).
- In China, some wind turbines are not connected to the grid partly because of stability problems.



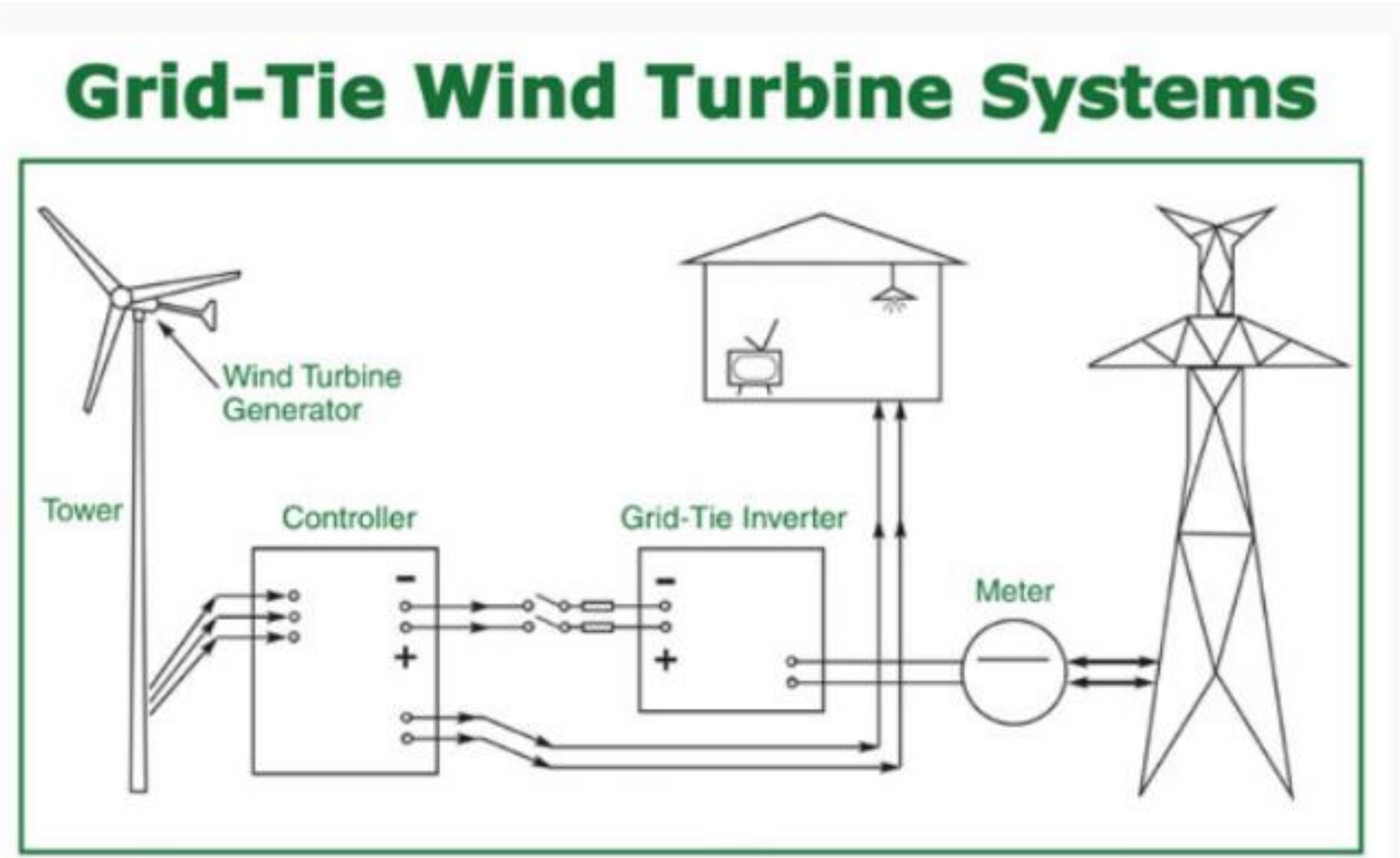
Effects of increasing blade diameter and a larger generator on power output of the wind turbine. (*Adapted from Masters, 2004.*)

Operation and maintenance

- Both onshore and offshore wind turbines have instruments on top of the nacelle, an anemometer and a wind vane, which respectively measure wind speed and direction.
- When the wind changes direction, motors turn the nacelle and the blades along with it, around to face into the wind.
- The blades also ‘pitch’ or angle to ensure that the optimum amount of power is extracted from the wind.
- All this information is recorded by computers and transmitted to a control centre, which can be many miles away.
- Wind turbines are not physically staffed, although each will have periodic mechanical checks, often carried out by local firms.
- The onboard computers also monitor the performance of each turbine component and will automatically shut the turbine down if any problems are detected, alerting an engineer that an onsite visit is required.

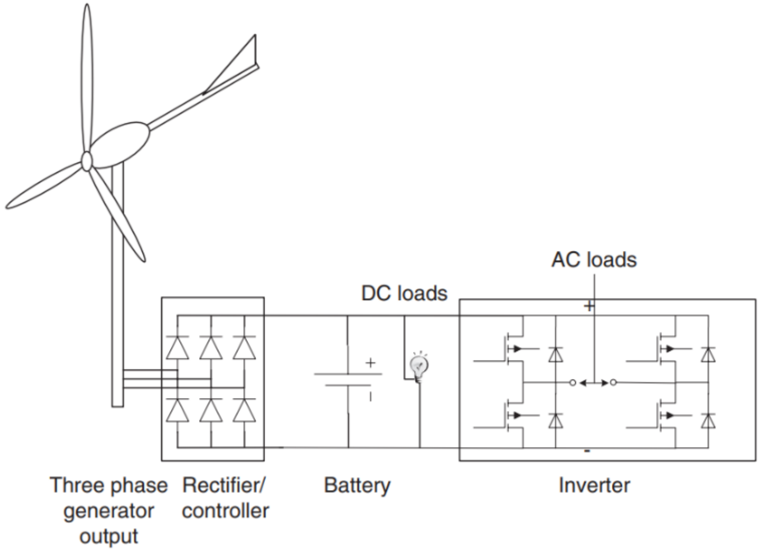
Grid-connected small wind turbines

- Small scale wind turbines can be used in domestic, community and smaller wind energy projects and these can be either stand-alone or grid-connected systems.
- Stand alone systems are used to generate electricity for charging batteries to run small electrical applications, often in remote locations where it is expensive or not physically possible to connect to a mains power supply.
- Such examples include rural farms and island communities, with typical applications being water heating or pumping, electric livestock fencing, lighting or any kind of small electronic system needed to control or monitor remote equipment.
- With grid-connected turbines the output from the wind turbine is directly connected to the existing mains electricity supply.
- This type of system can be used both for individual wind turbines and for wind farms exporting electricity to the electricity network.
- A grid-connected wind turbine can be a good proposition if the consumption of electricity is high.



http://www.aponew.com/Windpowersystem.html

- The design of a stand-alone wind turbine power system is based on the expected energy required and the expected wind speeds.
- Despite the available information, such expectations may be wrong for unforeseen reasons, and in our experience, often in the most difficult direction.
- One of the uncertainties is that of the climate change – what effect it will have on average wind speeds is uncertain, but in some areas, it appears that cyclonic and tornado activity is expected to increase significantly.
- In the worst case this may mean that the average wind speeds may decrease, but the peak wind speeds may increase, making it difficult to decide how to choose the turbine.
- The best approach for relatively small systems is to start with a smaller and inexpensive turbine, battery and inverter system to power a limited number of loads to determine if this performs as expected.
- It will test if there is enough wind, if the battery storage is sufficient, if the loads are manageable and if the system can start the load, such as the particular refrigerator in use.



Basic electrical system for a stand-alone, battery wind power system

Operating characteristics of wind mills

All wind machines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds.

Cut-in speed

1. Cut-in speed is the minimum wind speed at which the blades will turn and generate usable power.

2. This wind speed is typically between 10 and 16 kmph.

Rated speed

1. 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 40 kmph.

2. Rated speed for most machines is in the range of 40 to 55 kmph.

Future of wind

Deployment, investment, technology, grid integration and socio-economic aspects

- Accelerated wind power deployment, coupled with increased electrification, could deliver one-quarter (or nearly 6.3 gigatonnes) of the annual CO_2 emission reductions needed by 2050.
- Wind power could cover more than one-third of global power needs (35%), becoming the world's foremost generation source.
- To fulfil this aim, the world's installed wind power capacity must reach 6 000 gigawatts – over 10 times the current level – by 2050.
  - This would include 5 000 GW of onshore wind and 1 000 GW of offshore wind (International Renewable Energy Agency, 2019)

(https://www.irena.org/publications/2019/Oct/Future-of-wind#:~:text=Wind%20power%20could%20cover%20more,the%20current%20level%20%E2%80%93%20by%202050.)

- Asia is poised to become the world's dominant wind market, accounting for more than 50% of onshore and 60% of offshore wind installations by 2050.
  - Asia's onshore wind capacity could grow from 230 GW in 2018 to over 2 600 GW by 2050.
- Increasing economies of scale, more competitive supply chains and further technological improvements should reduce electricity costs from onshore wind to less than three cents (USD 0.03) per kilowatt hour by 2050, IRENA's analysis shows.
- Prices from offshore wind are expected to fall below seven cents, also towards the lower end of cost range for power generation based on fossil fuels.
- To fulfil climate goals and help to contain the rise of global temperatures, annual investment in onshore wind needs to triple from USD 67 billion in 2018 to USD 211 billion globally in 2050.
  - Annual investment in offshore wind would have to more than quintuple, from USD 19 billion in 2018 to USD 100 billion in 2050.
- The resulting transformation could bring socio-economic benefits. The global wind industry drives the creation of new jobs and could employ over six million people worldwide by 2050, compared to about one million currently (International Renewable Energy Agency, 2019)

(https://www.irena.org/publications/2019/Oct/Future-of-wind#:~:text=Wind%20power%20could%20cover%20more,the%20current%20level%20%E2%80%93%20by%202050.)

References

M. Kanoğlu, Y. A. Çengel, John M. Cimbala. 2020. Chapter 5- Wind Energy In: Fundamentals and Applications of Renewable Energy. McGraw-Hill Education.