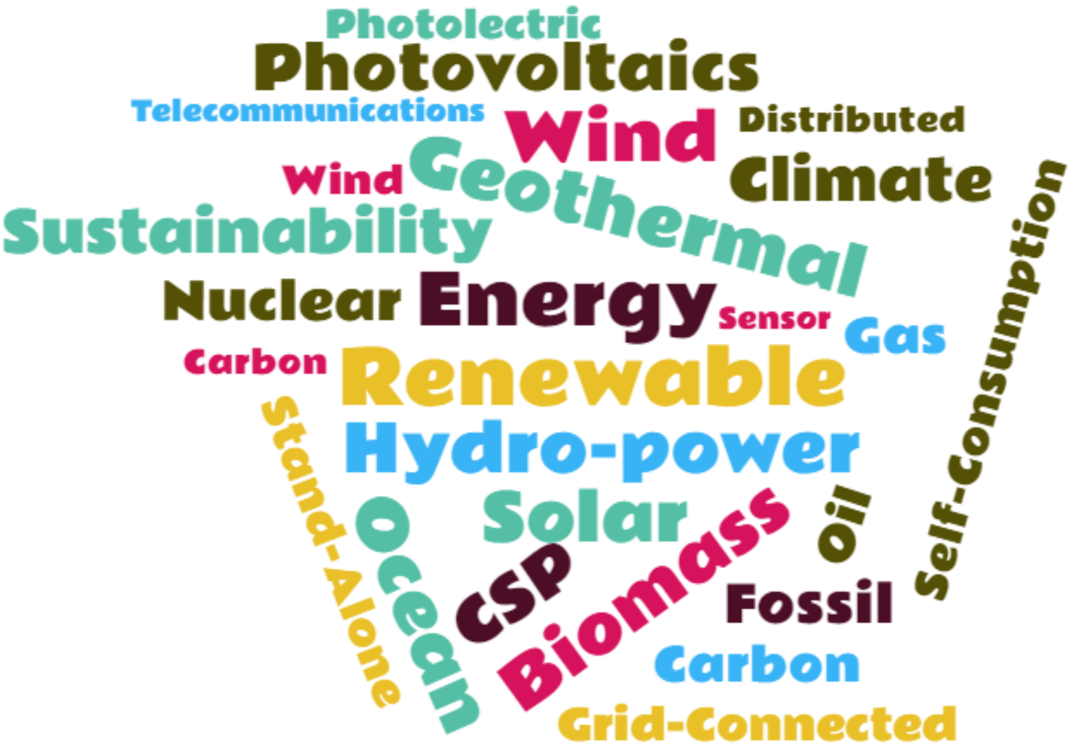
ENERGY AND TELECOMMUNICATIONS

Lecture Notes

Jesús Mirapeix Serrano

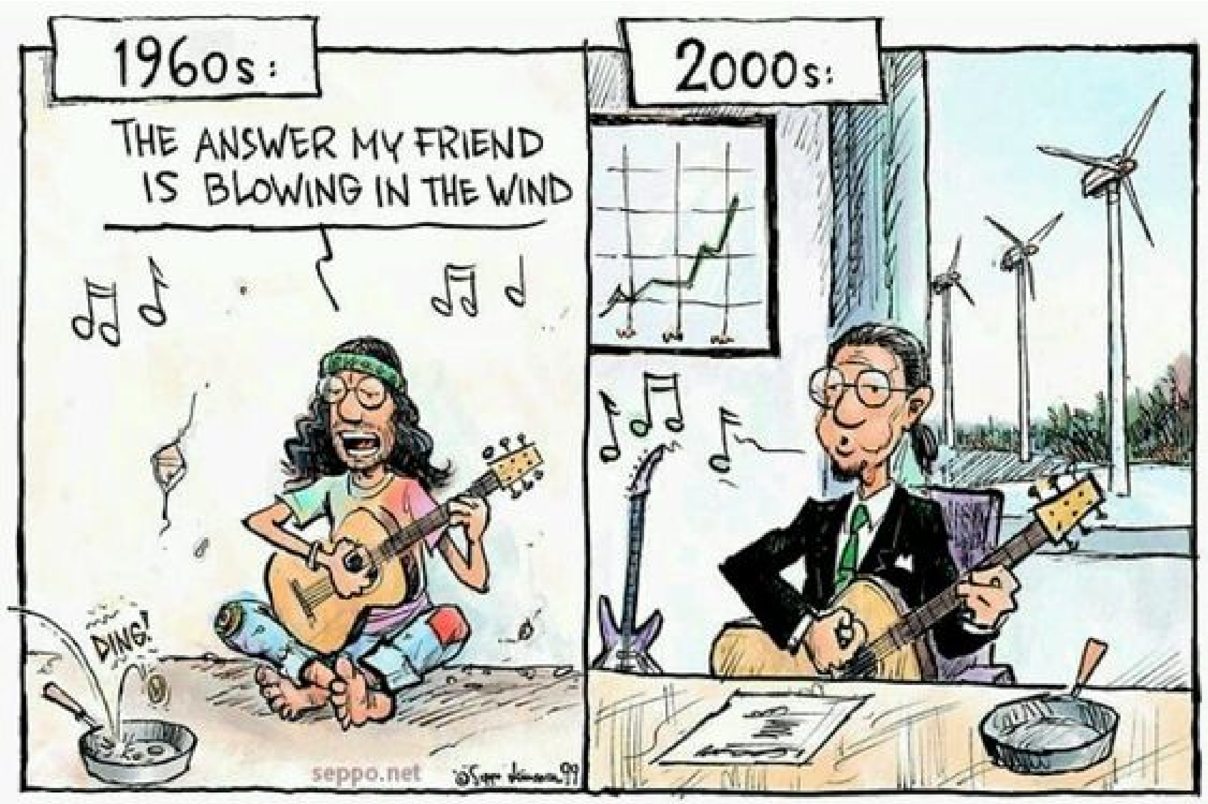
Photonics Engineering Group
University of Cantabria

Revision of the English version by
Karen Louise Murphy



"As yet, the wind is an untamed and unharnessed force, and quite possibly one of the greatest discoveries hereafter to be made will be the taming and harnessing of it."

Abraham Lincoln. President of the United States of America (1861-65).



Cartoon: Seppo Leinonen, www.seppo.net. Permission granted by the author.

Energy and Telecommunications

Mirapeix Serrano, Jesús

University of Cantabria
39005 Santander

Energy and Telecommunications: Renewable Energies

Wind Energy

Wind Energy is undoubtedly one of the main renewable energies today, with remarkable figures of energy production worldwide.

This chapter will start with a historical overview of the evolution of wind energy. The basics of wind as an energy source will be briefly explained and then some basic notions on wind turbine theory will be provided. Finally, an analysis of a modern wind turbine and all its components will be presented.

The main goals of this chapter devoted on wind energy are:

To obtain a basic knowledge and understanding of the current worldwide situation of wind energy

To become familiar with the fundamentals of wind energy

To become familiar with the working principle and components of a wind turbine

Energy and Telecommunications: Renewable Energies

Course Structure

This course has been divided into 4 chapters devoted to an introduction to renewable energies and related concepts, solar energy (including thermal and photovoltaics technologies) and wind energy. The final chapter will be focused on other REs, such as hydro-power, biomass, ocean energies, etc.

- **Chapter 1: Introduction to REs**

  The goal is to make the student familiar with the basics of REs. This includes the understanding of the reasons that provoked the origin of these technologies, with a special focus on climate change. It is also important to have a basic knowledge of the current situation in terms of renewable energies around the world and, obviously, in our country: Spain. Which country is leader in Photovoltaics or wind energy? How has the evolution of China been in the last decade? Which is the situation of Spain now and in the foreseeable future?

- **Chapter 2: Solar Energy**

  Solar Energy can be divided into thermal and photovoltaics. We will devote little time to the former, talking about solar thermal installations (and their design) but also about CSP (Concentrating Solar Power), where the energy of the sun is converted into heat and, afterwards, into electricity. Solar Photovoltaics (PV) will be the main topic of this course, given its relevance to telecom engineers. PV basics and practical issues will be dealt with, and some grid-connected and stand-alone installation examples will be analyzed.

- **Chapter 3: Wind Energy**

  Wind energy is a well-known technology, with several installations in Spain. From a different perspective, more related to communications and sensing, this technology is also associated with the telecom industry. Wind turbine theory basics, the structure of a modern wind turbine and current technological trends will be briefly explained.

- **Chapter 4: Other Renewable Energies**

  Hydro, biomass, geothermal and ocean energies will be dealt with in this final chapter. The relevance of hydro-power for electricity production will be discussed. In addition, the fundamentals of both biomass and geothermal energy will be also discussed. Finally, the different technologies associated with ocean energy will be briefly reviewed.

Acronyms

CORE	Centro de Control de Energías Renovables
CORE	[Renewable Energy Control Center]
PLC	Programmable Logic Controller
LCOE	Levelized Cost of Energy
REE	Red Eléctrica Española
SCADA	Supervisory Control and Data Acquisition
TSR	Tip Speed Ratio

Symbols

a	Axial Induction Factor
A	Scale Factor (Weibull Distribution)
η_c	Electrical Efficiency (of a Wind Turbine)
η_m	Mechanical Efficiency (of a Wind Turbine)
C_D	Drag Coefficient
C_L	Lift Coefficient
C_p	Power Coefficient (of a Wind Turbine)
D	Diameter (of a wind turbine rotor)
k	Form Factor (Weibull Distribution)
λ	Tip Speed Ratio
ρ	Air density
v	Wind Shear
z	Roughness

Units

°C	Celsius (temperature)
J	Joule (energy)
kg/m^3	Density
rpm	Revolutions per minute (rotation)
w	Watts (power)
wh	Watts-hour (energy)

Glossary

Active Stall Regulation This regulation strategy is similar to pitch regulation, as blade angle can be also controlled in this case. However, the final goal of the blade angle control is just the opposite. Instead of looking for a lower resistance, the goal of active stall regulated wind turbines is to modify the blade angle to find a stall situation.

Anemometric Tower These are lattice structures with triangular sections, used to estimate on field the feasibility of high power winds at a given location.

Betz Limit The maximum theoretical power that can be retrieved from an air stream with an ideal wind turbine can not exceed 59% of the power available in the incoming wind. This can be derived from Betz's Law and it is commonly known as the Betz Limit.

Direct Drive These wind turbines do not include a gear box, with the generator directly attached to the rotor. This implies advantages in terms of reliability (lifetime of gear box is reduced, although it has been improved lately) and noise.

Downwind Turbine A downwind turbine is designed to use the wind coming from the rear side of the turbine/nacelle (it can be understood that the rotor is at the back of the turbine).

Gear Box The gear box of a wind turbine is similar to the one of a conventional car, although the former is fixed. At its input the rotation speed will vary between 15 and 30 rpm and the output will be of 1000 to 1500 rpm.

Hub The hub allows connecting the blades to the low speed shaft. It is normally made of iron and there are basically 3 types: rigid, hinged and teetering.

Levelized Cost of Energy 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.

Offshore wind energy refers to wind farms deployed on the sea, typically a few kilometers away from the coast, thus avoiding the visual impact associated with *onshore* farms.

Pitch Regulation In this method the blade incidence angle (with respect to the incoming wind) can be varied. If the wind speed (or the produced power) is too high, blades are rotated over their longitudinal axis, thus decreasing their resistance to the wind and, consequently, the resulting power.

Roughness The roughness length defines the height (above a given surface) where the theoretical wind speed is 0. A rough surface (in comparison to a smooth one) will imply a slower wind speed at the surface.

Stall Regulation In stall regulated wind turbines, the blades are joined to the rotor at a fixed angle that can not be modified. However, the blade profile is designed to ensure that for higher wind speeds a turbulence will be created at the blade rear side. This will give rise (as already explained in previous sections) to a "to be in a stall " situation, which will derive in a sharp reduction of the lift force, and therefore the rotation speed of the rotor will decrease accordingly.

Tip Speed Ratio This is defined as the ratio between the tangential speed of the blade tip and the actual wind speed (before the rotor, at the entrance of the flow tube). The optimum TSR depends on the number of blades on the rotor: the lower the number of blades, the faster they should rotate to extract the power from the wind.

Turbulence is a perturbation of the wind laminar flow by obstacles (buildings, trees, wind turbines, etc.).

Upwind Turbine In an upwind turbine, the wind comes from the rotor side (rotor at the front) to reduce the effect of heavy loads derived from high speed winds.

Weibull Distribution In probability theory and statistics, the Weibull distribution is a continuous probability distribution used to model the wind energy resource at a given location.

Wind Farm Group of several large-scale wind turbines that acts as a power plant.

Wind Shear denotes the wind speed change with elevation, depending on the surface roughness. This wind speed change with altitude implies that wind forces will be larger on the rotor blades when they are in their top position (in comparison to their bottom position).

Index

Chapter 3
Wind Energy

3.1. Wind Energy: Introduction

We have already studied in detail the main concepts and current situation of renewable energies. We have also analyzed in detail solar PV energy in the previous chapter and now it is time to devote this final section to wind energy. By now, we know that wind energy plays a major role in modern REs, with a significant electricity production in many countries, Spain being within the top five in this regard.

The basics of wind energy will be briefly presented: we will understand why the wind makes a wind turbine rotor spin, why there is a theoretical limit to the turbine efficiency (Betz limit) and how the energy production in a wind turbine can be regulated in real time.

3.2. Wind Energy: a Historical Overview

It is difficult to precisely determine the very first time a human being used wind energy. Often reference is made to the first sailing ships built by different civilizations. Figure 3.1 shows two of the first representations of these ships:

- The first image, showing the oldest known sailing ship, was found painted on a glass discovered in the Nubian desert (6000 BC?).
- The second image (on the right) belongs to an Egyptian relief (3000 BC), where a wooden sailing ship with a curved hull is represented.

Mechanical extraction systems based on wind energy were known in China and the Middle East (7th century BC). Many centuries later, windmills were extensively employed in Holland in the water drainage system, in an attempt to move water to higher levels. **100.000 windmills** were supposed to have been in operation in those days, only in Holland!

The first use of a windmill for electricity production dates from 1892 and, with a 25 kW capacity, was designed by **Poul la Cour**. La Cour is one of the pioneering contributors to modern aeronautics, as he also built his own wind tunnel, founded the *"Society of Wind Electricians"* and published the first wind power journal.

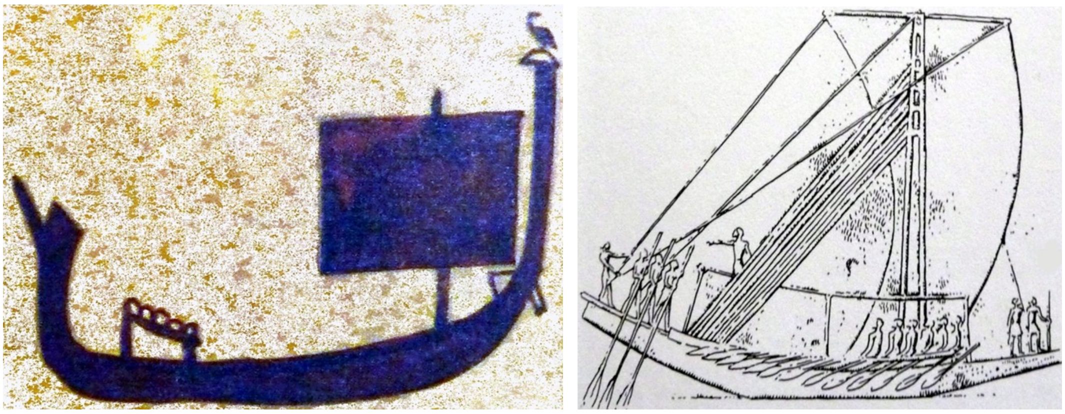


Figure 3.1. First representations of sailing ships.

Figure 3.2. Two test wind turbines by Poul la Cour in the Askov Folk Institute, Askov (Denmark, 1897). Sourcee: http://bit.ly/2mFUIfm. License: Copyright 1997-2003 Danish Wind Industry Association.

By 1918, about 120 Danish companies had wind power system, with a global production of 3 MW (approximately 3 % of the national demand).

New turbine designs appeared in 1920s, for example the Savonius (1924) and Darries (1927) models. Both were vertical-axis turbines (see Figure 3.3), thus being different from current large-scale wind turbine models.

Wind power experienced a huge boost in 1973, due to the oil crisis that motivated a serious study of alternative energy sources. Wind resource maps were created to allow a first estimation of potential locations. The capacity of wind turbines was significantly increased, being grouped

Figure 3.3. Savonius and Darrieus wind turbines: Savonius wind turbine in Taiwan (left); Darrieus wind turbine in Baden-Württemberg (Germany). Source (left): `http://bit.ly/2mG2mWV` (License: CC BY-SA 3.0 (Attribution: Dietrich Krieger)); Source (right): `http://bit.ly/2mAbNXf` (License: CC BY-SA 3.0).

in the so-called "wind farms" with large capacities.

Important! 2.1: Poul la Cour

Poul la Cour is considered "the founding father" of current wind turbines. He was not only concerned by electricity production, but also about the possible uses of that electricity:

"La Cour thought about energy storage and used the electricity generated in his turbines to implement electrolysis and get hydrogen for the gas lamps of his school."

The main drawback associated with these experiments is that he had to repair the windows of these buildings several times, as hydrogen was prone to explode due to the amount of oxygen found[a].

[a] More information: `http://bit.ly/2mFUIfm`

The evolution of wind energy has been quite remarkable in recent years. If we look at Figure 3.4 again (already shown in the Introduction section of this course), it is easy to notice the increasing trend in terms of total installed capacity.

3.2.1. Wind Energy: Pros and Cons

This evolution is based on the **various advantages provided by wind energy**, such as:

- Safe and renewable energy
- Energy without associated emissions or wastes (apart from the manufacturing, transportation and oils used during maintenance)

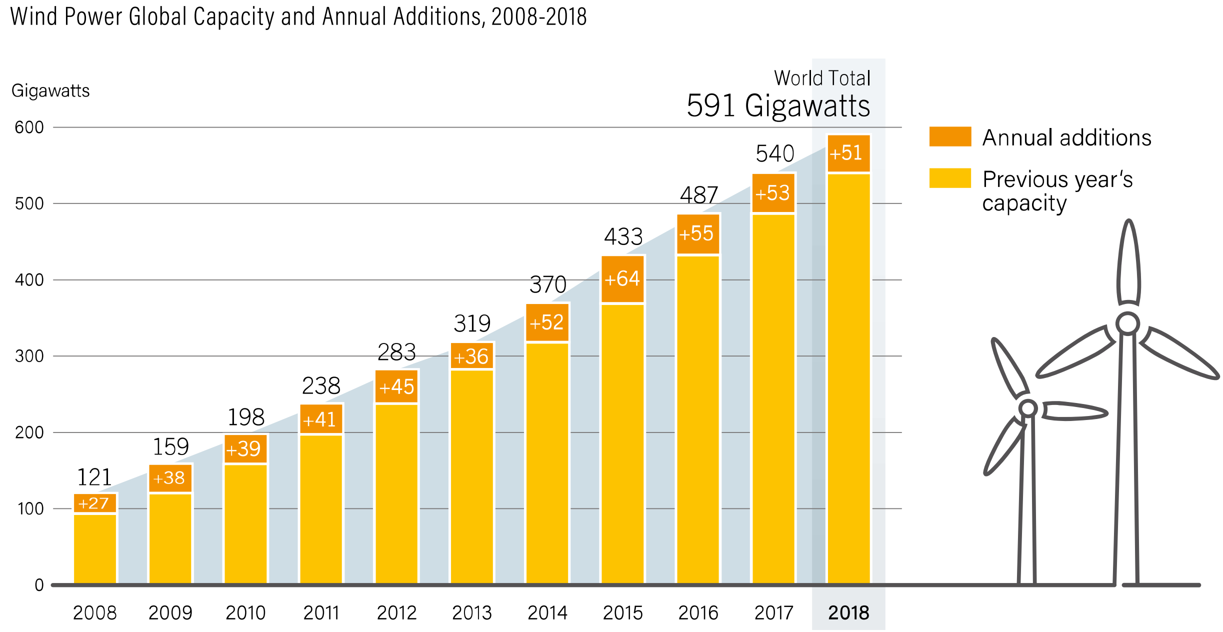


Figure 3.4. Wind Power Global Capacity and Annual Additions, 2008-2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

- Installations easyly dismantled: the land can be recovered for other activities
- Installations compatible with other activities, such as the cattle industry
- Energy production can be regulated in real time (depending on the current demand)
- *Offshore*[1] systems can also be deployed.

Are there any drawbacks associated with wind energy? The answer is YES.

The first problem that comes to mind is the inherent **intermittent nature of this technology** (as with solar PV). We know that wind energy belongs to the so-called **"fluctuant REs"**, as it depends on an energy source (the wind) that is not constant. This implies that energy availability can not be guaranteed at any given moment.

On the other hand, it is well known that there is also some resistance to this technology because of the associated **visual impact**.

There is also some influence on animals, specifically **birds** (some studies indicate a ratio of 0.3 dead birds/turbine per year).

Finally, wind turbines generate some **noise**, which can obviously be understood as a drawback, especially for people/houses located in the vicinity of the turbines. Manufacturers often indicate the noise level generated by these machines. These noise levels have been depicted in Figure 3.5.

Important! 2.2: Oil and Wind Turbines

Around **300 to 400 liters** of oil are estimated to be used in a single wind turbine per year.

[1] *Offshore* wind energy refers to wind farms deployed on the sea, typically a few kilometers away from the coast, thus avoiding the visual impact associated with *onshore* farms.

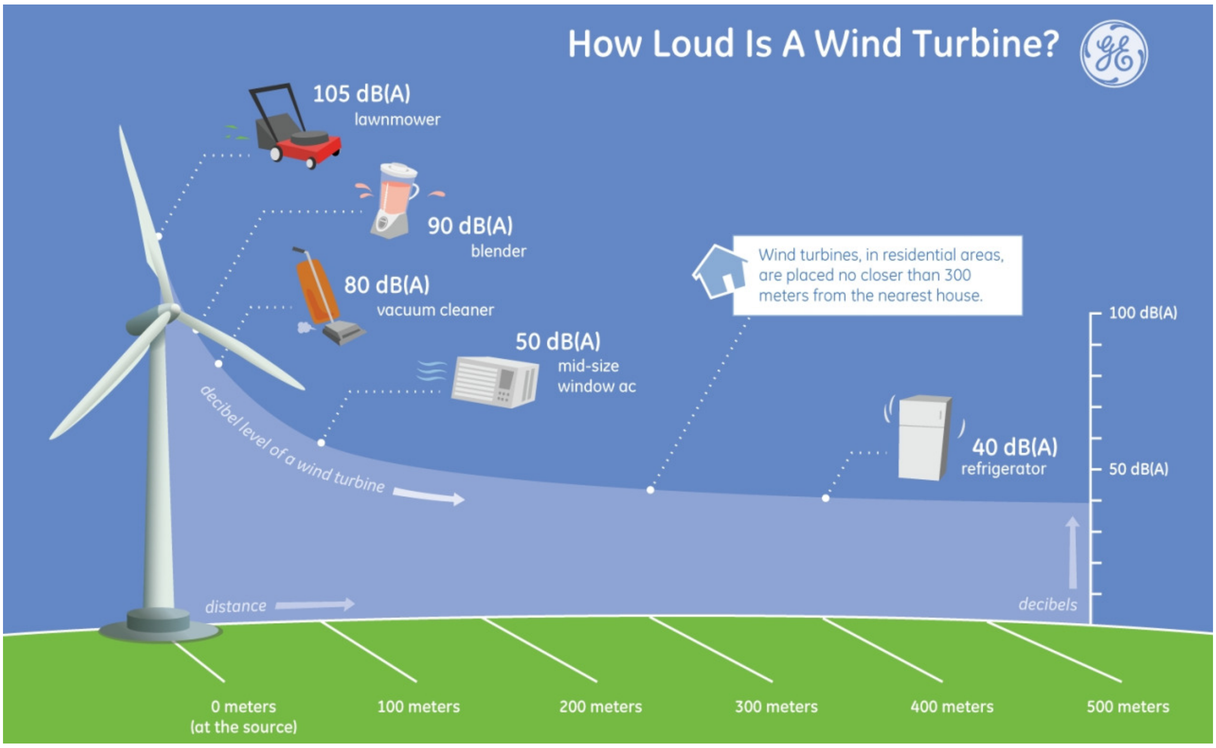


Figure 3.5. Noise generated by a wind turbine. Source: GE Global Research / National Institute of Deafness and Other Communication Disorders.

3.2.2. Wind Energy: Levelized Cost of Energy

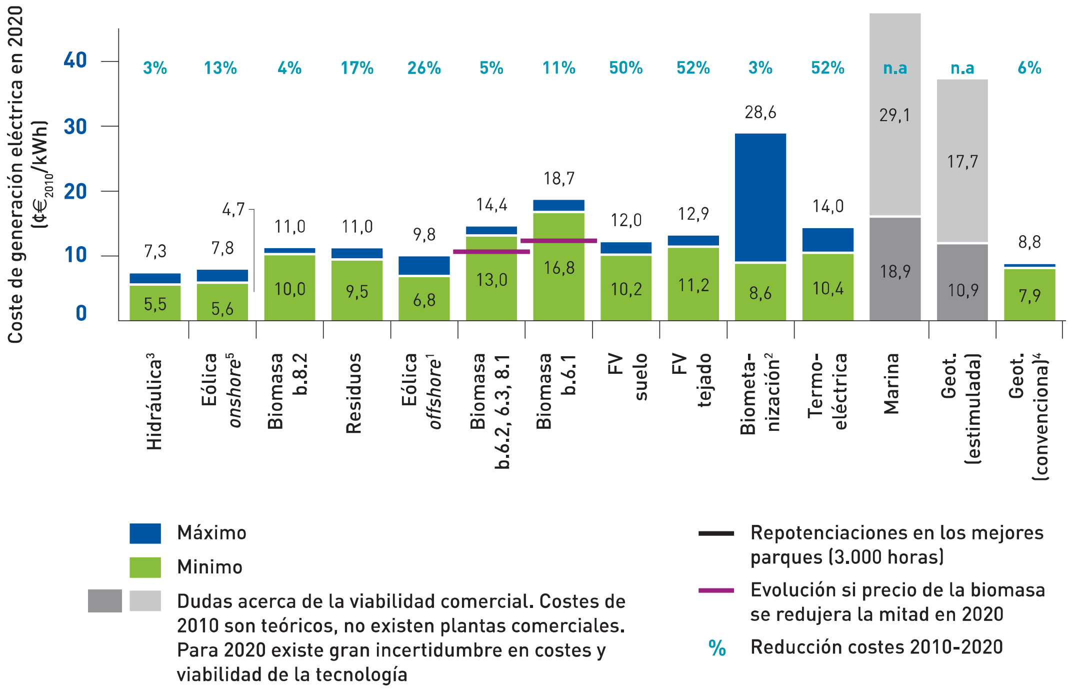


Figure 3.6. Levelized cost of energy forecast for RE technologies. Source: (IDAE) Evolución tecnológica y prospectiva de costes de las energías renovables. Estudio Técnico PER 2011-2020. `http://bit.ly/2nRALmR`

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.

Figure 3.6 presents a study of the costs forecast for 2020 (in blue the % cost decrease for each technology in comparison to 2010 values). It can be clearly appreciated how wind energy, both onshore and offshore, shows the lowest costs, with the only exception of hydro-power. This study clearly indicates the maturity of this technology.

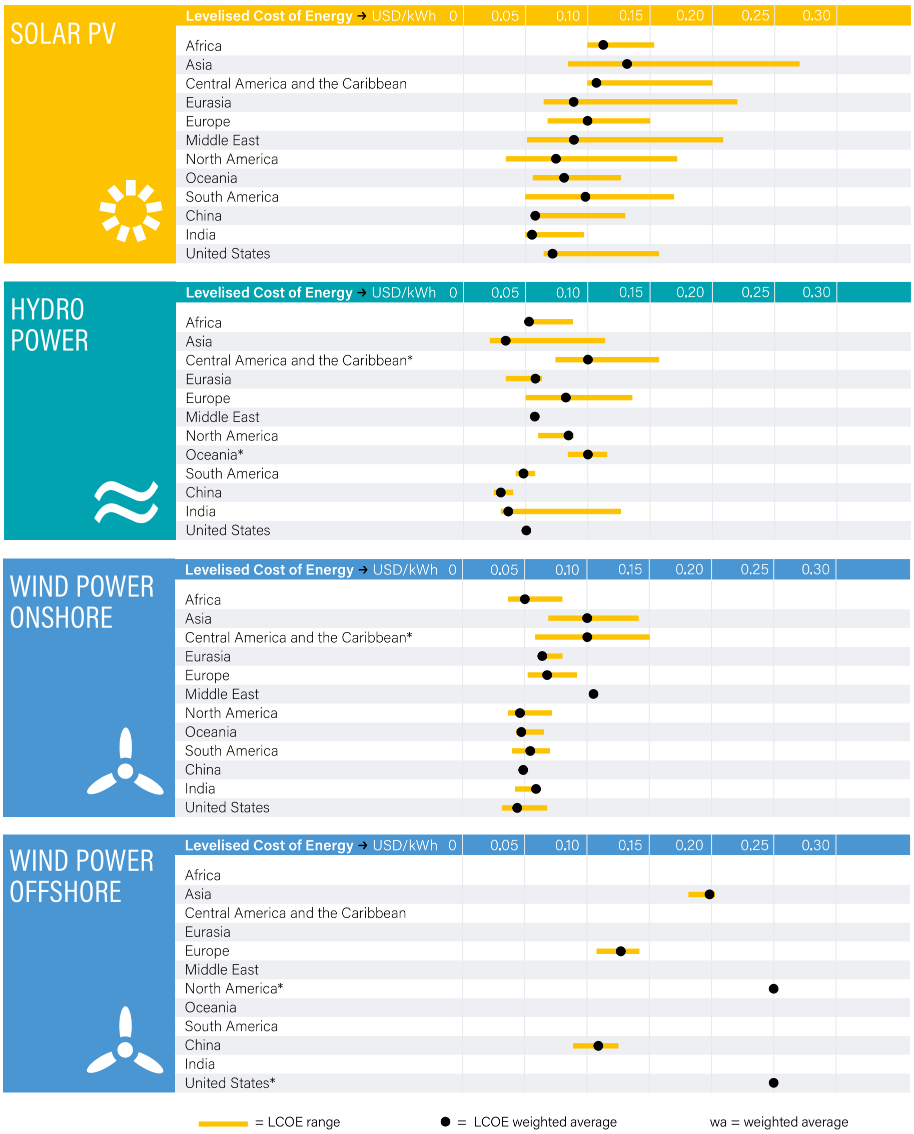
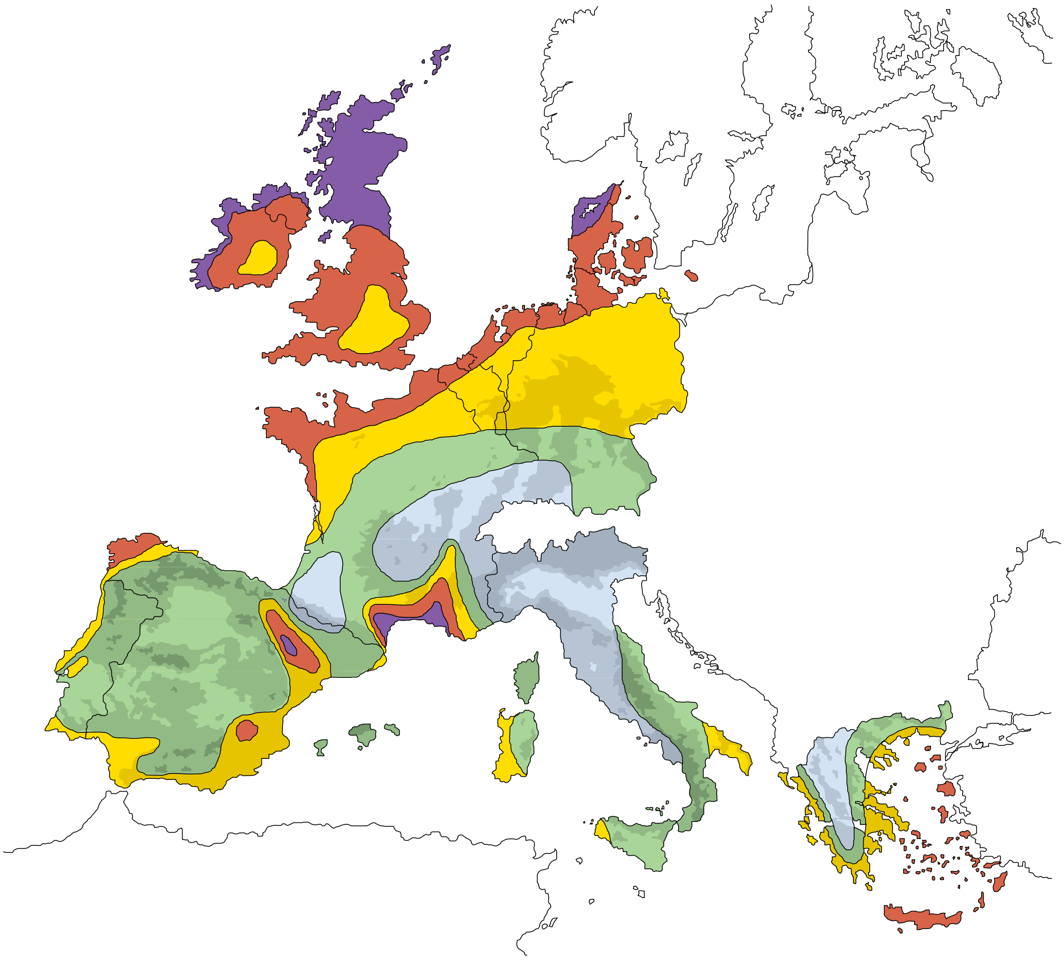


Figure 3.7. LCOE for hydro and wind power (2018). Source: Renewables 2019 Global Status Report (REN21). `http://bit.ly/2rTdoy3`

It is also interesting to analyze the most recent data regarding the LCOE of different modern renewable technologies. Figure 3.7 shows a comparison of the LCOEs associated with wind power (both onshore and offshore) and hydro power and solar PV (data for 2018). It can be appreciated how onshore wind power shows LCOEs close to those of hydro power, still below solar PV. On the contrary, offshore wind power shows less maturity (and a limited deployment to date) and therefore higher costs.

3.3. The Wind as an Energy Source

A detailed study of the wind is beyond the scope of this course. However, some hints on how to select an optimum location for a wind farm will be discussed.



Recurso eólico a 50 metros por encima del nivel del terreno para cinco condiciones topográficas distintas

	Terreno resguardado		Llanuras		Zonas costeras		Alta mar		Colinas y crestas	
	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.6-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 3.8. Wind map: Europe. Source: Plantas eólicas/ABB Cuaderno técnico.

The wind can exhibit large variations, for example its speed, between nearby locations (only a few kilometers away). If a suitable location has been determined, the normal procedure consists

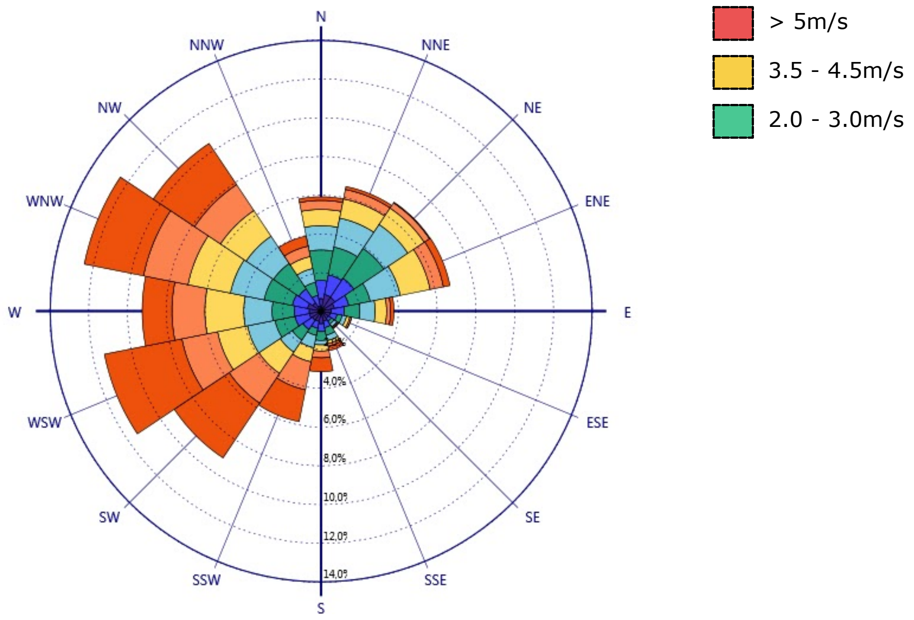


Figure 3.9. Wind rose plot for Bombay. Source: Arquitectura Abisal Bombay `http://bit.ly/2Df8nV1`.

in the installation of an anemometric tower or similar instrumentation to acquire **data on wind speed and direction**.

Turbulences at different heights should be also evaluated. Turbulences (in this framework) are defined as the wind speed standard deviation, considering time intervals of 10 minutes[1]. Turbulences are very relevant for wind turbines as they indicate the variations of the wind strength applied to the turbine blades, which may greatly influence the lifetime of the blades-rotor-turbine ensemble.

Once these meteorological data has been obtained, there are different ways of processing this information.

A wind rose plot (see Figure 3.9) enables the representation (and identification) of the prevalent wind directions, as well as the relative frequency associated with each direction[2].

Another useful tool is the **histogram of wind speeds**, as represented in Figure 3.10. It allows identifying the time duration associated with each wind speed. This wind speed temporal distribution is usually modeled by means of a **Weibull distribution**, as it is a good fit for these data.

The Weibull distribution can be described in terms of two parameters:

The scale factor A expressed in m/s, directly related to the mean speed.

The form factor k dimensionless, which modifies the symmetry of the distribution: values close to 1 give rise to very asymmetric distributions, while higher values ($k \geq 2-3$) are associated with symmetric distributions, like Gauss.

[1] Source: Plantas eólicas/ABB Cuaderno técnico.

[2] The wind rose plot indicates the direction from which the wind blows (and not in which direction it is blowing).

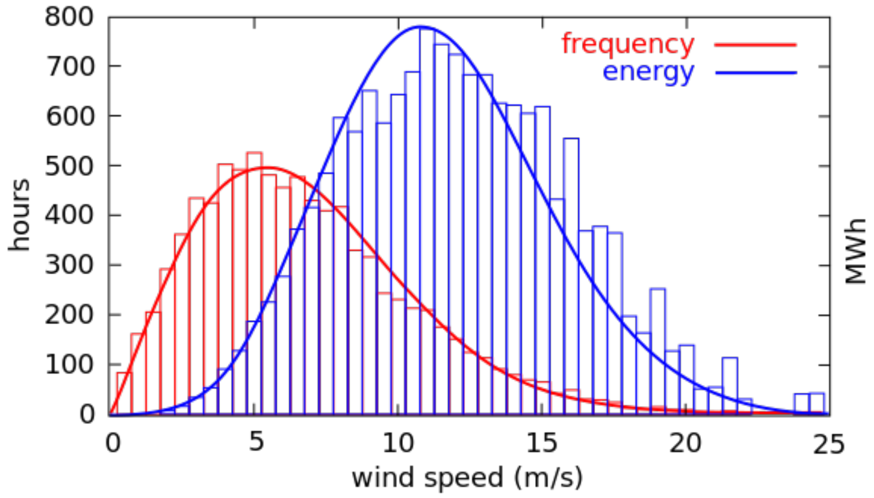


Figure 3.10. Example of Weibull distribution (red) used to model wind speed data. The energy produced by the wind turbine has been represented in blue. Source: `http://bit.ly/2FEQZGz`. License: CC-BY-SA 3.0.

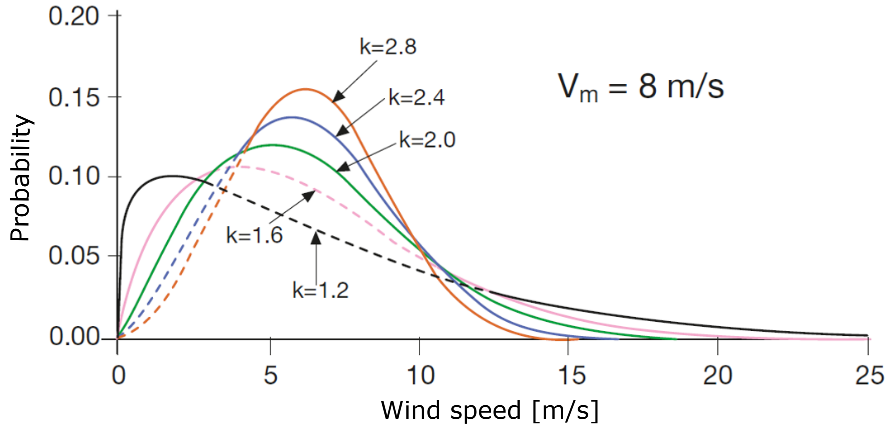


Figure 3.11. Weibull distributions for an average wind speed of 8m/s and different values of k.

$$f(v) = \frac{k}{A}(\frac{v}{A})^{(k-1)} \cdot e^{-(\frac{v}{A})^k} \tag{3.1}$$

The form factor k depends on land morphology. The wind regime at the chosen location will also depend on that morphology (see Table 3.1).

It is also important to note that wind speed depends on height. It may seem intuitive that wind speed increases with increasing height, as represented in Figure 3.12. However, the concepts of **roughness** and **wind shear** should be introduced:

Surface Roughness The roughness length defines the height (above a given surface) where the theoretical wind speed is 0. A rough surface (in comparison to a smooth one) will imply a slower wind speed at the surface.

Table 3.1. Form factor *k* (Weibull distribution).

Form Factor k	Land Morphology	Wind Regime
1.2-1.7	Mountains	Very variable
1.8-2.5	Plains/Hills	Variable
2.6-3.0	Open areas	Constant
3.1-3.5	Coastal areas	Somewhat Constant
3.6-4.0	Islands	Very Constant

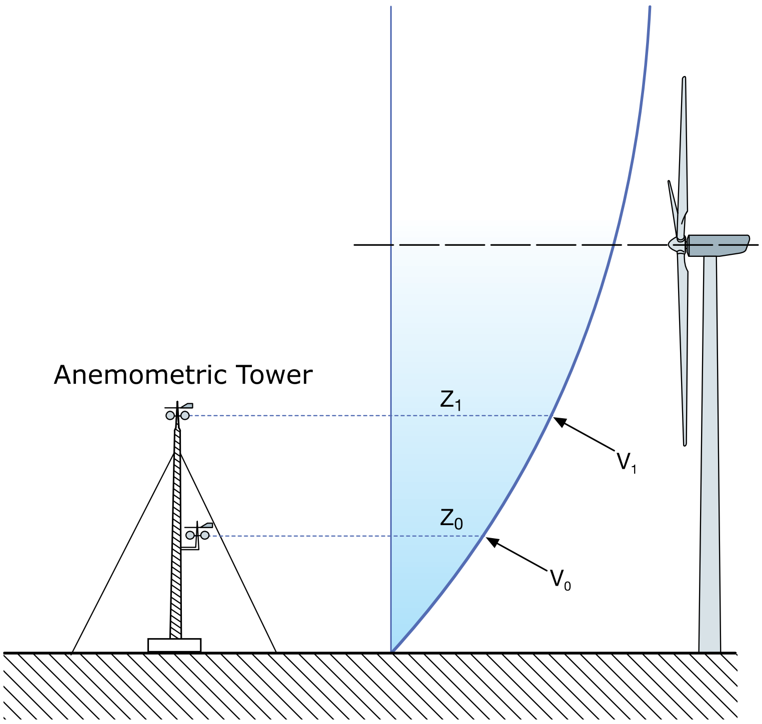


Figure 3.12. Wind speed increase with height. Source: Plantas eólicas/ABB Cuaderno técnico.

$$z_0 = 0.5\frac{(h \cdot S)}{A_H} \tag{3.2}$$

Where H denotes height, S the section of the surface roughness that interacts with the wind and A_H the mean horizontal area of the surface elements.

Wind Shear denotes the wind speed change with elevation, depending on the surface roughness. This wind speed change with altitude implies that wind forces will be larger on the rotor blades when they are in their top position (in comparison to their bottom position).

$$v = v_{ref} \cdot \frac{ln(z/z_0)}{ln(z_{ref}/z_0)} \tag{3.3}$$

Where v is the wind speed at height z, z_0 is the roughness length in the wind direction, v_{ref} the reference speed (known speed at h_{ref}) and z_{ref} the reference height.

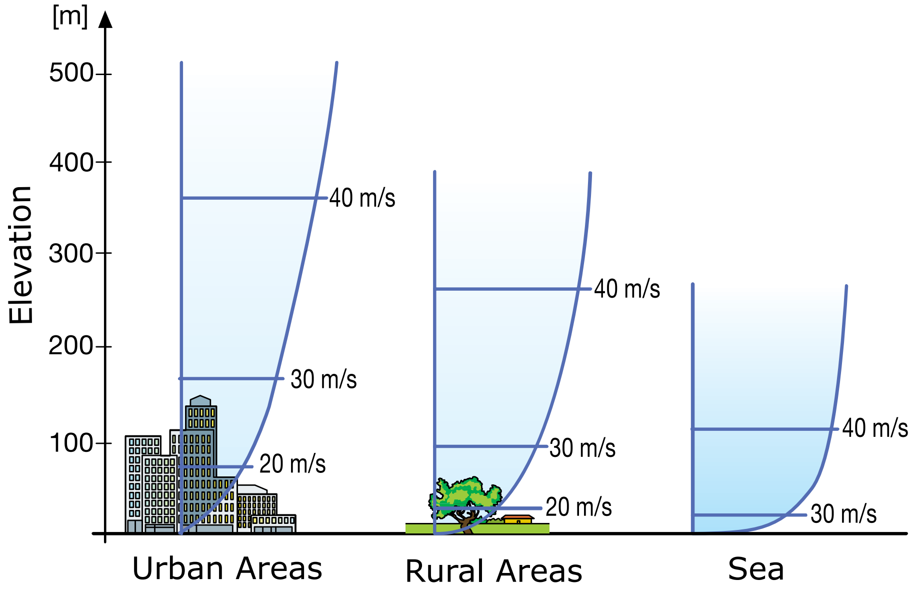


Figure 3.13. Effect of surface roughness on wind speed. Source: Plantas eólicas/ABB Cuaderno técnico.

Question 3.1: Wind Shear Example

Suppose that a 40 m rotor (diameter) wind turbine is under analysis. The wind speed at 20 m is known (7.7 m/s). We would like to know the wind speed at 60 m provided that roughness length = 0.1 m. **Determine the wind speed at 60 m.**

The effect of **surface roughness** on wind speed is clearly illustrated in Figure 3.13. If roughness is high (buildings, trees, etc.), the height where wind speed is 0 will be higher than for lower roughness. The logical conclusion is that locations for wind farms should exhibit a low roughness.

On the other hand, **wind shear** is a key factor associated with the structural health of the turbine, as the uneven force distributions on the rotor/blades should be considered in the design stages of these components.

It is also important to point out the relevance of turbulence in the wind farm design. Turbulence, which can be understood as the perturbation of the wind laminar flow by obstacles (buildings, trees, wind turbines, etc.), should be avoided in the vicinity of rotor/blades. In practical terms this implies considering a distance between consecutive turbines (e.g. 5 rotor diameters), as the wind flow through a rotor will give rise to turbulence at the back side of the turbine (see Figure 3.14).

3.4. Wind Turbines: Theory

It is necessary to check the basics of wind turbine theory to understand the working principle of wind turbines. The first key factor to consider is the expression indicating the wind power transferred to the blades of a wind turbine:

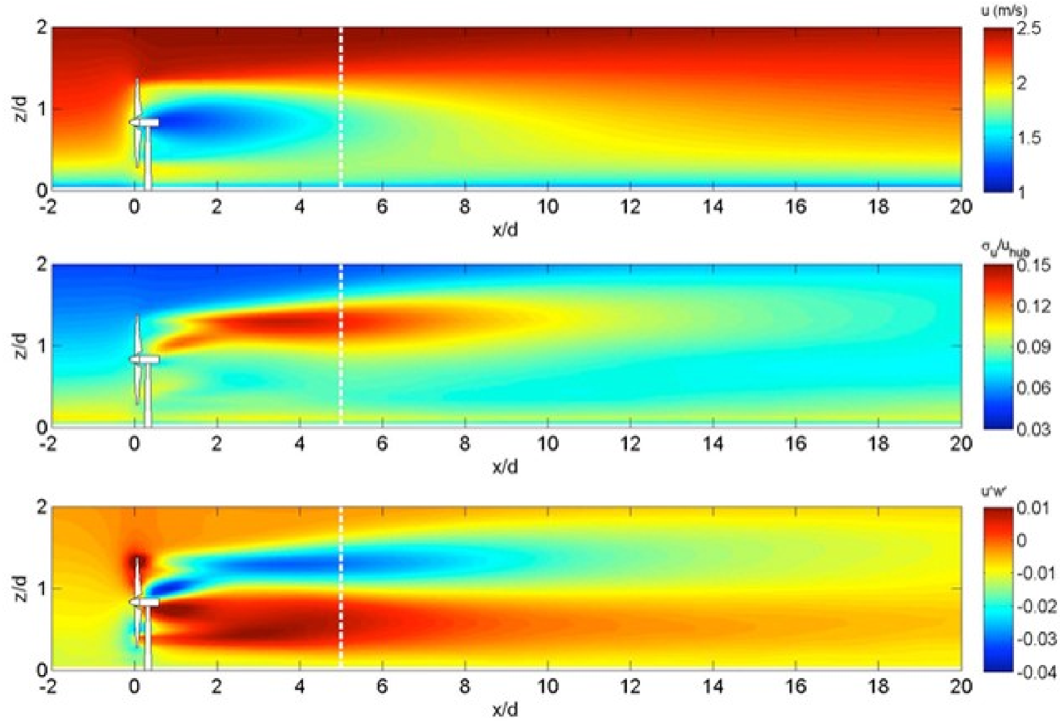


Figure 3.14. Turbulence at the back side of a wind turbine. Source: Wind Engineering and Renewable Energy Laboratory Wire `http://bit.ly/2EMfh0n`

$$P = \frac{1}{2} mass \cdot v^2 = \frac{1}{2}(volume \cdot \rho) \cdot v^2 = \frac{1}{2}(\pi \cdot R^2 \cdot v \cdot \rho) \cdot v^2 = \frac{1}{2}\rho \cdot \pi \cdot R^2 \cdot v^3 = \frac{\pi}{8}\rho \cdot D^2 \cdot v^3 \qquad (3.4)$$

Where P denotes power (W), ρ is the dry air density[1], R the rotor radius (D diameter) expressed in meters and v the wind speed (m/s).

Two main conclusions can be derived from this equation:

If the rotor diameter is doubled, the power is increased 4 times (square factor)

If wind speed is doubled, the power is increased 8 times (cube factor)

3.4.1. Betz Limit

Betz's law established the maximum efficiency achievable by a wind turbine. To understand this, Figure 3.16 shows how the air mass that goes through the rotor is expanded in the process.

The wind turbine is designed to extract energy (kinetic energy) from the air: the air mass that goes through the rotor is obviously slowed down: in fact, the air stream losses speed before reaching the rotor. The cylindrical section of the air mass is expanded after going through the rotor due to this loss of velocity.

[1] At standard atmospheric pressure and $T = 15°C$ $\rho = 1.225 kg/m^3$.

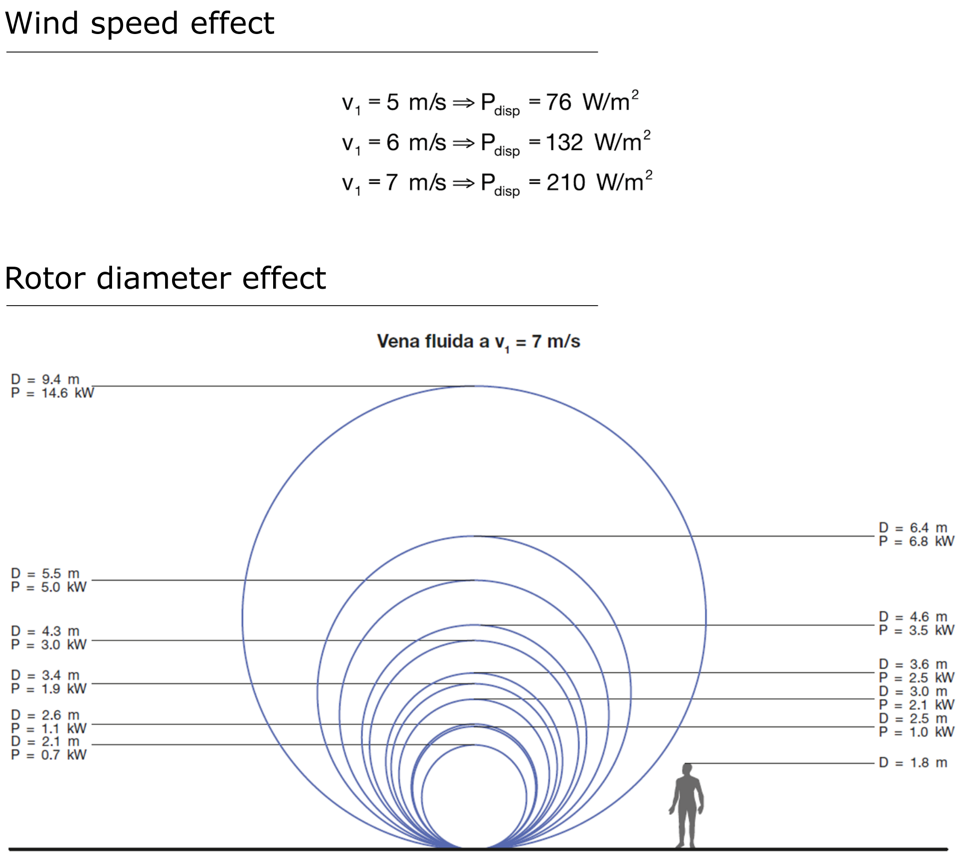


Figure 3.15. Wind turbine generated power in terms of wind speed and rotor diameter. Source: Plantas eólicas/ABB Cuaderno técnico.

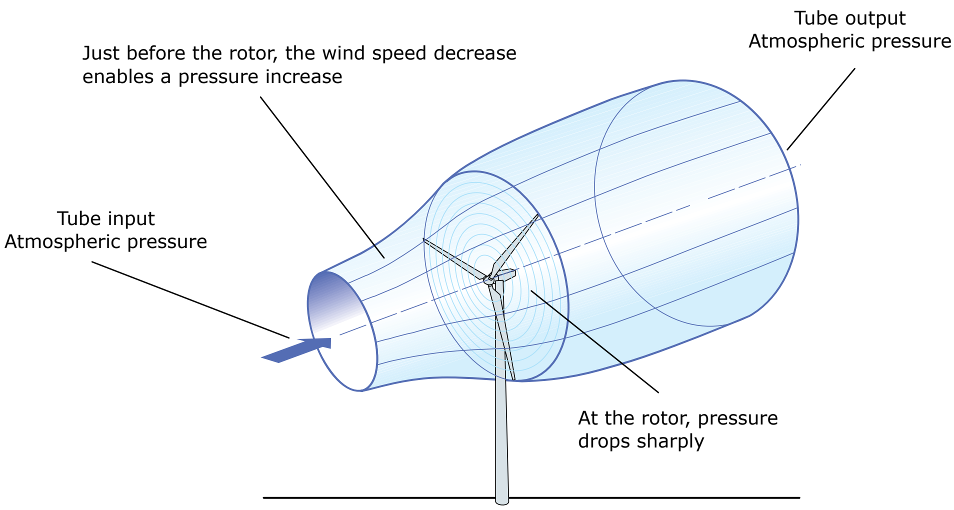


Figure 3.16. Schematic representation of the air mass going through a wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

Let's analyze this situation in more detail. In Figure 3.17, v_1 is the air flow speed at the input of the turbine, while v_2 is the speed after the rotor. Obviouslly, v_2 will be lower than v_1.

The following expression describes the wind speed at the rotor plane with v_1 and v_2:

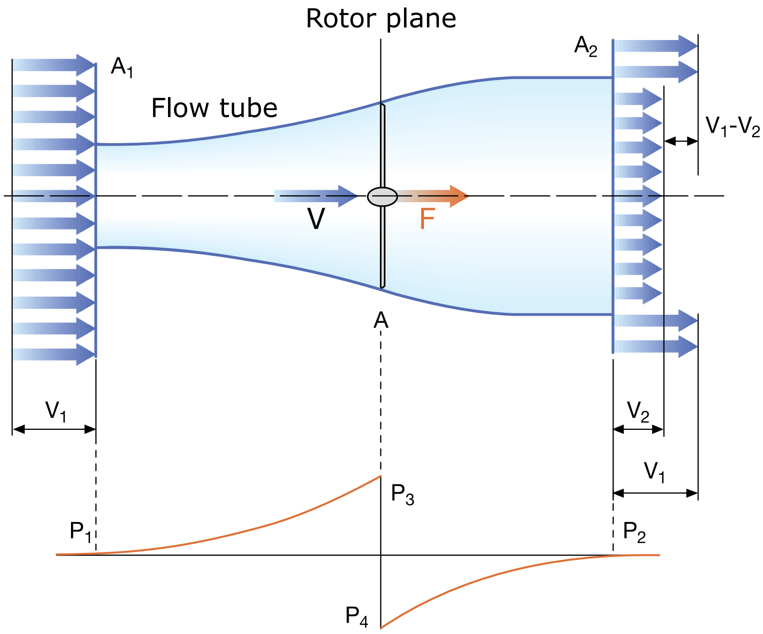


Figure 3.17. Variations in the speed and pressure of the air mass that goes through the wind turbine rotor. Source: Plantas eólicas/ABB Cuaderno técnico.

$$v = \frac{1}{2} \cdot (v_1 + v_2) \tag{3.5}$$

And now a, the so-called **axial induction factor**, which represents the wind speed decrease before the rotor, is defined as:

$$a = \frac{v_1 - v}{v_1} = 1 - \frac{v}{v_1} \tag{3.6}$$

Equation 3.4, which determines the wind power transferred to the turbine, can be also expressed in terms of a, so that:

$$P = 2 \cdot \rho \cdot A \cdot {v_1}^3 \cdot a \cdot 1 - a^2, \tag{3.7}$$

where A is the rotor area.

3.4.2. Wind Turbine: Efficiency

The efficiency achievable with a wind turbine can be defined as the mechanical power in the turbine axis[1] divided by the power available in the wind. This efficiency is normally expressed as

[1] Wind turbines often convert the rotation of the axis (caused by rotor rotation) into electricity by means of a generator.

the power coefficient Cp:

$$C_p(a) = \frac{P}{Pdisp} = \frac{2 \cdot \rho \cdot A \cdot {v_1}^3 \cdot a \cdot 1 - a^2}{\frac{1}{2} \cdot \rho \cdot A \cdot {v_1}^3} = 4 \cdot a \cdot (1-a)^2 \tag{3.8}$$

C_p reaches its maximum value for $a = \frac{1}{3}$, with $C_p = 0.59$. This value is known as the **Betz Limit**, and can be expressed like this:

*"The maximum theoretical power that can be retrieved from an air stream with an ideal wind turbine can not exceed **59 %** of the power available in the incoming wind."*

This limit can be clearly appreciated in Figure 3.18, where C_p has been represented versus a.

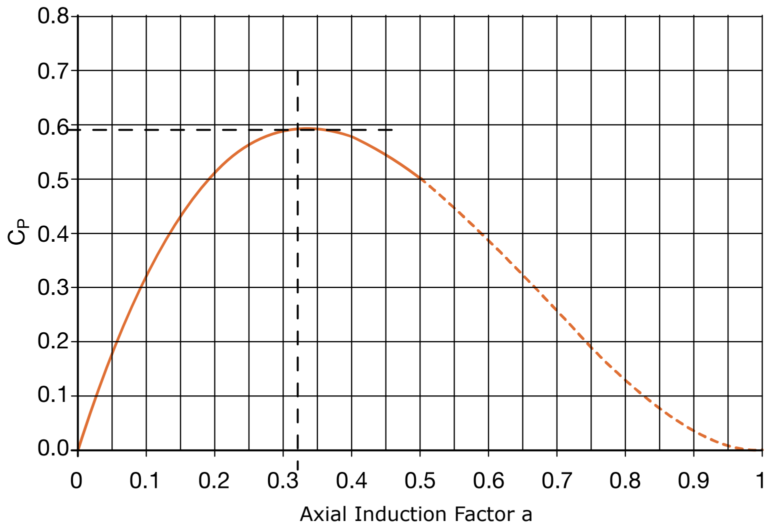


Figure 3.18. Power coefficient C_p versus the axial induction factor a. Source: Plantas eólicas/ABB Cuaderno técnico.

Betz's Law therefore indicates that **only 59 %** of the kinetic energy of the wind can be converted into mechanical energy to move the turbine rotor. 59 % is the efficiency theoretical limit of a wind turbine. This value would be achievable without friction and with a blade efficiency of 100 %.

In practical terms, there are three factor that limit the maximum power coefficient that can be obtained:

- Turbulence rotation after the rotor
- Finite number of blades
- Aerodynamic resistance $\neq 0$

Modern wind turbines exhibit $Cp \approx 0.5$, thus not far from the Betz Limit.

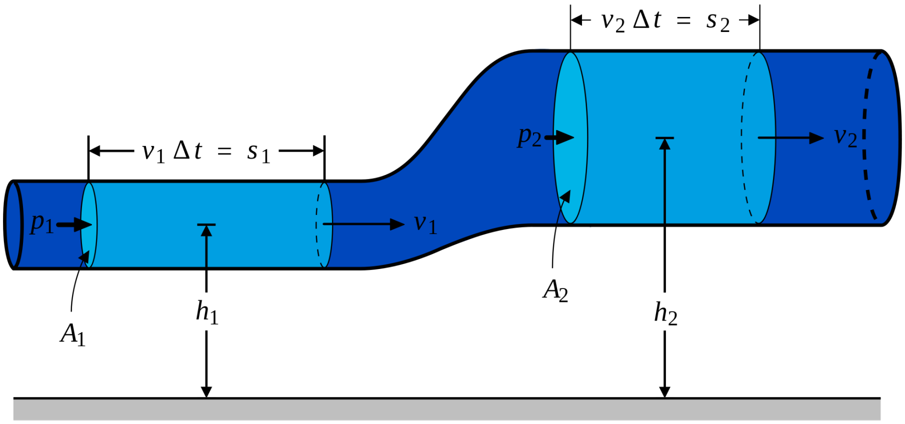


Figure 3.19. Schematic representation of Bernoulli's Theorem. Source: Wikimedia http://bit.ly/2DCneFZ

Question 4.1: Bernoulli's Theorem

Betz's Law can be related to Bernouilli's Theorem. Briefly explain this relationship **in your own words**.

3.4.3. How do wind turbines work?

Once we have gained some basic knowledge on wind turbine theory, it is now time to see how wind turbines work. The blades of a wind turbine are designed in a similar way to the wings of a plane.

Let's analyze Figure 3.20, where wind forces have been divided into **lift and drag forces**. For a wind turbine (and also for a plane), the ratio (lift-force)/(drag-force) should be as high as possible.

As can be appreciated, the blade profiles (and, again, also the wing profiles) are designed to create a **pressure difference** that will contribute to the the lift force, thus causing the rotation of the blades/rotor. A typical plane wing profile has been depicted in Figure 3.21, which shows how the length of the upper surface of the wing is greater than the length of the bottom surface.

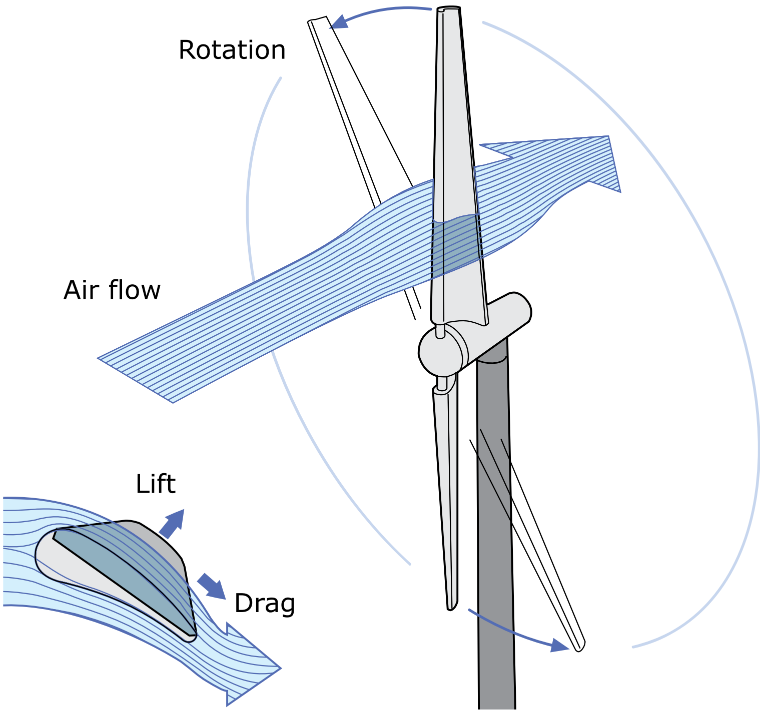


Figure 3.20. Working principle of a wind turbine: lift and drag forces. Source: Plantas eólicas/ABB Cuaderno técnico.

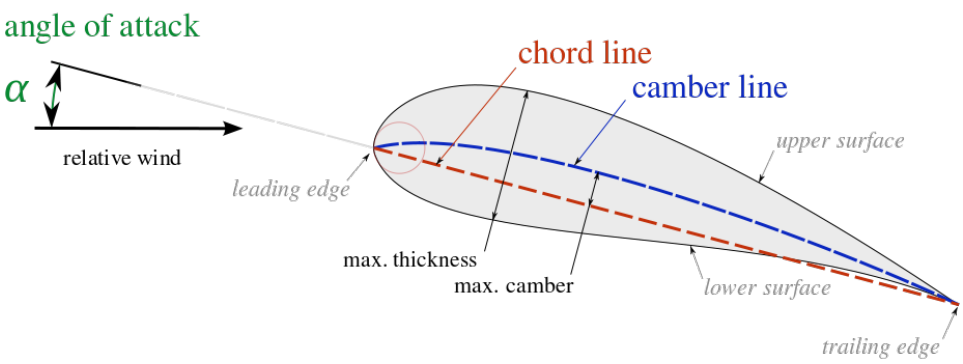


Figure 3.21. Plane wing profile (aerofoil). Source: Wikimedia.

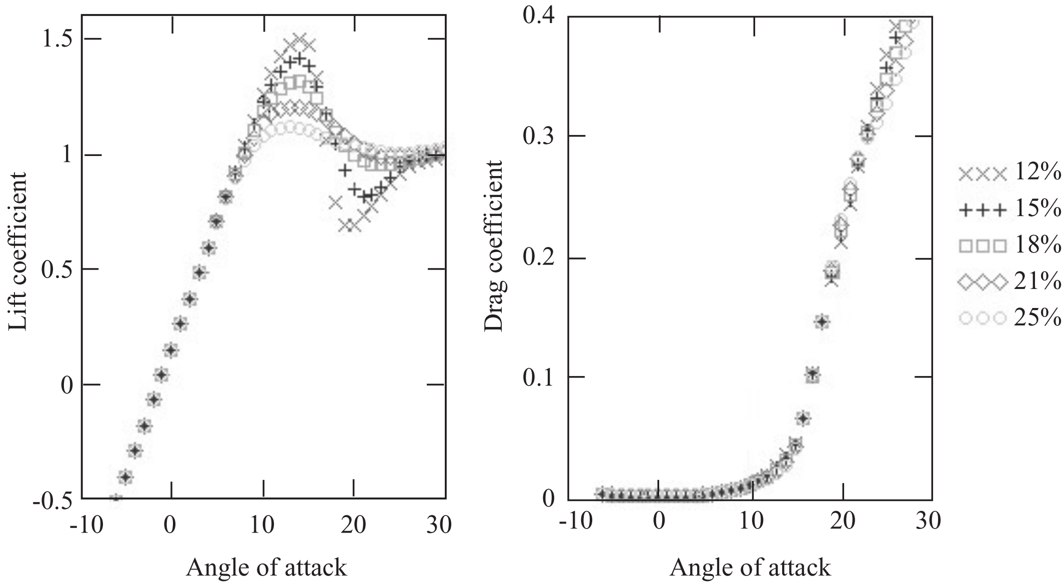


Figure 3.22. Evolution of lift and drag coefficients in terms of the angle of attack. Source: Wind Energy Handbook (Wiley), p. 94.

Question 4.2: Wings and Blades

The explanation of the working principle of the flight of a plane (or the rotation of the blades/rotor of a wind turbine) often refers to Bernouilli's Theorem, using the pressure difference between both sides of the wing/blade. However, this problem is quite complex and there are other processes that come into play, like the Venturi or Coanda effects, or the Law of Action/Reaction.

Look for information and try to explain **in your own words** the working principle of a wind turbine using these effects (at least one of them).

For a better understanding of this, it is very useful to use the **lift** C_L **and drag** C_D **coefficients**. Both coefficients can be employed to express their associated forces, so that:

$$F_L = \frac{1}{2}(C_L \cdot \rho \cdot A \cdot v^2) \tag{3.9}$$

$$F_D = \frac{1}{2}(C_D \cdot \rho \cdot A \cdot v^2) \tag{3.10}$$

C_L and C_D depend on the aerodynamic profile of the blade and on the angle of attack. Figure 3.22 shows the evolution of both coefficients for the wing model NACA632XX, although it can be extrapolated to a standard wind turbine blade. As the angle of attack increases, C_L also increases and C_D is almost constantly 0. This situation goes on until a given angle of attack is reached (a little above 10°), where C_L sharply decreases and C_D sharply increases.

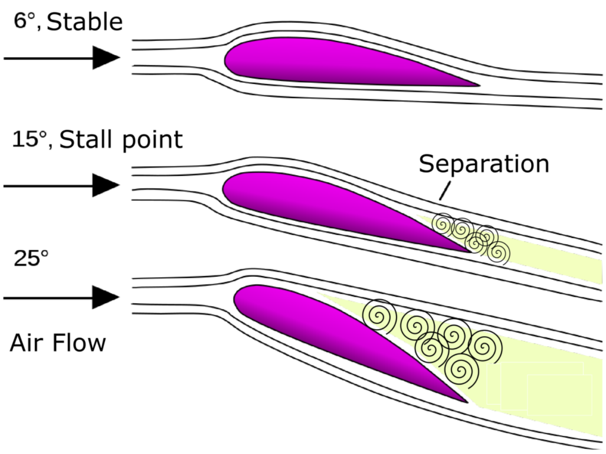


Figure 3.23. . Wing stall in terms of angle of attack. Source: Wikimedia `http://bit.ly/2mCu8mg` (Public Domain).

This situation should be avoided as it implies a sharp decrease in the blade/wing performance. In fact this situation is known in aeronautics as "to be in a stall"[1] (see Figure 3.23.), which implies a highly unsteady flight in the plane example, with rapid variations of lift with time.

3.4.4. Wind Turbines: Produced Electrical Power

The expressions that allow estimating the power extracted by a wind turbine from the wind and the power coefficient C_p have been already introduced. The former can be expressed in terms of C_p, so that:

$$P = C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot {v_1}^3 \tag{3.11}$$

And then, the electrical output power produced by a wind turbine can be calculated with:

$$P = \eta_m \cdot \eta_e C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot {v_1}^3 \tag{3.12}$$

Where η_m is the mechanical efficiency of the turbine, from the rotor to the generator, also considering the gear box[2] and η_e that refers to the electrical efficiency.

If the expression that relates the rotor area to its diameter D is used with Equation 3.12, the following expression can be derived, where the rotor diameter necessary to generate a given electrical power is determined:

$$D = \sqrt{\frac{8 \cdot P_e}{\eta_m \cdot \eta_e C_p \cdot \pi \cdot \rho \cdot {v_1}^3}} \tag{3.13}$$

[1] "Entrar en pérdida" en castellano.

[2] These components will be explained in the following section.

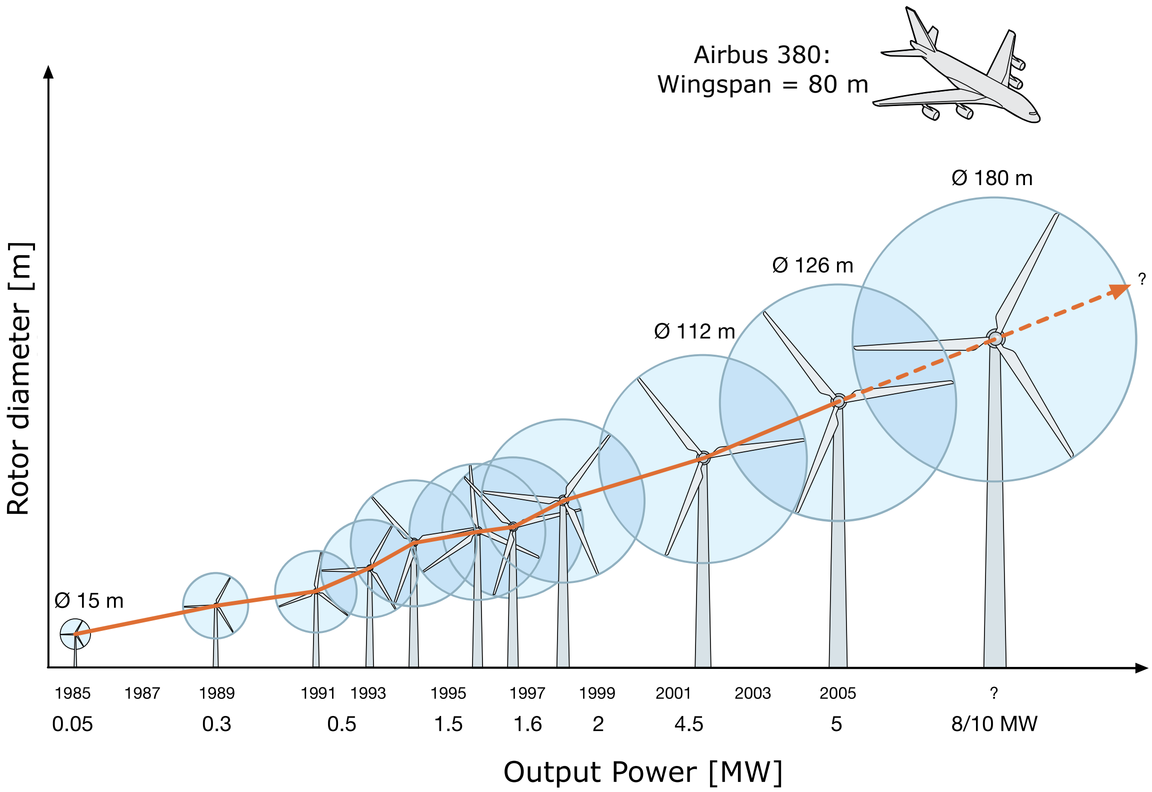


Figure 3.24. Rotor size versus output electrical power: evolution over the previous years. Source: Plantas eólicas/ABB Cuaderno técnico.

Figure 3.24 shows the rotor diameter evolution (y-axis) and the associated electrical power (x-axis) for large-scale wind turbines.

Important! 4.1: Wind Turbine Efficiency

Apart from the already mentioned mechanical and electrical efficiencies, there are other factors to be considered in this regard:

Atmospheric Pressure Atmospheric pressure variations will affect air density

Temperature Temperature also affects air density (air density decreases 3 % with each 10°C step)

Turbulence In wind farms a so-called aerodynamic interference can be generated between different wind turbines

Blade aerodynamics Ice formation or the appearance of dirt may affect the aerodynamic performance of the blades

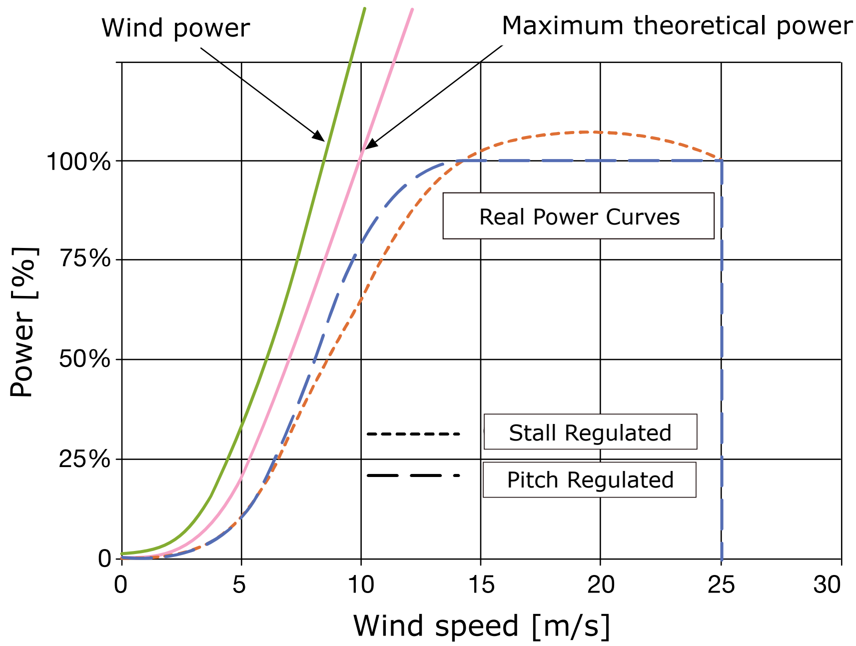


Figure 3.25. Wind speed versus output power in a wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

Question 4.3: Turbulence at the back the Turbine

Briefly explain, in your own words, why turbulence is formed at the back of a wind turbine.

What measures can be adopted to avoid the occurrence of turbulence at a wind farm?

It is important to understand the curve that relates the output power to wind speed for a given wind turbine. As has been represented in Figure 3.25, conventional wind turbines require a minimum wind speed, the so-called **cut-in speed** (typically between 3 and 5 m/s) to start operating. The nominal power is reached for wind speeds of 12 to 14 m/s, while speeds above 25 to 30 m/s (**cut-off speed**) required the disconnection or regulation of the wind turbine, in an attempt to avoid possible structural damages.

The maximum power available in the wind, as well as the maximum achievable according to the Betz Limit have been indicated. In addition, two possible regulation strategies have been also considered (stall and pitch regulation, which will be explained later on).

A very interesting analysis is also presented in Figure 3.26, where the efficiency (expressed by means of C_p) of different wind turbine models is compared. Modern turbines with three blades, but also with one or two, or different models like Savonius, Darrieus or the traditional American wind-mill have been included.

Tip Speed Ratio (TSR) λ has been represented on the x-axis. It is defined as the ratio between the tangential speed of the blade tip and the actual wind speed (before the rotor, at the entrance of the flow tube). The optimum TSR depends on the number of blades in the rotor: the lower the number of blades, the faster they should rotate to extract the power from the wind.

The following wind turbine classification can be established in terms of the TSR:

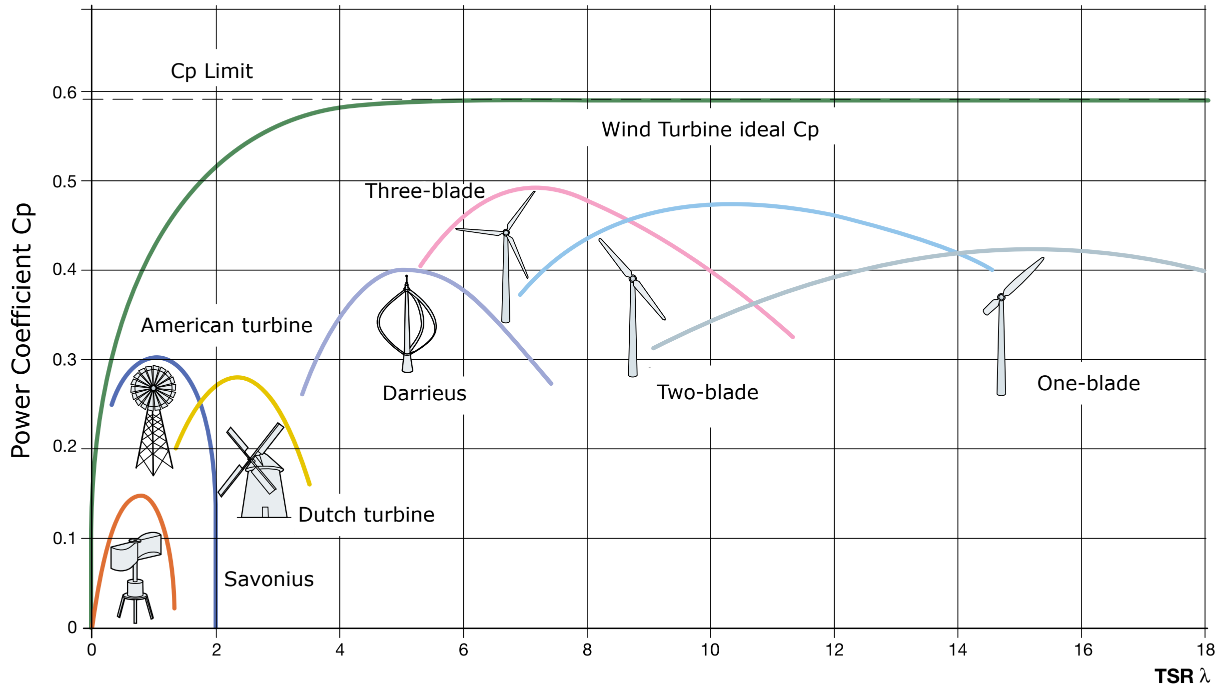


Figure 3.26. Power coefficient versus tip speed ratio for different wind turbine models. Source: Plantas eólicas/ABB Cuaderno técnico.

Table 3.2. Main features of 4 wind turbine designs.

Wind Turbine Design	Optimum TSR	Tangential Speed (m/s)	Rotor Radius (m)	Angular Speed (rpm)
Savonius (vertical)	1	7	1	67
Darrieus (vertical)	5	35	1.5	223
Two-blade (horizontal)	10	70	28	24
Three-blade (horizontal)	7	49	45	10

Fast Wind Turbines High optimum TSR

Slow Wind Turbines Slow optimum TSR

Common modern wind turbines can be classified into the “fast” group (see Figure 3.26).

For maximum energy production, it is necessary to operate at C_p values close to its optimum for as long as possible, independently of wind speed. To achieve this, the rotor speed should vary to give rise to a TSR that maximizes C_p. Table 3.2 presents TSR data and associated parameters for 4 wind turbine models: Darrieus, Savonius, two-blade and three-blade.

3.4.5. Wind Turbines: Power Regulation

The typical wind speed range for modern wind turbine operation could be established between 3 and 25 m/s. The upper limit is established to avoid possible structural problems/damage on the turbine, mainly on the rotor/blades group. This, however, does not mean that modern wind turbines can not operate at higher wind speeds, as there are some regulation strategies that can be used in this regard:

Pitch Regulation With this method, **the blade incidence angle (with respect to the incoming wind) can be varied**. If the wind speed (or the produced power) is too high, blades are rotated over their longitudinal axis, thus decreasing their resistance to the wind and, consequently, the resulting power.

An electronic system monitors wind speed, output power and blade position (angle), being responsible for the latter in terms of the incoming wind.

Pitch regulated wind turbines require a very demanding design to ensure the correct blade positioning.

The advantages of this strategy are **longer turbine lifetimes**, as dynamic loads are reduced. **Increased performance** is also achieved, as the optimum incidence angle can be used at any moment. Finally, **low wind speed regimes** can be also employed.

Stall Regulation In stall-regulated wind turbines, the blades are joined to the rotor at a fixed angle that can not be modified. However, **the blade profile is designed to ensure that for higher wind speeds a turbulence will be created at the blade's rear side**. This will give rise (as already explained in previous sections) to a "to be in a stall " situation, which will lead to a sharp reduction in the lift force, and therefore the rotation speed of the rotor will decrease accordingly.

It is worth noting that these blades are slightly curved along their longitudinal axis. This ensures a gradual (not so sharp) loss of lift.

The main advantage of this solution is that both mobile components on the rotor and a complex control system are avoided. On the other hand, stall regulation requires a very complex aerodynamic design of the blades and the whole turbine, as vibrations derived from the stall situation must also be considered.

Active Stall Regulation This regulation strategy is similar to pitch regulation, as blade angle can also be controlled in this case. However, the ultimate objective of blade angle control is just the opposite. Instead of looking for a lower resistance, **the goal of active stall regulated wind turbines is to modify the blade angle to find a stall situation.** This is consequently a mixture of the two regulation strategies described above.

Power generation can be more exactly controlled in this case in comparison to "passive" stall regulation. Additionally, these turbines may operate very close to their nominal power at all wind speeds.

Other Regulation Methods Flaps, also used in airplanes, can also be integrated into the blades to control the output power. An alternative solution is based on movement of the rotor out of the wind direction (horizontal displacement) to decrease the resulting power. This solution, known as yaw control, is only used in small-scale turbines.

3.5. Wind Turbines: Components

A modern wind turbine is formed by several elements to perform all the required actions for an efficient conversion of the wind kinetic energy into electricity. These components are[1] (see Figure 3.27):

[1] The specific case of modern horizontal-axis wind turbines has been considered. These are the turbines commonly found in wind farms.

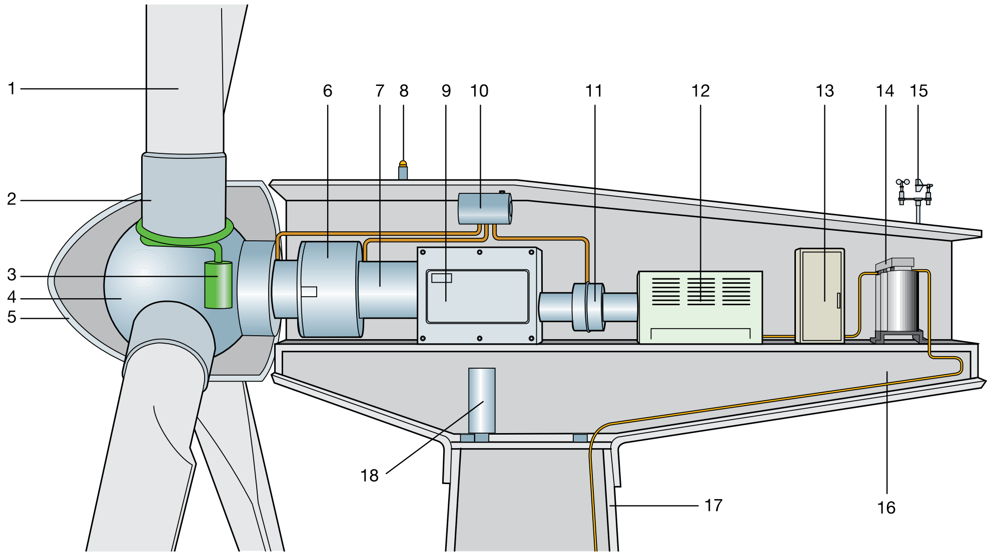


Figure 3.27. Components of a wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

1. blade
2. blade support
3. pitch actuator
4. hub
5. cover
6. main support
7. low speed shaft
8. lights
9. gear box
10. refrigeration system
11. brakes
12. generator
13. power converter and electrical control and protection devices
14. transformer
15. anemometers
16. nacelle
17. tower
18. yaw motor

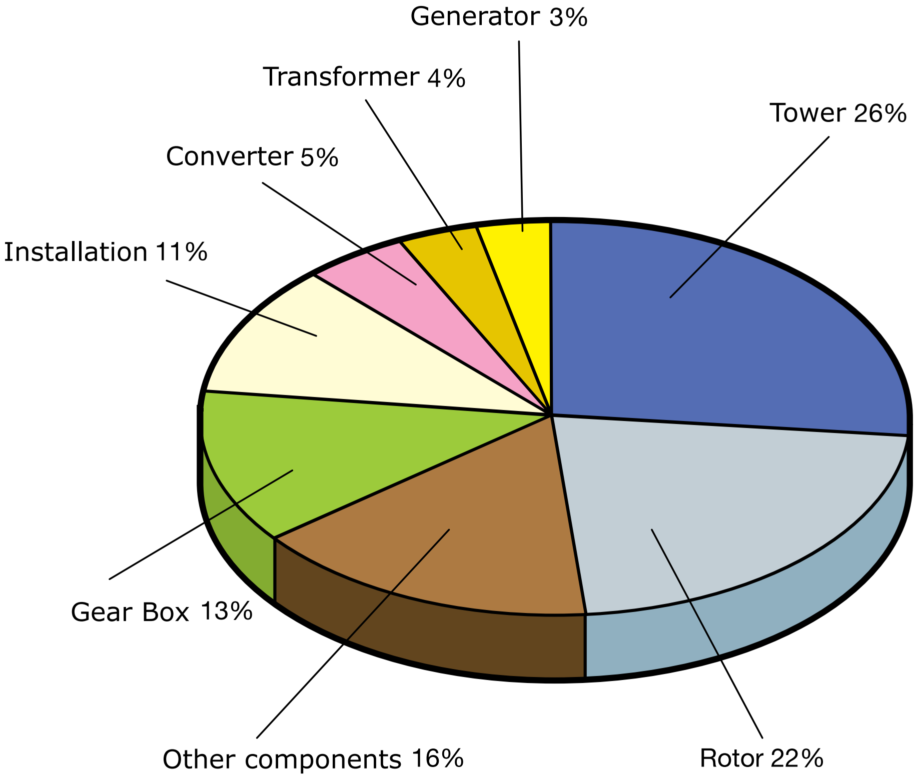


Figure 3.28. Cost associated with wind turbine components. Source: Plantas eólicas/ABB Cuaderno técnico.

It is very interesting to analyze the cost associated with the different elements, even if it is a mere approximation. As indicated in Figure 3.28, almost half of the total cost is for both tower and rotor (including the blades). The gear box (14%) and costs derived from installation (11%) are also signifcant parts of the overall cost. **Note that the total cost of a modern wind turbine may be in the order of *1 million euros per installed megawatt* (and 5 to 10 MW turbines are planned to be deployed in the near future).**

3.5.1. Wind Turbine Elements: Tower

Modern wind turbines often use **tubular towers** (Figure 3.30). **Lattice towers** were used some years ago, but drawbacks such as the use of bolts have led to their disuse. **Guy-wired pole tower**s are used for low-scale wind turbines.

Tubular towers are common nowadays due to their advantages, like lower requirements in terms of maintenance or safe access to the nacelle, for example. Onshore wind turbines are often deployed via concrete foundations, while offshore installations need alternative solutions.

3.5.2. Wind Turbine Elements: Rotor

A wind turbine rotor can be considered as the sum of different elements, such as blades, yaw (orientation) system, etc.

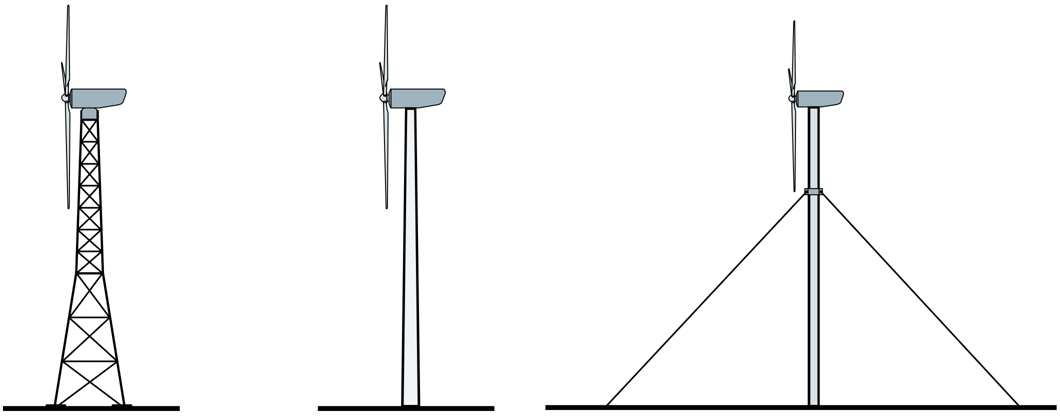


Figure 3.29. Tower designs for wind turbines. Source: Plantas eólicas/ABB Cuaderno técnico.

Figure 3.30. Foundations of an onshore wind turbine. Source: Wikimedia. License: CC BY-SA 2.0. `http://bit.ly/2mLQ6nZ`

Rotor: Blades

Figure 3.31. Siemens wind turbine blade (49 m long). Source: Wikimedia. License: CC BY-SA 3.0. http://bit.ly/2DrA646

Some considerations about wind turbine blades have already been discussed. It is worth noting that the blade profile is not constant, but usually exhibits a curvature of around 25° from base to tip (Figure 3.32. On the one hand, it is very important that the blade tip design allows a good lift and a low resistance (to the air), as it will have to withstand higher relative speeds.

On the other hand, the cross-section of the blade is large enough to provide the required strength to bear the variable mechanical loads appearing during normal operation conditions, but also to endure the occurrence of turbulence.

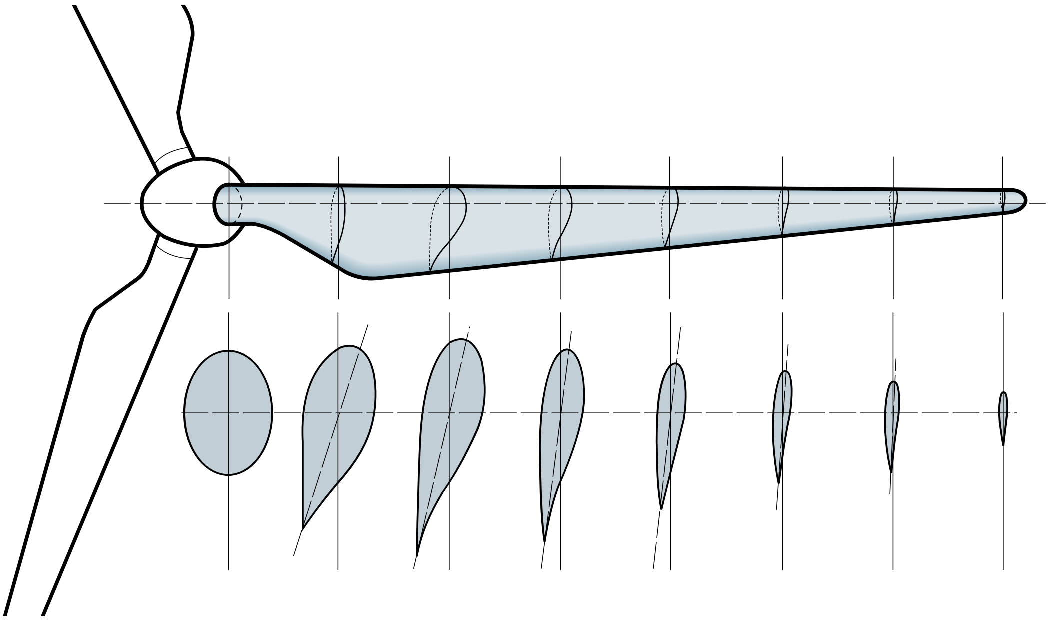


Figure 3.32. Blade profile from base to tip: cross-section. Source: Plantas eólicas/ABB Cuaderno técnico.

What is the structure of a blade like? A wind turbine blade is not solid, but is normally formed by a hollow aerodynamic profile with a main spar that goes from base to tip (see Figure 3.33).

The material used to manufacture the blades of large-scale turbines is **carbon fiber**, while medium and small-scale ones can be made of glass fiber or aluminium. As can be appreciated, a blade is formed by two halves joined with adhesive materials.

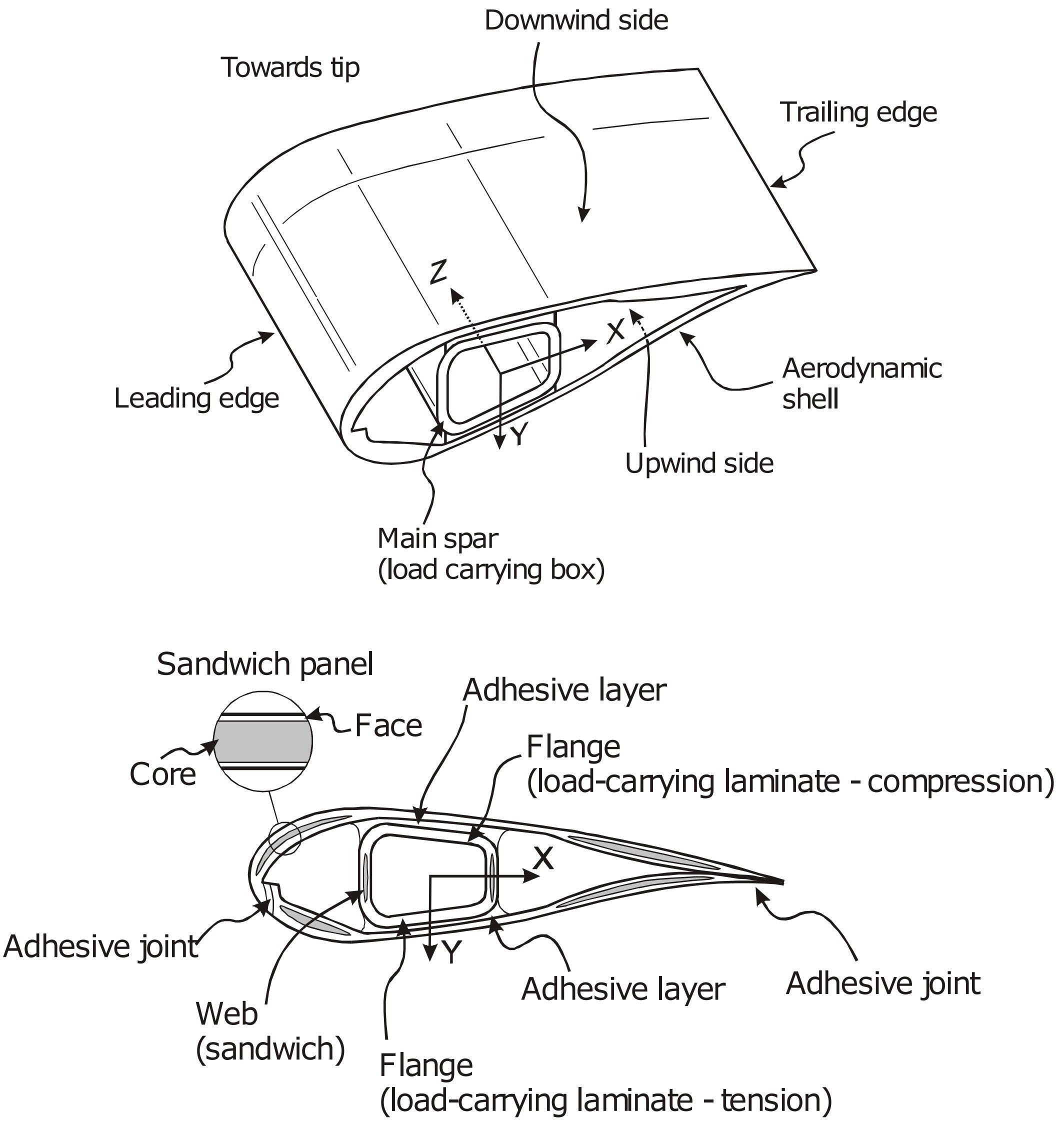


Figure 3.33. Detail of the cross-section of a wind turbine blade. Source: Riso R-1390: *Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report*.

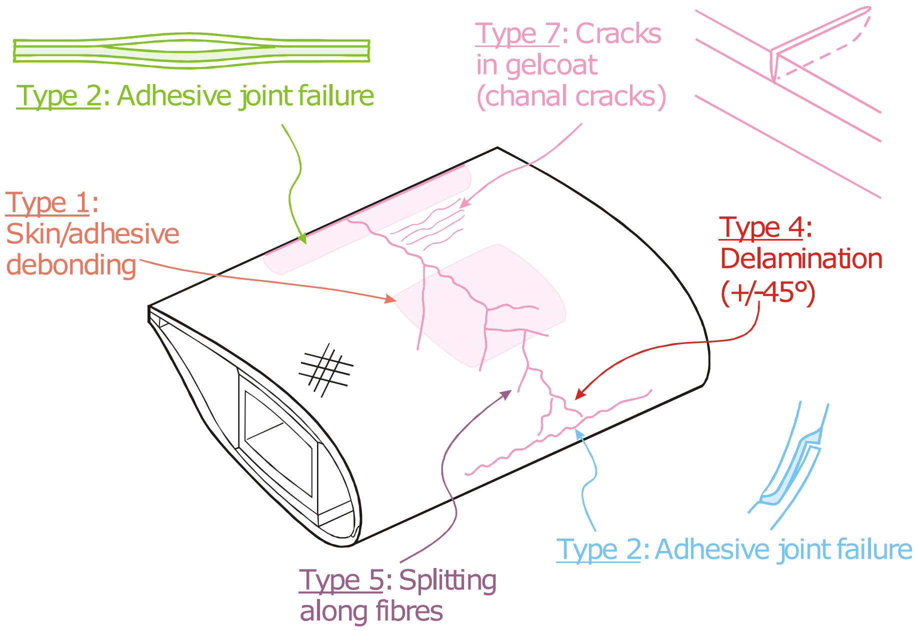


Figure 3.34. Detail of the cross-section of a wind turbine blade: possible defects. Source: Riso R-1390: *Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report*.

Important! 5.1: Blade's appearance (I)

The visual impact of wind turbines is a key issue for all the sectors involved. In this regard, a gel is typically applied to the blade surface to avoid material discoloration due to UV exposure.

Question 5.1: Blade's appearance (II)

Why are wind turbines white?

Look for information and in your own words briefly explain why.

Different defects may appear in a blade due to the manufacturing process, the materials involved, etc. (see Figure 3.34). Some of these defects concern the adhesive joints, the appearance of cracks, delamination, etc. There are monitoring technologies that enable real-time monitoring of the structural health of these renewable infrastructures.

Important! 5.2: Wind Turbine Test Laboratory

There is a large laboratory in Sangüesa (Navarra, Spain) for testing complete wind turbines and their different components. More information at: `http://bit.ly/2DnoRu0`. Some of the above mentioned tests are presented in this video: `http://bit.ly/2DhnUzw`.

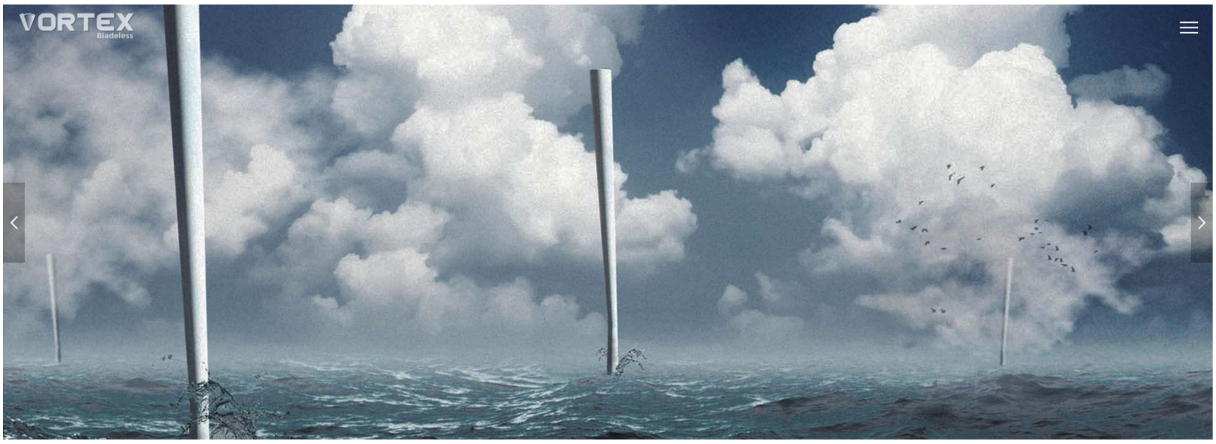


Figure 3.35. Vortex Bladeless: wind turbines without blades. Source: Vortex Bladeless.

Question 5.2: Bladeless Wind Turbines

Vortex Bladeless has designed a wind turbine without blades[a].

Explain (**in your own words**) the working principle of these devices, as well as the pros and cons of this technology.

[a] http://www.vortexbladeless.com/

Rotor: Hub

The hub allows connecting the blades to the low speed shaft. It is normally made of iron and there are basically 3 types: rigid, hinged and teetering.

A rigig hub is typically used in three (or more) blade turbines. Although it keeps a fixed blade position, pitch angle variation is feasible.

A hinged hub is mainly chosen for two-blade models, in an attempt to compensate for the different aerodynamic loads that the blades will have to withstand.

A teetering hub is the option for downwind turbines[2].

Rotor: Yaw system

The yaw system allows rotation of the nacelle over the tower by means of an active orientation and rotation control system. The purpose of the system (normally, unless it is being used as a power regulation strategy) is to keep the rotor in an orthogonal direction to the wind. Obviously, wind direction and speed should be constantly monitored using different sensors. Typically, 10 minute averaging is used to estimate the most suitable nacelle position.

[2] A **downwind turbine** is designed to use the wind whose direction comes from the rear side of the turbine/nacelle (it can be understood that the rotor is at the back of the turbine); in contrast to an **upwind turbine**, the most common approach, where the wind comes from the rotor side (rotor at the front) to reduce the effect of heavy loads derived from high speed winds.

Figure 3.36. Wind turbine hub being connected to the nacelle. Source: Wikimedia. License: CC-BY-SA 2.0

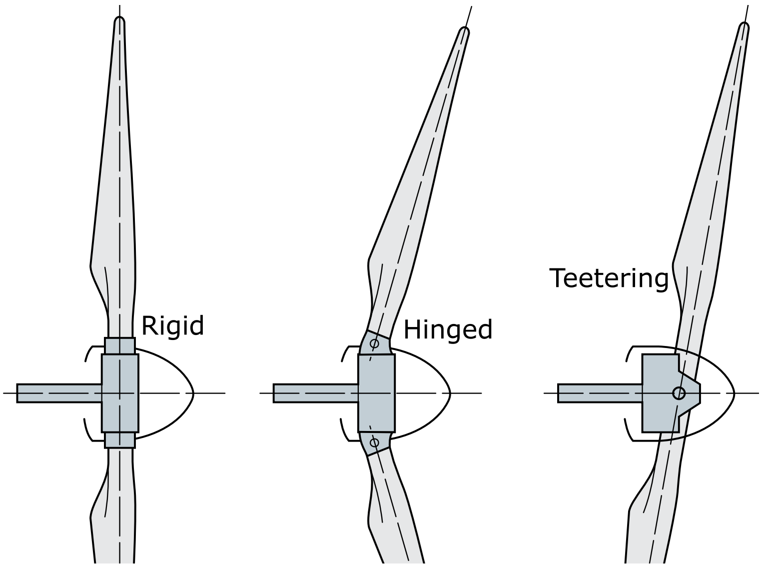


Figure 3.37. Hub types for wind turbines: rigid, hinged and teetering. Source: Plantas eólicas/ABB Cuaderno técnico.

Downwind turbines do not require yaw systems, as the nacelle positions itself according to following the wind direction like a weather-vane. Both upwind and downwind turbines have been represented in Figure 3.39, and their main features are:

Upwind Turbines In these turbines the rotor is at the front of the turbine. The main advantage of this design is that it avoids the influence of the aerodynamic shadow of the tower. There is however an influence in this regard caused by the tower, what will give rise to a decrease in the power of the wind just in front of the tower.

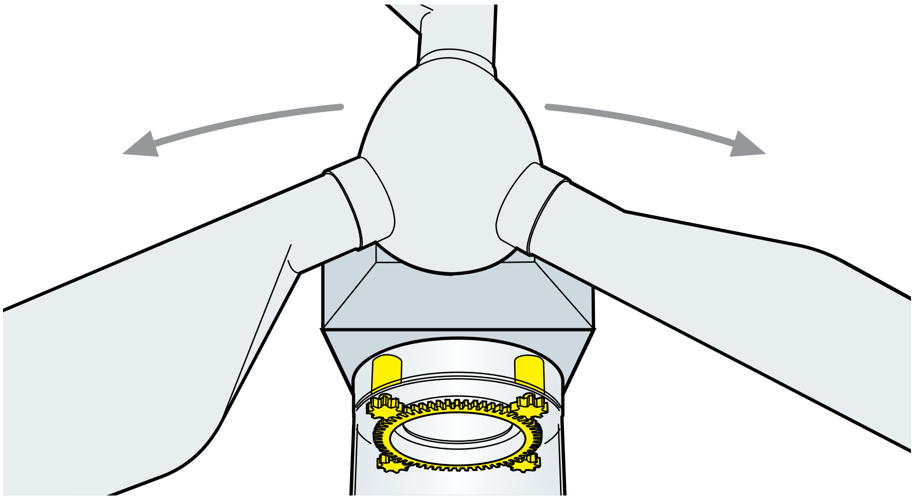


Figure 3.38. Yaw system in a horizontal-axis wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

Figure 3.39. Upwind and downwind turbines. Source: Wikimedia. License: CC BY-SA 4.0 Attribution © Hans Hillewaert) `http://bit.ly/2EPJ0Fp`.

A drawback of this configuration lies in the fact that a more robust rotor is required. In addition, the rotor must be located at a given distance from the tower, as blade bending might result in a collision with it.

The main drawback is that these turbines require an active or passive yaw system:

An active yaw system needs wind direction sensors and motorized actuators.

A passive yaw system uses a tail fin.

Downwind Turbines The rotor is in this case located at the rear side of the turbine (in terms of wind direction).

Figure 3.40. Gear box, rotor shaft and brake in a wind turbine. Source: Wikimedia. License: CC BY-SA 2.0. `http://bit.ly/2ERH8Mx`

> There is no need for a yaw system, provided that rotor and nacelle are correctly designed. The main advantage is that more flexible materials can be involved in blade manufacturing. This is very important, as it implies less height (which will influence the tower design, for example) and a better balance of the dynamic loads for high speed winds.
>
> The main drawback in this case is wind power fluctuation due to the nacelle and tower shadows. This implies higher fatigue loads than in a similar upwind turbine.

3.5.3. Wind Turbine: Gear Box

The gear box of a wind turbine is similar to that of a conventional car, although the former is fixed. At its input, the rotation speed will vary between 15 and 30 rpm and the output will be 1000 to 1500 rpm.

3.5.4. Wind Turbine: Brakes

Wind turbines brakes are used if there is a failure in the system or during maintenance. Almost all wind turbines include mechanical brakes throughout their transmission system. Apart from the previously mentioned functions, they can also be used if weather conditions could jeopardize the turbine's integrity.

Disk brakes, which are one of the most common options, are similar to those used in cars or on bikes: a metallic disk is attached to the axis to be stopped. If it is activated, the brake shoes will press against the disk, thus generating the required braking torque.

Brakes can be installed at both sides of the gear box (50 or 1000 rpm): the required torque and the associated wear should be considered.

Figure 3.41. Detail of brake (and gear box and rotor shaft) assembly for a Nordex N80 wind turbine (tower height: 60 m; blade length: 40 m). Source: Paul Anderson (CC BY-SA 2.0). http://bit.ly/2ES1HbK

Brake specifications typically indicate response times below 5 s and the capability of operating without an external power supply, as well as being able to completely stop the rotor for more than 1 hour[1]

3.5.5. Wind Turbines: Generators

Different kinds of generators are used in modern wind turbines. In this regard, it is necessary to distinguish between fixed or variable rotation speed turbines:

Fixed-Speed Wind Turbines These turbines (common during the 90s) (see Figure 3.42) have a fixed rotor rotation speed, regardless of wind speed. The rotation speed is determined by the grid frequency, as well as by the gear box and the number of poles of the generator. Induction generators directly connected to the grid are typically employed. These generators, commonly known as synchronous machines, are typically used as motors in industrial applications. The soft starter is used to reduce the required start current.

These turbines are designed to achieve a maximum efficiency for a given wind speed. Their main advantages are their simplicity (reduced cost of the electrical system), robustness and reliability. On the other hand, they consume reactive power, thus requiring the use of capacitors. This design also implies large mechanical loads and limited control over the power injected into the grid: wind speed fluctuations will give rise to power fluctuations.

The generator has two operation modes: the rotor accelerates until synchronization speed is reached and then the turbine is connected to the grid; or connection is carried out first to start the generator as a motor and reach synchronization speed. In the former the turbine operates with an automatic starter, using a pitch regulation scheme. In the latter, stall regulation is considered and a control system has to monitor the wind speed to establish the speed range for generator start-up.

[1] Standard IEC-61400-1. Source: Plantas eólicas/ABB Cuaderno técnico.

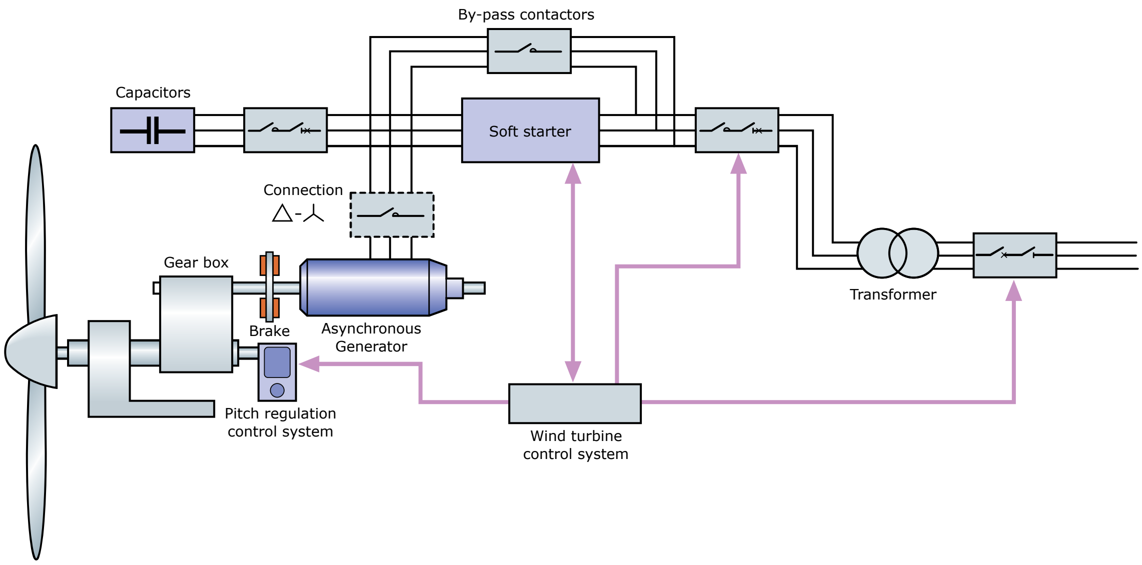


Figure 3.42. Schematic representation of a fixed-speed wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

Variable-Speed Wind Turbines These are the most commonly used turbines in recent years. In this case, maximum efficiency is achieved for a wide range of wind speeds. This can be done by continuously adapting the blades rotation speed to the wind speed, thus achieving an optimum TSR, as explained in Figure 3.26.

In these systems the rotor, with its speed variations, will “absorb” the wind speed changes. In this case the electrical system is more complex, involving synchronous or asynchronous generators connected to the grid via power converters.

The main advantages of this design are:

Increased efficiency as more power can be extracted from the wind

Better quality of the power injected into the grid

Lower mechanical stress

As drawbacks, the cost of the associated electrical system is higher, while the power converter implies some additional losses.

Different configurations can be considered in terms of the chosen generators:

Asynchronous generators including wound rotor with variable external resistance

Asynchronous generators including wound rotor with a power converter between rotor and grid (doubly-fed configuration)

Asynchronous generators including an electronic power converter between the stator and the grid (total converter configuration)

Synchronous generators (alternators) with an electronic power converter[1]

Let’s briefly explain the **synchronous generator** depicted in Figure 3.43. It is formed by a rotor where the magnetic field is created and a stator that contains the windings. The magnetic field is generated by an electric current that goes through these windings.

[1] Fuente: Plantas eólicas/ABB Cuaderno técnico

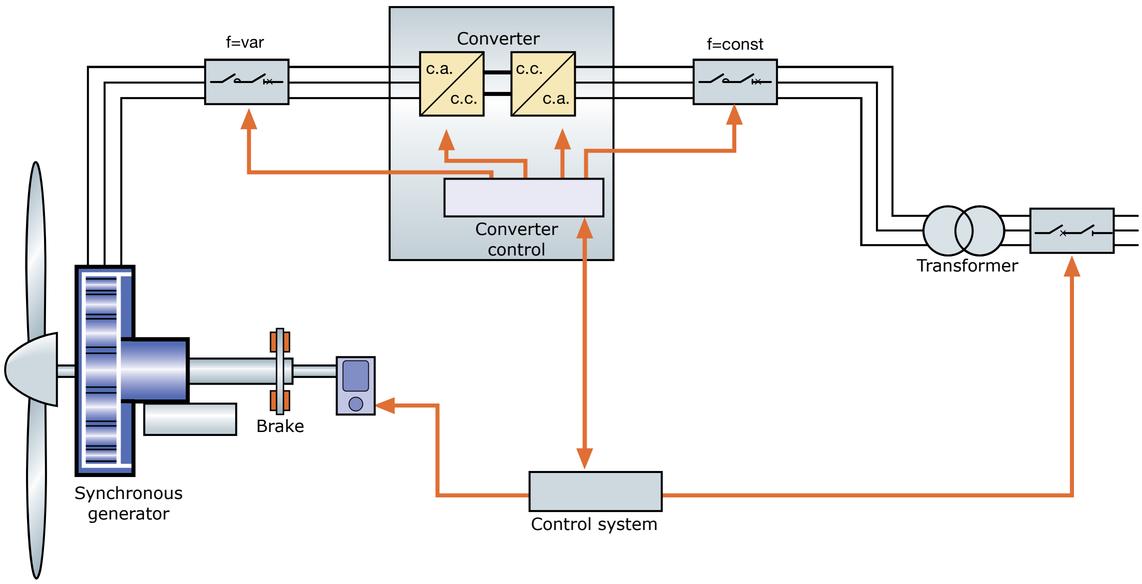


Figure 3.43. Schematic representation of a variable-speed wind turbine with synchronous generator. Source: Plantas eólicas/ABB Cuaderno técnico.

This kind of generator allows control of the voltage and of the associated reactive power.

Synchronous generator turbines often start their operation with the wind, using a speed control for synchronization purposes. To achieve a constant grid frequency, a power converter is required (usually implemented in two stages, a AC-DC conversion via rectifier and a DC-AC conversion by means of an inverter).

Important! 5.3: Synchronous generators

Most of the generators used in power plants are synchronous. They imply a higher cost, but allow a perfect voltage and reactive power control.

Important! 5.4: Generators: refrigeration

Generators involved in wind turbines need refrigeration. Normally refrigeration using air is used, although water is also employed as it provides a more compact solutions.

3.5.6. Wind Turbines: Direct and Indirect Grid Connection

Although it has not been explicity mentioned, it is implicit that there are two ways of connecting a wind turbine generator to the grid:

Direct Grid Connection the generator is directly connected to the grid.

Indirect Grid Connection the generator is not directly connected to the grid, but there are devices after the generator used to adapt the current to the grid. As advantages, it should be mentioned that a variable rotor speed can be considered, with the possibility of taking advantage of fast wind gusts by means of regulation strategies. The reactive power can be controlled and all this enables a subtle increase in the annual energy production. On the other hand, a power electronics stage is required, with the possibility of loosing efficiency in the AC-DC-AC conversion process.

3.5.7. Wind Turbines: Control System

The control system of a wind turbine can be understood as its “brain”, as it controls all the required operations: wind turbine start and stop processes, control of wind/rotor speeds, regulation strategies, yaw control, etc.

The control system will also be in charge of the electrical systems. If a potentially dangerous situation occurs, the system will isolate the turbine from the grid.

Implementation of this control system can be performed via a *Programmable Logic Controller* (PLC).

Question 5.3: Control System: PLCs

Briefly explain if you have ever used a PLC or a similar device and try to find information about a commercial model used in modern wind turbines.

Is it really important to use a control system in a wind turbine? The answer is: **Absolutely!** To better understand this issue, let’s check some of the parameters that should be monitored in a wind turbine: rotor speed, rotor yaw, generator (voltage and current), lighting, temperature (outside the turbine, within the nacelle, gear box oil, generator windings, etc.), hydraulic pressure, blade pitch, wind speed and direction, nacelle and blade vibrations, tower door (alarm), etc.

Question 5.4: SCADA

SCADA (*Supervisory Control and Data Acquisition*) systems are widely used in many applications, including the monitoring and control of wind farms. Briefly answer **in your own words** some of these questions:

What is a SCADA system? What are its main components? Indicate a specific example of SCADA implementation in a wind turbine. Mention an example of SCADA implementation in a different application.

3.5.8. Wind Turbines: Control Centers

There are also some control centers whose mission is to monitor and control several wind farms and, additionally, other renewable power plants. An example is the CORE (Centro de Control de Energías Renovables[1]) of Iberdrola, which controls more than 5500 wind turbines, apart from 68 mini hydro-power plants and 1 CSP plant.

[1] [Renewable Energy Control Center]

Several telecommunication technologies are involved in these systems, from satellite or optical fiber communications, to a wide variety of sensors, artificial vision, integration of SCADA systems, etc.

In 2005, it was made compulsory for all plants exceeding 10 MW to be attached to a control center. This limit was lowered to 5 MW in 2015.

Important! 5.5: Cecre

The CECRE is an operative unit integrated within the Electric Control Centic (CECOEL). According to the Spanish RD 1454/2005, and then RD 661/2007 and RD 413/2014, plants with capacities over 10 MW must be attached to a Generation Control Center. These centers should be verified by the Red Eléctrica Española (REE) as the system operator. RD 413/2014 established that, as from June 1, 2015, the capacity limit would be reduced to 5 MW. Consequently, CECRE controls and monitors the production of all renewable plants with capacities over 5 MW. Source: REE[a]

[a] http://bit.ly/2mSFQKN

Control centers should operate in real-time:

- Forecasts must be provided every 48h
- They must be recalculated every 4h
- The REE may ask an operator to regulate the produced energy within 15 minutes. The CECRE receives real-time information every 12 seconds.

3.5.9. Wind Turbines: Current Trends

The current trend in wind energy seems to indicate that near-future models will be direct-drive models. These wind turbines do not include gear box, with the generator directly attached to the rotor (Figure 3.44). This implies advantages in terms of reliability (gear box lifetime is short, although it has been improved lately) and noise.

There are also disadvantages, as we are talking about more expensive and heavier machines, although these issues are supposed to improve with expected developments.

Important! 5.6: Direct Drive

A key factor in the development of these systems lies in the use of **permanent magnets**, allowing the design of lighter and less expensive generators: less copper (its cost has significantly increased lately) is required.

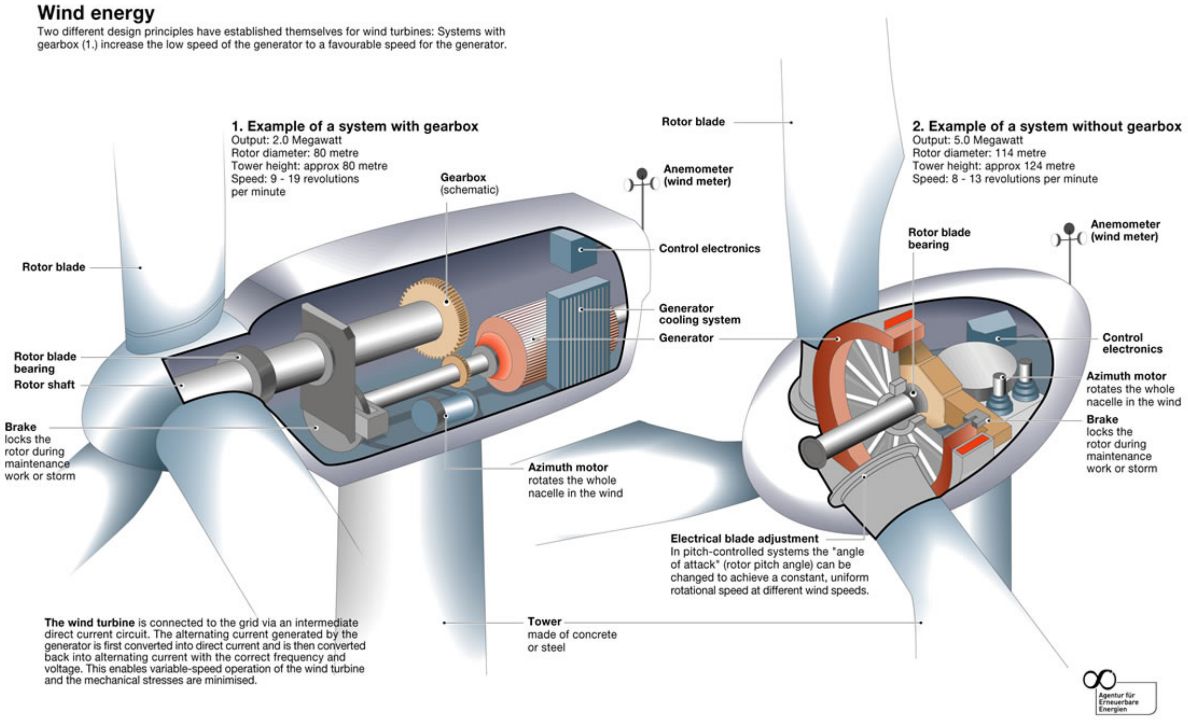


Figure 3.44. Comparison between a gear-box (left) and direct-drive (right) wind turbines. Source: Wikimedia. License: CC BY-SA 4.0.

3.6. Conclusions: Current Situation and Future Trends

There is no question or doubt that wind energy is one the key players in the global energy scenario, especially in terms of onshore installations. Offshore farms are growing with huge projects in different countries, like the United Kingdom. Figure 3.46 shows the main wind energy companies, where onshore and offshore farms have been analyzed separately. Gamesa (a Spanish company) appears in fourth position.

Important! 6.1: Offshore Farms

The largest offshore wind farm to date will be installed in the UK, *Hornsea Project One*, with a total capacity of 1.2 GW. This farm has been promoted by DONG Energy and it will consist of 7 MW turbines provided by Siemens[a].

[a] http://bit.ly/1QFT9W2

We know that the **LCOE is a key parameter in evaluating the maturity of a given energy technology**. As expected, onshore farms (in green) are associated with a lower LCOE than offshore installations (in blue), as indicated in Figure 3.48. However, it is expected that the offshore LCOE will experience a sharp decrease in the coming years.

Figure 3.45. Direct-drive wind turbine. Source: Wikimedia. License: CC BY-SA 2.5 http://bit.ly/2Dex1Rn

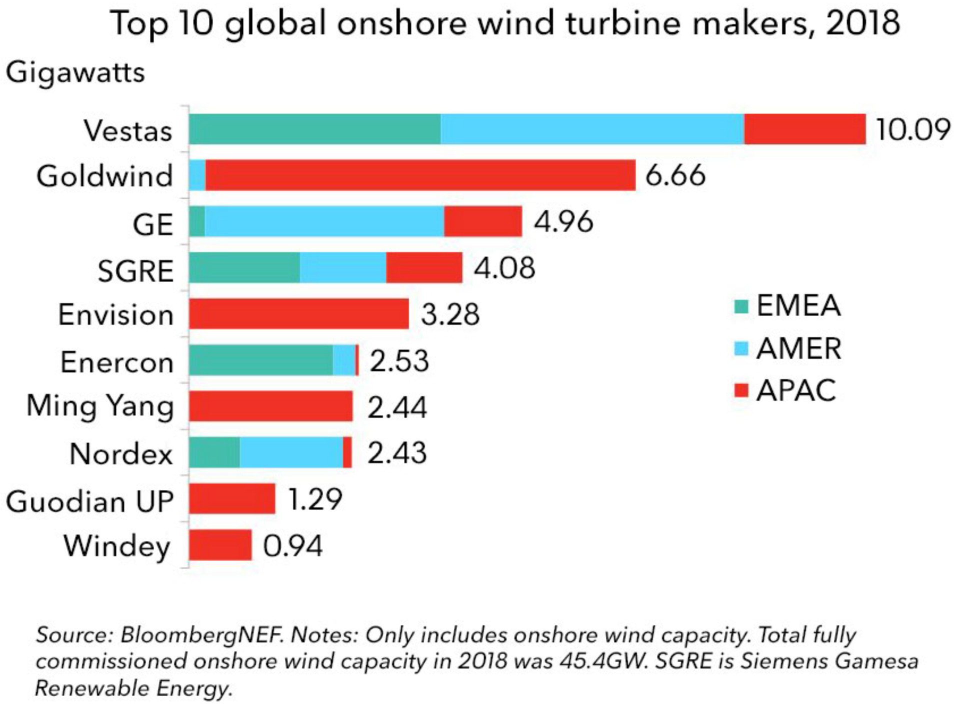


Figure 3.46. Top 10 onshore wind turbine manufacturers. Source: Bloomberg New Energy Finance. `http://bit.ly/2NkkIJ5`

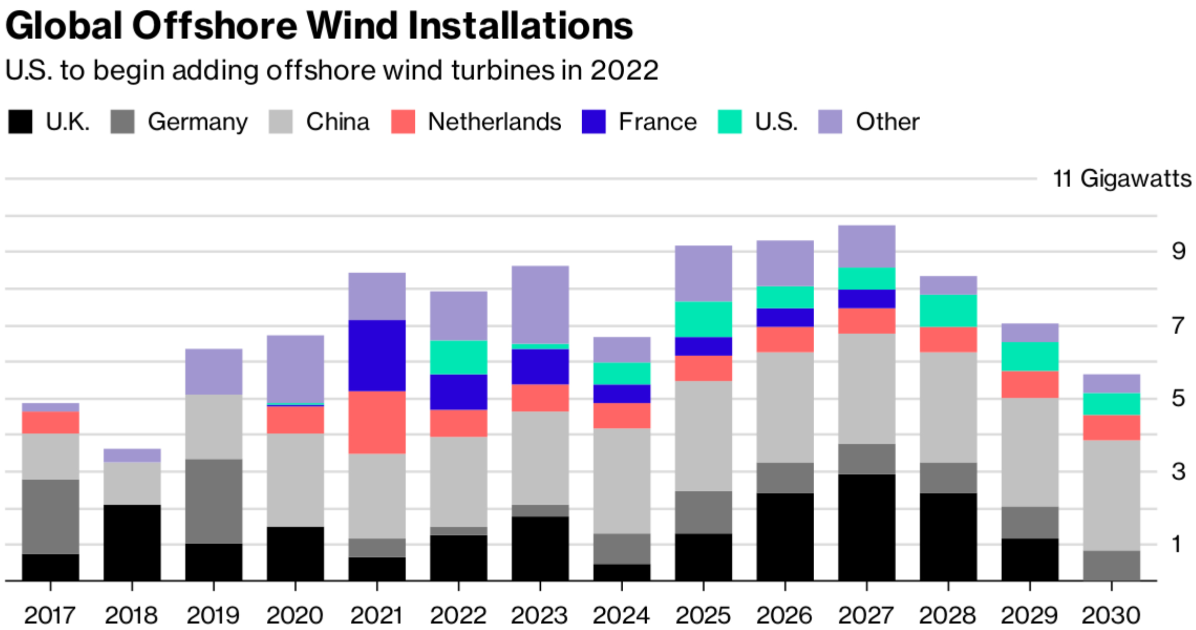


Figure 3.47. Forecast of the evolution for offshore wind farms. Source: Bloomberg / Bloomberg New Energy Finance. `https://bloom.bg/2Nk2urg`

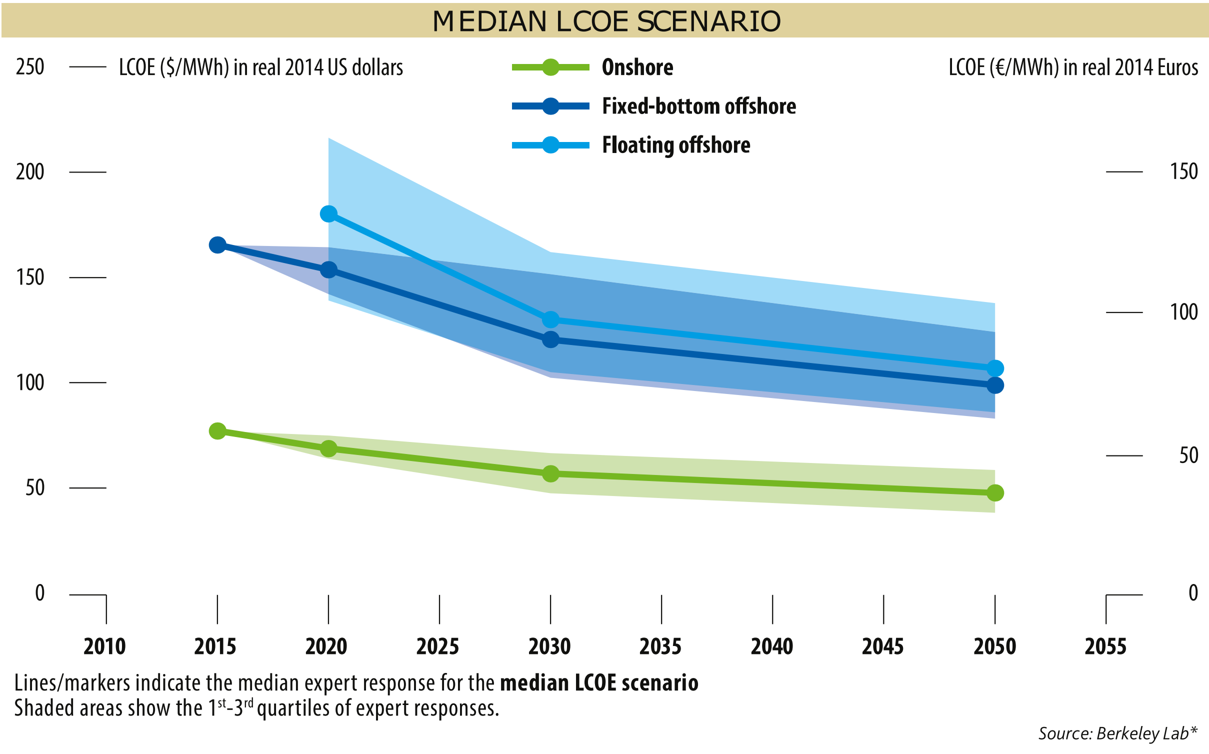


Figure 3.48. Forecast of the LCOE evolution for onshore and offshore wind farms. Source: Berkeley Lab / Global Wind Energy Outlook 2016. `http://bit.ly/2DmrzjB`

Finally, information regarding some of the **currently largest wind turbines has also been included**.

Model **Vestas V-164** is shown in Figure 3.49. It has been designed for offshore deployment, with a nominal power around 8-9 MW, and rotor diameter and height of 164 and 187 meters, respectively.

The **Enercon E-126** model implements a **direct-drive design**, i.e. without gear box, which gives rise to a smaller nacelle. It has a 8 MW nominal power, and rotor diameter and height are 126 and 198, respectively.

Finally, the **MINGYANG SCD6.5** is a Chinese 6.5 MW wind turbine, whose rotor diameter and height are 164 and 187 meters. It is worth noting that it shows a two-blade design, a distinctive feature in the current trend of three-blade turbines.

To end this part of the course, it is very interesting to note the project developed by Saitec, which will imply the deployment in 2020 of the scale-model of a wind turbine in front of El Sardinero. The goal of the project is to demonstrate the feasibility of a new floating system patented by the company. You can find more information about this interesting project in the following video:

`https://youtu.be/vKYBzZHnuhU`

Figure 3.49. Vestas V-164 wind turbine. Source: Garvarduniversity. `https://bit.ly/2Z3YOhT`. License: CC BY-SA 4.0

Figure 3.50. Enercon E-126 wind turbine. Source: Wikimedia Commons `https://bit.ly/2MpjmQx`. License: CC BY-SA 3.0

Figure 3.51. MINGYANG SCD6.5 wind turbine. Source: YouTube `https://youtu.be/PFPSvxeFw3A`. License: YouTube Standard

Figure 3.52. Representation of the floating wind turbine that Saitec will install in El Sardinero (Santander). Source: YouTube `https://youtu.be/vKYBzZHnuhU`. License: YouTube Standard

List of Figures