Energy and Telecommunications

Lecture Notes

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Revision of the English version by
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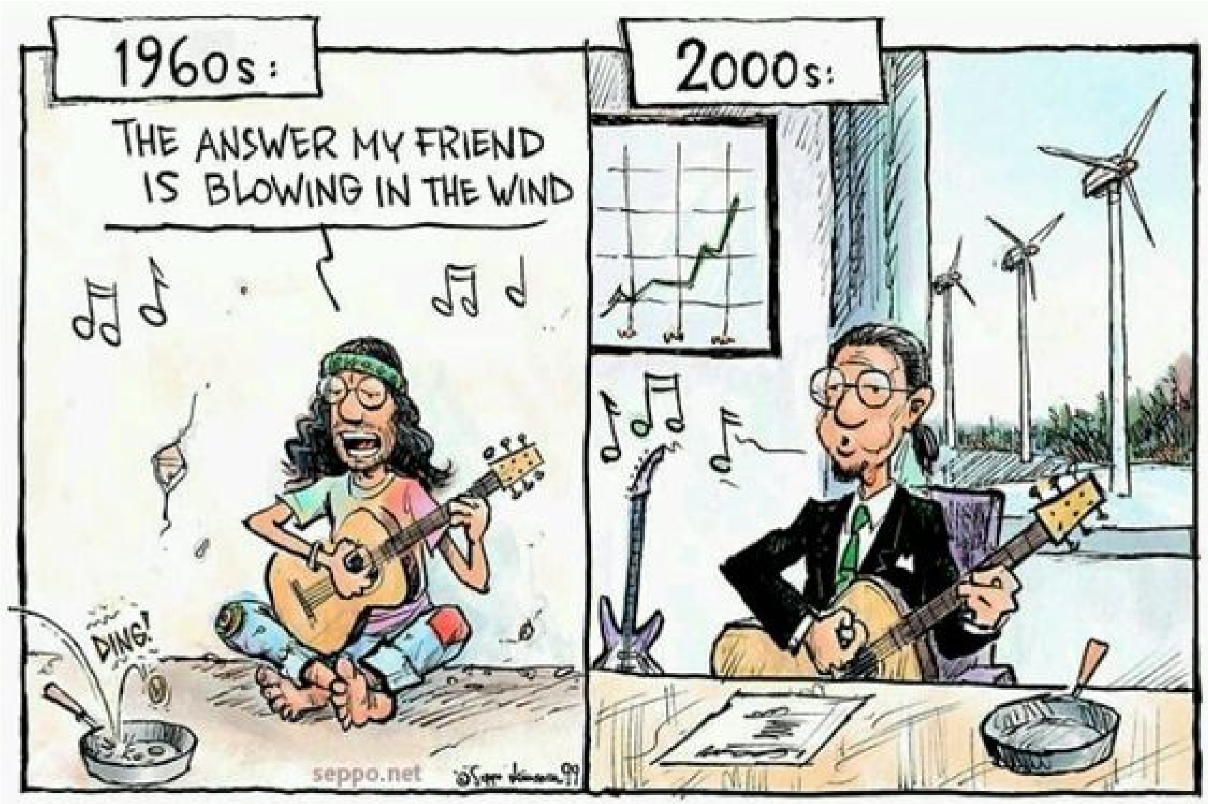

Cartoon: Seppo Leinonen, www.seppo.net. Permission granted by the author.

"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).

Energy and Telecommunications

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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 covering 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 of this chapter is for students to become familiar with the basics of REs. This includes understanding the reasons why these technologies came about, with a special focus on climate change. Basic information is also provided on the current situation in terms of renewable energies around the world and, obviously, in our country: Spain. Which is the leading country Photovoltaics or wind energy? How has the situation in China evolved over the last decade? What is Spain's current situation 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) and also about CSP (Concentrating Solar Power), where the sun's energy 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

BTS Base Transceiver Station

CAES Compressed Air Energy Storage

CSP Concentrating Solar Power

E Energy

EU European Union

GH Green-house

GHG Green-house Gas

IDAE Instituto para la Diversificación y Ahorro de la Energía [The Institute for the Diversification and Saving of Energy]

IPCC Intergovernmental Panel on Climate Change

IR Infrared

LCOE Levelized Cost of Energy

PV Photovoltaics

RE Renewable Energy

REE Red Eléctrica Española [Operator of the Spanish Electricity Grid]

SHM Structural Health Monitoring

TFC Total Final Consumption

TPES Total Primary Energy Supply

UV Ultraviolet

Symbols

°C	Celsius (temperature)
J	Joule (energy)
K	Kelvin (temperature)
Mtoe	Million Tonnes of Oil Equivalent
ppm	Parts per million
ppb	Parts per billion
ppt	Parts per trillion
Wh	Watt-hour (energy)
W	Watt (power)(capacity)

Glossary

Biomass is an industrial term for obtaining energy by burning wood, and other organic matter. Burning biomass releases carbon emissions, but has been classed as a renewable energy source in the EU and UN legal frameworks, because plant stocks can be replaced with new growth. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel.

Concentrating solar power (also called concentrated solar thermal, and CSP) systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electricity is generated when the concentrated light is converted to heat, which drives a heat engine (usually a steam turbine) connected to an electrical power generator.

Dynamic calibration (of power lines) refers to the possibility of transmitting a higher current than the one associated with the nominal ampacity of the line by measuring weather parameters such as sun radiation and wind speed and estimating their cooling effect upon the line.

End-Use Energy is the energy directly consumed by the user, like electricity, gasoline or natural gas.

Feed-in solar PV installation operates as a power plant, generating energy and injecting it into the power grid for its distribution.

Fossil fuel is a fuel formed by natural processes, such as anaerobic decomposition of buried dead organisms, containing energy originating in ancient photosynthesis. Examples of fossil fuels are oil, carbon and natural gas.

Greenhouse gas is an atmospheric gas able to trap or reflect heat (infrared radiation). Example of green-house gases are CO2 or methane.

Grid Parity occurs when an alternative energy source can generate power at a levelized cost of energy (LCOE) that is less than or equal to the price of purchasing power from the electricity grid. The term is most commonly used when discussing renewable energy sources, notably solar power and wind power

Hydro Power refers to the power derived from the energy of falling water or fast running water.

Levelized Cost of Energy is a parameter that allows making a direct comparison between different energy technologies, as it measures the lifetime costs of a given power plant (cost of building, operation, etc.) divided by the energy production. Its units are $\$/Wh$.

Photoelectric effect is the emission of electrons or other free carriers when light shines on a material.

Primary Energy is the energy that is directly harvested from natural resources.

Pumped-Hydro Power is based on the transportation of water to a higher reservoir, where that potential energy can be recovered by letting the water run to the base reservoir and activating a turbine located between both sites.

Renewable Energy is the energy obtained from the continuous or repetitive currents of energy recurring in the natural environment.

Self-consumption solar PV installation designed to provide energy to the building/system where it is located, for example a single-family home.

Solar PV Energy is based on the conversion of sun radiation (photons) to electricity (electrons) by means of the photoelectric effect.

Sustainable Development Development which meets the needs of current generations without compromising the ability of future generations to meet their own needs.

Sustainable Energy is the energy that does not significantly decrease with a continuous use, does not imply significant contaminant emissions or other environmental risks and does not imply the perpetuation of health risks or social injustices.

Contents

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 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!

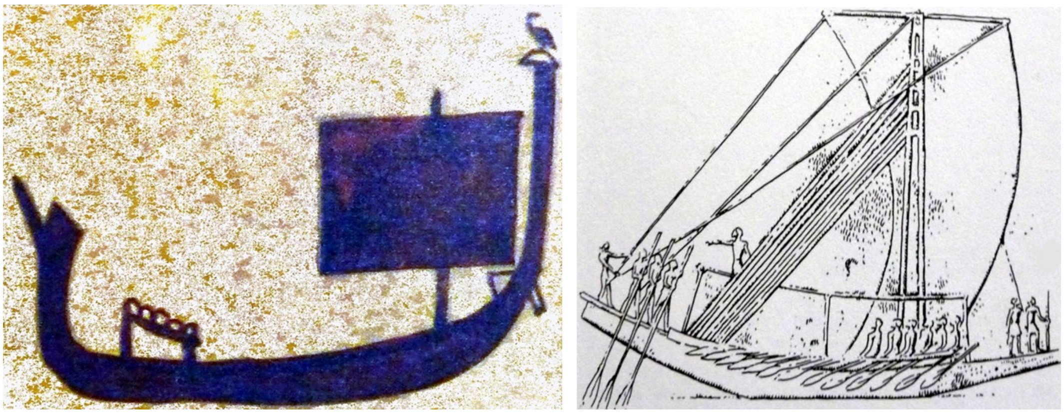


Figure 1. First representations of sailing ships.

Figure 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.

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.

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 **Darrieus**

Figure 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).

(1927) models. Both were vertical-axis turbines (see Figure 3), thus being different from current large-scale wind turbine models.

Figure 4. Screenshot of the videogame *Dyson Sphere Program*.

Question 3.1: Dyson Sphere Program [400 XP]

A curiosity: the game **Dyson Sphere Program**, which is having great success on Steam, proposes the player the challenge to raise the resources and develop the infrastructure necessary to build a **Dyson** sphere. Among the available resources is wind energy and, as you might recognize in the Figure 4, it includes some models that resemble the Savonius and Darrieus designs.
Do these models exist in the real world?

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

Important! 3.1: 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

3.3 Current situation

Approaching the present time, wind energy underwent a strong boost in **1973**, motivated by the **oil crisis** that caused the serious study of alternative energy sources. For example, maps were created to quantify the wind potential, essential to be able to properly select an optimal location, and increasingly powerful wind turbines were designed. These wind turbines were grouped into large facilities called **wind farms**, allowing the generation of parks with large nominal powers.

The evolution of wind energy has been spectacular in recent years. If we remember the figure already seen in the introduction, we can appreciate the remarkable growth in total installed power, including the capacity added each year.

3.3.1 Current Situation: Spain

As can be seen, the evolution of wind energy seems to follow a linear trend of continuous growth: **has the same growth been experienced in Spain?** Let's analyze it through Figure 6.

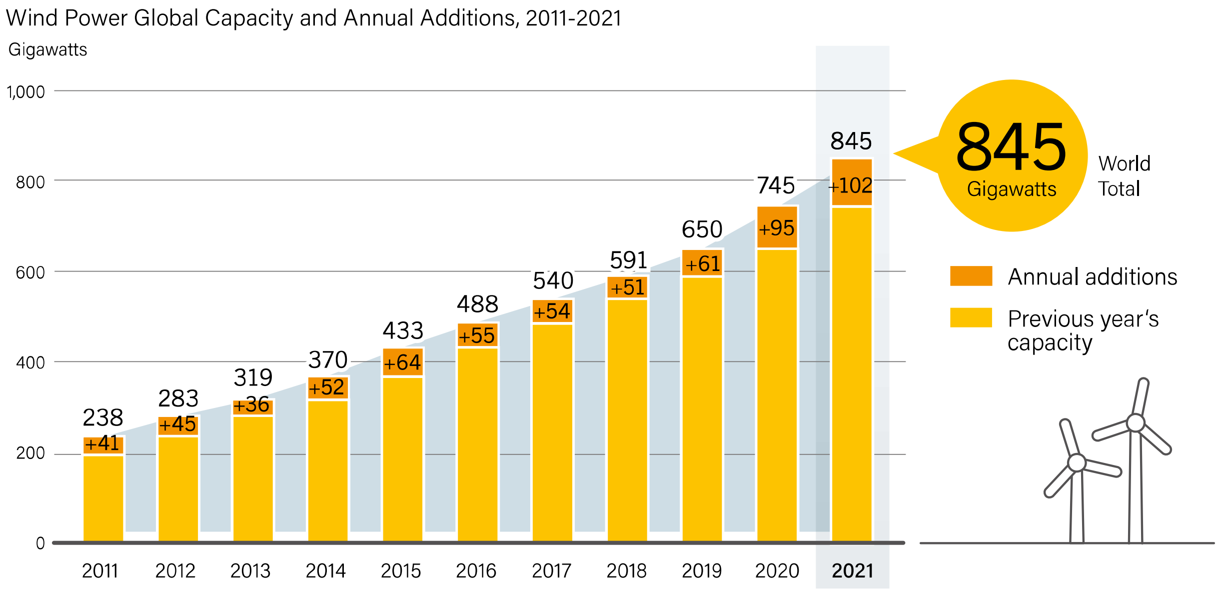


Figure 5. Evolution of wind power capacity between 2011 and 2021. Source: REN21 (2022 Report). Link: `https://bit.ly/3MR1R7x`.

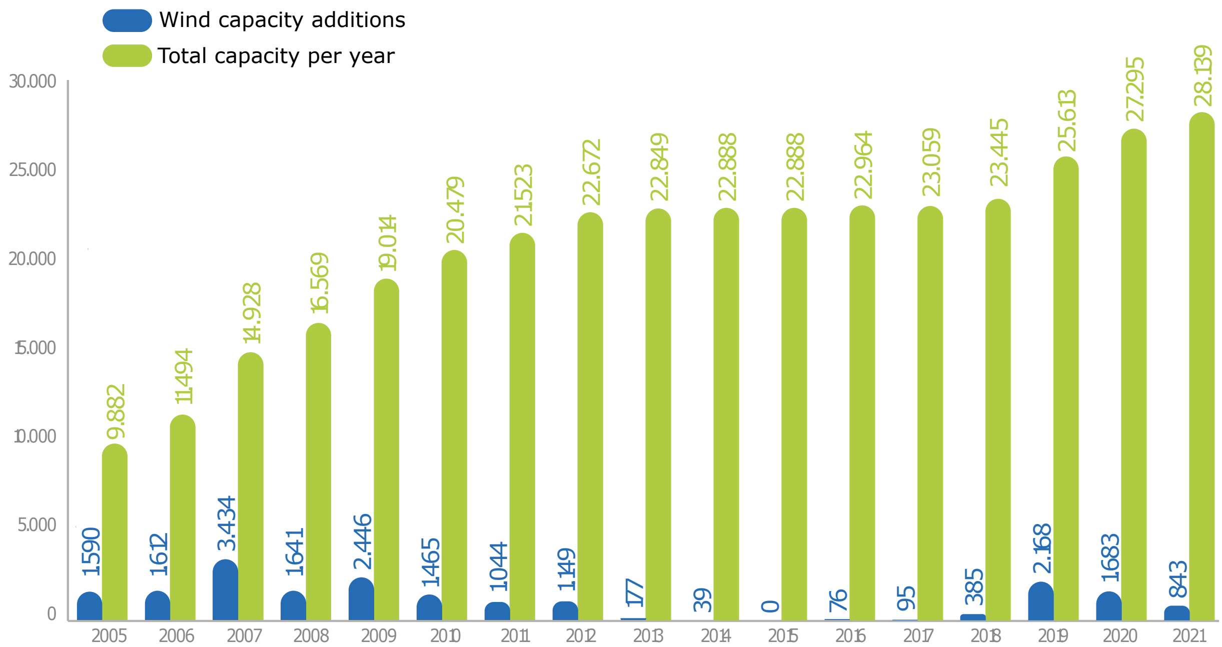


Figure 6. Annual and accumulated evolution of wind capacity in Spain. Source: Anuario Eólico 2022 (AEE). `https://bit.ly/3HkBZQ6`

In Figure 6 it can be clearly seen how the trend in Spain has not exactly followed that experienced globally, since the increase in installed power experienced a clear standstill in our country between **2012 and 2018**, broken by the clear growth associated with **2019 and 2020**. **What are the reasons behind this standstill?** As we saw in the case of solar PV, both the economic-financial crisis of 2010 and the specific problem of premiums for renewables generated great uncertainty in the sector, reflected in the lack of investment in recent years. This trend is clearly broken in 2019 and 2020 with a large increase in wind capacity linked to auctions in previous years, for example in 2017, and a generally more favorable situation for REs. **It is worth noting that wind power has been the first technology for electricity generation in Spain in 2021, with a installed capacity (as of December, 2021) of 27,446 MW and a power generation (in 2021) of 54,899 GWh.**

DM .
Santander
Lunes, 30 noviembre 2020, 13:35

Una veintena de colectivos de Cantabria han pedido este lunes que se establezca una moratoria para la tramitación de todos los proyectos eólicos en la comunidad autónoma, hasta que la aprobación definitiva del Plan de Ordenación del Territorio (PROT). Entre esas asociaciones se encuentran **SEO/BirdLife, ADIC** (la Asociación para la Defensa de los Intereses de Cantabria), el sindicato ganadero **UGAM-COAG, Cantabria No se Vende**, el sindicato de docentes **STEC**, las plataformas para la defensa de los **Valles Pasiegos y la Cordillera Cantábrica** o la **Fundación para la recuperación del Quebrantahuesos**.

Figure 7. Article in El Diario Montañés (November, 2020) on the opposition to the development of wind energy in Cantabria. Source: El Diario Montañés. https://bit.ly/2JyvD4r

Despite all this, not everyone is in favor of wind energy. For example, Figure 7 shows a recent article related to wind energy in **Cantabria**, in particular with **various groups opposing this type of energy**.

> *Question* **3.2: Opposition to wind power [400 XP]**
>
> Before continuing reading, try to answer these questions in your own words: what factors do you think that are key in generating the opposition of these groups to wind energy? What energy sources do you think are acceptable for these groups? What opinion do you have on this subject?

To better understand the **arguments of defenders and detractors** of wind energy, let's briefly analyze its advantages and disadvantages:

What **advantages** does wind energy offer to have experienced this evolution? Does it have any **disadvantage**?

Among the **advantages** it is worth highlighting:

- 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* [1]

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 [2].

Figure 8. Painting and using vinyls in wind turbines to avoid affecting birds. Source: https://bit.ly/31Wn2c8. License: YouTube Standard.

Important! **3.2: Impact on birds**

One of the main disadvantages that are often mentioned in relation to wind energy is its **impact on birds**, since wind turbines can cause the death of birds that come very close to the set formed by the blades and the rotor. In this sense, different initiatives are being studied and even put into practice to solve this situation, including painting the wind turbines black and even installing vinyls that simulate eyes on the towers, as can be seen in Figure 8. Iberdrola, a company that is testing these initiatives in several wind farms in the Spanish province of Burgos, has commented the following:
"This method has been tested at the Lourdes-Tarbes-Pyrénnés airport in southwestern France, and it has proven to be the most efficient to scare away birds with a 65% decrease in the number of raptors observed in the areas of the airport where the vinyls were placed"
In this short video (3:24) you can get more information: https://bit.ly/31Wn2c8.

[1] 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*.

[2] Some studies indicate figures of 0.3 dead birds/wind turbine per year.

***Important!* 3.3: Oil and Wind Turbines**

It is estimated that a conventional wind turbine needs between **300 and 400 liters of oil** per year: a remarkable figure! This is one of the arguments used against wind energy, in relation to the associated CO_2 footprint and the recycling of used oil.

Lastly, 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). The noise level (and its similarity to other "known" noise types) can be seen in Figure 9.

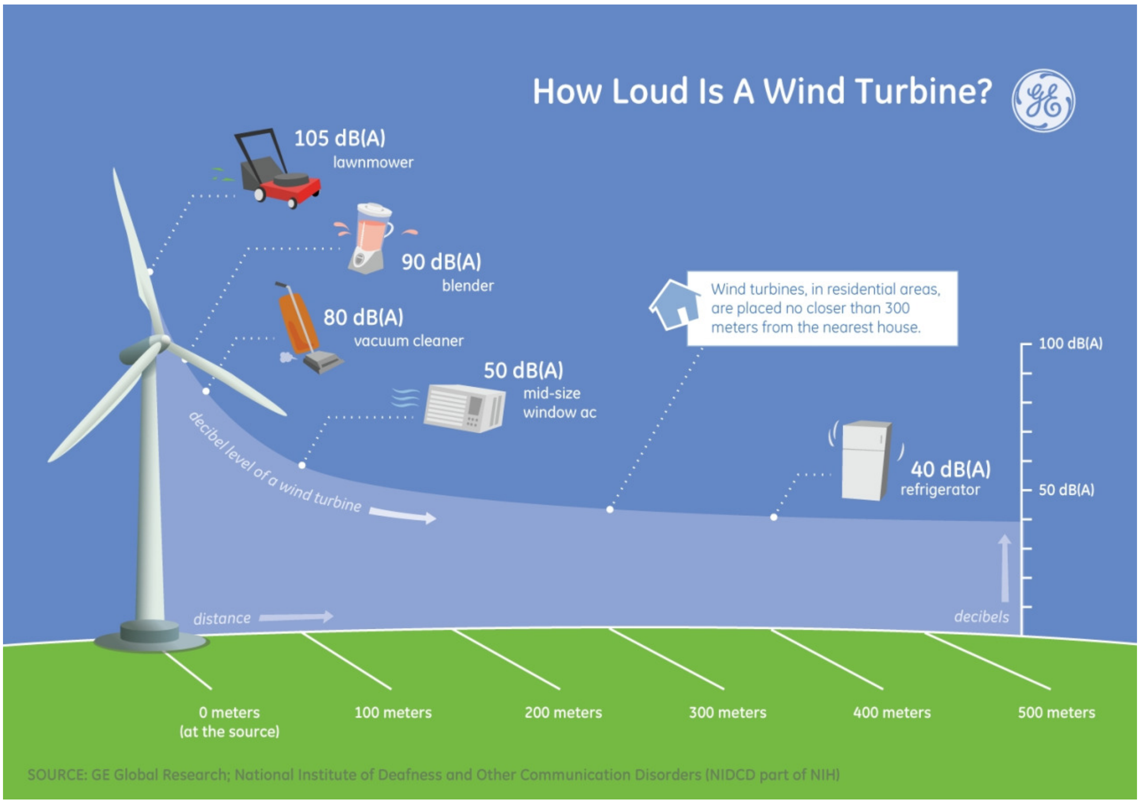


Figure 9. Noise associated with a wind turbine. Source: GE Global Research / National Institute of Deafness and Other Communication Disorders.

3.3.2 Situation of wind energy in Cantabria

If you have traveled the region and, in addition, you have visited other Spanish provinces, you will have noticed how wind energy in Cantabria is practically non-existent, in clear contrast to other nearby regions, such as the north of Burgos. Why this situation? Among others, probably two of the key factors have been:

Regulatory insecurity since in 2009 a contest took place in which different projects were assigned for the development of several wind farms, but it was declared illegal, forcing the regional government to compensate several of the participating companies, as

Viesgo Renovables or Eolican, for the expenses derived from their participation in the process.

Excessive bureaucratic procedures that imply more time needed in some communities than in others, which in the end translates into more money invested, which discourages the development of these projects in regions with these types of problems.

Opposition by various groups such as different environmental groups.

Important! **3.4: APPA: why is there (almost) no wind power in Cantabria**

In a recent talk by the APPA (Spanish association of the renewable sector) in Cantabria, José María González Moya, (General Director of the APPA), commented, among other aspects, his opinion on why wind power has not been developed in our region. All the talk is very interesting, but if you want to go directly to this section that lasts only 3 minutes, you can check the following video (go to 1:13:00): Link to the video on YouTube: https://youtu.be/ypEQstJaceE

Currently, the only active wind farm in Cantabria is **Cañoneras**, in the municipality of Soba, very close to the border with Burgos. It is a wind farm built in 2008 by Gamesa, with a total of 38 wind turbines that add up to a capacity of 32.3 MW for an investment of 17 million euros. 17 of these wind turbines were developed entirely by Gamesa in Reinosa. In addition, the location of this wind farm implied the need to develop a new model of wind turbine, given that its altitude and exposure means that the wind conditions can be more intense than those usual for these devices. Some of the improvements that had to be developed [1]:

Rotor A shorter and more robust rotor was created, going from 52 to 47 meters in height, and installing reinforcing fabrics on it.

Hub some components that support the greatest efforts were reinforced, such as the blade pitch change mechanism.

Nacelle Specific modifications were designed to the interior structure of the nacelle, reinforcing various parts of the powertrain.

Tower a completely new design was developed, using a higher elasticity steel.

Foundation a new design of the foundation was carried out, to increase its resistance and adapt it to extreme loads.

[1] Source: iberdrola.com url https://bit.ly/39Iu2Uu

Figure 10. Wind farm of Cañoneras, in Cantabria. Source: elfaradio.com https://bit.ly/37Aod8N.

Important! **3.5: Cantabria: a new wind energy future?**

The government of Cantabria has recently expressed that the development of new wind projects in the region is a priority, so it is possible that we will see new wind farms in the coming years. For now, the first of these new projects seems to be the one to be installed **in Sierra del Escudo, with 151.2 MW, 36 wind turbines and an investment of 114 million euros**.
IMPORTANT! Note that while in the Cañoneras park its 38 wind turbines totaled 32.3 MW, in the new 36 wind turbines they will imply a total of 151.2 MW. This implies going from slightly less than **1MW per wind turbine (2009) to more than 4 MW per unit (2020)**, **giving a clear idea of the progression of technology in 10 years**.

Important! **3.6: Wind farms in Spain**

In Spain, the total installed wind power capacity amounts (as of December **2021**) to **27,446 GW**, which represents **more than 25% of the total installed power in Spain** . The wind farm with the highest power in Spain is located in Huelva: it is the **El Andévalo 282 MW** wind farm, a wind complex made up of 8 farms in total. Furthermore, in a news item from December 2020, the construction in Gran Canaria of the **largest offshore (marine) wind farm in Spain with 12 generators and a total of 144 MW** is announced: **each generator contributes 12 MW!**. Link to the news: https://bit.ly/2VB12Z5 **NOTE! I suggest you take a look at the comments as they are very interesting for this part of the subject ...**

This section will be finished with an interesting figure: data regarding new additions to the Spanish wind power capacity are presented in Figure 12.

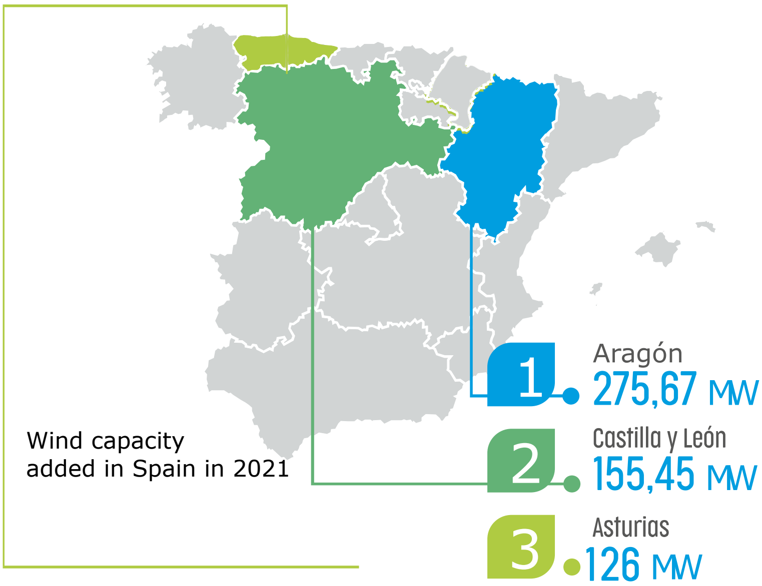


Figure 11. . Wind capacity added in Spain in 2021. Source: Anuario Eólico 2022 (AEE). Link: https://bit.ly/3b0Qdoh.

3.3.3 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.

It is therefore interesting to analyze the most recent data regarding the LCOE of different modern renewable technologies. Figure 13 shows a comparison of the LCOEs associated with wind power (both onshore and offshore) and hydro power and solar PV (data for 2020). 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. The trend for this renewable technologies, as well as for solar PV and CSP, is clearly decreasing, thus showing that they are expected to be even more competitive in the near future.

As a summary of the current situation, let's see (Figure 14) what are the key aspects (*key facts*) for the wind sector according to the 2022 report of the REN21 "Renewables 2022 Global Status Report":

Question 3.3: Wind Power LCOE [600 XP]

Pay attention to the LCOE of different technologies displayed in Figure 13. There are 2 renewable technologies (hydro and geothermal) that show an increasing LCOE over recent years.
Try to find/explain the causes that might be behind this situation.

Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020

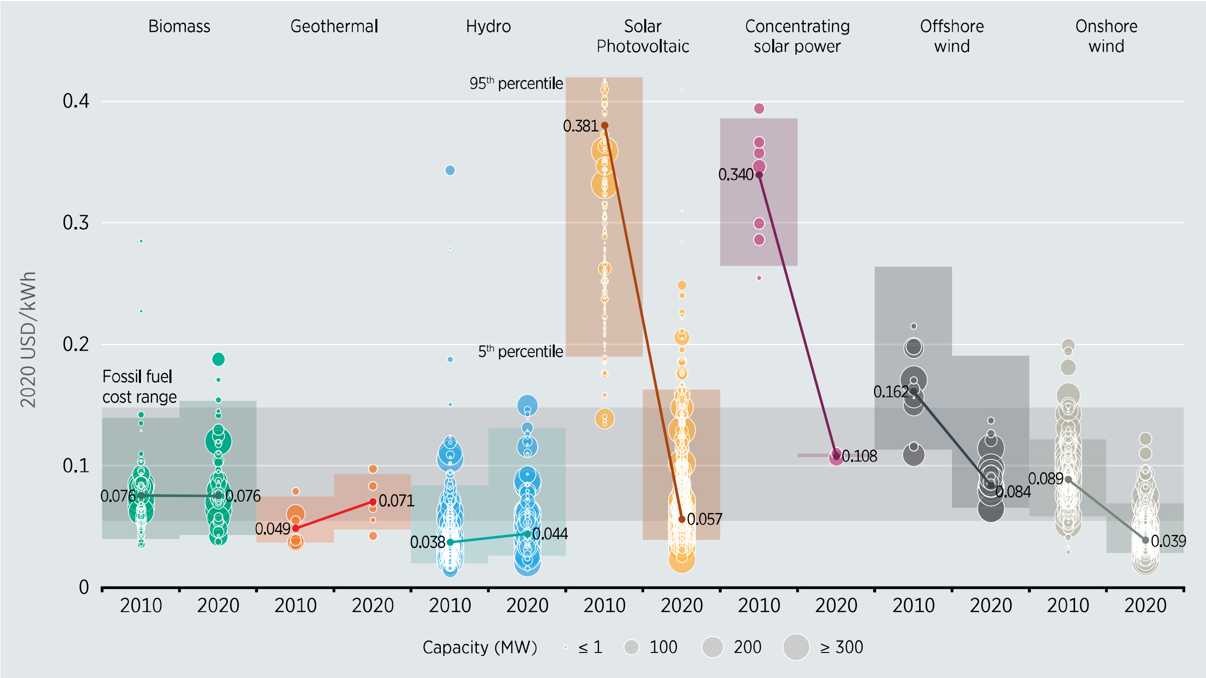


Figure 12. LCOE for renewable technologies (2020). Source: Renewable Power Generation Costs in 2020 (IRENA). https://bit.ly/3AWyUzr

KEY FACTS

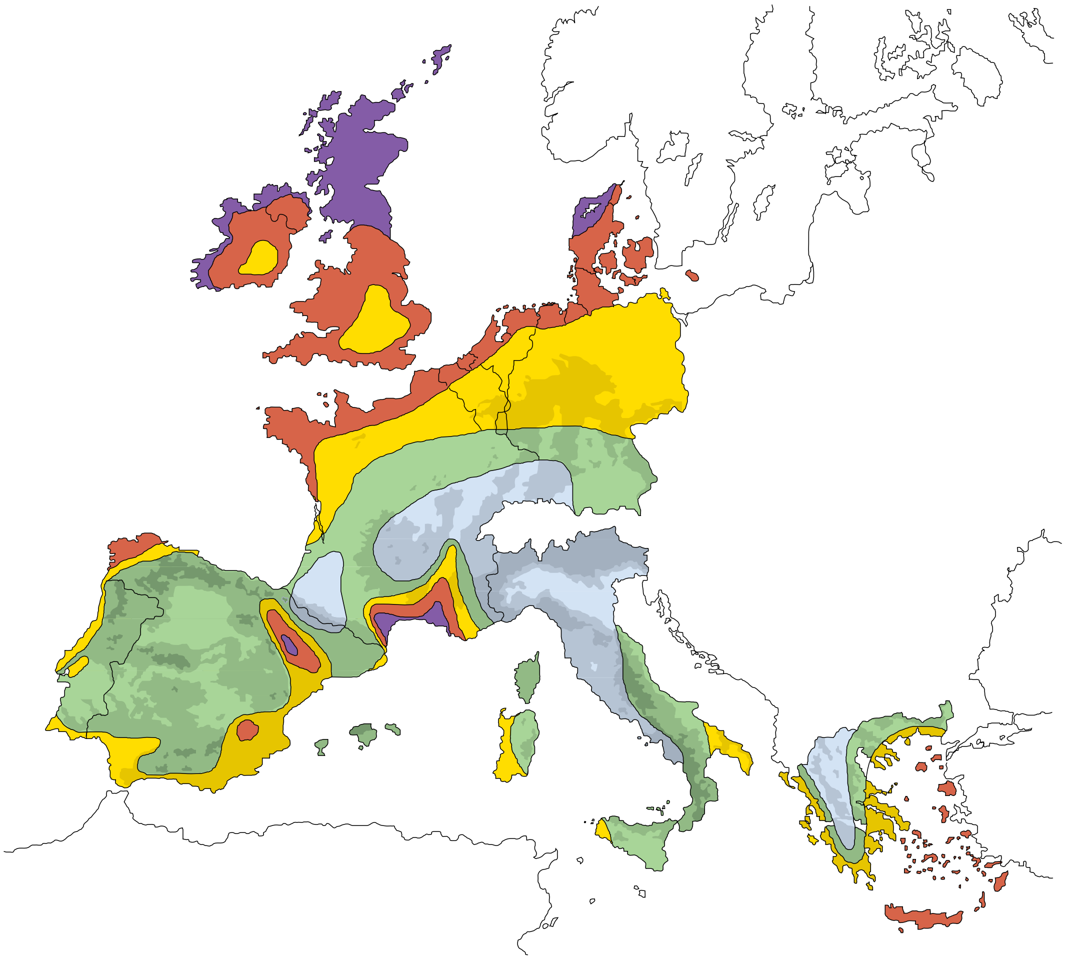
- **The global wind power** installed capacity grew by 102 GW in 2021, again led by China. Onshore additions fell relative to 2020 and offshore additions surged to new highs, driven largely by policy changes in China and the United States. Not including China, annual global installations rose more than 14%.
- **The offshore wind sector** attracted increasing attention from governments, project developers, oil and gas majors and other energy providers. By one estimate, the offshore wind power pipeline reached 517 GW by early 2022.
- **Rising costs** due to supply chain constraints, labour shortages, shipping backlogs and rising raw material prices compounded ongoing challenges, including a lack of grid infrastructure and permitting. Outside of China, average turbine prices reached levels not seen since 2015, and the industry is urging greater focus on the system value of wind energy rather than solely on continually declining costs and prices.

Figure 13. *Key facts* for wind power according to REN21. Source: REN21 (2022 Report). Link: https://bit.ly/3MR1R7x.

3.4 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.

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



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/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2
	> 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 14. Wind map: Europe. Source: Plantas eólicas/ABB Cuaderno técnico.

consists 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.

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

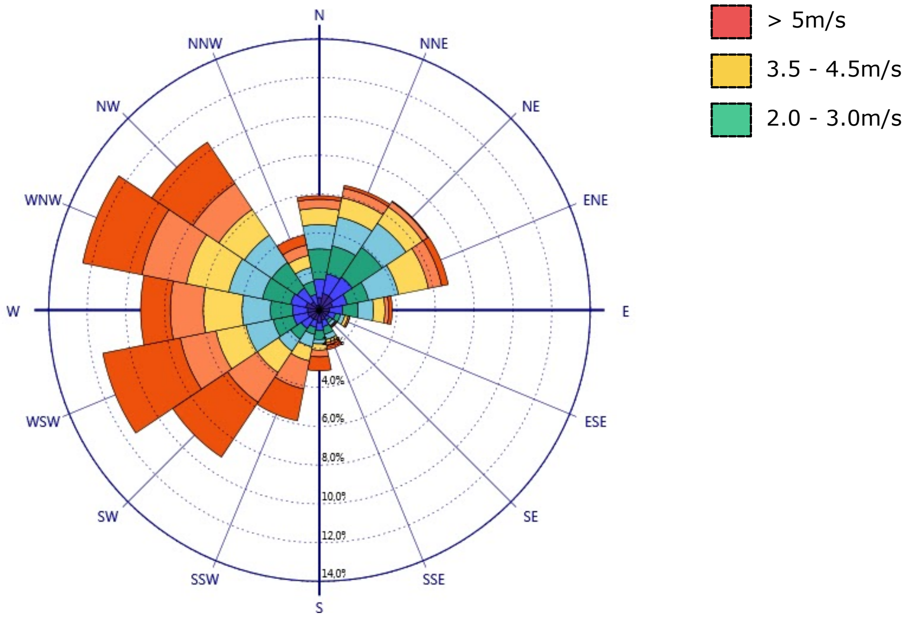


Figure 15. Wind rose plot for Bombay. Source: Arquitectura Abisal Bombay `http://bit.ly/2Df8nV1`.

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

A wind rose plot (see Figure 16) 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 17. 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.

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

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).

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

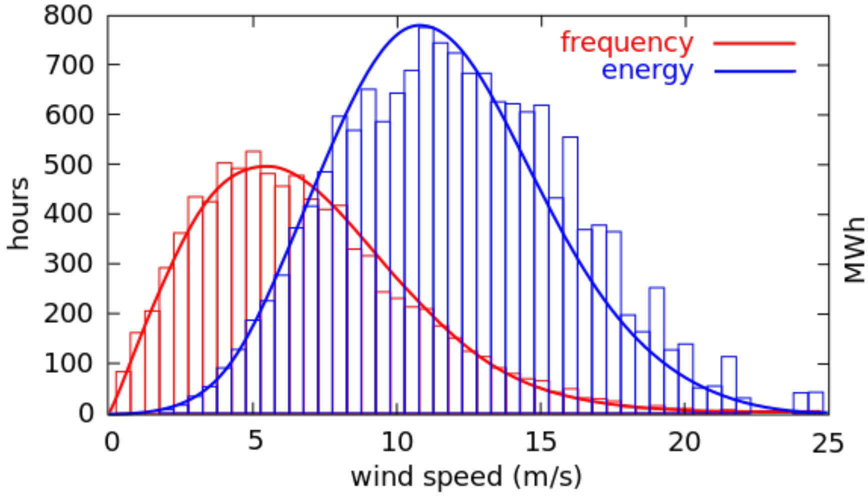


Figure 16. Example of Weibull distribution (red) used to model wind speed data. The energy produced by the wind turbine has been represented in blue. Source: http://bit.ly/2FEQZGz. License: CC-BY-SA 3.0.

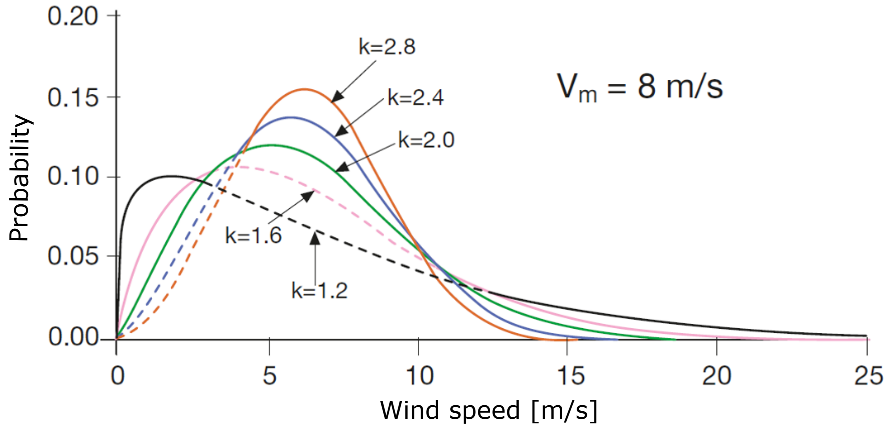


Figure 17. Weibull distributions for an average wind speed of 8m/s and different values of *k*.

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

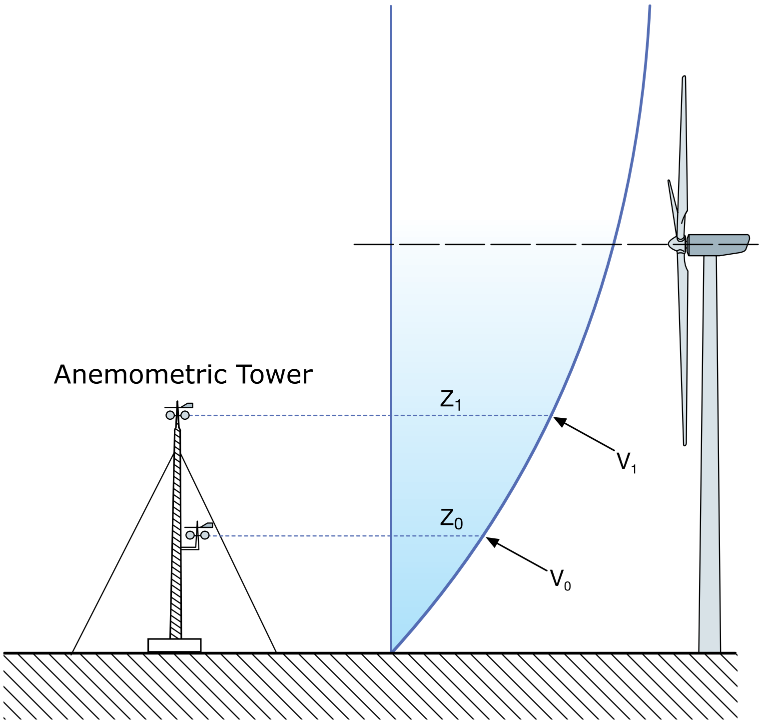


Figure 18. Wind speed increase with height. Source: Plantas eólicas/ABB Cuaderno técnico.

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 19. 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.

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

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).

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

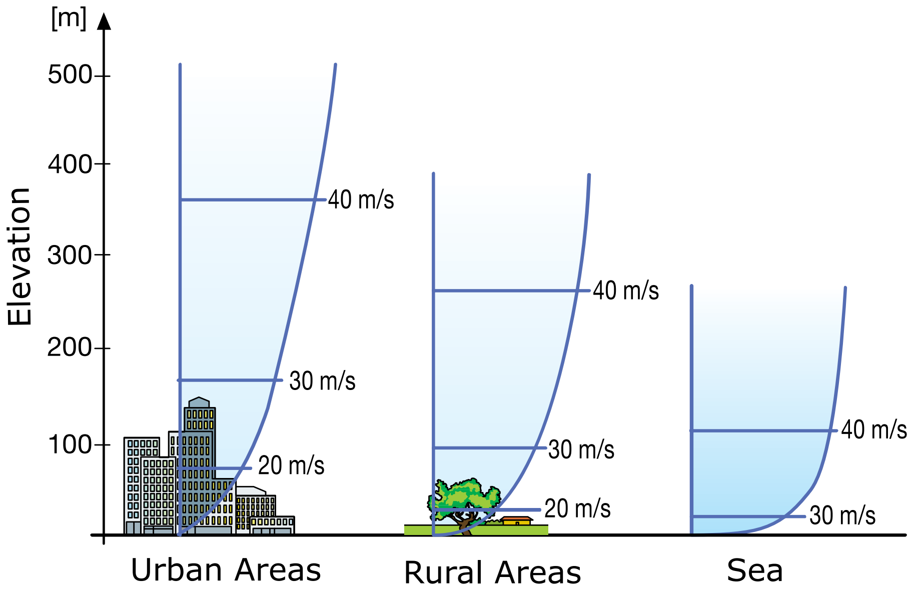


Figure 19. Effect of surface roughness on wind speed. Source: Plantas eólicas/ABB Cuaderno técnico.

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.

Question 3.4: Wind Shear Example [300 XP]

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 20. 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 21).

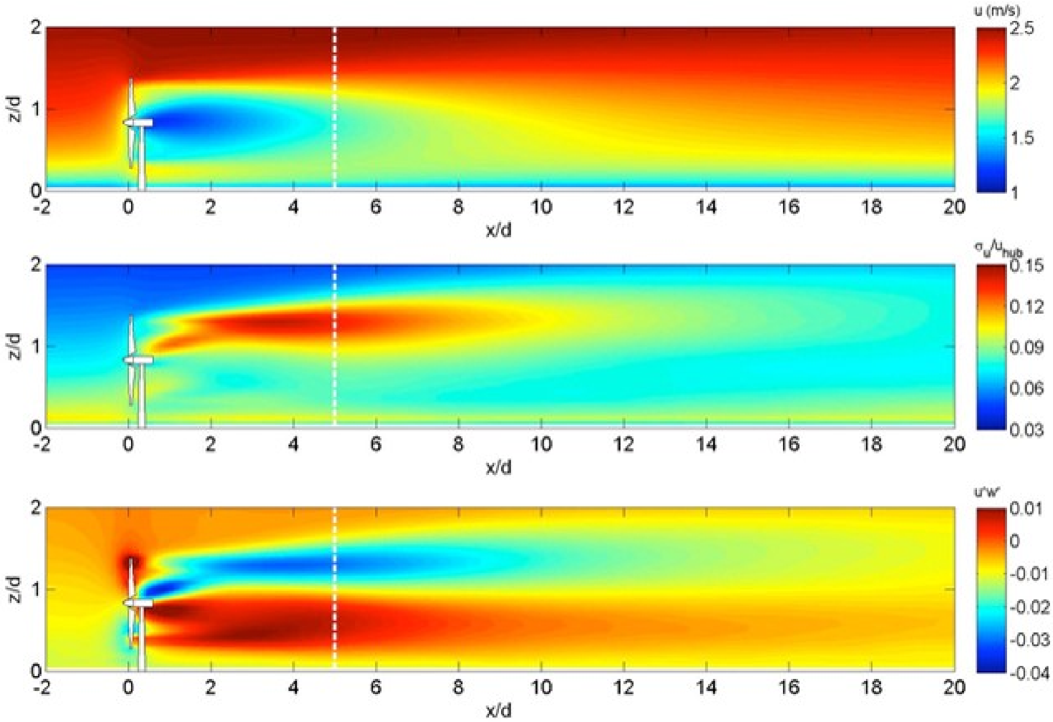


Figure 20. Turbulence at the back side of a wind turbine. Source: Wind Engineering and Renewable Energy Laboratory Wire http://bit.ly/2EMfh0n

3.5 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:

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

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)

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

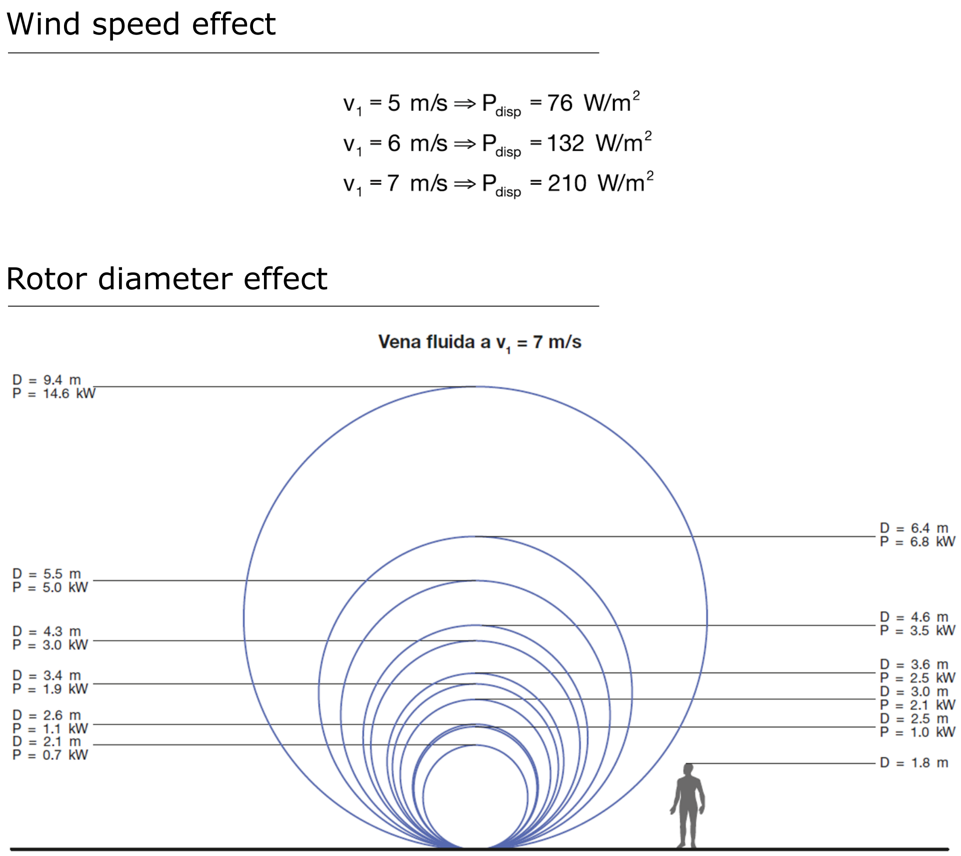


Figure 21. Wind turbine generated power in terms of wind speed and rotor diameter. Source: Plantas eólicas/ABB Cuaderno técnico.

3.5.1 Betz Limit

Betz's law established the maximum efficiency achievable by a wind turbine. To understand this, Figure 23 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.

Let's analyze this situation in more detail. In Figure 24, 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:

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

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

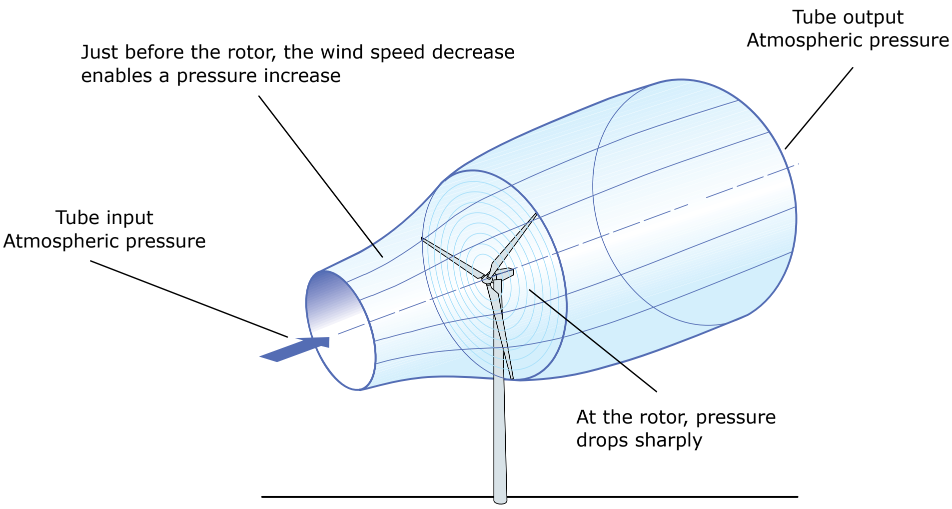


Figure 22. Schematic representation of the air mass going through a wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

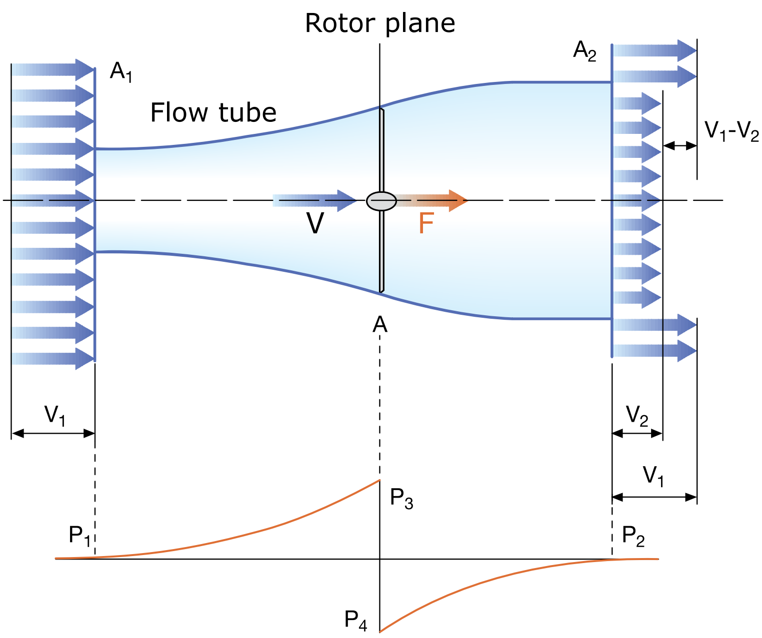


Figure 23. Variations in the speed and pressure of the air mass that goes through the wind turbine rotor. Source: Plantas eólicas/ABB Cuaderno técnico.

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

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.

3.5.2 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 the power coefficient *Cp*:

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

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 25, where C_p has been represented versus *a*.

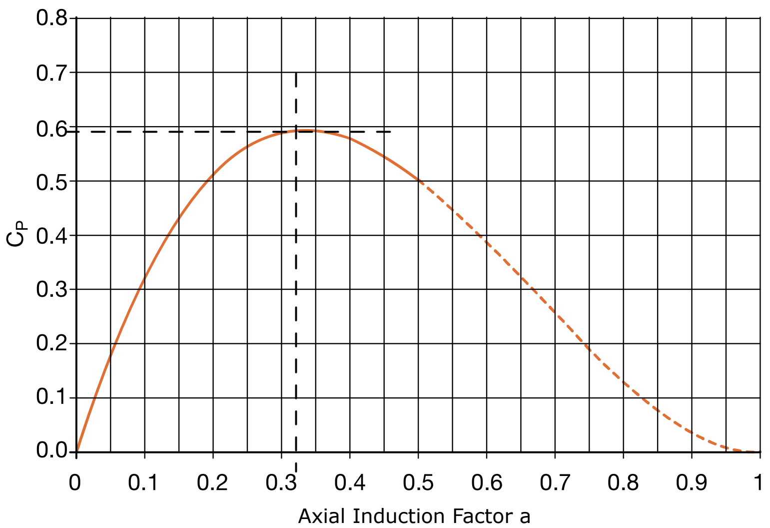


Figure 24. Power coefficient C_p versus the axial induction factor *a*. Source: Plantas eólicas/ABB Cuaderno técnico.

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

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

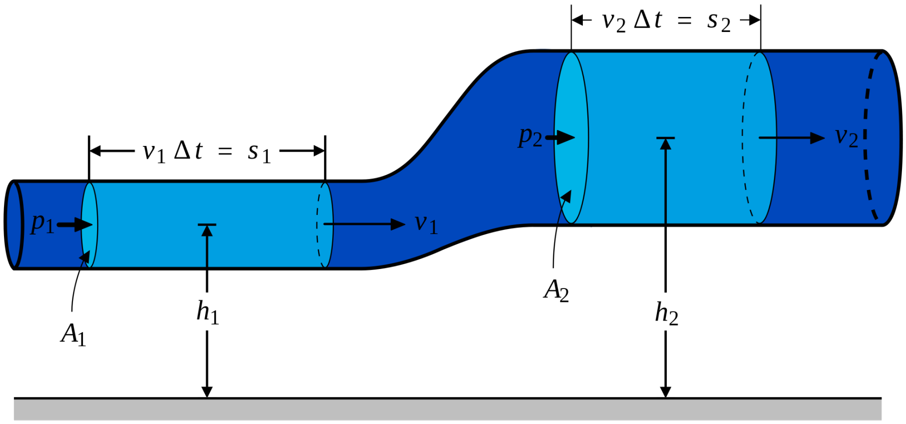


Figure 25. Schematic representation of Bernoulli's Theorem. Source: Wikimedia http://bit.ly/2DCneFZ

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.

Question **3.5: Bernoulli's Theorem [400 XP]**

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

3.5.3 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 27, 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 28,

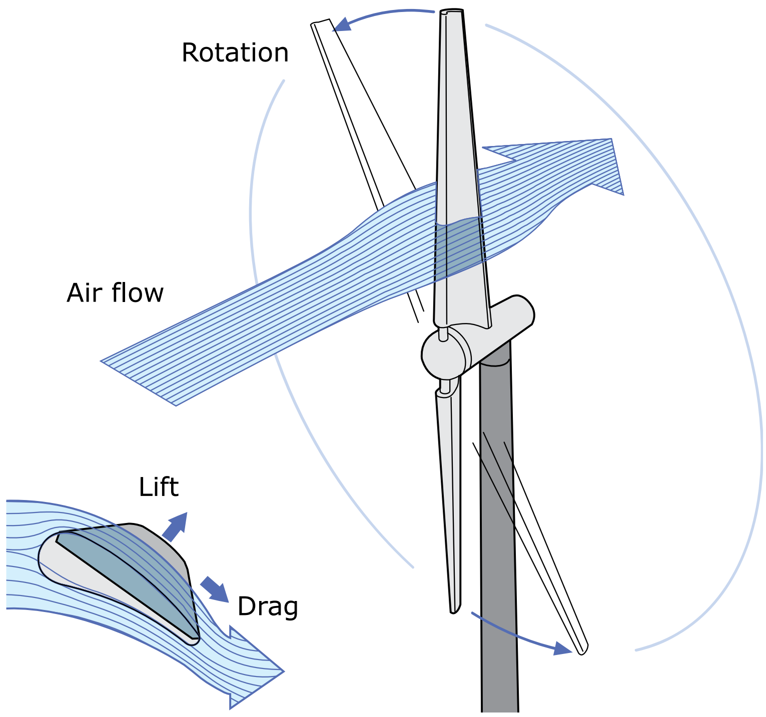


Figure 26. Working principle of a wind turbine: lift and drag forces. Source: Plantas eólicas/ABB Cuaderno técnico.

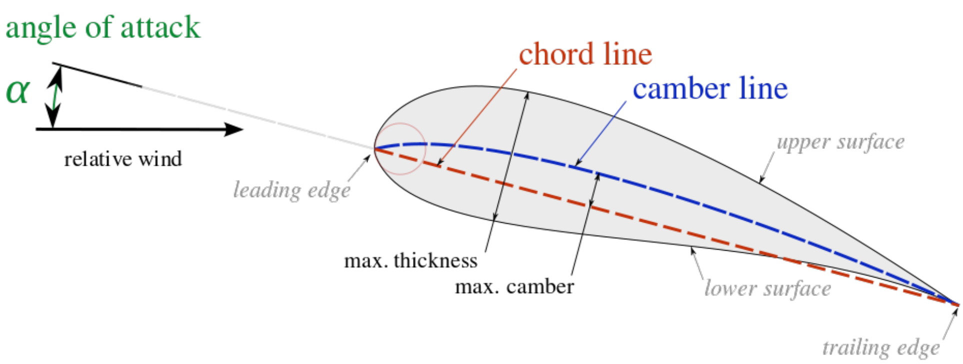


Figure 27. Plane wing profile (aerofoil). Source: Wikimedia.

which shows how the length of the upper surface of the wing is greater than the length of the bottom surface.

***Question* 3.6: Wings and Blades [500 XP]**

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 29 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.

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 30.), which implies a highly unsteady flight in the plane example, with rapid variations of lift with time.

3.5.4 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:

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

[1] "Entrar en pérdida" en castellano.

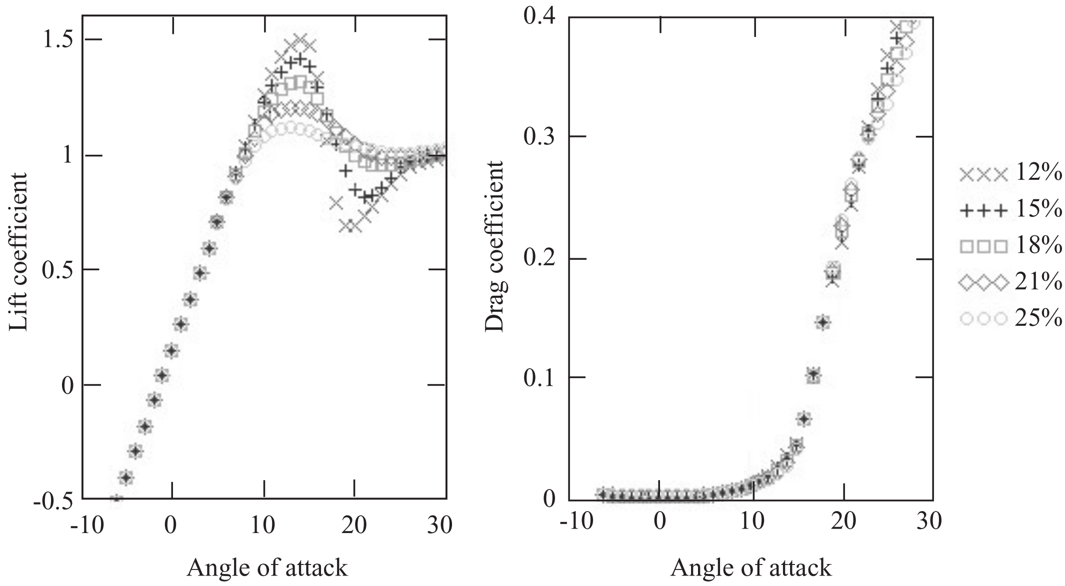


Figure 28. Evolution of lift and drag coefficients in terms of the angle of attack. Source: Wind Energy Handbook (Wiley), p. 94.

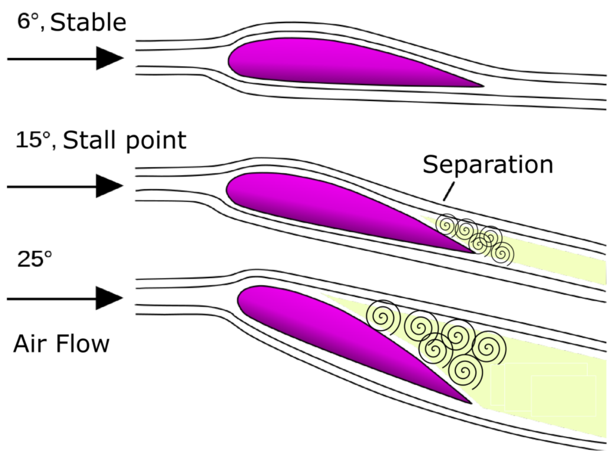


Figure 29. . Wing stall in terms of angle of attack. Source: Wikimedia http://bit.ly/2mCu8mg (Public Domain).

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[1] 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:

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

Figure 31 shows the rotor diameter evolution (y-axis) and the associated electrical power (x-axis) for large-scale wind turbines.

***Important!* 3.7: 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

***Question* 3.7: Turbulence at the back the Turbine [400 XP]**

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 negative impacts of turbulences on wind turbines 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 32, conventional wind turbines require

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

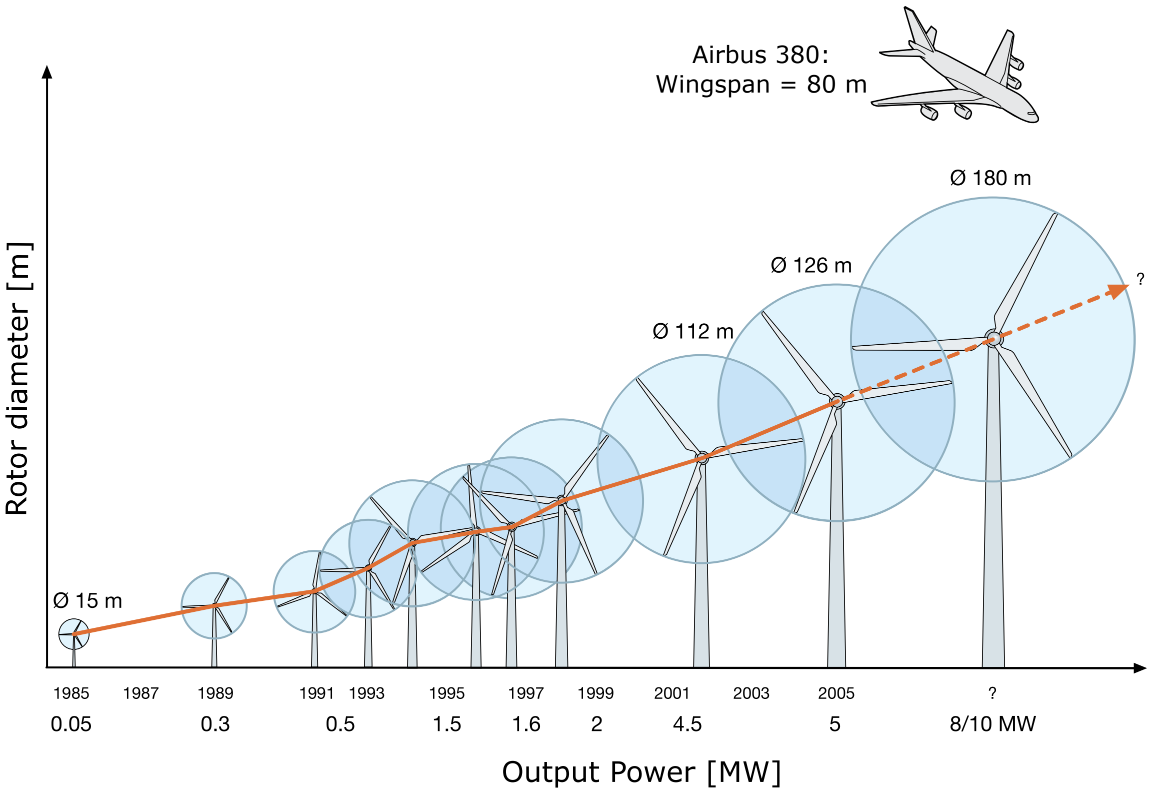


Figure 30. Rotor size versus output electrical power: evolution over the previous years. Source: Plantas eólicas/ABB Cuaderno técnico.

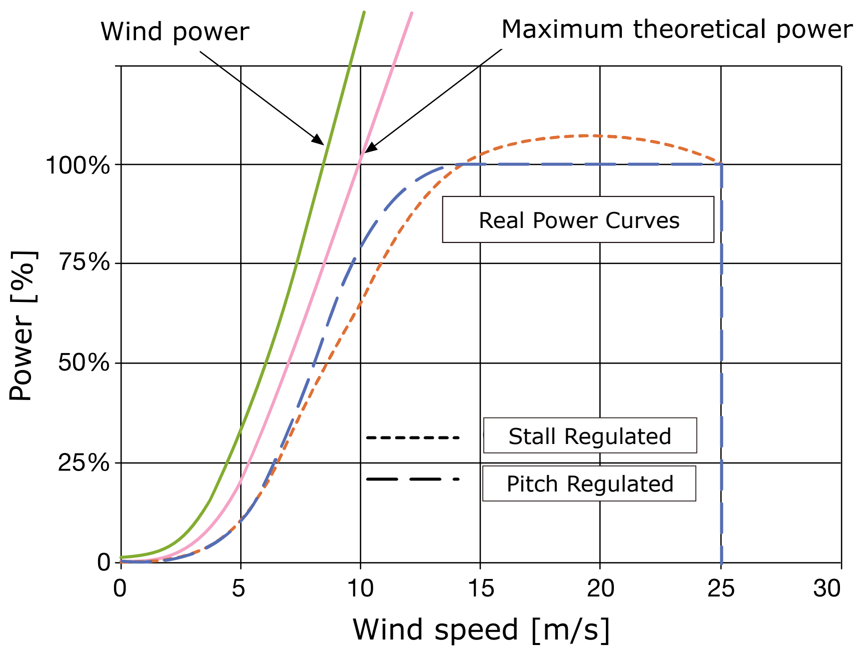


Figure 31. Wind speed versus output power in a wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

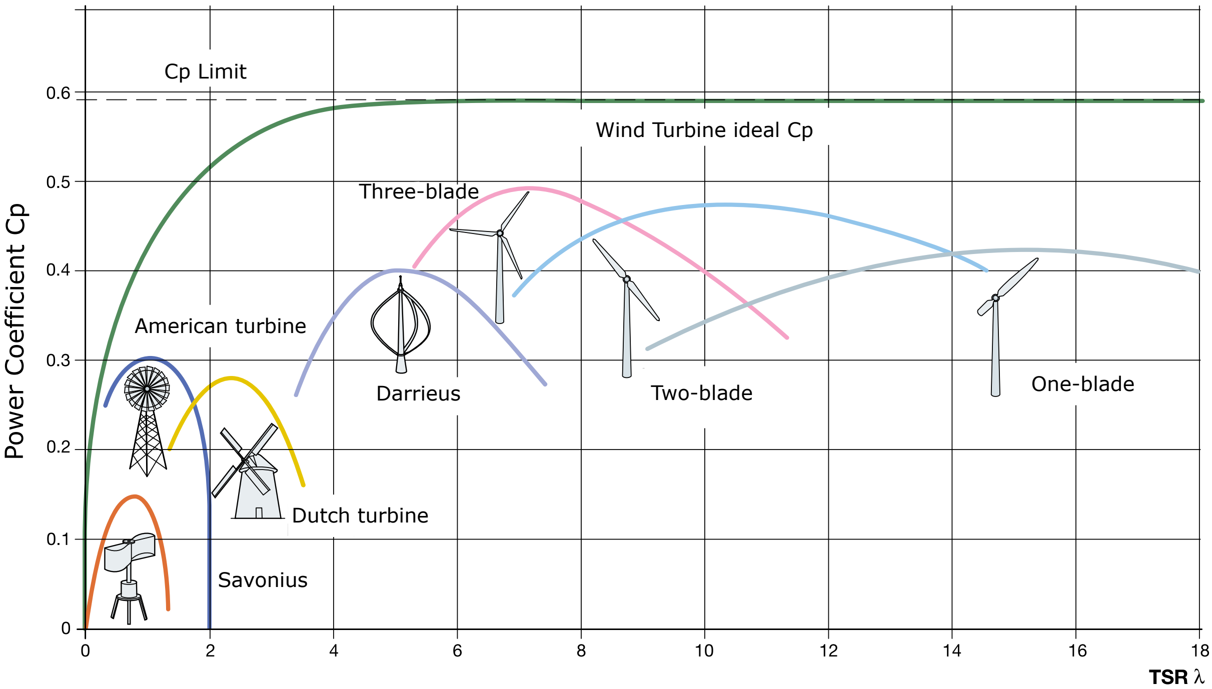


Figure 32. Power coefficient versus tip speed ratio for different wind turbine models. Source: Plantas eólicas/ABB Cuaderno técnico.

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 33, 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:

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 33).

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

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.

3.5.5 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.

3.6 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 34):

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

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

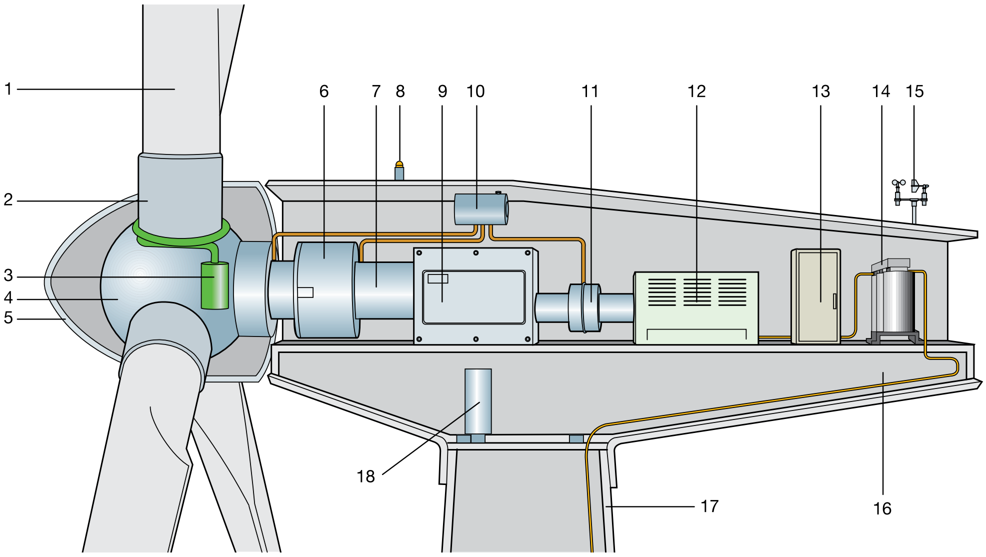


Figure 33. Components of a wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

12. generator
13. power converter and electrical control and protection devices
14. transformer
15. anemometers
16. nacelle
17. tower
18. yaw motor

It is very interesting to analyze the cost associated with the different elements, even if it is a mere approximation. As indicated in Figure 35, 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).**

3.6.1 Wind Turbine Elements: Tower

Modern wind turbines often use **tubular towers** (Figure 37). **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.

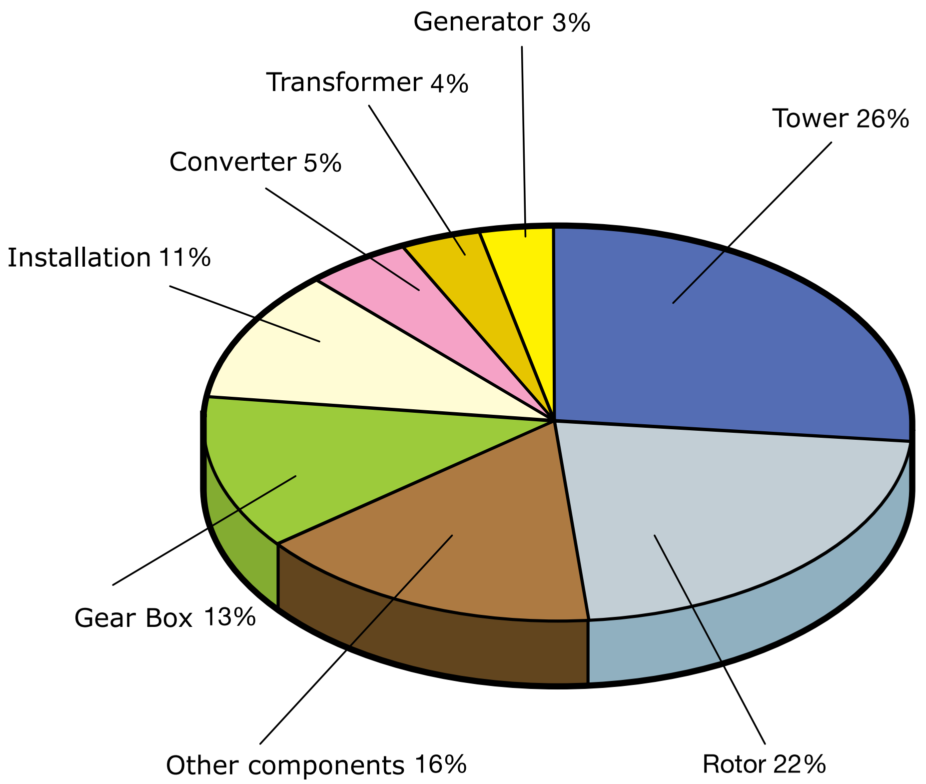


Figure 34. Cost associated with wind turbine components. Source: Plantas eólicas/ABB Cuaderno técnico.

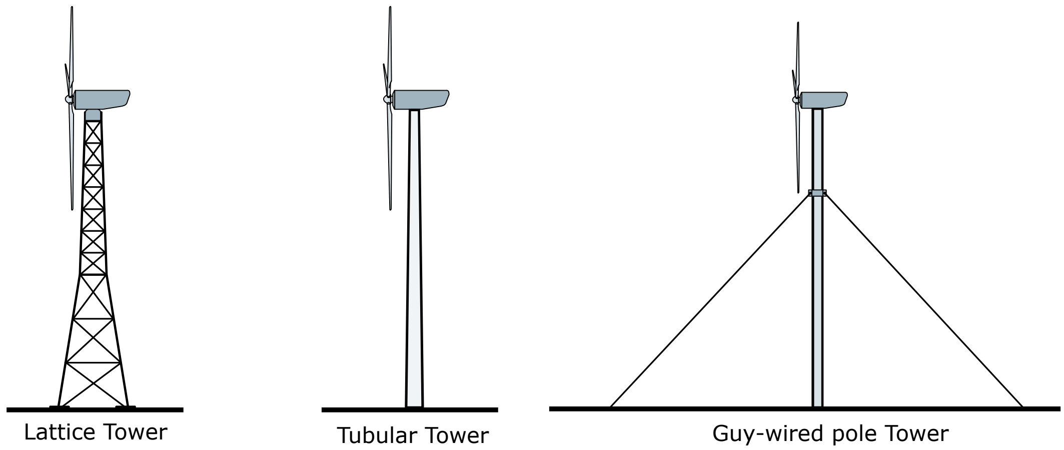


Figure 35. Tower designs for wind turbines. Source: Plantas eólicas/ABB Cuaderno técnico.

Figure 36. Foundations of an onshore wind turbine. Source: Wikimedia. License: CC BY-SA 2.0. http://bit.ly/2mLQ6nZ

3.6.2 Wind Turbine Elements: Rotor

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

Rotor: Blades

Figure 37. 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 39. 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.

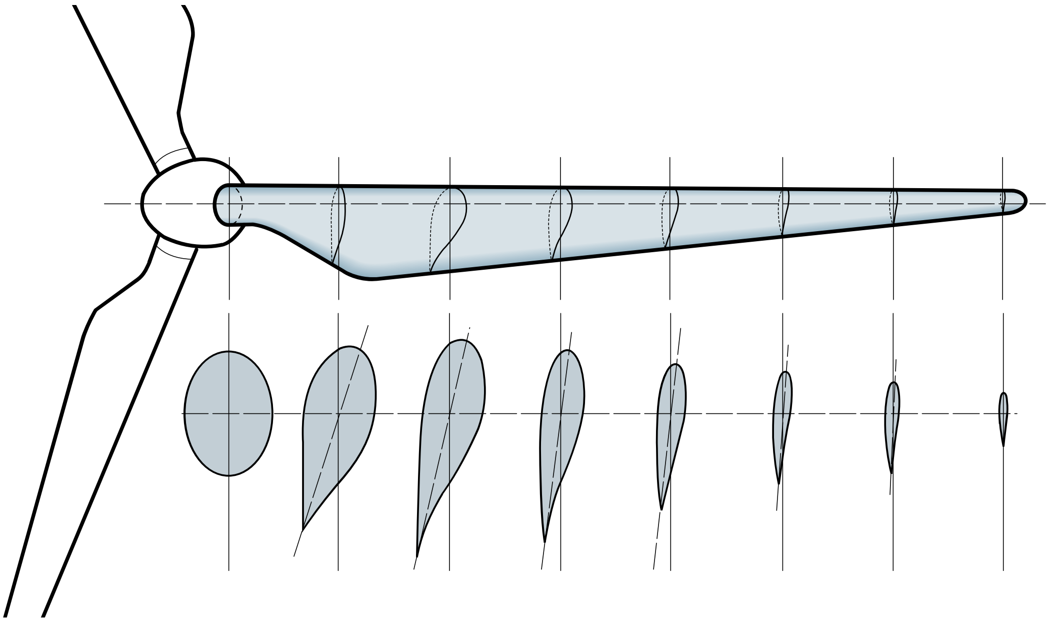


Figure 38. Blade profile from base to tip: cross-section. Source: Plantas eólicas/ABB Cuaderno técnico.

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 40).

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.

Important! **3.8: 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 **3.8: Blade's appearance (II) [400 XP]**

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 41). 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.

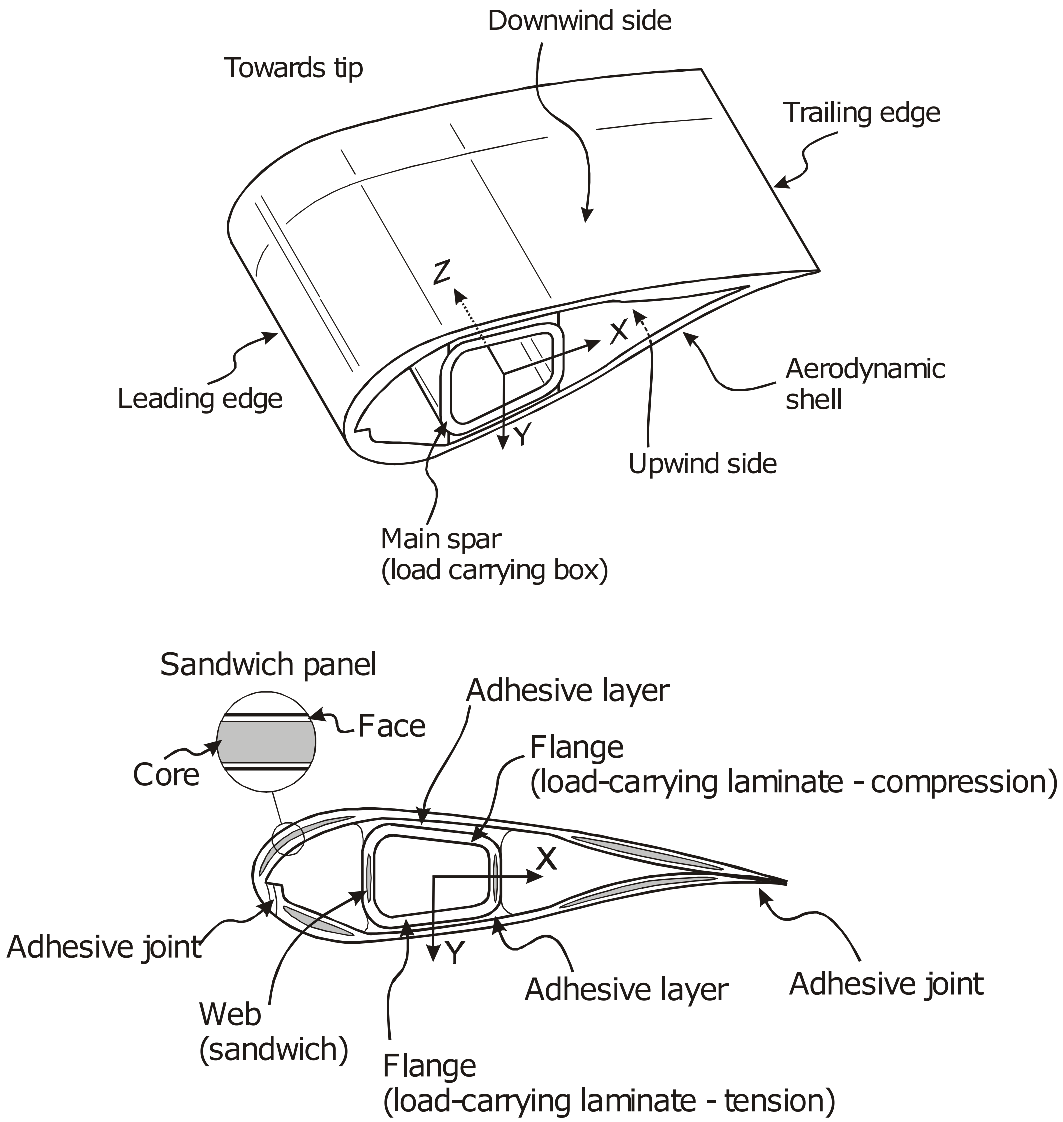


Figure 39. Detail of the cross-section of a wind turbine blade. Source: Riso R-1390: *Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report.*

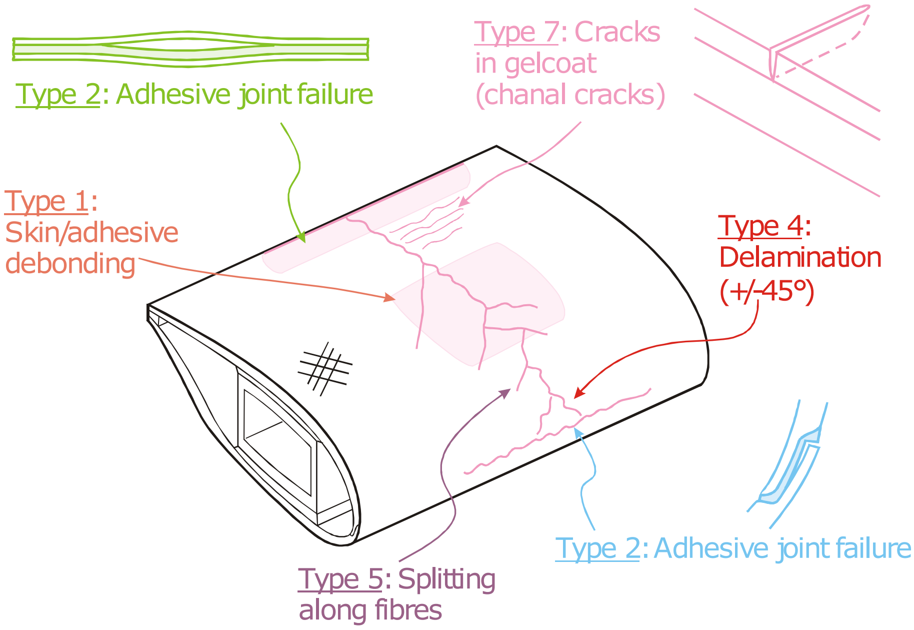


Figure 40. Detail of the cross-section of a wind turbine blade: possible defects. Source: Riso R-1390: *Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report*.

Important! 3.9: 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`.

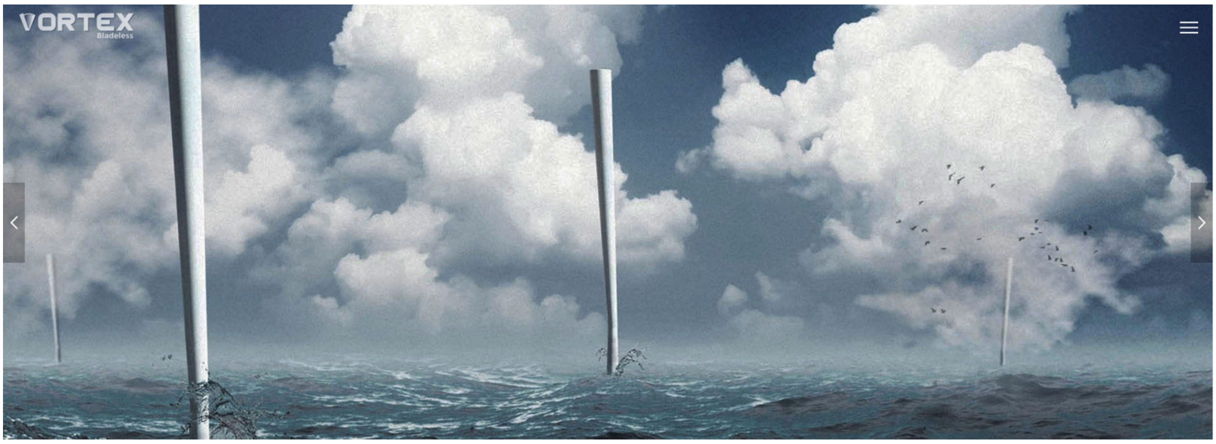


Figure 41. Vortex Bladeless: wind turbines without blades. Source: Vortex Bladeless.

Figure 42. Wind turbine hub being connected to the nacelle. Source: Wikimedia. License: CC-BY-SA 2.0

Question 3.9: Bladeless Wind Turbines [400 XP]

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].

[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.

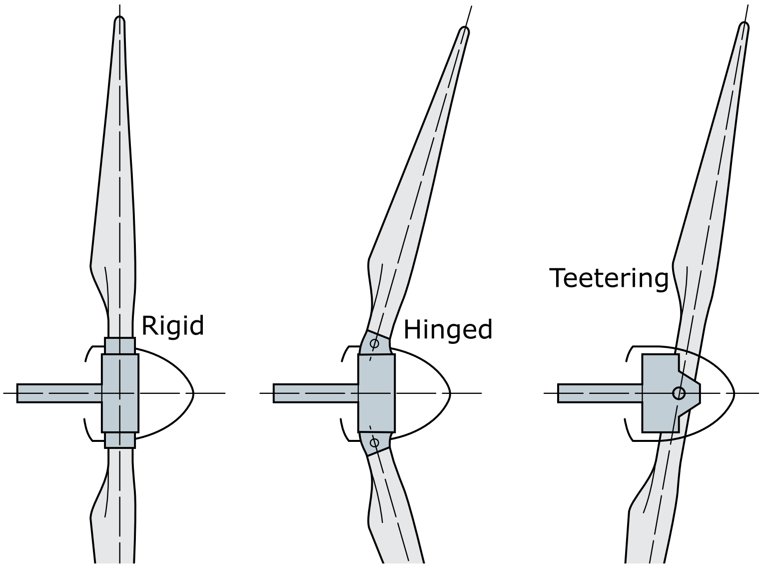


Figure 43. Hub types for wind turbines: rigid, hinged and teetering. Source: Plantas eólicas/ABB Cuaderno técnico.

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.

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 46, 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.

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).

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

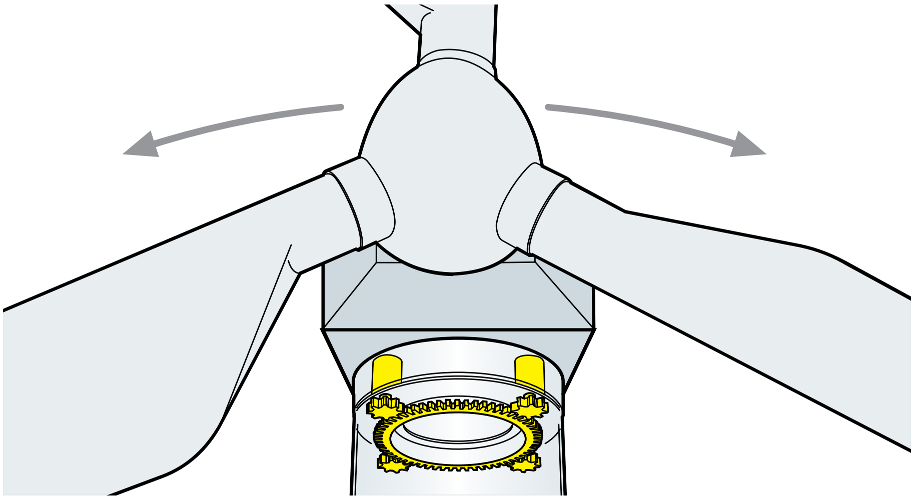


Figure 44. Yaw system in a horizontal-axis wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

Figure 45. Upwind and downwind turbines. Source: Wikimedia. License: CC BY-SA 4.0 Attribution © Hans Hillewaert) http://bit.ly/2EPJ0Fp.

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.

Figure 46. Gear box, rotor shaft and brake in a wind turbine. Source: Wikimedia. License: CC BY-SA 2.0. http://bit.ly/2ERH8Mx

3.6.3 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.

3.6.4 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.

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]

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

Figure 47. 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

3.6.5 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 49) 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.

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.

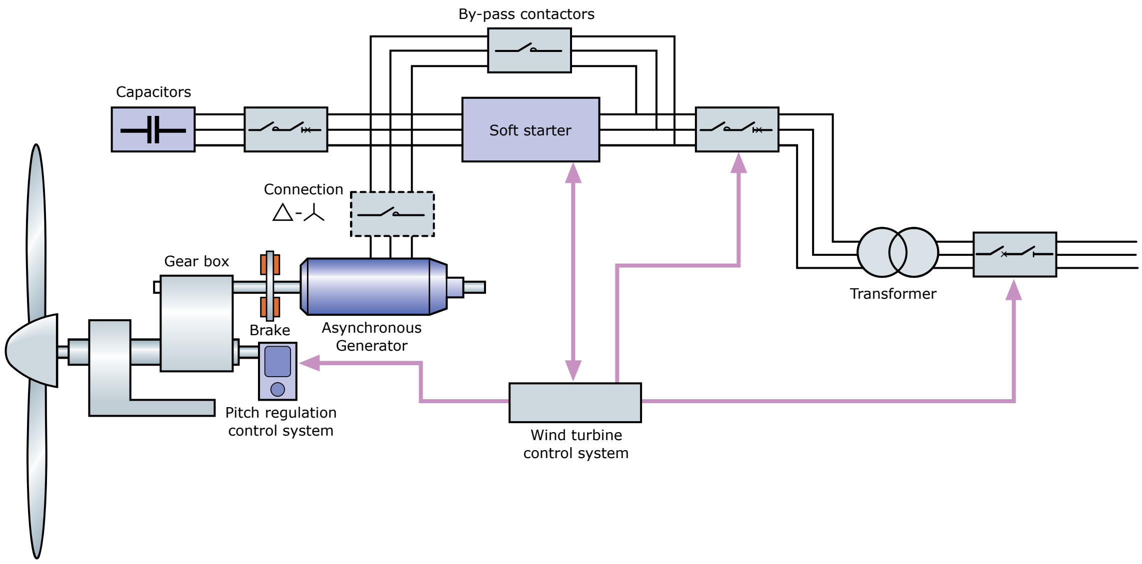


Figure 48. Schematic representation of a fixed-speed wind turbine. Source: Plantas eólicas/ABB Cuaderno técnico.

This can be done by continuously adapting the blades rotation speed to the wind speed, thus achieving an optimum TSR, as explained in Figure 33.

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 50. 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

[1]Fuente: Plantas eólicas/ABB Cuaderno técnico

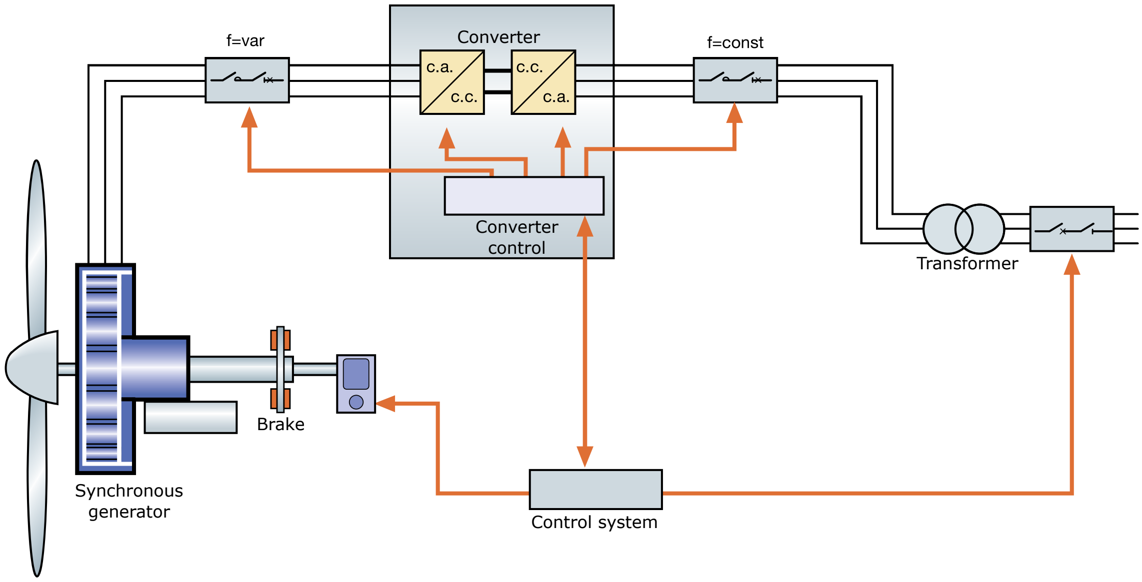


Figure 49. Schematic representation of a variable-speed wind turbine with synchronous generator. Source: Plantas eólicas/ABB Cuaderno técnico.

through these windings. 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!* **3.10: 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!* **3.11: 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.

3.6.6 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.

3.6.7 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 **3.10: Control System: PLCs [400 XP]**

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 **3.11: SCADA [700 XP]**

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.

3.6.8 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! **3.12: 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.

3.7 Wind Turbines & telecommunications

It is obvious that wind turbines and wind farm operators require **high-performance communication infrastructures** to manage the whole system and to achieve an efficient operation. First of all, each turbine will generate and transmit information regarding its status and the data gathered by all its sensors. In this way, that operation can be automated always looking for optimization of the electricity yield. A typical wind farm communication system will be formed by several wind turbines generating and sending all the information generated by its many sensors to a **park control system**, being all the turbines connected with a ring topology. Additionally, internet connection is required to provide communications with the **control center**, which will manage several wind power plants.

The **control center** of a wind power farm (WPF) is responsible for the autonomous monitoring, managing and controlling the operation of the farm, thus leaving aside human intervention just for specific configuration, maintenance or failure repairs [1]. Figure 51 shows a possible implementation of the communication system in a wind farm, where each wind turbine includes its own turbine control and all the turbines are connected to the park control via industrial ethernet.

[1] Source: *"Communication Network Architectures for Smart-Wind Power Farms´´. Link: https://bit.ly/3BfL1Yk*.

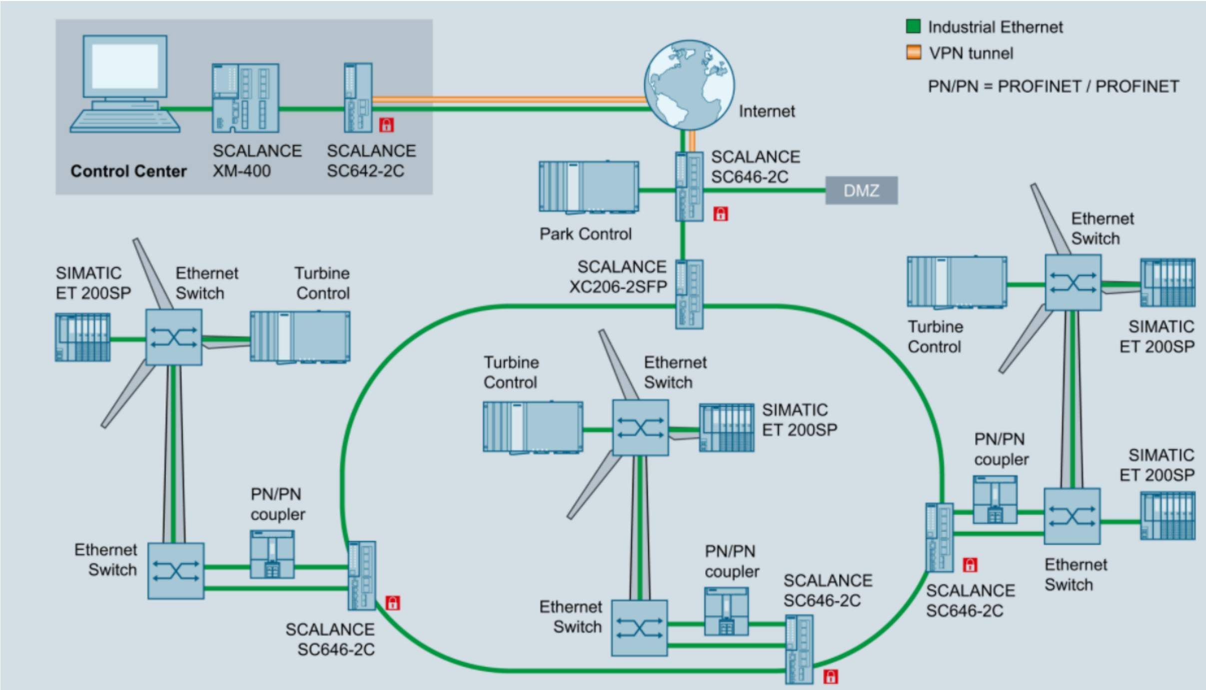


Figure 50. Communications in a wind power plant. Source: Siemens. Link: https://sie.ag/3GleHHq.

Communications within wind turbines should be also considered, as there is a lot of information that has to be acquired and transmitted: rotation speed of the rotor, rotation speed of the secondary axis (gear box), temperature and levels of oil, wind speed and direction, positioning of the rotor, angle of attack of the blades, etc. This information will be sent to the control room and it will be used to automate their operation and achieve a greater electricity yield. Industrial Wireless LAN (IWLAN) in the nacelle can also be used to allow network access via mobile communications, e.g. by maintenance technicians moving freely inside and outside the installation with an operator panel[1].

***Important!* 3.13: Implementation example using SIEMENS devices**

Both Figure 51 and Figure 52 show example of possible implementations using instrumentation and devices by SIEMENS. For example, the SCALANCE SC646-2C is an industrial security appliance for protection of industrial communications with firewall and VPN, while the SIMATIC HMI is a panel display that allows representation and management of the information provided by PLCs, for example.

Regarding the near future, it seems that the next stage for communications in wind power farms will be probably focused on the deployment of passive optical networks (PON).

Finally, it is also interesting to think about the special requirements that **off-shore wind farms** may require. Figure 54 shows a possible solution to this situation, where broadband wireless communications will be required, for example via WiMAX and the **IEEE 802.16e** standard. Normally, this kind of solution will be only needed during construction, as a wired

[1] Source: Siemens. Link: https://sie.ag/3GleHHq

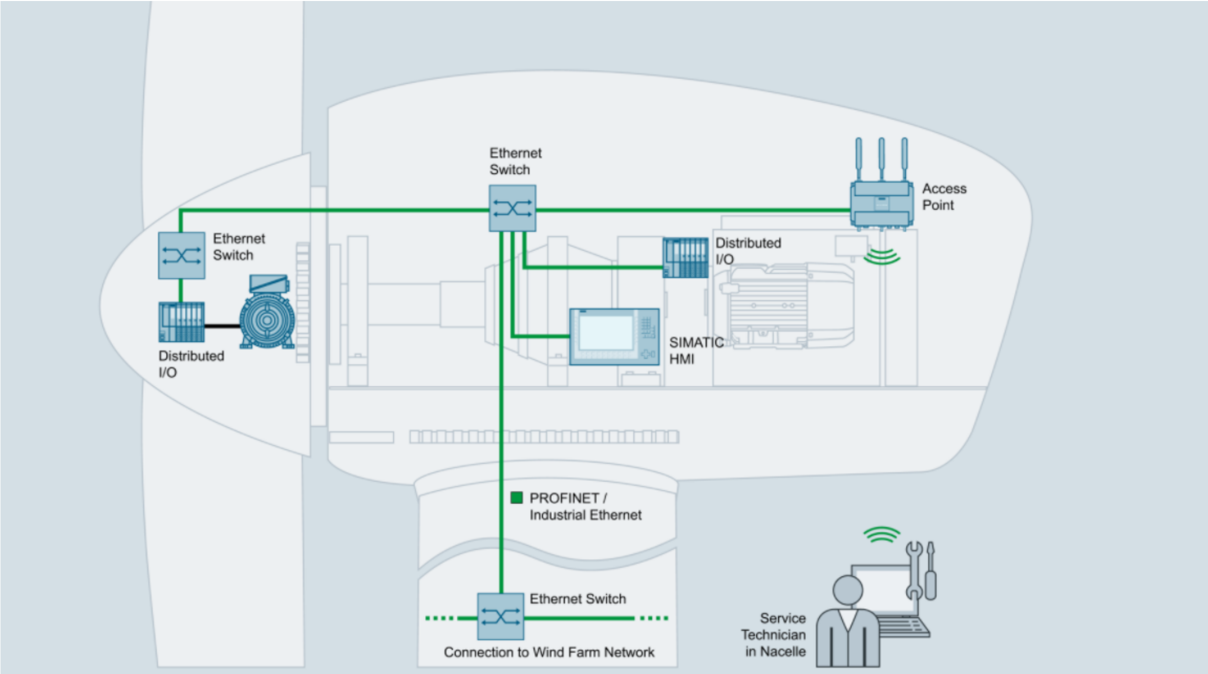


Figure 51. Communications inside a wind turbine. Source: Siemens. Link: https://sie.ag/3GleHHq.

infrastructure will be finally deployed, but it can also serve as a fallback solution in the event of a failure of the wired communication system.

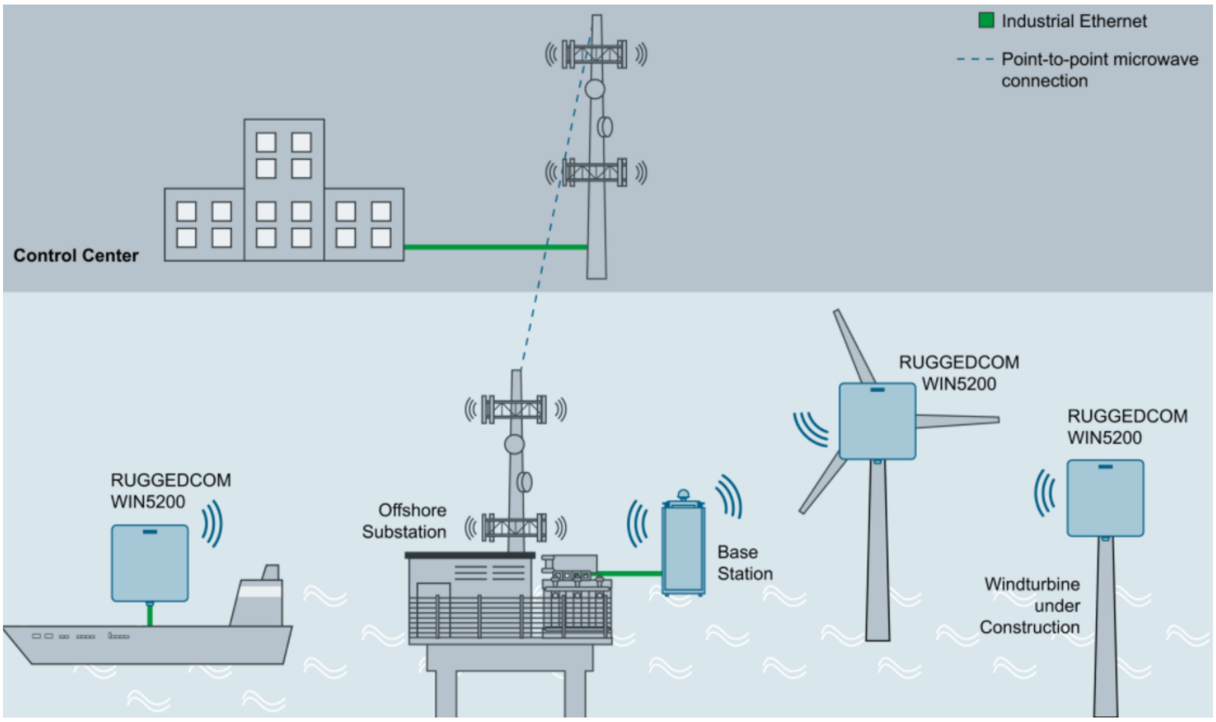


Figure 52. Example of a communication system for an off-shore wind farm. Source: Siemens. Link: https://sie.ag/3GleHHq.

***Important!* 3.14: Deployment of off-shore power plants**

Deploying an off-shore power plant may prove difficult, both for the telecommunication systems but also for the wind turbines. In the following video you can see how sometimes (not very often) things go wrong ...
Enlace al vídeo en Twitter: https://bit.ly/3EDsXJP.

In summary, conventional wind power farm communication infrastructures are switch-based architectures, where each wind turbine is equipped with an industrial Ethernet switch (ESW) at the base of the tower, and optical fiber cables are used to connect between wind towers. In the case of large-scale WPFs, independent sets of switches and communication links are considered to interconnect different applications such as those involved in monitoring, operation, and protection. The transmitted data from the wind turbines may take a path through many ESWs in order to reach the control center side, based on the turbine location and the WPF topology[1]

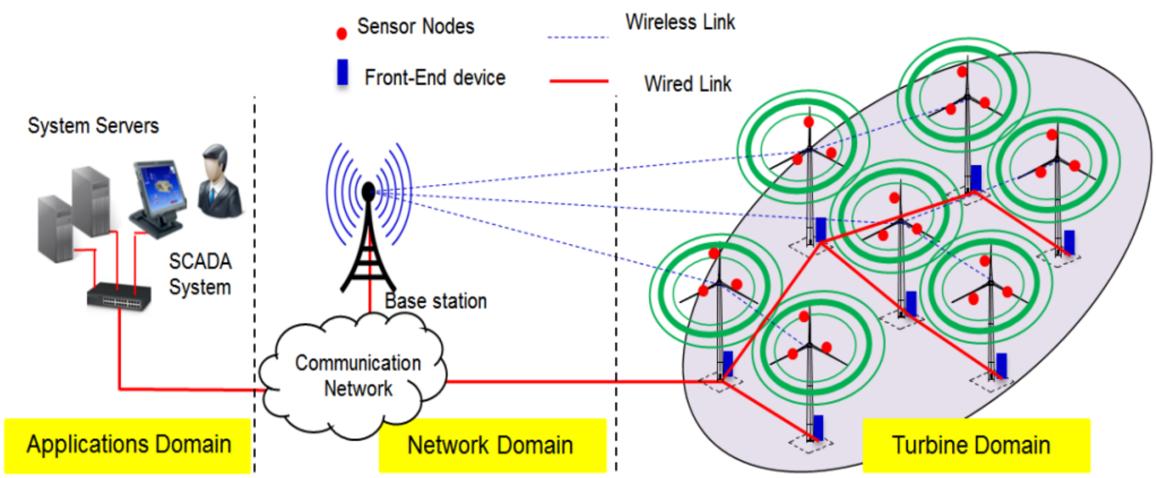


Figure 53. Scheme of a conventional communications system for a wind power farm. Source: "Communication Network Architectures for Smart-Wind Power Farms". Link: https://bit.ly/3buBK4m.

The conventional architecture of communication systems of WPFs exhibit some limitations, such as:

Low reliability the failure in a wind turbine ESW may affect the remaining turbines preventing them from connecting with the control center

High cost the price of the ESW is too expensive, and independent sets of switches and communication links add more costs to the WPF

Difficulty in guaranteeing real-time monitoring and control in case of sharing the same physical link with all wind turbine traffic

[1] Source: "Communication Network Architectures for Smart-Wind Power Farms". Link: https://bit.ly/3buBK4m.

A new concept, the so-called "smart wind power farms" has been created to solve these problems. The main features of these Smart-WPFs are described as follows[1]:

- Wind turbines communicate with other wind turbines, and wind turbines are not blind machines
- Wind turbines have many SNs that help to react to different conditions
- Wind turbines with a malfunction can use monitoring information of neighboring wind turbines
- Wind turbines integrate energy storage system and forecasting algorithms
- Wind turbines decide the time to store energy and the time to feed to the grid based on electric demand
- Each turbine can know the amount of power it generates relative to other turbines

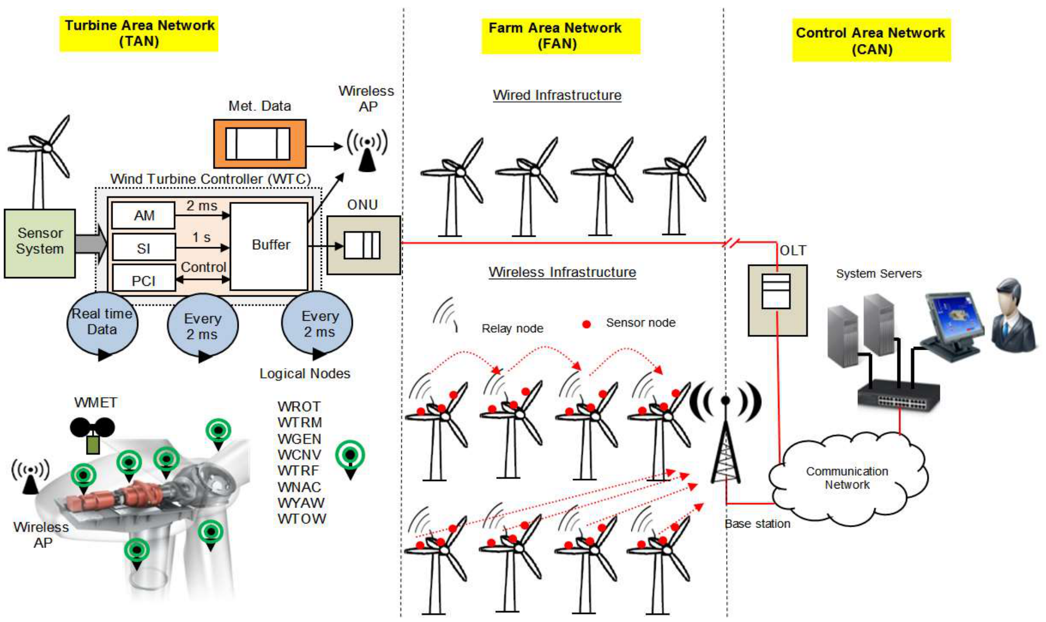


Figure 54. Proposal of a communication network architecture for a Smart-WPF. Source: "Communication Network Architectures for Smart-Wind Power Farms". Link: `https://bit.ly/3buBK4m`.

A possible communication network architecture for the Smart-WPF is presented in Figure 55 and consists of three networks: the turbine area network (TAN), the farm area network (FAN), and the control area network (CAN). It consists of hierarchical architectures with 4 levels: Level 1 is a sensor network in a single wind turbine, Level 2 is the wind turbine-to-wind turbine interaction in the WPF, Level 3 is the local control center to wind turbine interaction, and Level 4 is the farm-to-farm interaction to optimize grid operation. In order to implement hierarchical network architectures, a hybrid communication implementation based on

[1]Source: "Communication Network Architectures for Smart-Wind Power Farms". Link: `https://bit.ly/3buBK4m`.

and EPON-based architecture (wired solution) and ZigBee-Pro (wireless solution) might be considered[1].

3.8 Wind Turbines: Current Trends

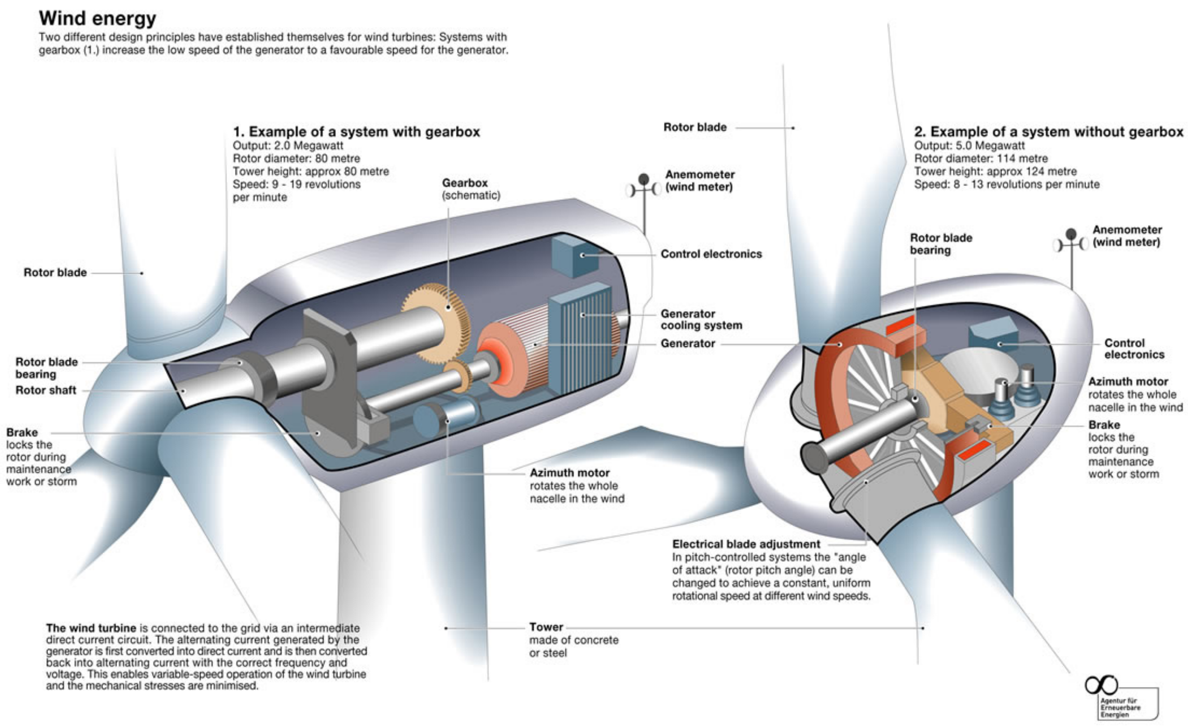


Figure 55. Comparison between a gear-box (left) and direct-drive (right) wind turbines. Source: Wikimedia. License: CC BY-SA 4.0.

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 56). 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!* 3.15: 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.

[1] Source: "Communication Network Architectures for Smart-Wind Power Farms". Link: https://bit.ly/3buBK4m.

Figure 56. Image taken from the 2020 REN21 report introducing the concept of "repowering". Source: REN21 (2020 Report). https://bit.ly/39IvYMz

Question 3.12: Repowering! [300 XP]

Take a look at Figure 57 and try to answer the following question: What does **repower** refer to?

Figure 57. Direct-drive wind turbine. Source: Wikimedia. License: CC BY-SA 2.5 http://bit.ly/2Dex1Rn

3.9 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, and its associated LCOE is expected to fall in the next decade. The following table shows the main wind turbine manufacturers: Siemenes-Gamesa (a Spanish-based company) appears in second position with a strong market associated with offshore deployments.

Table 3.3. Top 10 wind turbine manufacturers (2022)

Rank	Company	Headquarters	Total Capacity (GW)
1	Vestas	Aarhus, Denmark	9.60
2	Siemens Gamesa	Biscay, Spain	8.79
3	Goldwind	Beijing, China	8.25
4	GE	Boston, USA	7.37
5	Envision	Shanghai, China	5.78
6	MingYang	Zhongshan, China	4.50
7	Windey	Zheijiang, China	2.06
8	Nordex	Hamburg, Germany	1.96
9	Shanghai Electric	Shanghai, China	1.71
10	CSIC	Chongqin, China	1.46

Important! **3.16: 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 59. However, it is expected that the offshore LCOE will experience a sharp decrease in the coming years.

To end this part of the course, it is very interesting to note the project developed by **Saitec**, which deployed in 2020 of the scale-model of a wind turbine in front of El Sardinero. The goal of the project was 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

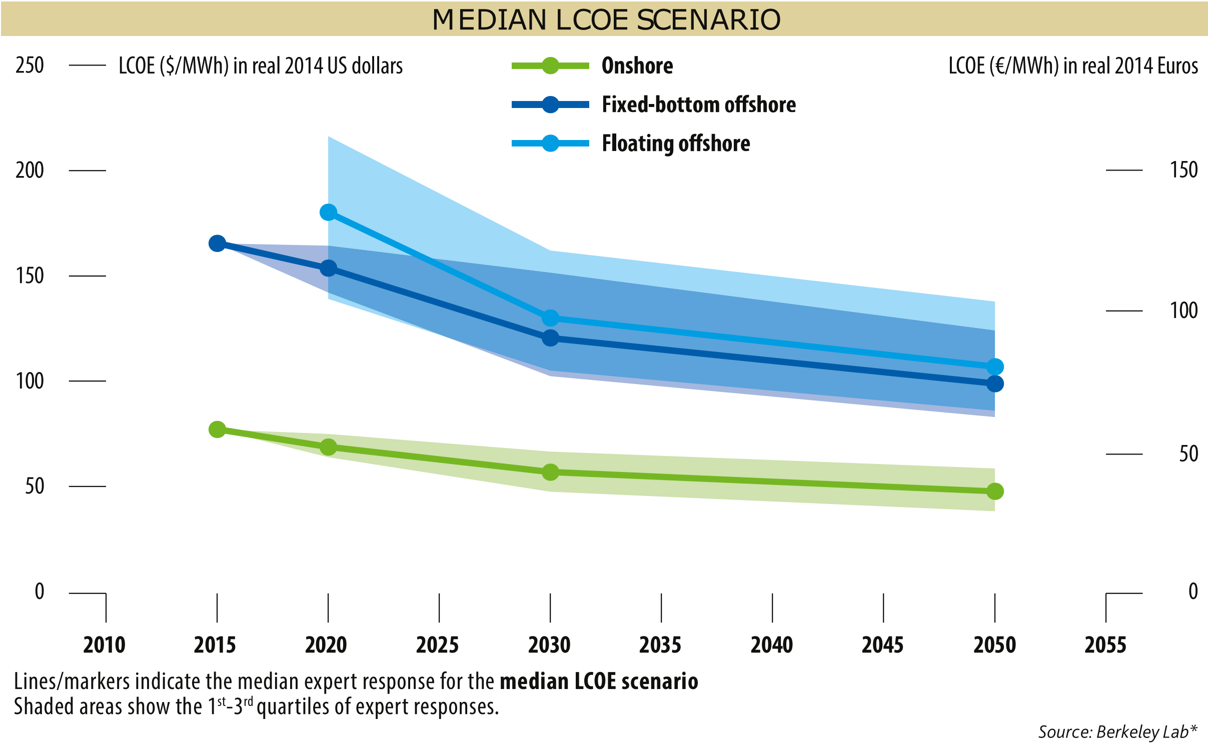


Figure 58. Forecast of the LCOE evolution for onshore and offshore wind farms. Source: Berkeley Lab / Global Wind Energy Outlook 2016. http://bit.ly/2DmrzjB

Figure 59. Representation of the floating wind turbine that Saitec installed in El Sardinero (Santander). Source: YouTube https://youtu.be/vKYBzZHnuhU. License: YouTube Standard

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

Model **Vestas V-164** is shown in Figure 61. 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.

Figure 60. Vestas V-164 wind turbine. Source: Garvarduniversity. https://bit.ly/2Z3YOhT. License: CC BY-SA 4.0

Figure 61. Enercon E-126 wind turbine. Source: Wikimedia Commons https://bit.ly/2MpjmQx. License: CC BY-SA 3.0

Figure 62. MINGYANG SCD6.5 wind turbine. Source: YouTube https://youtu.be/PFPSvxeFw3A. License: YouTube Standard