Test and measurements; Wind data analysis

Lecture 1.1

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Learning outcomes

- To evaluate the different wind sources
- To estimate the wind speed and the influence of external parameters like temperature, pressure, density, etc.
- To estimate numerically the influence of site’s characteristics and orography
- To graph wind speed in value, frequency, direction
- To have confidence with the main tools for the estimation of the wind sources.

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Table of contents

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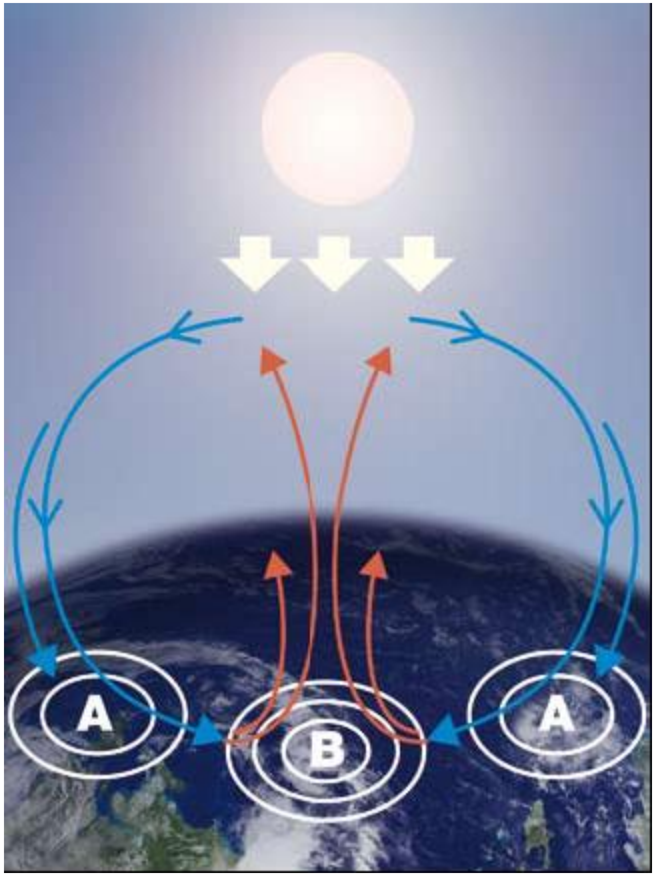
The wind source and formation



2% of the solar radiation is converted into energy of Moving Masses of Air!

The movements are due to the different solar radiation on Earth's surface that causes pressure distributions.

The Earth continually transfer the heat received from the Sun, but not in a uniform way.

In the areas of cold air the pressure of atmospheric gases increases, while where more heat is transferred, the air is heated and the gas pressure decreases.

This creates a macro-circulation due to convective motions:

air masses heat up, decrease their density and rise, recalling colder air flowing on the earth's surface.

This motion of hot and cold air masses produces the high pressure areas and the low pressure areas permanently present in the atmosphere, also influenced by the Earth's rotation.

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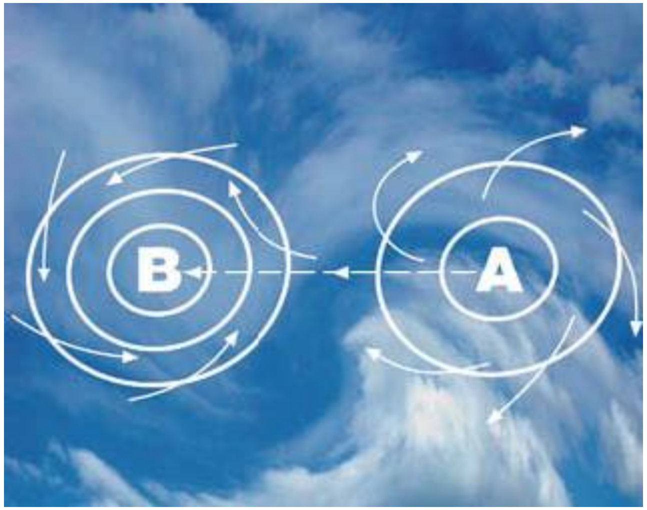
The wind source and formation



The atmosphere tends to constantly restore the balance of pressure, the air moves from areas where the pressure is higher towards those in which it is lower.

The wind does not blow in the direction of the high pressure center with that of the low pressure, but diverts in the northern hemisphere to the right, circulating around the centers of high pressure clockwise and around those of low pressure in the opposite direction.

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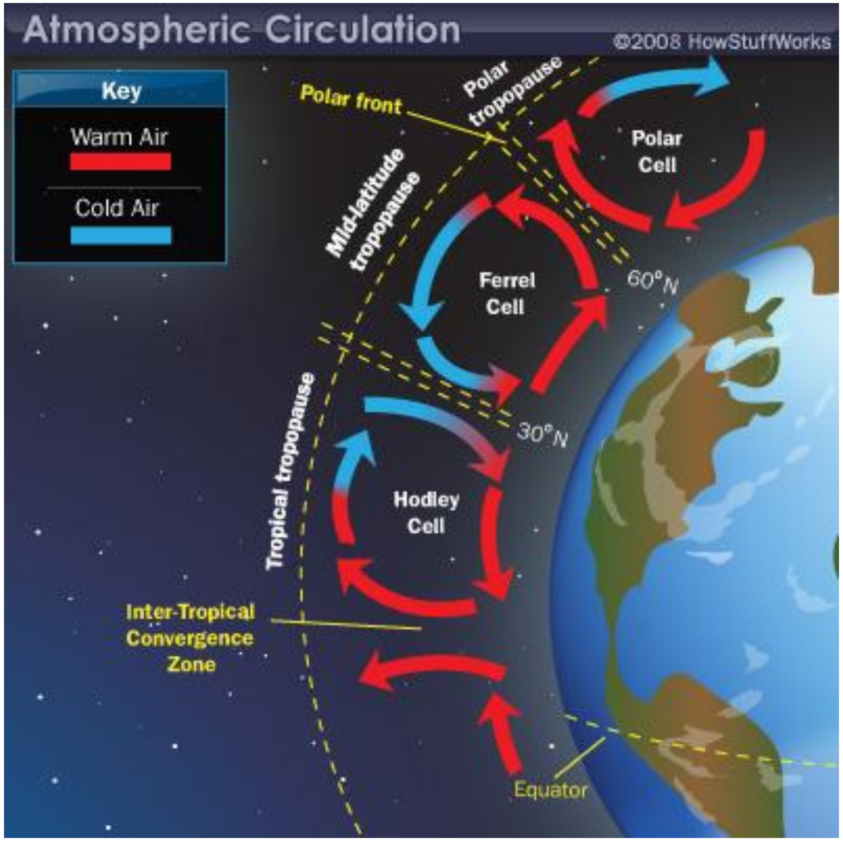
The wind source and formation

Types of wind:
✓ Global wind
✓ Local wind



Global Wind: called geostrophic winds, formed by air masses moving from the poles to the equator. The Poles are subject to less sunlight due to the strong inclination of the sun's rays.

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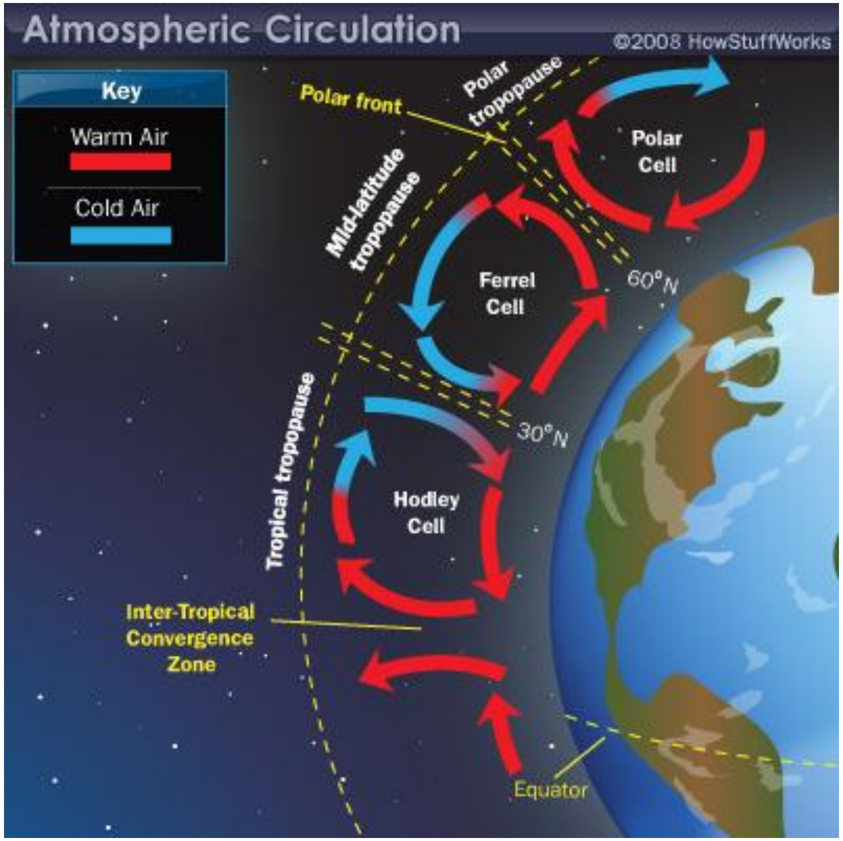
The wind source and formation

The Ferrel cell and the Hadley cell are generated by the downward flow due to air masses moving from warmer areas to colder areas.

These cells also give rise to the

- ❑ Trade winds
- ❑ The westerlies.

Finally, the Earth's rotation through the Coriolis force tends to rotate the air masses:
Clockwise in the Northern Hemisphere;
Counter-clockwise in the Southern Hemisphere



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The wind source and formation

Coriolis effect: a mass moving in a rotating system experiences a force acting perpendicular to both the direction of motion and the axis of rotation.

⇩

Hadley cells: closed loops of air circulation, begin near the equator as warm air is lifted and carried towards the poles. At around 30◦ latitude, north and south, they descend as cool air and return to complete the loop, producing the north-east and south-east trade winds.

Polar cells: similar mechanism produces in the Arctic and Antarctic regions.

Ferrel cells: air flows poleward and eastward near the surface and equatorward and westward at higher altitudes

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The wind source and formation

Breeze

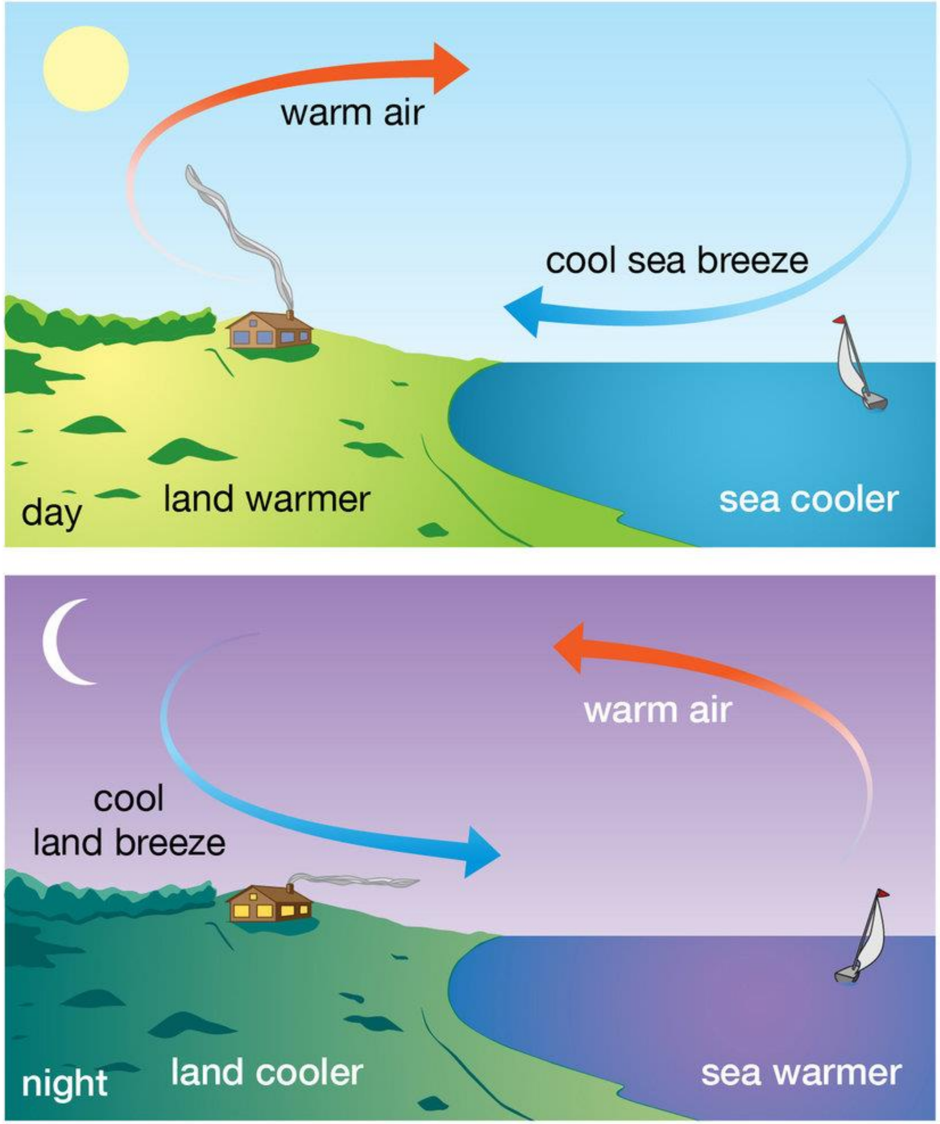
During the Daytime:

Air masses that dominate the oceans, the seas and all the ponds of water are heated less than those located above the masses.

The air above the land surface is warmer and the decrease in density results in a lifting: the colder air coming from the mirrors and heavy water is forced to take its place (sea breeze, land breeze).

During the Night:

the motion is reversed.



Source: Garrison 1993: fig. 8.13, ResearchGate

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The wind source and formation

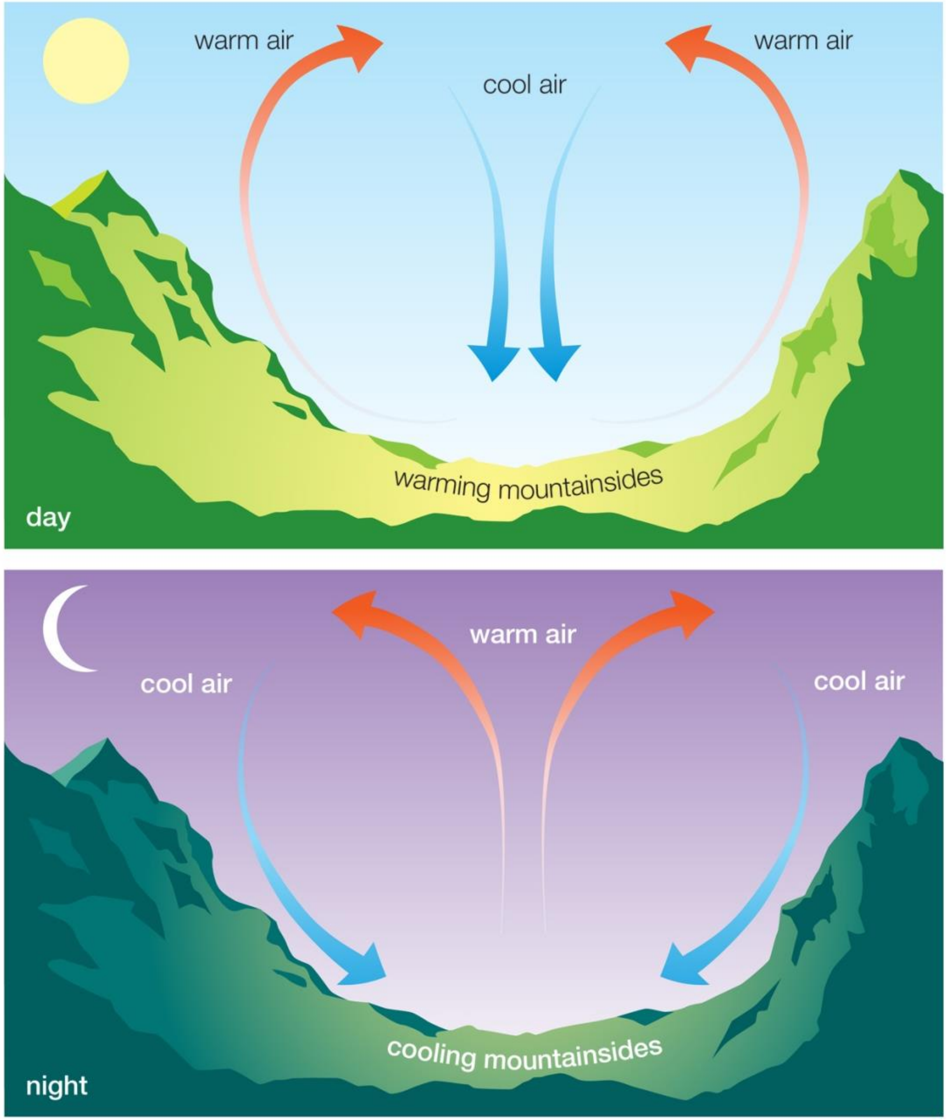
Mountain areas

During the Daytime:

the diurnal winds go back down the slopes during the day, because the air in the valley is more heated and tends to rise in altitude.

During the Night:

the motion is reversed.



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Windiness of a site - measurement

The power depends on the cube of the wind speed.
It is therefore necessary to accurately measure this value in order to avoid errors in the calculation of the manufacturability of a site.

Methods:

1.Using elaborate existing long-term data. The data of interest are obtained by interpolation (only for preliminary investigations);

2.Direct measurement of wind speed (cup anemometer).

The wind speed is proportional to the:

- number of revolutions per unit of time measured by a counter;
- voltage of a dynamo connected to the rotor of the instrument.

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Windiness of a site - measurement

There are also laser or ultrasonic anemometers, digital and devoid of moving parts.

They are normally fitted with two anemometers at different heights.

Cup anemometer

Ultrasonic anemometers

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Windiness of a site - measurement

The measurement campaign takes at least one year

Installation of the anemometric stations

- The measurement points needs to account for the average hub height, blade lengths and roughness
- The placement follows the feasibility study on the land

Anemometric towers →
- Anemometer (velocity and direction measurement)
- Pole and supporting cables (20 – 100 m)
- Data acquisition system

All the measurement chain and procedures needs to follow what prescribed by the standard regulation (e.g. **IEC 61400-12**)

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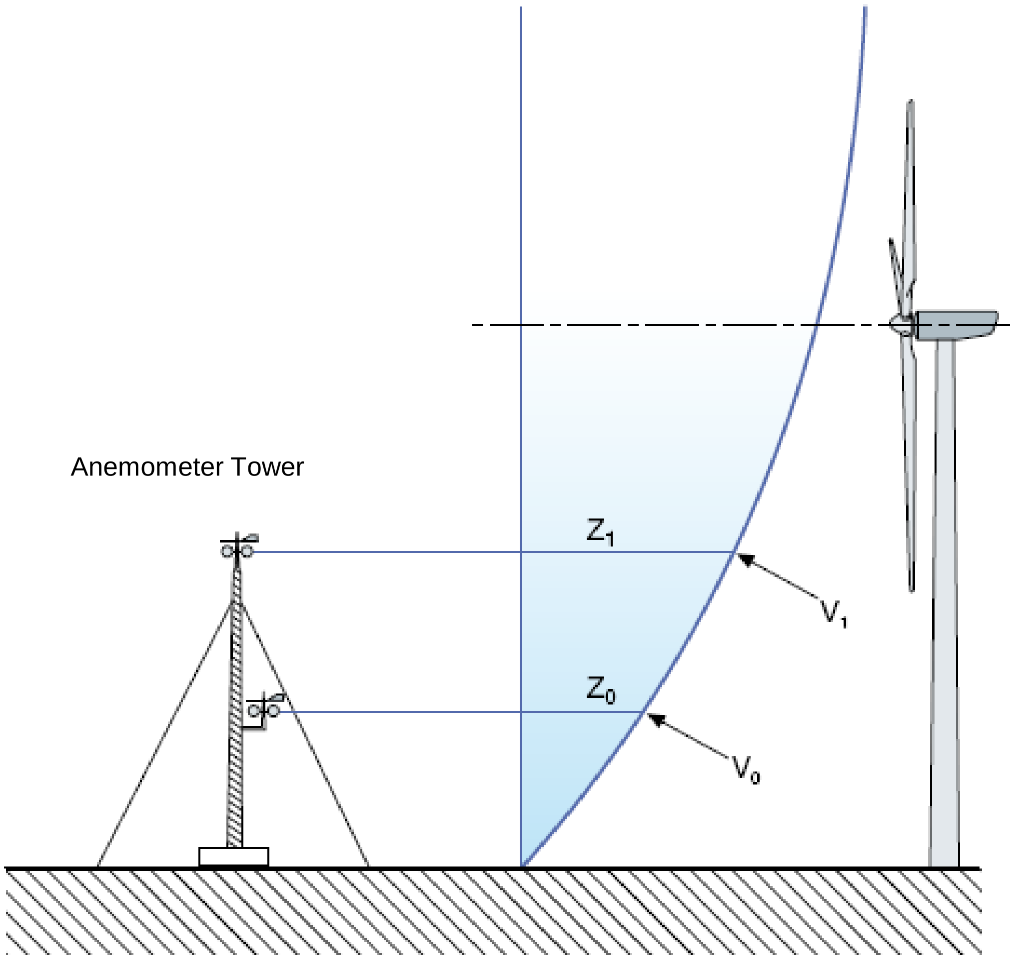
Windiness of a site - measurement



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Windiness of a site - measurement

SODAR (SOnic Detection And Ranging), also written as sodar, is an alternative instrument used as a wind profiler to measure the scattering of sound waves by atmospheric turbulence. SODAR systems are used to measure wind speed at various heights above the ground, and the thermodynamic structure of the lower layer of the atmosphere.

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Windiness of a site - measurement

The difficulties involved in assessing the available energy are related

1. Unpredictability of the spring wind, the wind being a magnitude strongly dependent on the time (with variations in seasonal, daily and instantaneous)
2. the place, even with substantial differences in relation to the distance from the ground and the topography of the site.

The measurement of wind speed is averaged over time intervals of the order of 10 minutes, the data collected can then calculate the average hourly, daily, monthly and annual basis, as well as their maximum values within each interval.

The observations must last at least one year.

A good practice is to compare the first results obtained with time series available for the area of interest. If the difference between the two values is modest, it is possible to reduce the time of observation of the wind resource to a few months or decrease the uncertainty associated with the outcome a campaign anemometric.

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Windiness of a site - measurement

Limits of the measurement campaign:

- Measurements are local and referred to the placement of the equipment
- The height of the measurement can be not enough to cover all the rotor of the wind turbine
- The knowledge of the distribution of the wind resource all over the farm area is crucial for the optimum placement of the turbines

Measured data need to be extended over the farm area

- Orographic analysis
- Simulation software

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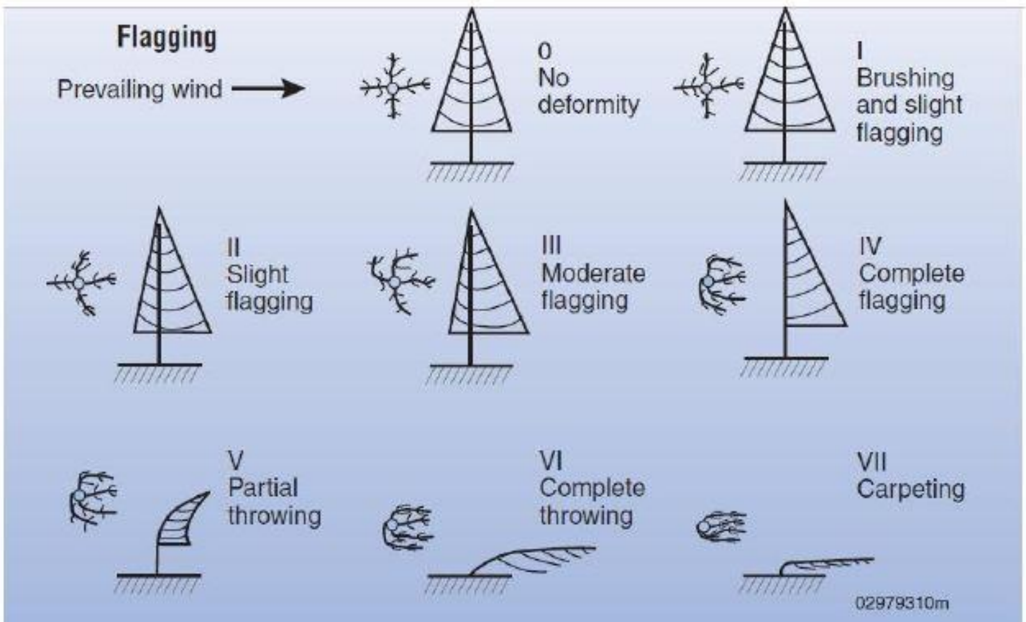
Windiness of a site - Randomness

The vegetation on the ground is also a good indicator of the prevailing winds.

The degree to which conifers have been deformed by the wind can be used as a rough gauge of average annual wind speed.



Griggs-Putnam Index of Deformity

Index	I	II	III	IV	V	VI	VII
Wind mph	7-9	9-11	11-13	13-16	15-18	16-21	22+
Speed m/s	3-4	4-5	5-6	6-7	7-8	8-9	10

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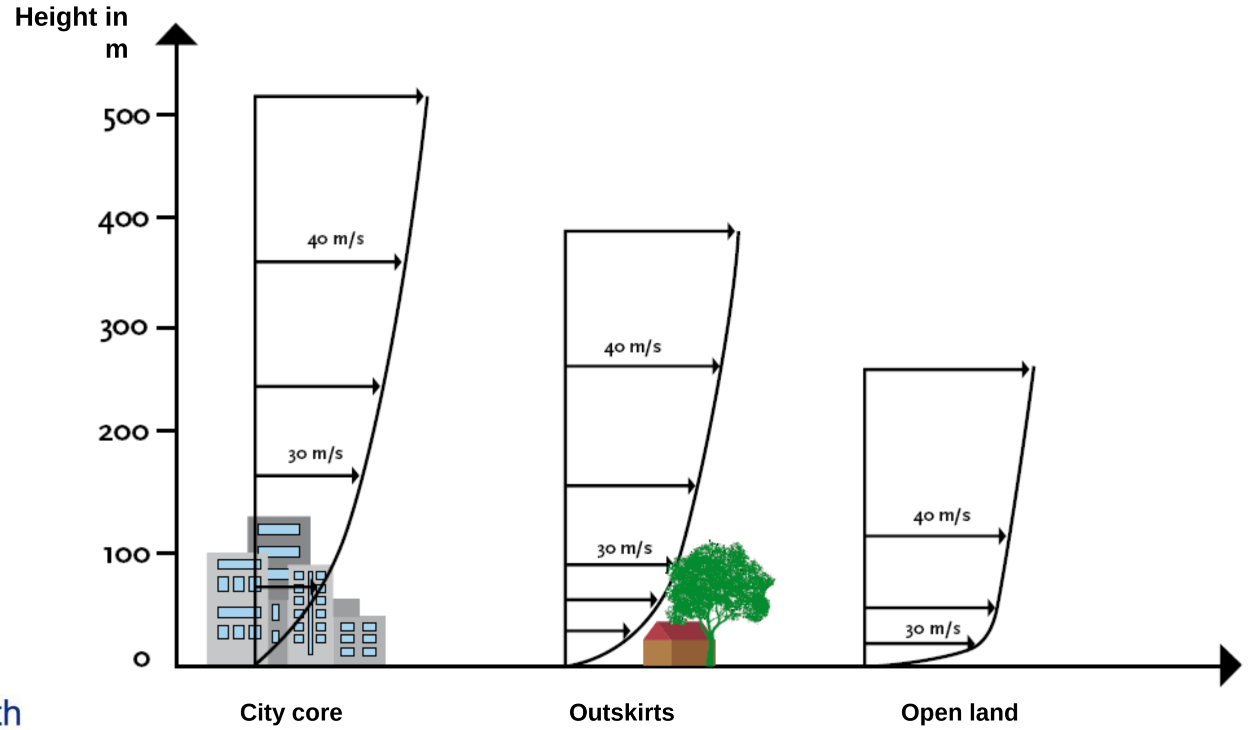
Windiness of a site - Randomness

The wind speed also varies greatly at different altitudes. The presence of obstacles and surface roughness results in a progressive decrease of the wind speed than the speed of the undisturbed flow (boundary layer).



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Windiness of a site - Randomness

Hellman model allows us to model the wind speed by tying its value to a reference height. The model takes into account the macroscopic roughness and average weather conditions of the site. The trend of wind speed V as a function of height z (vertical profile of speed) is usually expressed through relations of the type:

$$\frac{V}{V_1} = \left(\frac{z}{z_1}\right)^{\alpha}$$

Where V_1 is the wind speed measured at the height z_1 (typical value 10m) and α (*wind shear exponent*) depends on the roughness class of the soil and by the conditions of stability of the air.

Coefficient α	Description of terrain
0.095	Coastal waters of inland sea
0.121	Flat shore of ocean small islands
0.130 – 0.135	Open grasslands without trees
0.143	Open slightly rolling farm land
0.128 – 0.170	Open level agricultural land with isolated trees
0.170	Open fields divided by los stone walls
0.200	Rough coast
0.220	Gently rolling country with bushes and slam trees
0.230	Relatively level meadow land with hedges and trees
0.250 – 0.303	Level country uniformly covered with scrub oak and pine
0.357	Wooded and treed farm land

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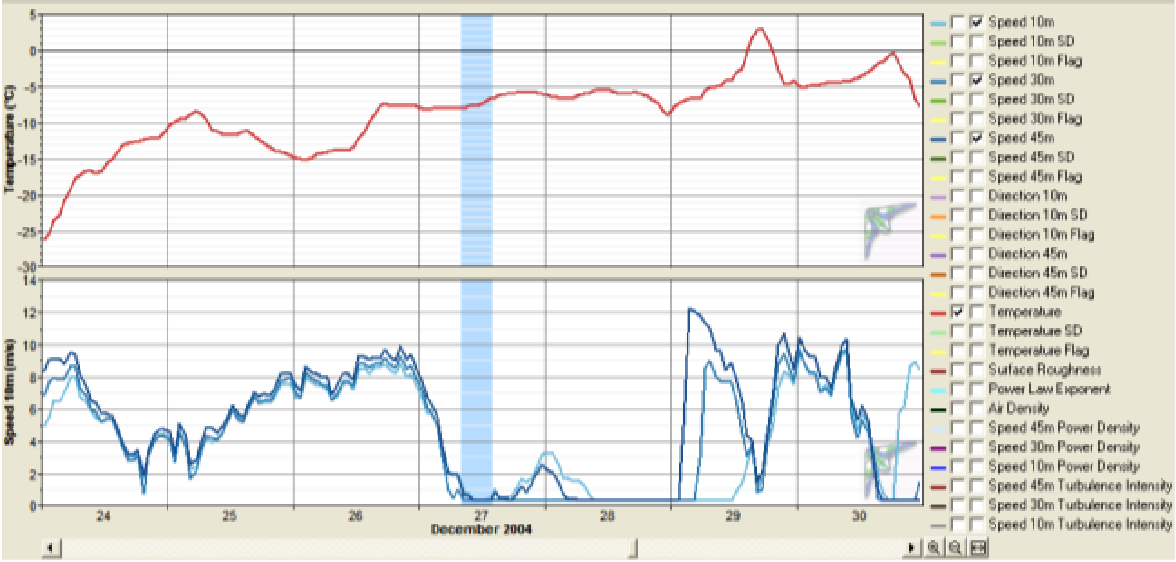
Windiness of a site – Data gathering

- Wind data are usually gathered in daily temporal series
- The acquisition trigger depends on the instrument (in general is 1 second)
- The data are averaged and collected in periods of 10 minutes
    - ➢ Average value
    - ➢ Maximum
    - ➢ Minimum
    - ➢ Standard deviation



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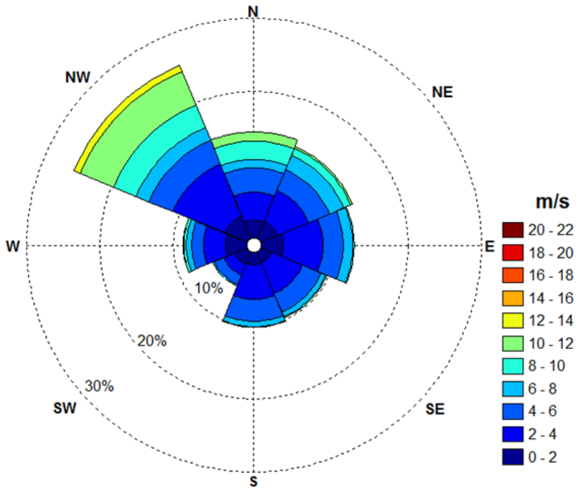
Windiness of a site – Data elaboration

- Filtering of anomalies and tower shadow
- Interpolation and integration with historical data over the periods with wrong records
- Filtering of direction data during periods of no-wind
- Elaboration of statistical quantities for daily, monthly and annual periods
- Weibull fitting
- Elaboration of the boundary layer profile
  - Exponential or logarithmic law
  - Verification of the roughness parameter (p)

$$V_z = V_0 \left(\frac{z}{z_0} \right)^p$$

$$V_2 = V_1 \frac{\ln z_2 - \ln z_1}{\ln z_1 - \ln z_0}$$



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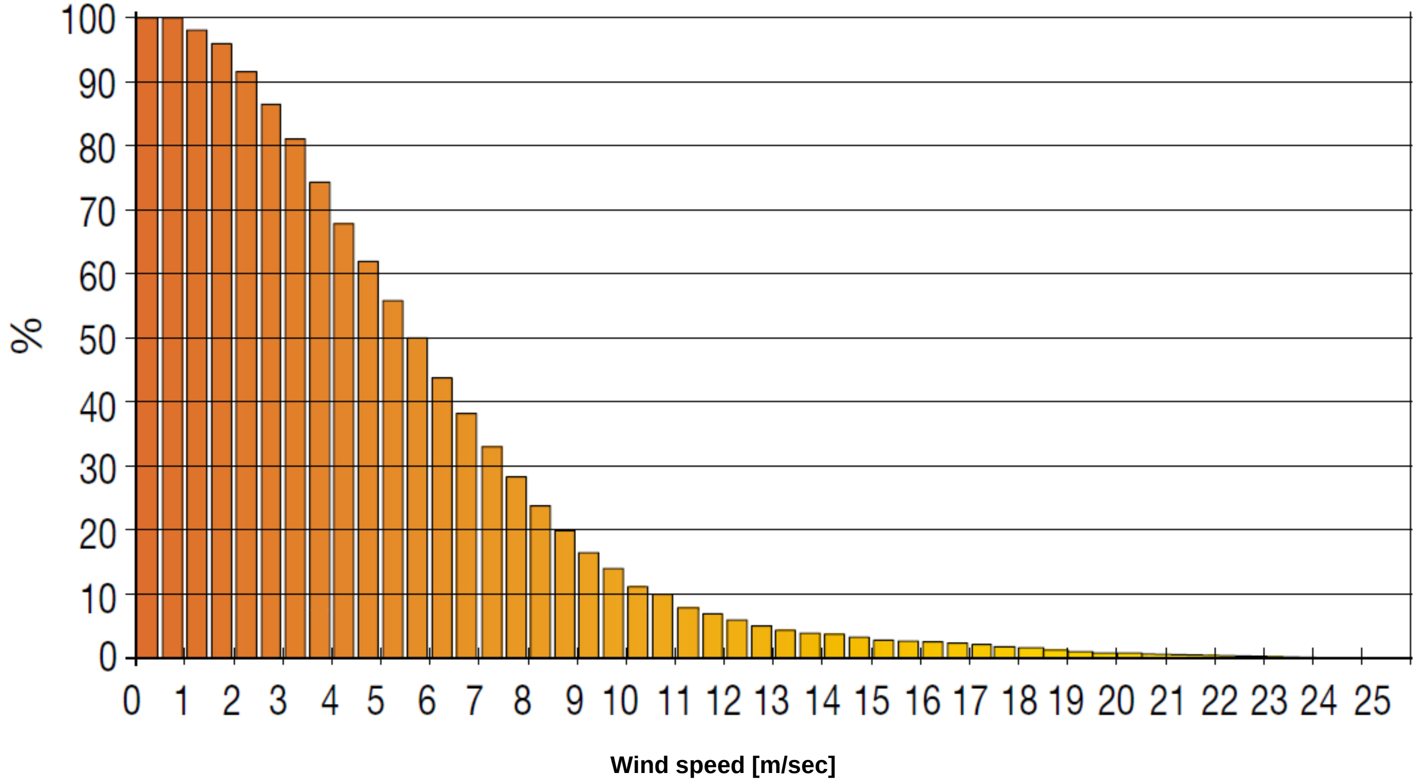
Windiness of a site - the frequency

Histogram of the percentage duration of wind speeds



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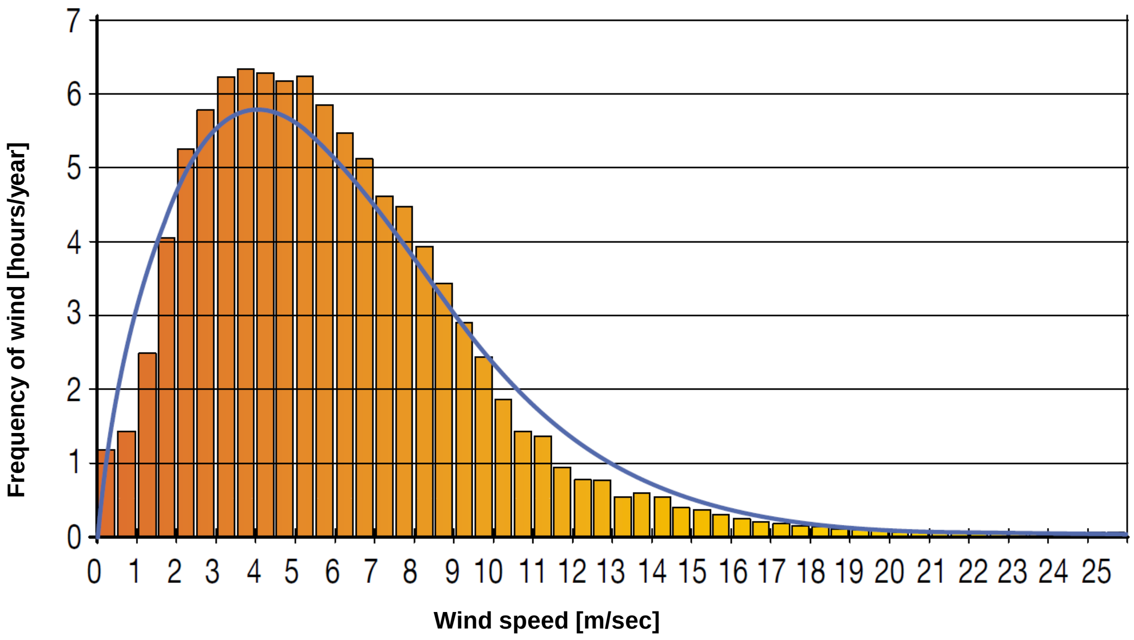
Windiness of a site - the frequency

The measurements obtained with the surveys are organized into classes of speed given amplitude. Each class is defined by a average value of the wind speed belongs to the same class, which is associated with the corresponding number of hours / year of persistence of the wind speed within the respective interval.

$$f_i = \frac{n_i}{n_{tot}}$$

n_i : the number of hours / year persistence of the speed of wind within the the class in question

n_{tot}: the total number of hours available during the year, or 8760.



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Windiness of a site - the frequency

The most common function to an analytic representation of the frequency distribution is the Weibull distribution, defined by the following Equation :

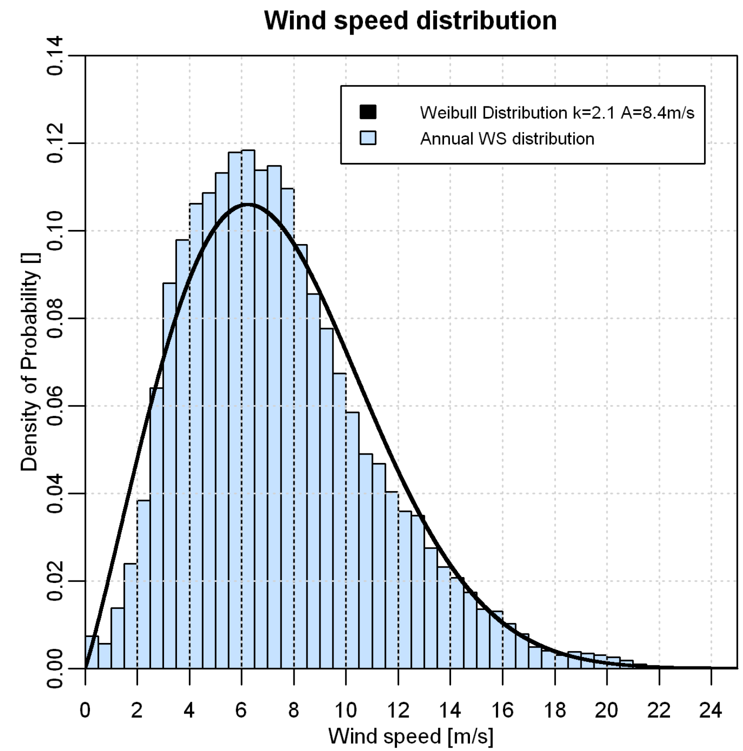
Shape parameter(k)

$$f(v) = \frac{k}{A} \cdot \left(\frac{v}{A}\right)^{k-1} e^{\left[-\left(\frac{v}{A}\right)^{k}\right]}$$

Scale Parameter (A)

Scale parameter A [m/s] is proportional to the average speed

Shape parameter k is, however, usually between 1.3 and 2.5 (with a typical value of reference equal to 2) in relation the characteristics of the site under analysis.



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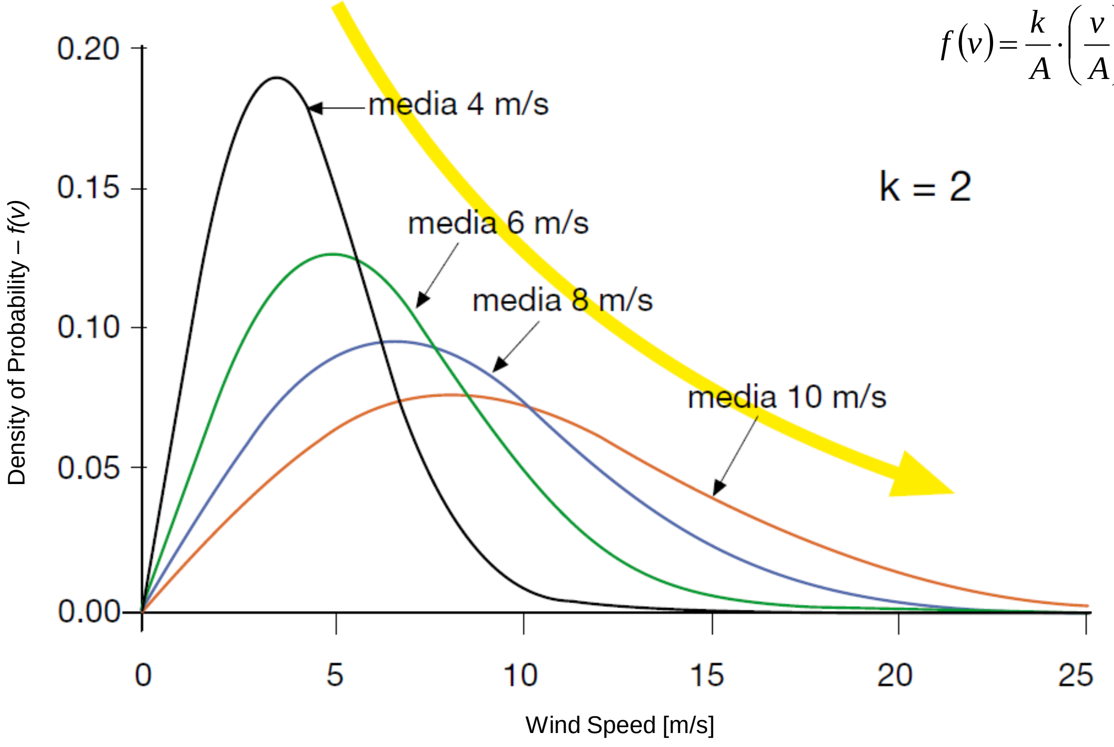
Windiness of a site - the frequency

Weibull distribution:

$$f(v)=\frac{k}{A}\cdot\left(\frac{v}{A}\right)^{k-1}e^{\left[-\left(\frac{v}{A}\right)^{k}\right]}$$

Shape parameter(k)

Scale Parameter (A)



* Media = Average

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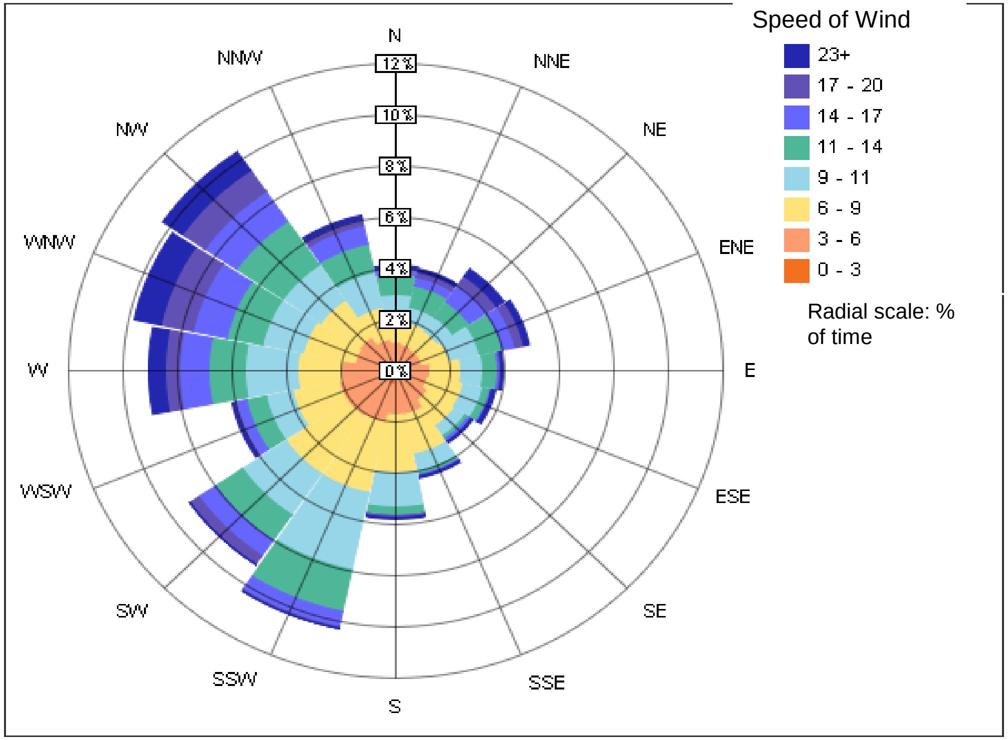
Windiness of a site - the frequency

To plot the information on the distribution of the speed and frequency of the main directions using the compass rose.

Divide a circular space in most sectors and trace the rays of these proportionally

The relative frequency, thus indicating the percentage of time during which the wind has been blowing in that direction.



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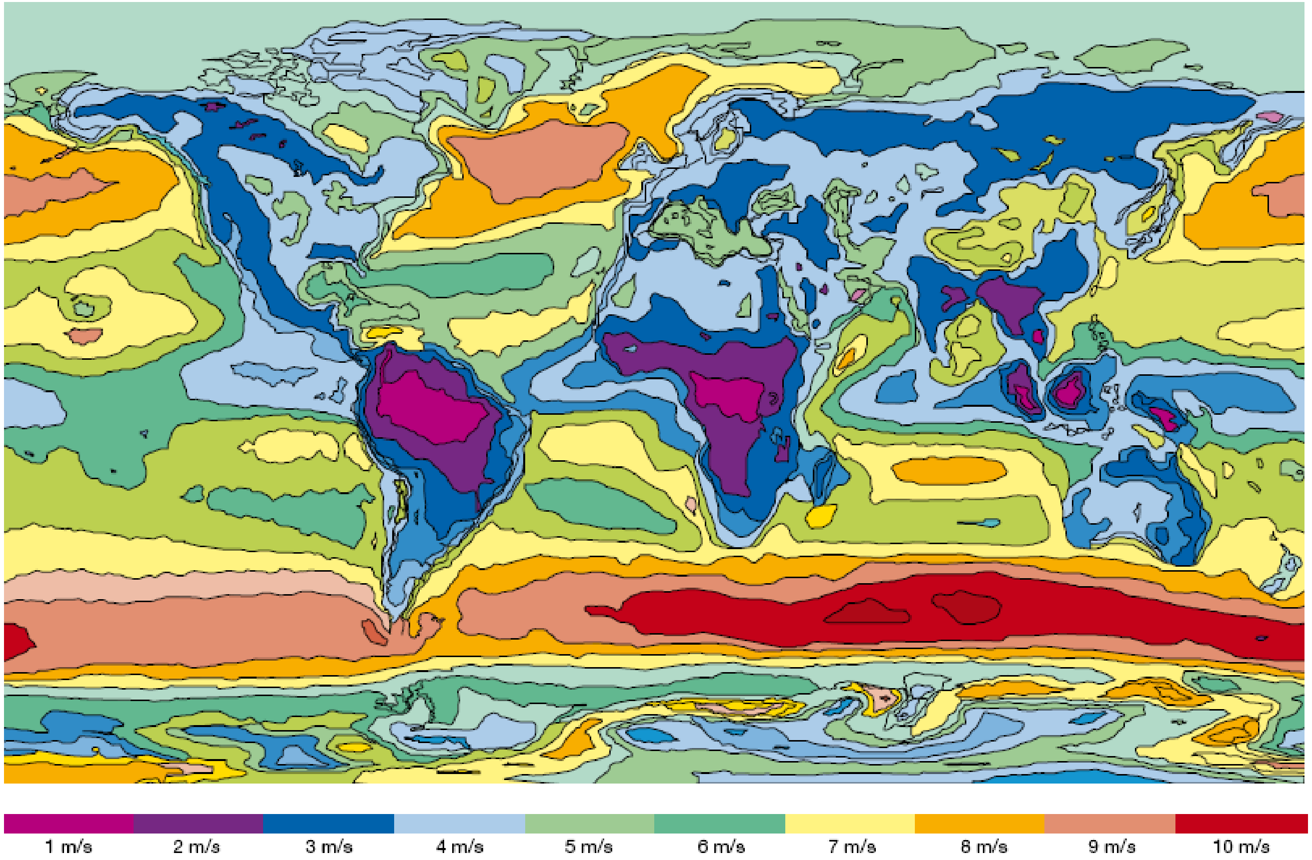
Wind Maps



World wind map: average wind speed in m/s at 10m of height

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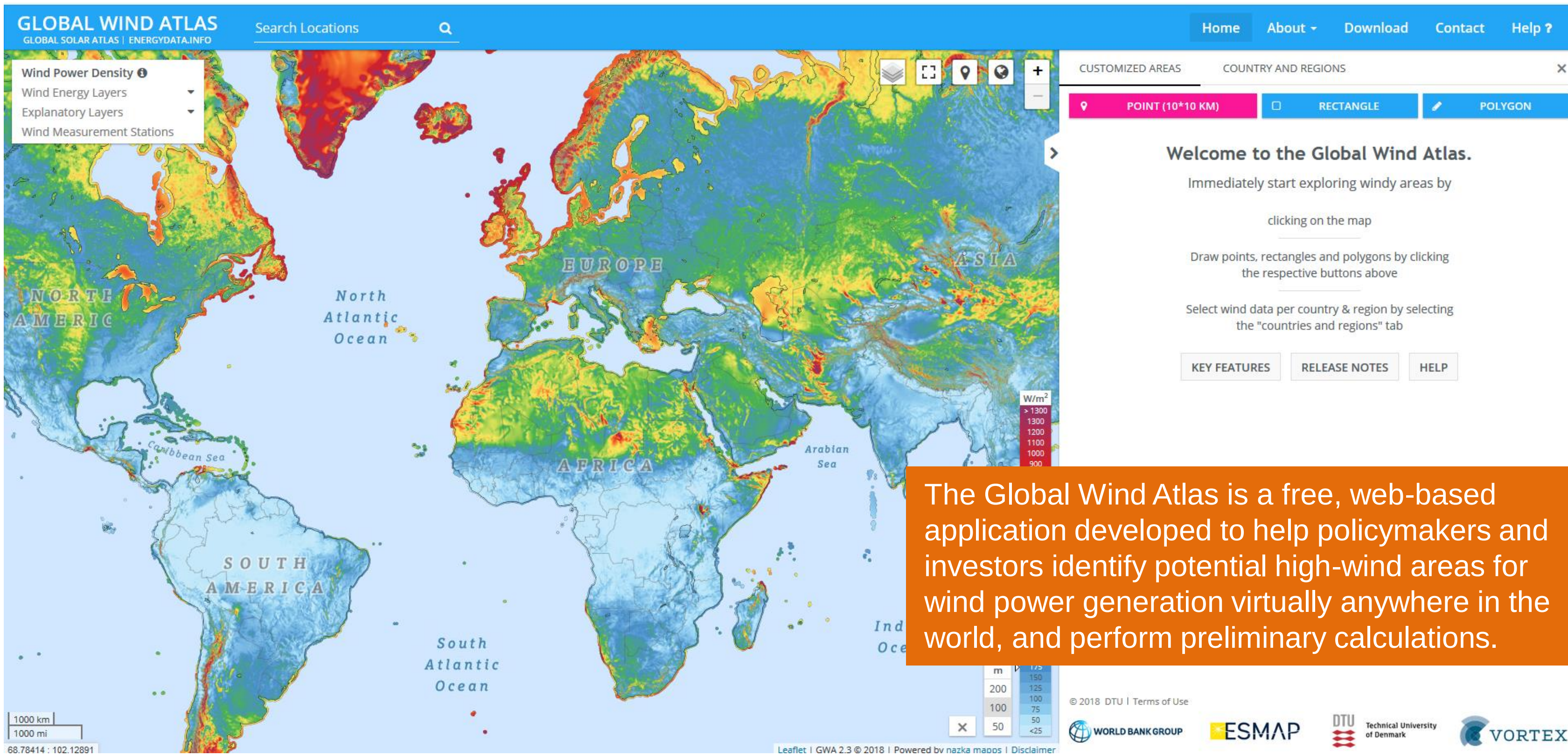
Tools and Software

https://globalwindatlas.info/



The Global Wind Atlas is a free, web-based application developed to help policymakers and investors identify potential high-wind areas for wind power generation virtually anywhere in the world, and perform preliminary calculations.

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Tools and Software

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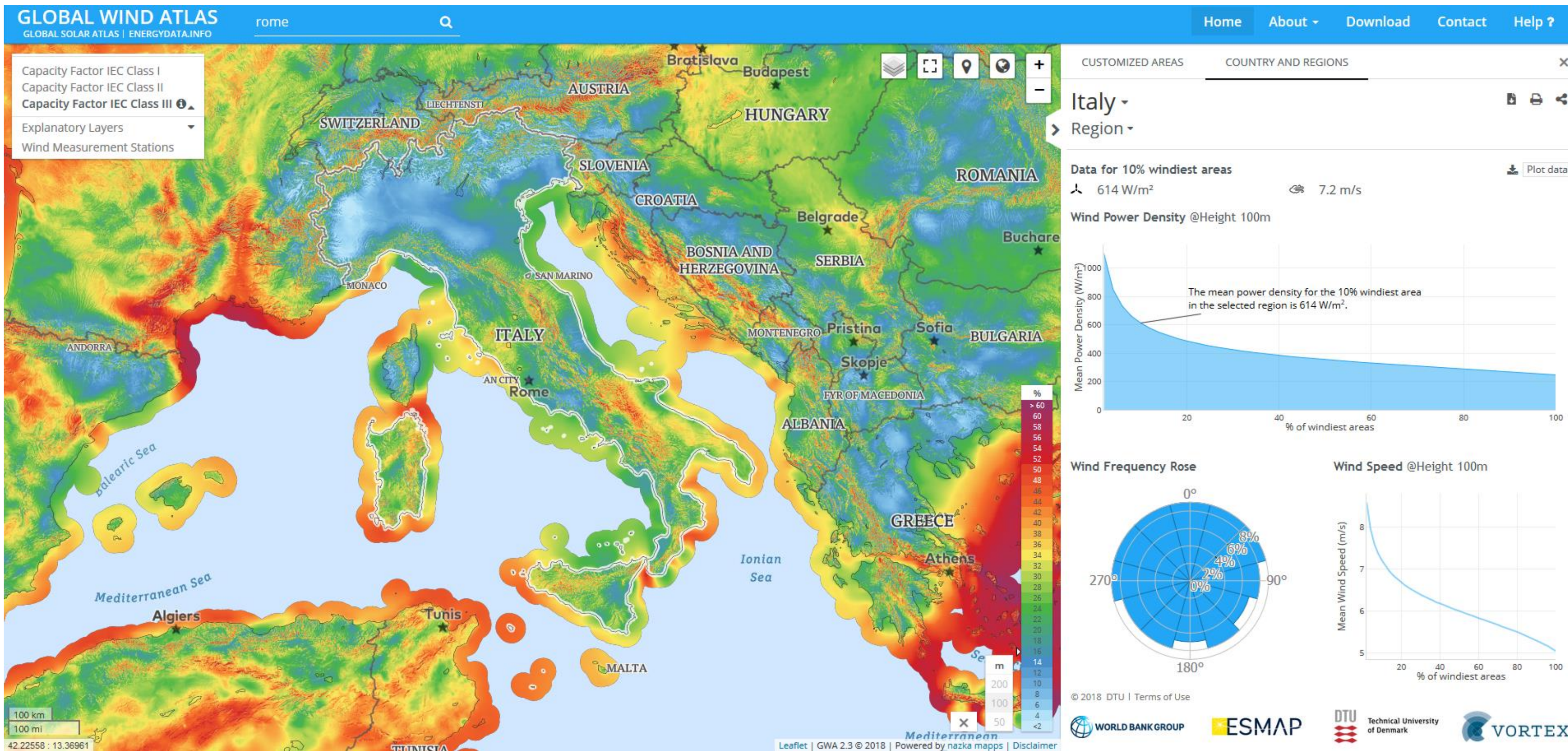

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Summary of the provided knowledge

- Wind source is generated by a no uniform solar radiation on Earth's surface that causes pressure distributions
- Winds can be divided in two groups: Global wind and Local wind
- Wind speed can be estimated using long-term data or direct measurement
- Wind speed varies greatly at different altitudes
- Hellman model allows to model the wind speed by tying its value to a reference height

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Summary of the provided knowledge

- The compass rose allows to plot the distribution of the speed and frequency of the main directions
- Wind maps give information about wind speed using appropriate colour scales
- Global Wind Atlas is one of the available tools to help the identification of potential high-wind areas for wind power generation

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References

Books and Reports:

- Quaderni di Applicazione Tecnica ABB [Translated in English]

Websites:

- https://globalwindatlas.info/

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Selection of Location and Sizing

Lecture 1.2

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Learning outcomes

- To evaluate the main characteristics of selected site
- To recognize the different simulation models micro-siting
- To identify local effects due to the orography
- To identify the main site’s characteristics must be considered for a correct dimensioning of a wind farm

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Table of contents

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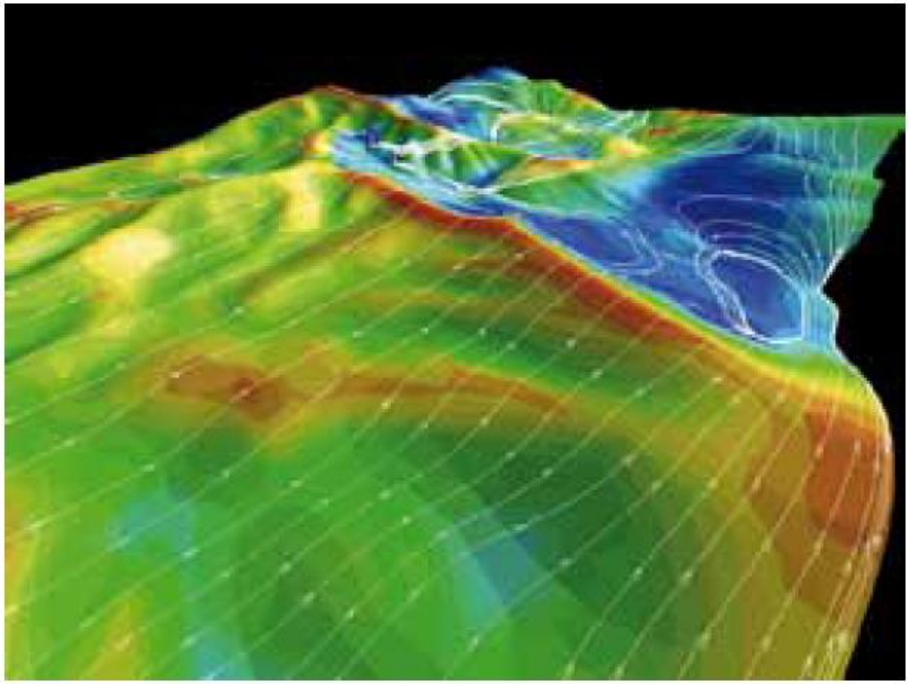
Windiness of a site - micro-siting

Once you have collected data from multiple measurement tools, the same are extended to the entire area under consideration. This procedure, known as micro-siting, may be performed by interpolating the numerical data of the campaign, making use of the classical equations of fluid dynamics such as the conservation of mass and the Navier-Stokes equations.

Example of computational techniques of micro-siting



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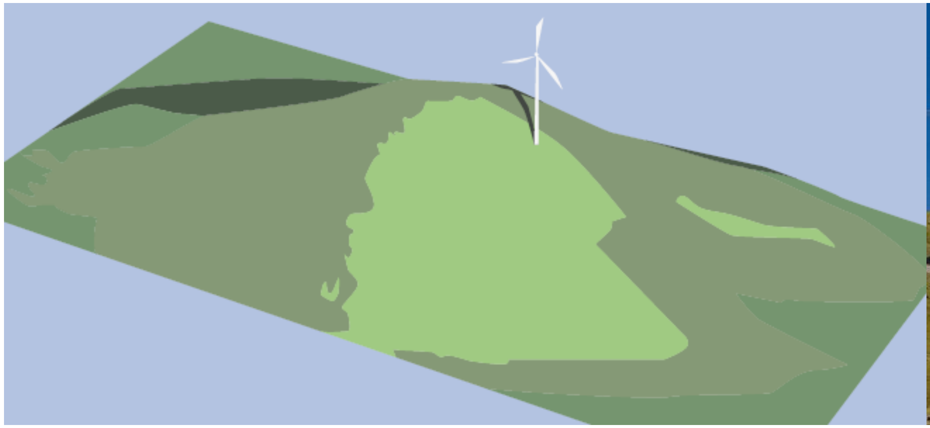
Windiness of a site - micro-siting

The micro-siting is used to calculate the productivity of a region, taking into account the roughness of the terrain and topography (topography of the Earth, as well as those of the surface that those submarines).

The micro-siting also allows to calculate the increase of local rate due to the configuration of the land: Tunnel Effect and Hill Effect.

Hill Effect: the increase of the wind speed is due to an increase of the slope of the relief in the direction of the wind.



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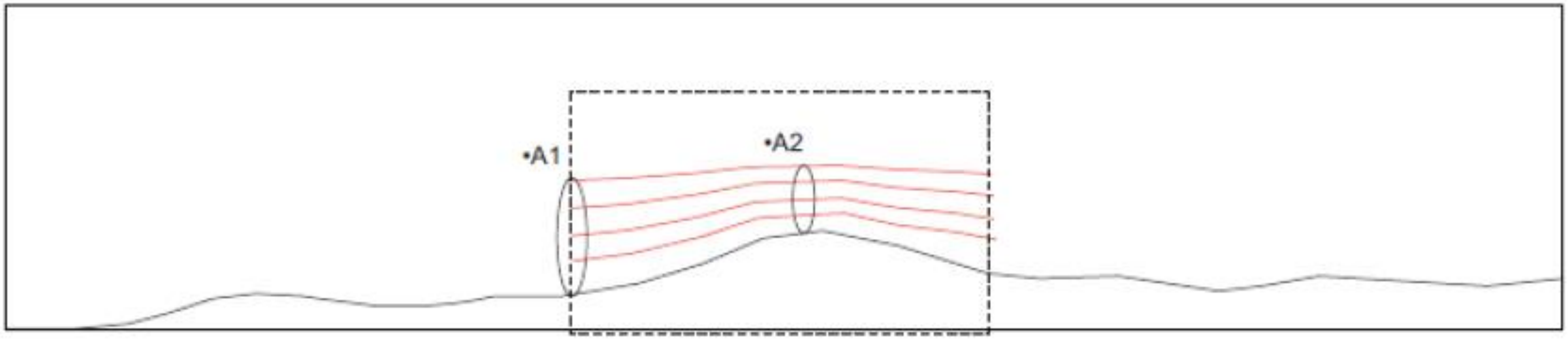
Windiness of a site - micro-siting

Hill effect, for low slope hills, the stream pipe get compressed by the rising of the ground surfaces and the pressure of the atmospheric stratification, generating a sort of venture effect on the wind which is then expanded and accelerated on the top of the hill (momentum conservation law)



For high slopes (>17 degrees) some non-linear effect as flow separation and vortices are generated downstream with following result of losses in wind velocity, direction and stability

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Windiness of a site - micro-siting

Tunnel Effect: The increase in speed is due to a narrowing of the section offered to the passage of the fluid vein. The fluid is in fact channeled through the area where you will install the wind turbine.

Also the effects of turbulence, both own the air current, is induced by the presence of other wind turbines, can be taken into account in the use of software micrositing, leading to minimization of losses to wake within the wind farm.

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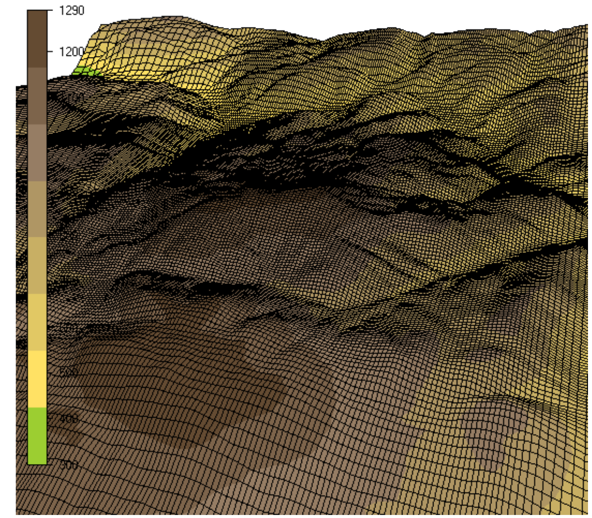
Windiness of a site - micro-siting



DEM, (Digital Elevation Model): digital representation of the distribution of ground local altitude

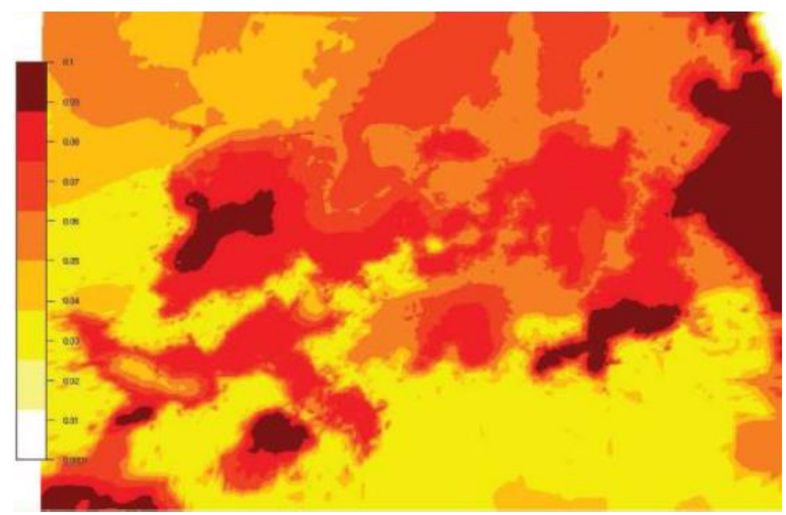
Remote sensing →
- Satellite
- Aeronautical
- Ground sensors

Ground roughness map

Location survey on-site to identify the roughness characteristics in terms of the z_0 parameter.

Values of z_0 are tabled with respect to the type of ground

Ground type	Z0 (m)
Heavy sea	0,005
Flat ground	0,1
Sparsely vegetated areas	0,3
Forest and wooded areas	0,5
Urban area	1,5



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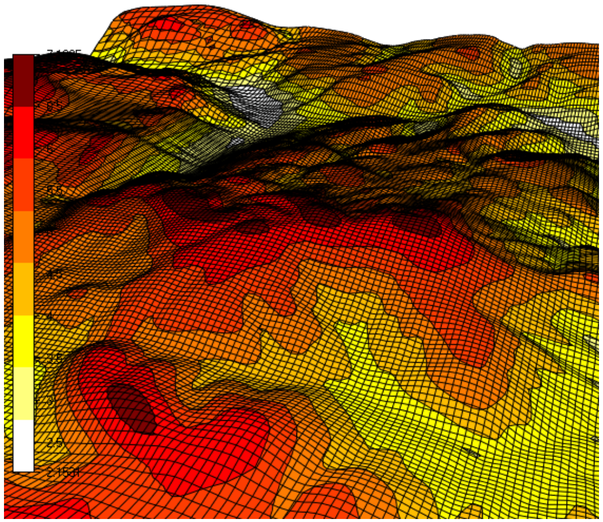
Windiness of a site - micro-siting

Simulation:

Starting from all the data collected in the previous steps, it is possible to use a software to predict the wind distribution over the selected area of the wind farm. This map is finally useful to:

- Analyse the potential energy production of the site
- Optimise the turbine placement (micro-siting)



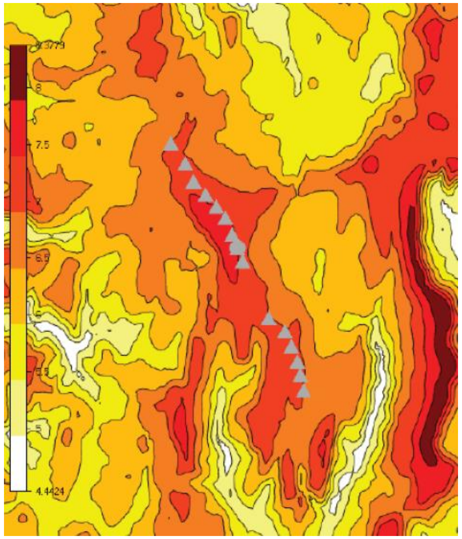
Some software

Linear. Calculation of the wind potential, of the wind energy (after the selection of a specific machine) and of the environmental impact (noise and view)

- WAsP
- Wind Pro
- Wind Farmer
- Wind Farm

Non Linear. CFD based calculation of the wind field (flow separations, speed-up, turbulence and 3d effects)

- WindSim
- MeteoDyn



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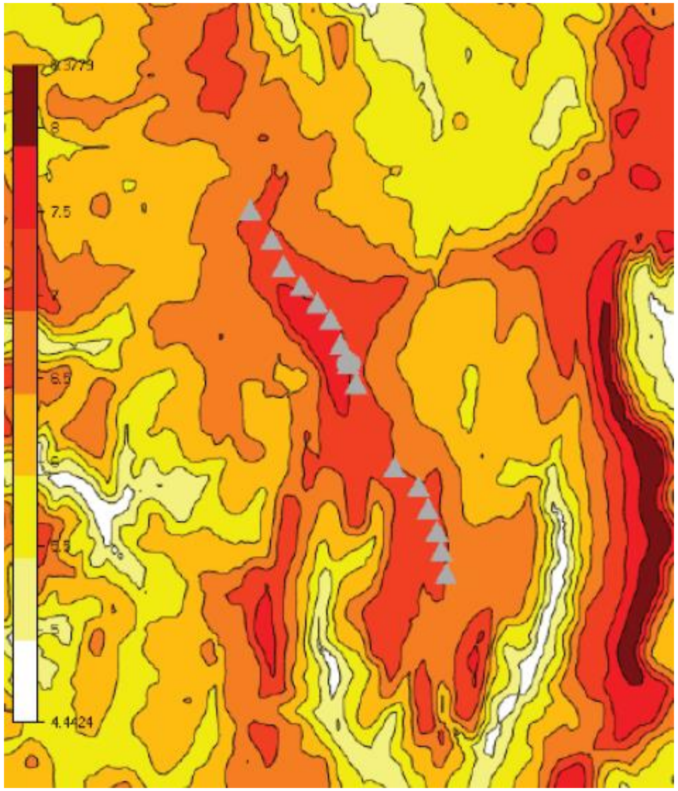
Windiness of a site - micro-siting

Once the iso-wind map is determined, it is possible to attempt the wind farm layout

Definition and optimiziation of the wind farm layout is a compromise solution between design specifications as:

- Wind availability
- Aerodynamic interferences
- Accessibility of the selected placements
- Internal viability
- Land availability
- Distance from electrical grid and auxiliary structures
- Aerodynamic issues
  - Turbulence
  - Vertical inflow angle
  - Boundary layer



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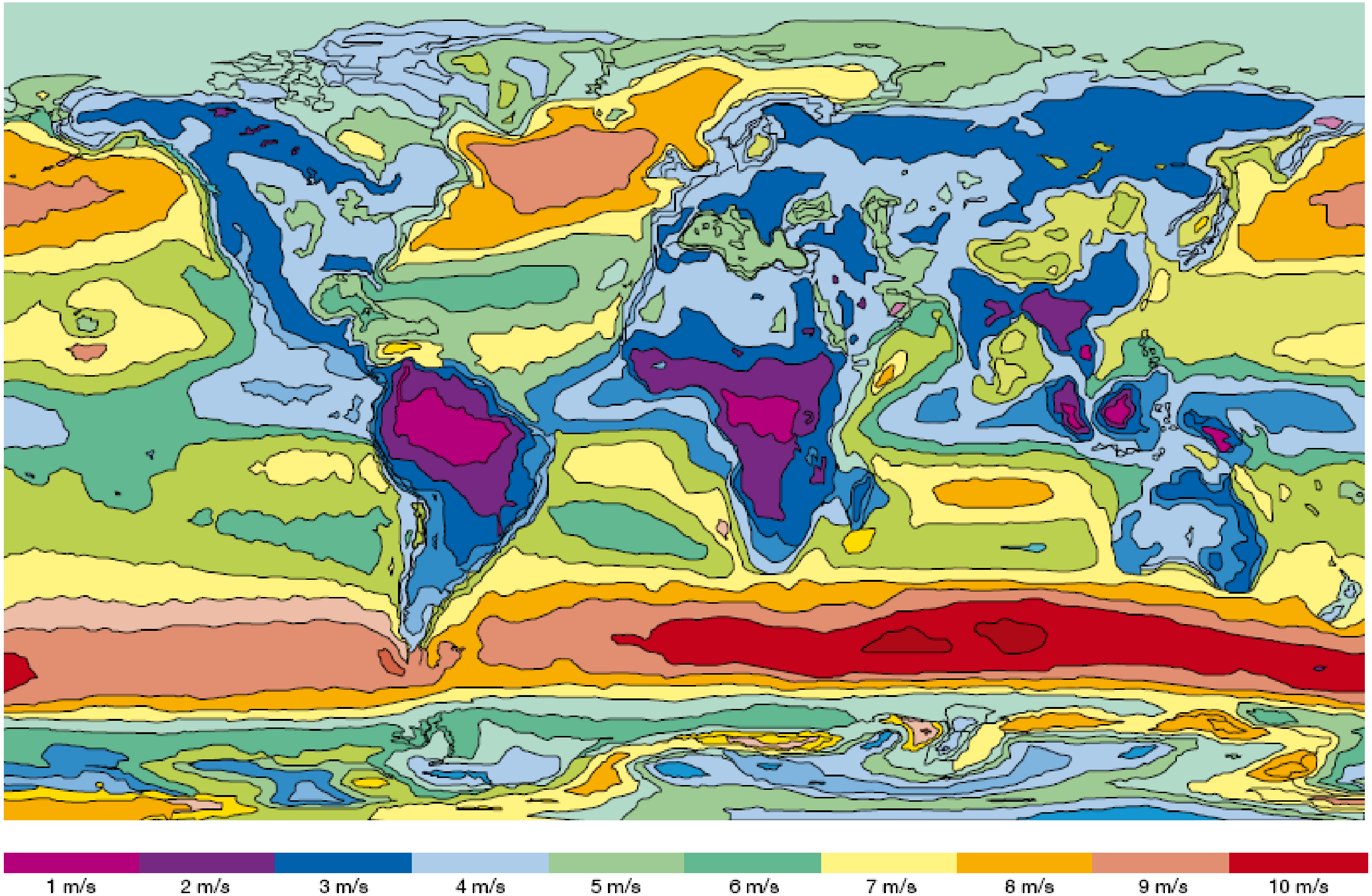
Wind maps



World wind map: average wind speed in m/s at 10m of height

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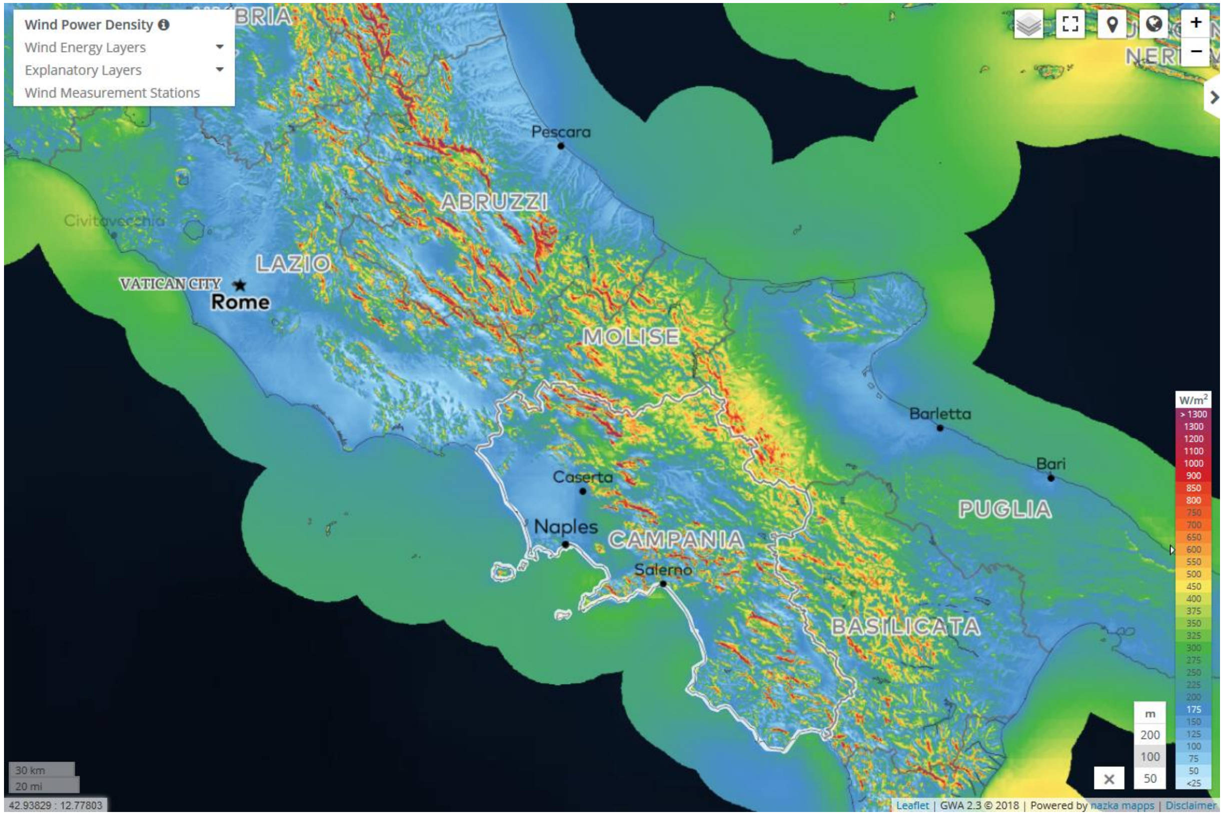
Wind Power Density

Wind Power Density



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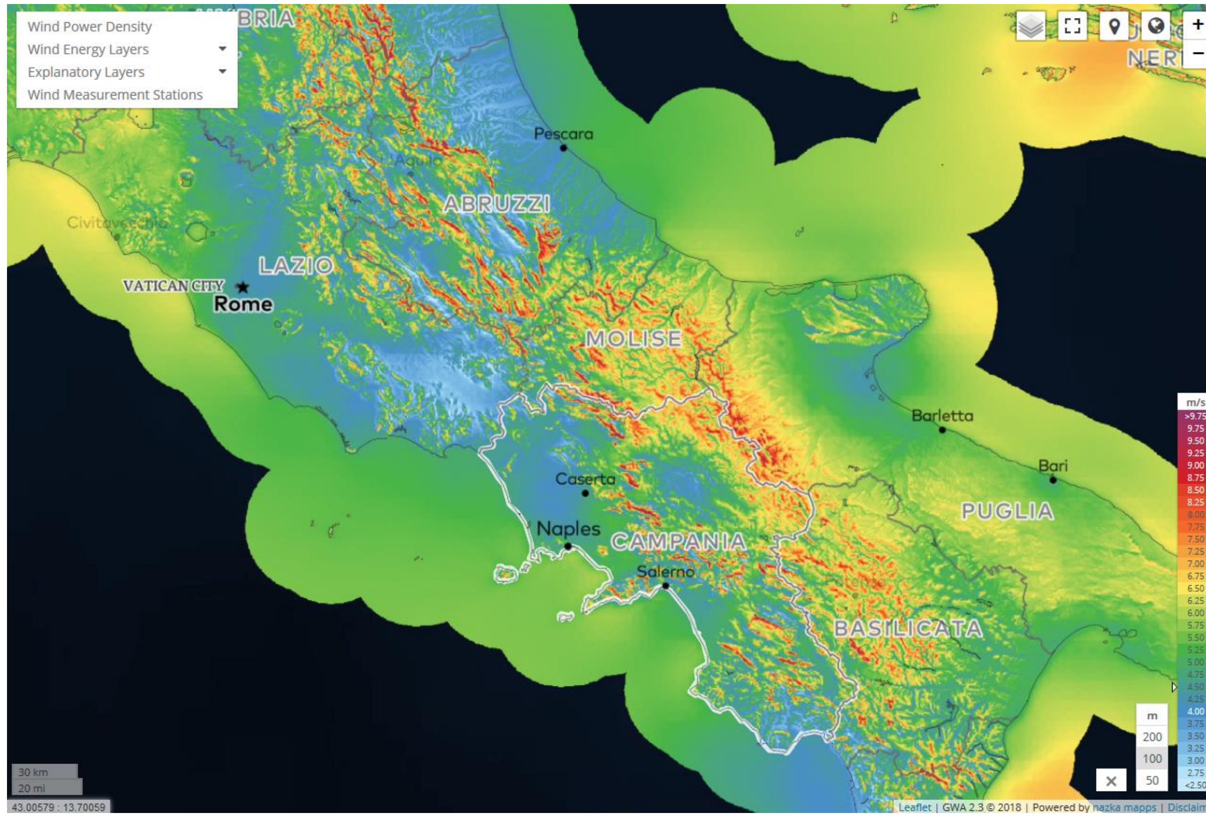
Wind Speed

Wind Speed



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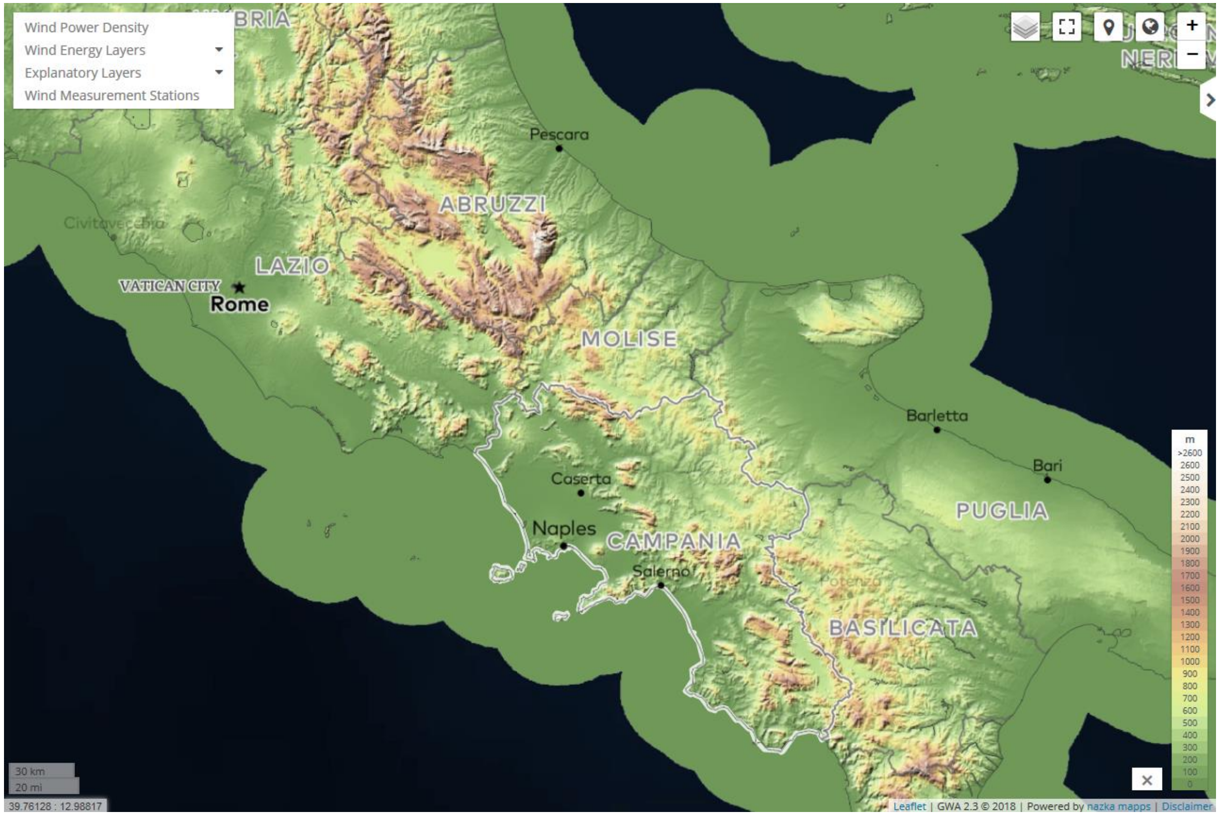
Orography

Orography



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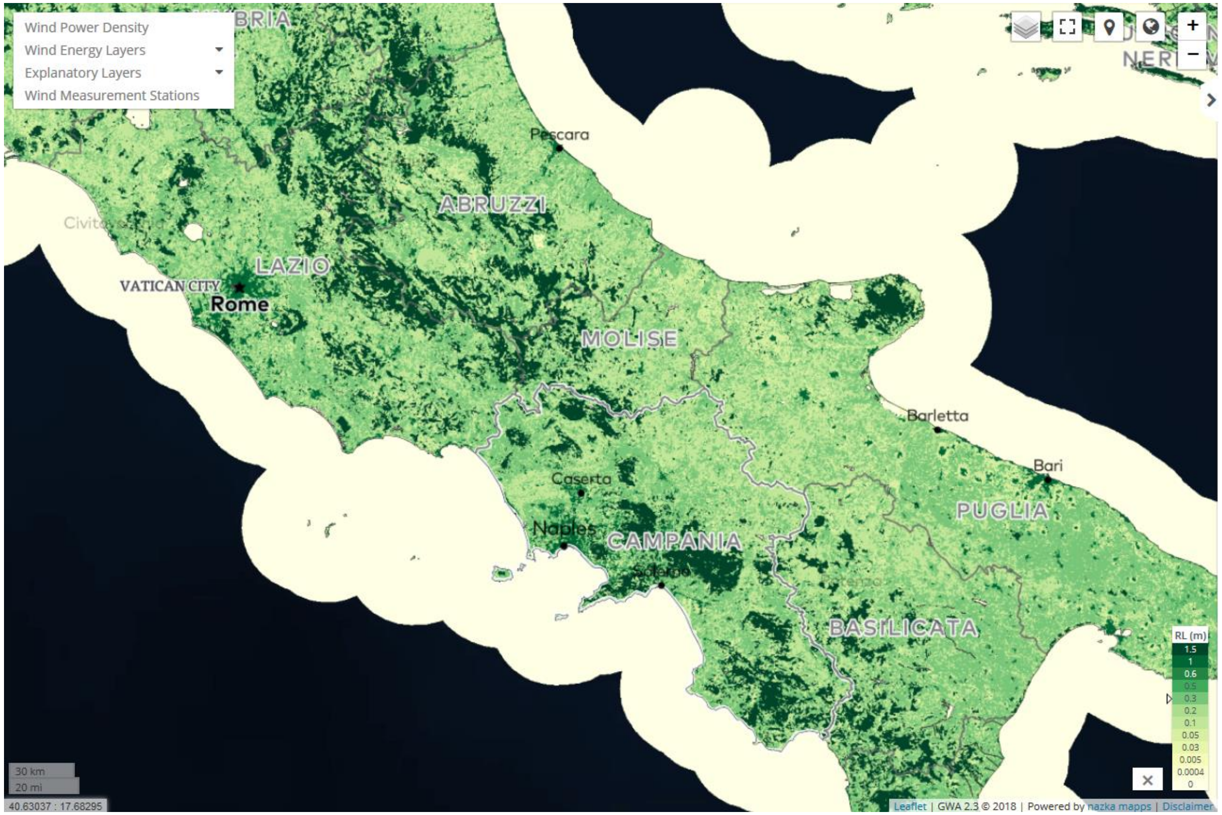
Roughness

The ruggedness index (RIX) is a measure of the steepness or ruggedness of a terrain.

The RIX layer represents ruggedness index and is an objective measure of the steepness or ruggedness of the terrain. Large RIX values lead to large errors in the flow modeling, most likely leading to an overestimation of mean wind speeds on ridges and hilltops.



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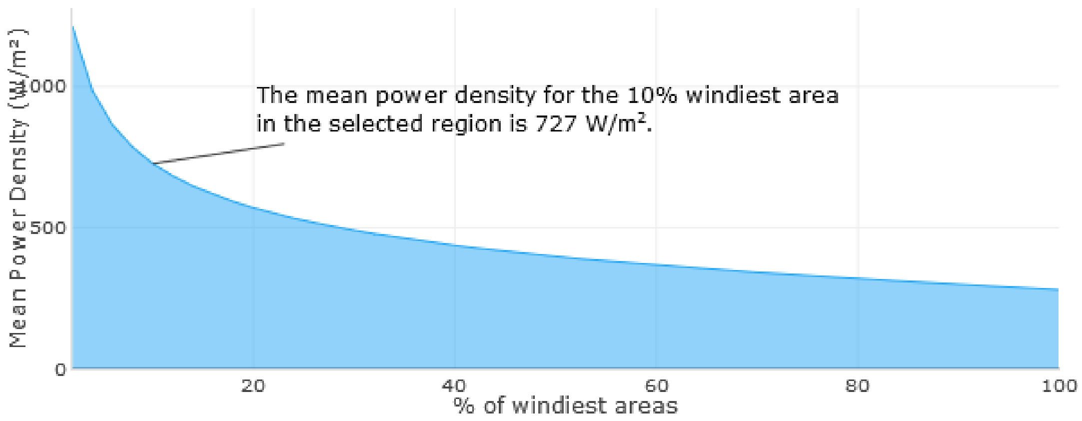
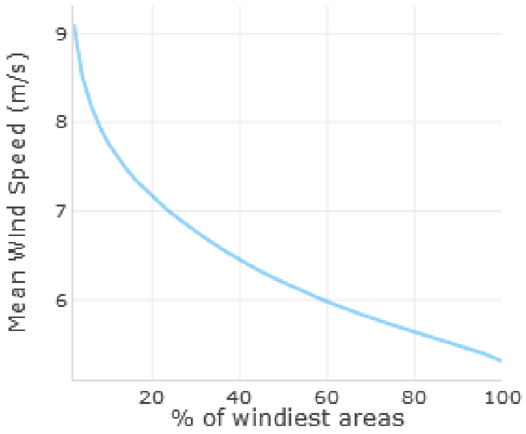
Wind Power Density @Height 100m

Wind Power Density (WPD) is a quantitative measure equal to the mean annual power available per square meter of swept area of a turbine. WPD is calculated for different heights above ground and includes the effect of wind velocity and air density.





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Summary of the provided knowledge

- Once collected data from multiple measurement tools, micro-siting allows to extend the wind properties to the entire area under consideration
- Local effects like Hill Effect increases the speed thanks to an increase of the slope of the relief in the same direction of the wind
- Available software use Linear and non linear approach. Non Linear models are CFD based calculation of the wind field

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References

Books and Reports:

- Quaderni di Applicazione Tecnica ABB [Translated in English]

Websites:

- https://globalwindatlas.info/

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www.weset-project.eu

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Analysis and design of wind farms, predictions of energy production

Lecture 1.3

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Learning outcomes

- To evaluate the power extractable from the wind source
- To estimate the relation among power, diameter and wind speed
- To evaluate the total energy efficiency of a wind system
- To select the more appropriate turbine looking at the cut-in, cut-out and nominal speeds
- To identify the main energy losses associated to the wind turbine operation

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Table of contents

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Power content of a free flowing wind stream

The power content in a cylindrical column of free unobstructed air moving at a constant speed V is the rate of change in its kinetic energy:

$$P = \frac{dE}{dT}$$

Expressing the kinetic energy as:

$$E = \frac{1}{2} m V^2$$

Substituting the kinetic Energy in the definition of Power, we have:

$$P = \frac{dE}{dT} = \frac{d}{dt}\left(\frac{1}{2} m V^2\right) = \frac{1}{2}\frac{d}{dt}\left(m V^2\right) = \frac{1}{2}\left[2mV\frac{dV}{dt} + V^2\frac{dm}{dt}\right]$$

For a constant wind speed V:

$$\frac{dV}{dt} = o$$

$$P = \frac{1}{2} V^2 \frac{dm}{dt} = \frac{1}{2}\dot{m} V^2$$

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Power content of a free flowing wind stream

If the cross sectional area of the column of air is A, and its density is ρ, the mass flow rate is:

$$\dot{m} = \rho A V$$

And the Power is:

$$P = \frac{1}{2}\dot{m}V^2 = \frac{1}{2}\rho AV \cdot V^2 = \frac{1}{2}\rho AV^3$$

If the diameter of the column of air is D, then:

$$P = \frac{1}{2}\rho \frac{\pi D^2}{4} V^3$$

The power content of the cylindrical column of air is proportional

- ❑ *to the square of its diameter D*
- ❑ *to the cube of its speed V.*

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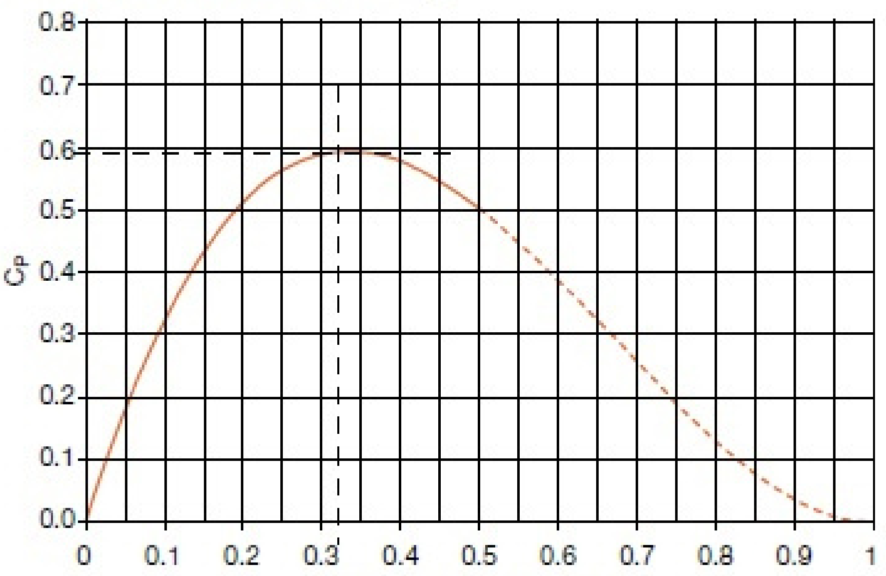
Performance coefficient (Power Coefficient) Cp

Define the Performance coefficient (power coefficient) as the ratio of the power extracted from the wind and the power available.

The performance coefficient is a dimensionless measure of the efficiency of a wind turbine in extracting the energy content of a wind stream.

$$C_p(a) = \frac{P}{P_{avail}} = \frac{2\,\rho\,A V_1^3 a\cdot(1-a)^2}{\frac{1}{2}\rho\,A V_1^3} = 4a\cdot(1-a)^2$$



Interference parameter, a

The power coefficient C_p grows first at the interference factor to grow, reaching the maximum at a = 1/3, and then decreases to a = 1/2 in which the output speed is nothing. The part for a> 1/2 does not have a physical sense indicating the condition of the negative speed in output from the terminal section of the rotor.

$$V_2 = V_1(1-2a)$$

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Performance coefficient (Power Coefficient) Cp

In practice, no. 3 effects which decrease the coefficient of power to reach:

1.Rotation of the wake behind the rotor;

2. Finite number of blades;

3. A drag force different to zero.

The power delivered by a wind turbine may be subject to reductions due to losses in the reality effect "external" to the turbine itself.

- ❑ "Altitude" due to the change in pressure - as the reference density is assumed that standard at sea level at 15°- as the altitude increases the density decreases by almost 1% per 100m above sea level;

$$\rho = \rho_0 - 1.194 \cdot 10^{-4} \cdot H$$

$$\rho_0 = density\ at\ sea\ level$$

$$H = height\ in\ meters\ on\ sea\ level\ of\ the\ turbine(s)$$

- ❑ "Altitude" due to temperature - as the temperature of the installation site, the density decreases by about 3% per 10 ° C;
- ❑ "Ghosting" - is manifested in wind farms for aerodynamic interference between the various turbines;
- ❑ Icing and fouling of the blades - reduce the aerodynamic efficiency of the blades.

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Electrical power

The power extracted by a wind turbine is a function of power coefficient Cp and the available power of the wind:

$$P = C_p \frac{1}{2} \rho A V_1^3$$

The electric power generated can be determined as:

$$P = \eta_e \, \eta_m \, C_p \frac{1}{2} \rho A V_1^3$$

where

η_m is the overall mechanical performance of the drive shaft between the turbine and rotor of the electric generator and gearbox;

η_e is the efficiency of the electric generator.

It is possible to express the diameter of the wind turbine with respect to power:

$$D = \sqrt{\frac{8P_e}{\eta_e \, \eta_m \, \pi \, C_p \, \rho V_1^3}}$$

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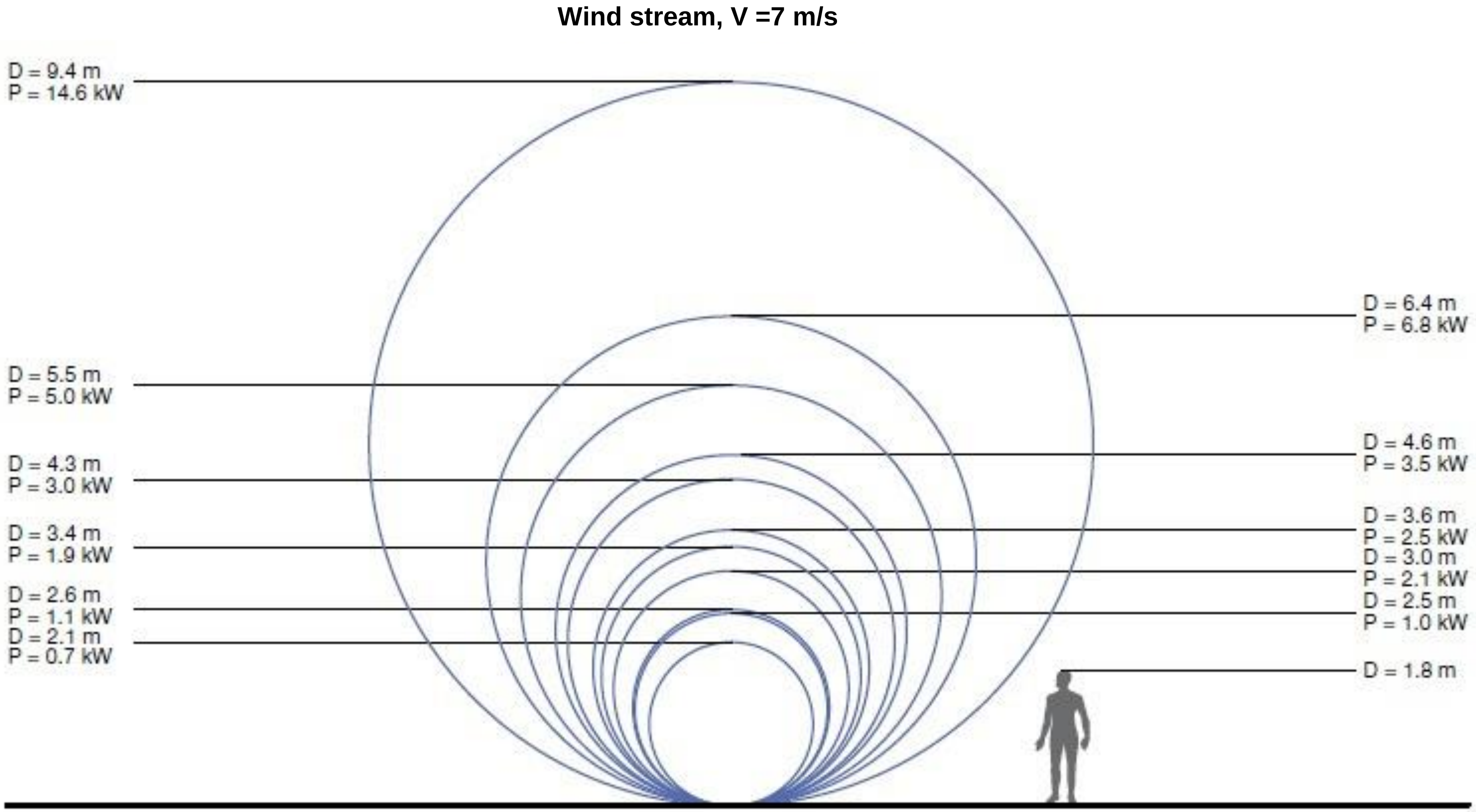
Electrical power

The power depends on the cube of the wind speed.



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Total efficiency of Wind system

The energy available from the wind is:

$$E_d = \int_{\Delta t} P_d dt = \frac{1}{2}\rho A \int_{\Delta t} V_1^3 dt = \frac{1}{2}\rho A \Delta t V_{1m3}^3 = E_{d,s} A \qquad \text{con} \qquad E_{d,s} = E_d / A$$

$$V_{m3} = \left[\frac{1}{\Delta t} \int_{\Delta t} V^3 dt \right]^{1/3}$$

The power produced by the turbine is:

$$P = C_P \eta_m \eta_{el} P_d = \eta P_d = \frac{1}{2}\rho \eta A V_1^3$$

η_m Mechanical efficiency

η_{el} Electrical efficiency

$$\eta = \eta_m \eta_{el} C_p = \frac{P}{\frac{1}{2}\rho A V_1^3}$$

Instantaneous efficiency

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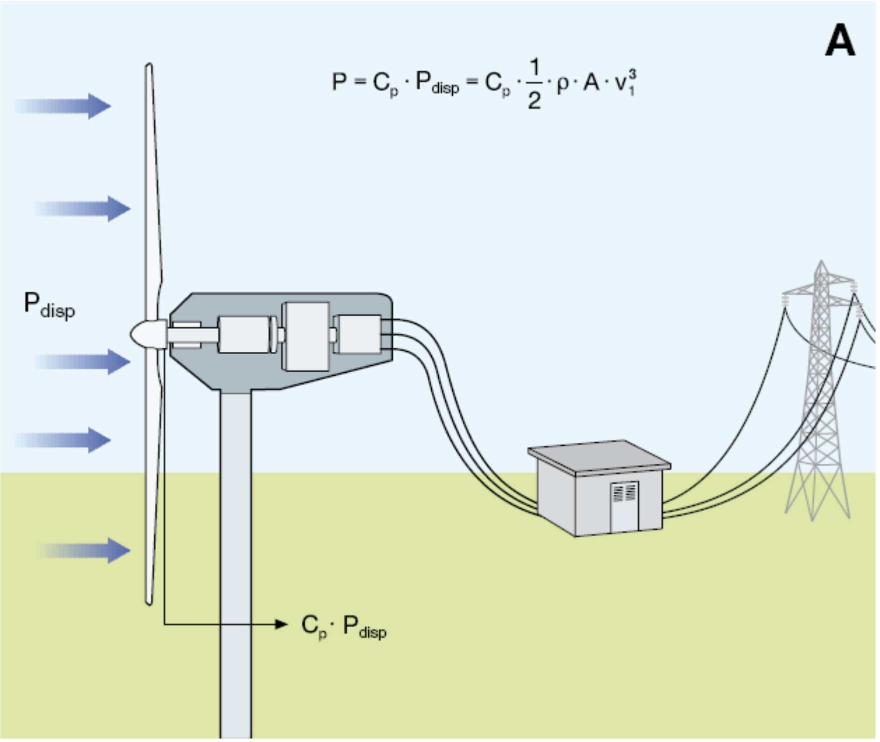
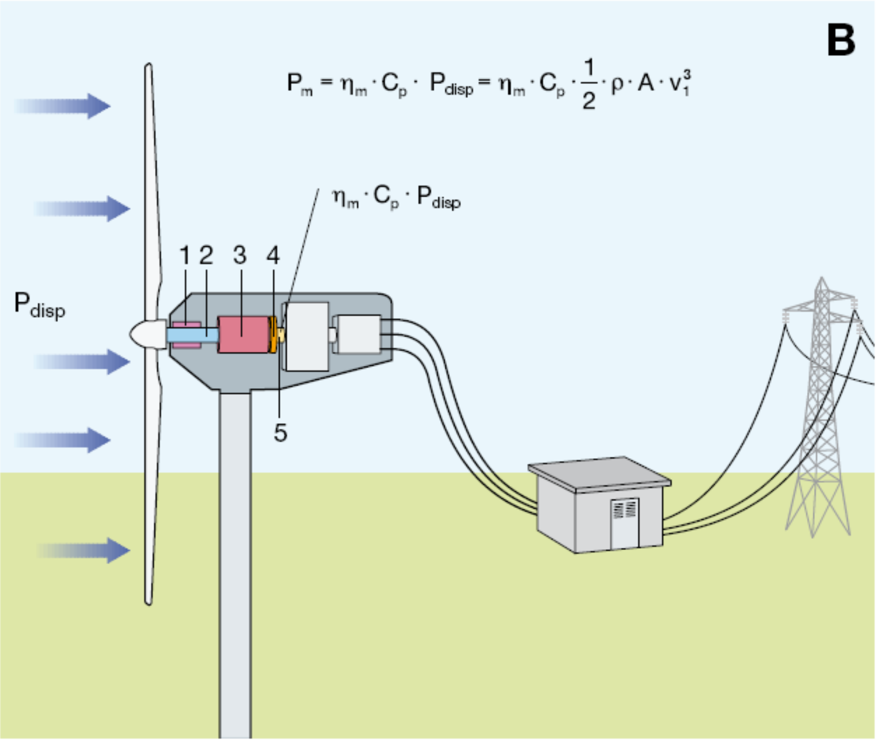
Total efficiency of Wind system





1. Bearing support
2. Low speed shaft
3. RPM multiplier
4. Brakes and yaw control systems
5. High speed shaft

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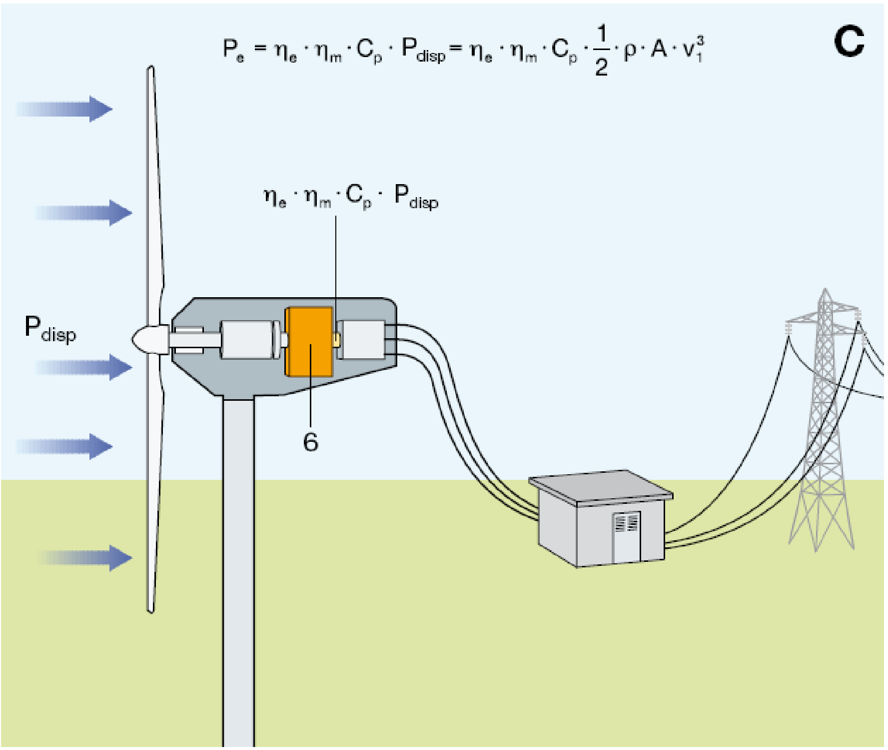
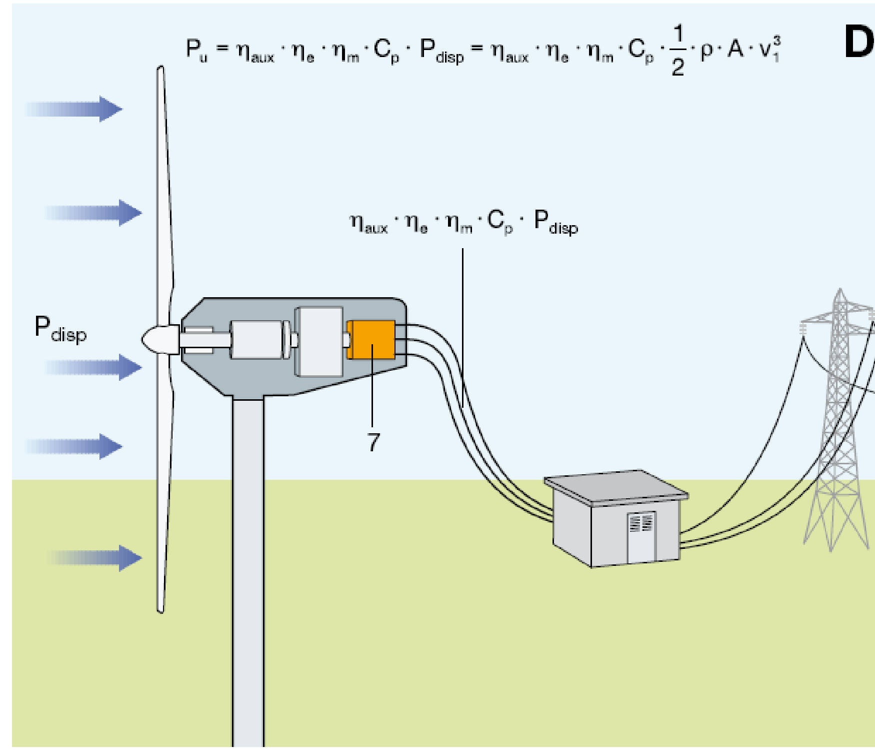
Total efficiency of Wind system





1. Bearing support
2. Low speed shaft
3. RPM multiplier
4. Brakes and yaw control systems
5. High speed shaft
6. Generator
7. Auxiliary systems

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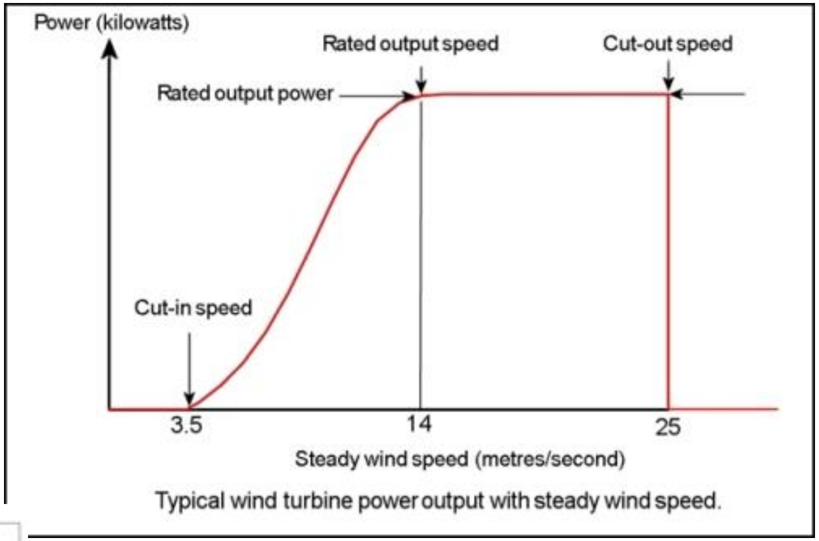
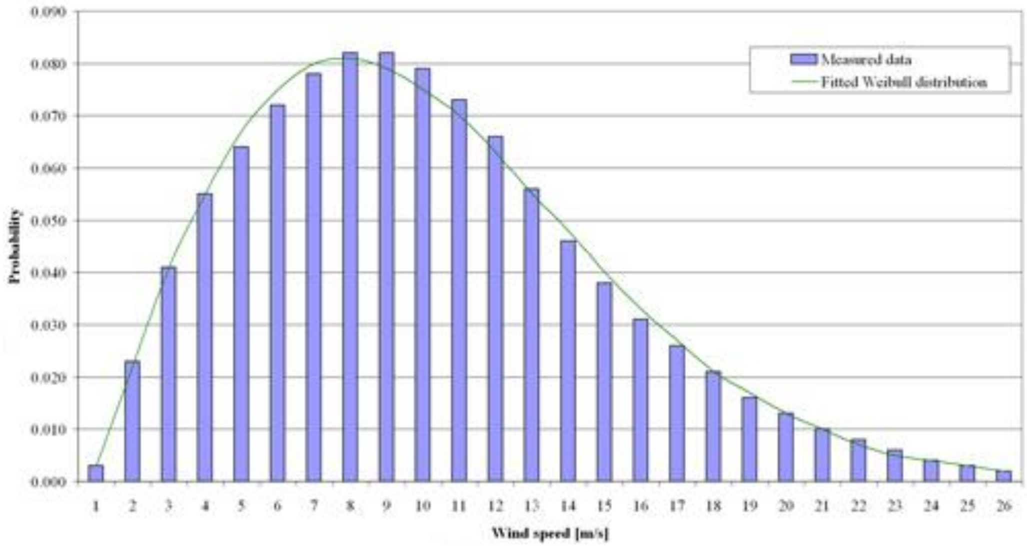
Selection of the turbine

The energy performance of the wind turbine can be modelled knowing:

- Cut-in speed
- Cut-out speed
- Nominal speed
- Control law



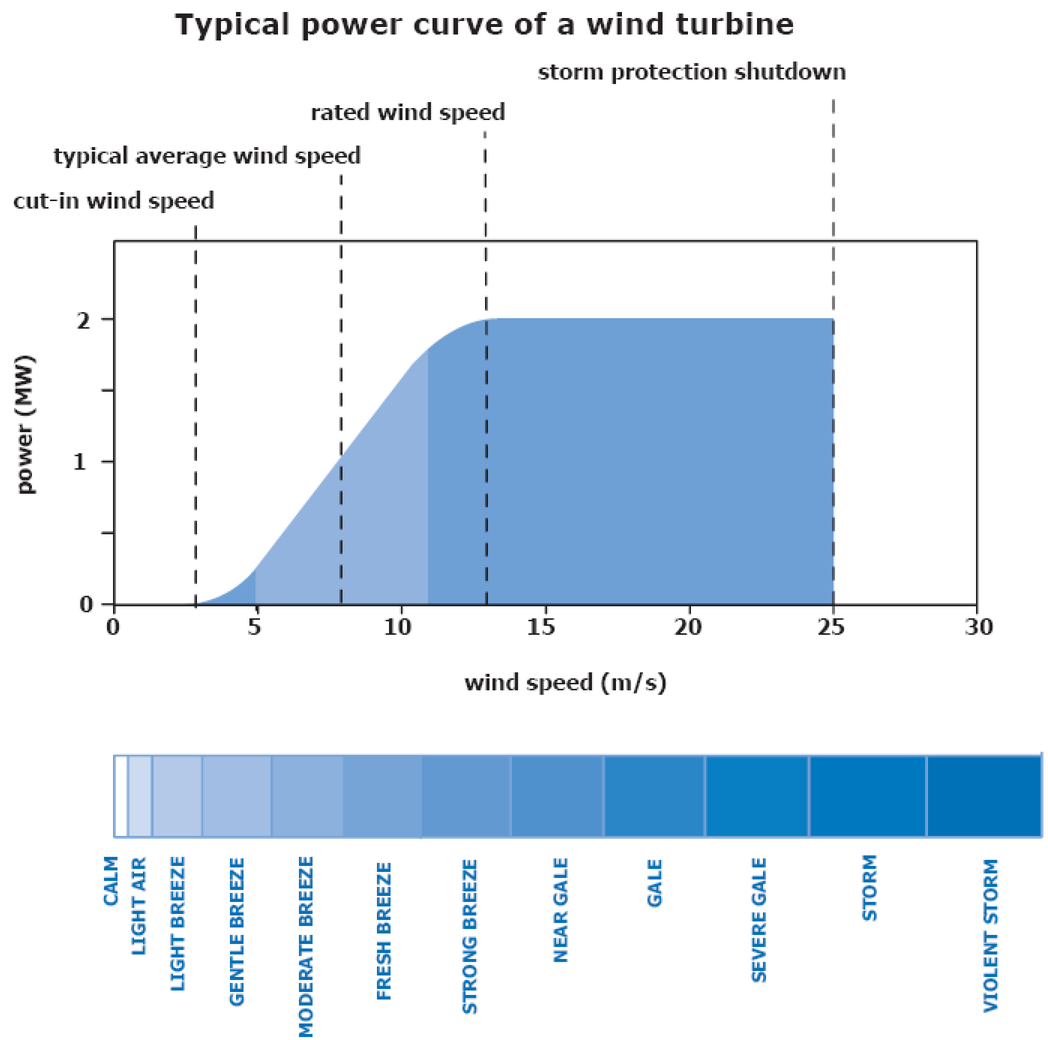


Starting from the anemometric data it is possible to choose the optimal number and model of wind turbines, by crossing the data of the machine with the wind data of the site

Selection of the turbine

Cut-in Wind Speed

At very low wind speeds, the wind exerts an insufficient torque on the turbine blades to make them rotate. However, as the speed increases, the wind turbine begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the cut-in speed and is typically between 2 and 4 m/s.



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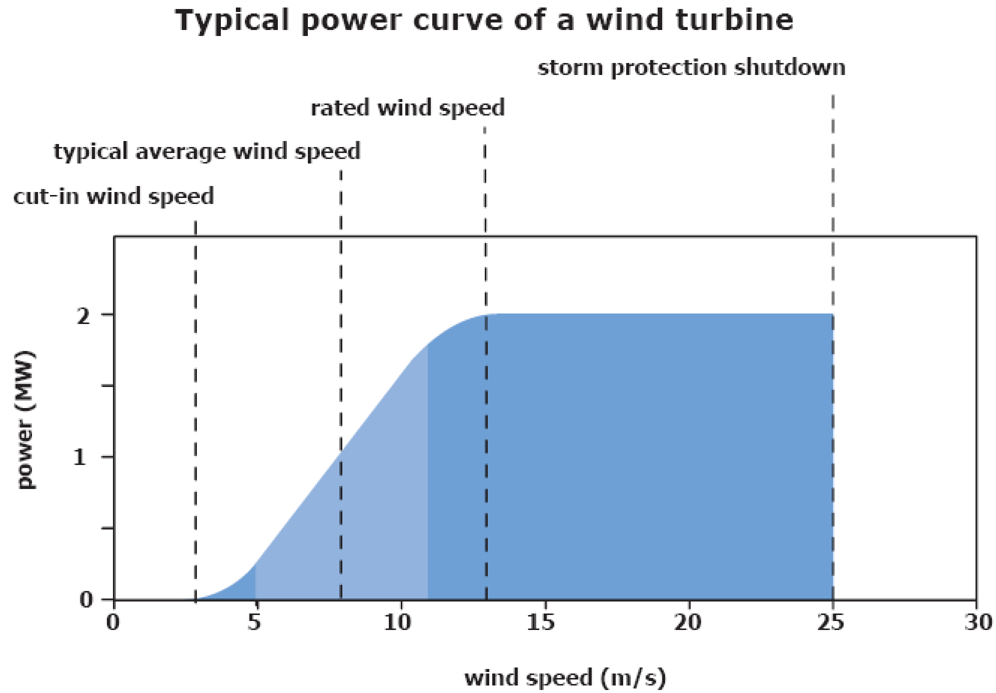
Selection of the turbine

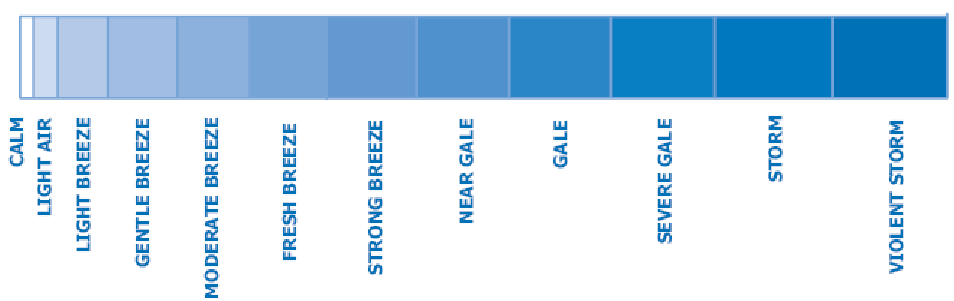
Rated output power and rate output wind speed

As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly.

Between 10 and 14 m/s, the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the rated power output and the wind speed at which it is reached is called the rated output wind speed.

At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. Typically with large turbines, the control is done by changing the blade angles so as to keep the power at the constant level.





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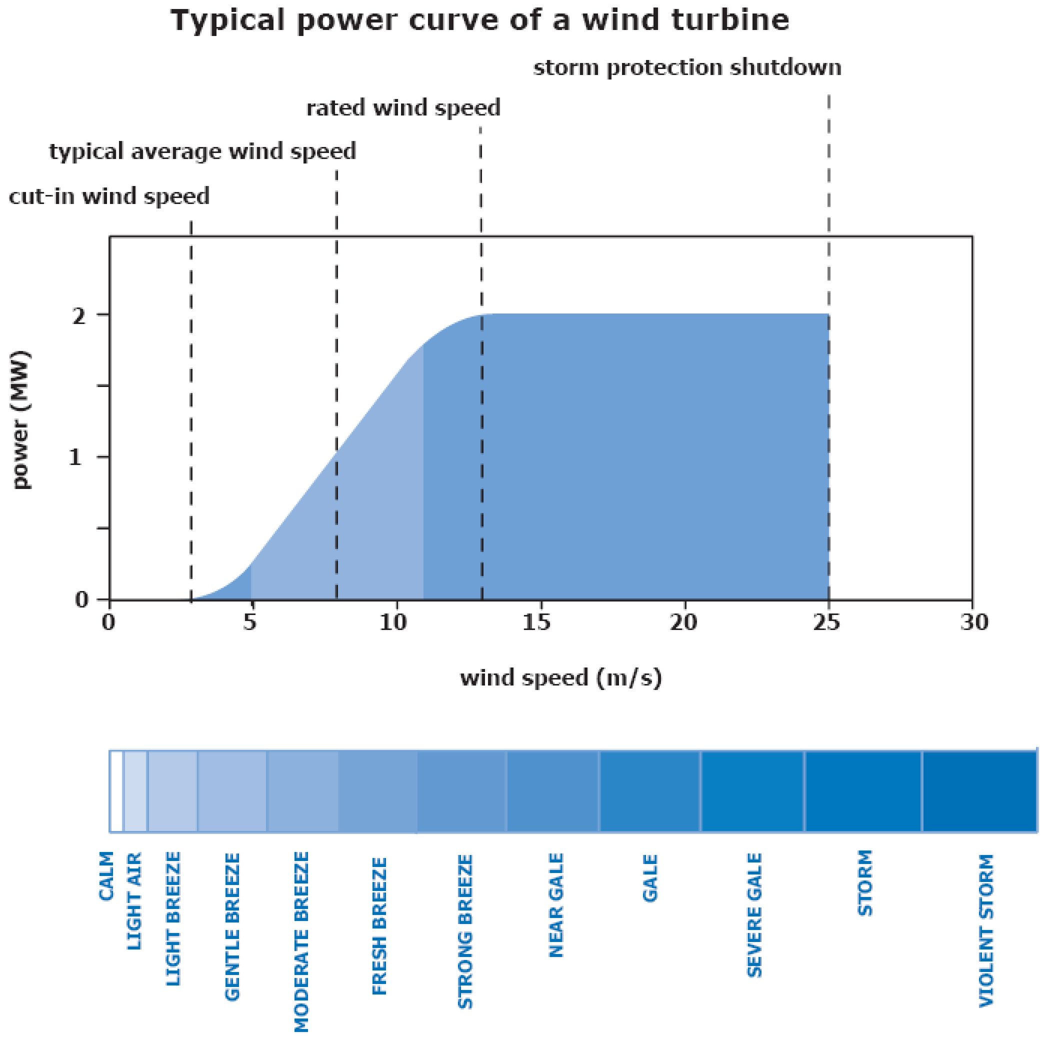
Selection of the turbine

Cut-out speed.

As the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and is usually around 20-25 m/s.



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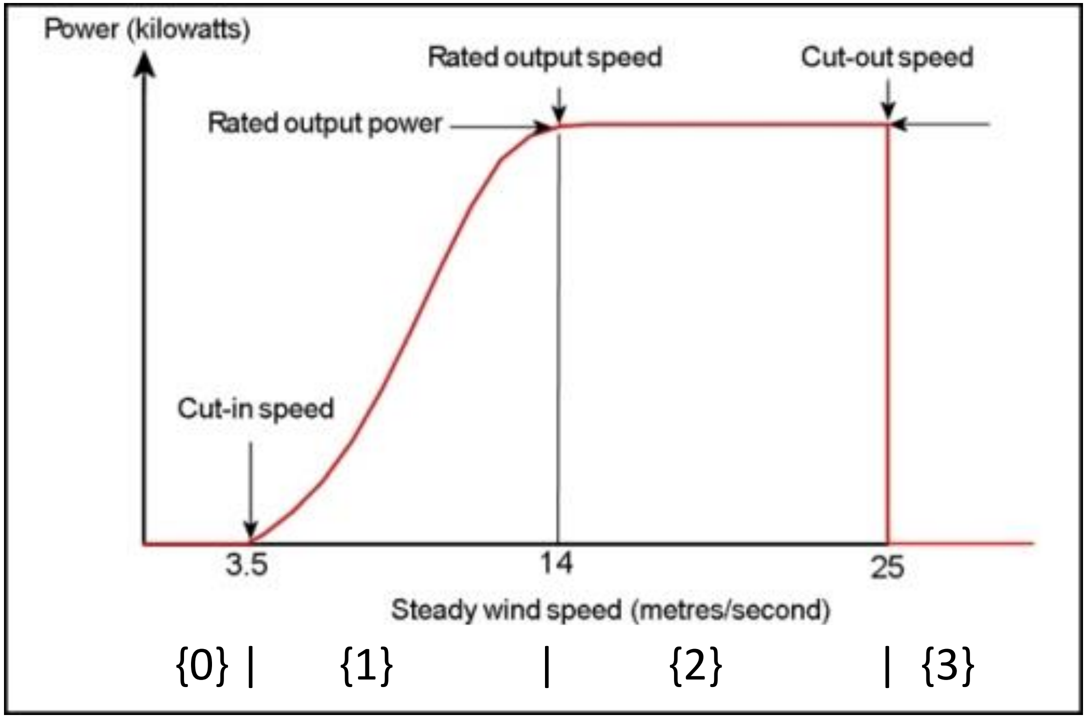
Selection of the turbine

Three characteristic velocities:

$V_{cut\,in}$ Cut-in

V_D Design

$V_{cut\,out}$ Cut-out



P_D *Design power*

$P(V_1)$ model law

Range [0] $\left(0 \div V_{cut\,in}\right)$

Range [3] $\left(V_{cut\,out} \div \infty\right)$

$P = 0$

Range [1] $\left(V_{cut\,in} \div V_D\right)$ Approximated to a 2nd order poly

$$P = P_D \frac{V_1^2 - V_{cut\,in}^2}{V_D^2 - V_{cut\,in}^2}$$

Range [2] $\left(V_D \div V_{cut\,out}\right)$ Constant $P = P_D$

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Selection of the turbine

Design (nominal) efficiency is the ratio between nominal power and the power available from the wind at nominal velocity V_D

$$\eta_D = \frac{P_D}{P_{d,D}} = \frac{P_D}{\frac{1}{2}\rho A V_D^3}$$

Depends ONLY on the turbine

With this model we can define the instantaneous efficiency as a function of the turbine and the wind:

$$\eta = \frac{P}{P_d} = \frac{P_D}{\frac{1}{2}\rho A V_1^3}\frac{V_1^2 - V_{cut\,in}^2}{V_D^2 - V_{cut\,in}^2}\left(\frac{V_D^3}{V_D^3}\right) = \eta_D \frac{V_D^3}{V_D^2 - V_{cut\,in}^2}\frac{V_1^2 - V_{cut\,in}^2}{V_1^3} = cost_{Macch} \cdot \frac{V_1^2 - V_{cut\,in}^2}{V_1^3}$$ range [1]

$$\eta = \frac{P_D}{\frac{1}{2}\rho A V_1^3} = \frac{P_D}{\frac{1}{2}\rho A V_1^3}\left(\frac{V_D^3}{V_D^3}\right) = \eta_D \frac{V_D^3}{V_1^3} = cost'_{Macch} \cdot \frac{1}{V_1^3}$$ range [2]

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Selection of the turbine

The maximum efficiency is achieved only in range [1]

$$\frac{d\eta}{dV_1} = -\frac{1}{V_1^2} + 3\frac{V_{cut\,in}^2}{V_1^4} = \frac{1}{V_1^2}\left(3\frac{V_{cut\,in}^2}{V_1^2} - 1\right) = 0 \rightarrow V_{1,op} = \sqrt{3}\cdot V_{cut\,in} = 1{,}732\cdot V_{cut\,in}$$

Putting $V_{1,op}$ in the expression for efficiency

$$\eta_{max} = \eta_D \frac{V_D^3}{V_D^2 - V_{cut\,in}^2}\frac{V_{1,op}^2 - V_{cut\,in}^2}{V_{op}^3} = \eta_D \frac{V_D^3}{V_D^2 - V_{cut\,in}^2}\frac{3V_{cut\,in}^2 - V_{cut\,in}^2}{(1{,}732)^3\cdot V_{cut\,in}^3} = \eta_D \frac{V_D^3}{V_D^2 - V_{cut\,in}^2}\frac{2V_{cut\,in}^2}{(1{,}732)^3\cdot V_{cut\,in}^3} =$$

$$\eta_{max} = \eta_D \frac{V_D^3}{V_D^2 - V_{cut\,in}^2}\frac{1}{2.598\cdot V_{cut\,in}} = \frac{P_D}{\frac{1}{2}\rho A V_D^3}\frac{V_D^3}{V_D^2 - V_{cut\,in}^2}\frac{1}{2{,}598\cdot V_{cut\,in}} = \frac{0.77 P_D}{\rho A V_D\left(V_D^2 - V_{cut\,in}^2\right)}$$

we see that the maximum value η_{max} is constant for a given turbine (at constant density) as the expression includes only quantities related to the turbine itself

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Selection of the turbine

We define $\Delta t_0, \Delta t_1, \Delta t_2, \Delta t_3$, as time periods in which the wind is inside of the four p_0, p_1, p_2 e p_3 relative frequency respect to the year Δt excluding the contribution of the range [0] e [3]:

$$p_1 = \frac{\Delta t_1}{\Delta t} = \int_{V_{cut\,in}}^{V_D} f(V)\,dV = \int_0^{V_D} f(V)\,dV - \int_0^{V_{cut\,in}} f(V)\,dV = C(V_D) - C(V_{cut\,in})$$

$$p_2 = \frac{\Delta t_2}{T} = \int_{V_D}^{V_{cut\,out}} f(V)\,dV = \int_0^{V_{cut\,out}} f(V)\,dV - \int_0^{V_D} f(V)\,dV = C(V_{cut\,out}) - C(V_D)$$

The energy harvested in Δt is:

$$E = \int_{\Delta T} P\,dt$$

can be separated in two contributions $E1$ for range [1] and $E2$ for range [2]:

For range [1] the power is: $P = P_D \frac{V_1^2 - V_{cut\,in}^2}{V_D^2 - V_{cut\,in}^2};$

For range [2] the power is: $P = P_D;$

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Selection of the turbine

In range [1]:

$$E_1 = \int_0^{\Delta t_1} P dt = \frac{P_n}{V_D^2 - V_{cut\,in}^2} \int_0^{\Delta t_1} \left(V_1^2 - V_{cut\,in}^2 \right) dt = \frac{P_n}{V_D^2 - V_{cut\,in}^2} \left[\int_0^{\Delta t_1} V_1^2 dt - V_{cut\,in}^2 \int_0^{\Delta t_1} dt \right]$$

$$= \frac{P_n}{V_D^2 - V_{cut\,in}^2} \left[\Delta t_1 V_{1,m2}^2 - \Delta t_1 V_{cut\,in}^2 \right] = \frac{P_D}{V_D^2 - V_{cut\,in}^2} p_1 \Delta t \left(V_{1,m2}^2 - V_{cut\,in}^2 \right)$$

where $V_{1,m2}^2$ is the mean square root velocity calculated in range[1]:

$$V_{1,m2} = \left[\frac{1}{\Delta t_1} \int_0^{\Delta t_1} V_1^2 dt \right]^{1/2} \rightarrow \int_0^{\Delta t_1} V_1^2 dt = \Delta t_1 V_{1,m2}^2 = p_1 \Delta t V_{1,m2}^2$$

In range [2]:

$$E_2 = \int_0^{\Delta t_2} P dt = P_D \int_0^{\Delta t_2} dt = P_D p_2 \Delta t$$

The total energy will be:

$$E = E_1 + E_2 = \frac{P_D}{V_D^2 - V_{cut\,in}^2} p_1 \Delta t \left(V_{1,m2}^2 - V_{cut\,in}^2 \right) + P_D p_2 \Delta t = \frac{P_D \Delta t}{V_D^2 - V_{cut\,in}^2} \left[p_1 \left(V_{1,m2}^2 - V_{cut\,in}^2 \right) + p_2 \left(V_D^2 - V_{cut\,in}^2 \right) \right] =$$

$$E = 1.299 \eta_{max} \rho A \Delta t V_{cut\,in} \left[p_1 \left(V_{1,m2}^2 - V_{cut\,in}^2 \right) + p_2 \left(V_D^2 - V_{cut\,in}^2 \right) \right]$$

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Selection of the turbine

The total energy harvested is:

$$E = E_1 + E_2 = 1.299\eta_{\max}\rho A\Delta t V_{cut\,in}\left[p_1\left(V_{1,m2}^2 - V_{cut\,in}^2\right) + p_2\left(V_D^2 - V_{cut\,in}^2\right)\right]$$

While the total energy available in the wind in Δt is:

$$E_d = \int_0^{\Delta t} P_d dt = \frac{1}{2}\rho A\int_0^{\Delta t} V_1^3 dt = \frac{1}{2}\rho A\Delta t V_{1,m3}^3$$

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Selection of the turbine

The energy efficiency in Δt is the ratio between the harvested and available energy:

$$\eta_T = \frac{E}{E_d} = 2.598\eta_{\max} V_{cut\,in} \frac{p_1\left(V_{1,m2}^2 - V_{cut\,in}^2\right) + p_2\left(V_D^2 - V_{cut\,in}^2\right)}{V_{1,m3}^3} = \varepsilon\eta_{\max}$$

where the parameter ε is the efficiency of the installation site

$$\varepsilon = \frac{E}{\eta_{\max} E_d} = 2.598 V_{cut\,in} \frac{p_1\left(V_{1,m2}^2 - V_{cut\,in}^2\right) + p_2\left(V_D^2 - V_{cut\,in}^2\right)}{V_{1,m3}^3}$$

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Selection of the turbine

- It is the ratio between the harvested and that that would be harvested if operated constantly at η_{max}
- Once the turbine is selected, η_{max} can be considered constant and the installation site efficiency can be considered proportional to the energy efficiency
- ε characterizes the coupling between turbine and installation site
- For a given V_D there is a $V_{cut\ in}$ that optimize the installation site efficiency

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Selection of the turbine

Another coefficient is the Capacity Factor of the plant F_u, defined as the ratio between the energy harvested and that which could be harvested from a turbine working in nominal conditions V_D.

$$E_D = \Delta t \cdot P_D = \Delta t \cdot \frac{1}{2}\eta_D \rho A V_D^3 \rightarrow F_u = \frac{E}{E_D} = \frac{E}{\Delta t P_D} = p_1 \frac{\left(V_{m2,1}^2 - V_{cut\,in}^2\right)}{V_D^2 - V_{cut\,in}^2} + p_2 = \varepsilon \frac{V_{m3}^3}{2.598 V_{cut\,in}\left(V_D^2 - V_{cut\,in}^2\right)}$$

- The nominal power defines the class of the turbine
- It is equal to equivalent hours: number of hours at nominal rate (2000-2500 hours)
- Decreases with increase of V_D
- With Fu > 0,25 and $V_{cut\,in}$ > 2 m/s, a study of the usability of a given turbine on a given installation site must be carried out a priori

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Effects of losses

To obtain the net power production, it is necessary to estimate the effect of the losses:

- Losses due to topographic effect. Already treated and included in the detailed anemological study
- Loss due to wake effect, losses from aerodynamic interference between wind turbines
- Electrical losses, energy losses due to the electricity grid inside the wind farm and to the connection with the electricity grid for production delivery
- Losses due to deterioration of blades, aerodynamic losses due to manufacture and wear
- Mechanical losses, internal friction, bearing wear and other transmission parts
- Losses due to the availability of machines, machines stopped for maintenance (ordinary and otherwise), winds and strong gusts, ...
- Other, interruption due to network overloading, vegetation growth, more ...

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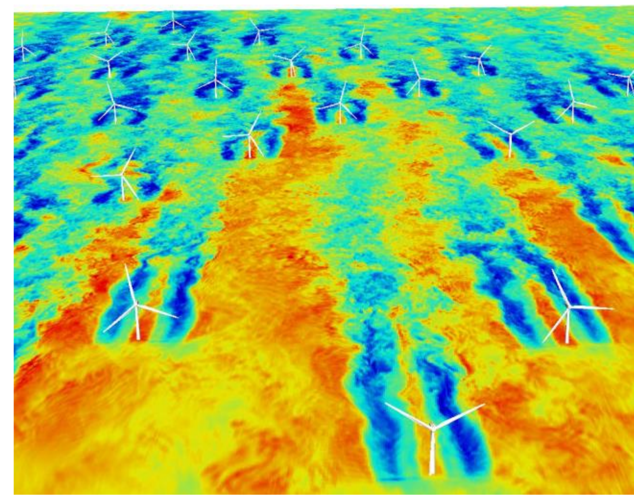
Effects of losses: Wake losses

A turbulent wake is generated downstream of the rotor which modifies the wind entering the next rotor

- Loss of power
- Vibrating loads

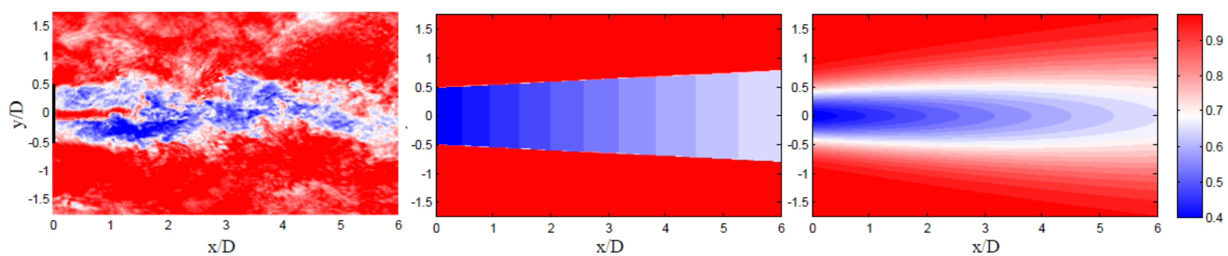
Manufacturers provide safety distances to minimize losses.

The relative position of the machines must be such as to minimize the shaded generators with respect to the main direction.



[Source NREL]

There are models for prediction of the wake of varying complexity depending on the effect to analyse



LES snapshot of full unsteady wake

Park

Eddy-Viscosity

[Source NREL]

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Effects of losses: Wake losses

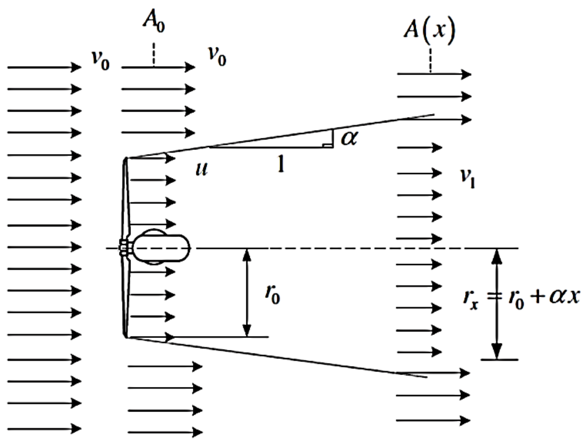
The losses due to wake effect depend on:

- Relative positions
- Ground
- Wind rose

Micrositing software is required for a correct evaluation.

If the turbines are not positioned correctly, they can incur in more than 20% of losses

Example, Laresen model



$$v_1 = v_0 + v_0\left(\sqrt{1 - C_T} - 1\right)\left(\frac{r_0}{r}\right)^2$$

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Effects of losses: Blade degradation

- Manufacturing imperfections
- Rain erosion
- Contact with birds
- Degradation of the leading edge due to erosion and accumulation of debris

If not properly protected the blades can present over the years a loss of producibility of more than 10%

The normal wear of the blades causes a reduction of the energy produced annually equal to about 2%

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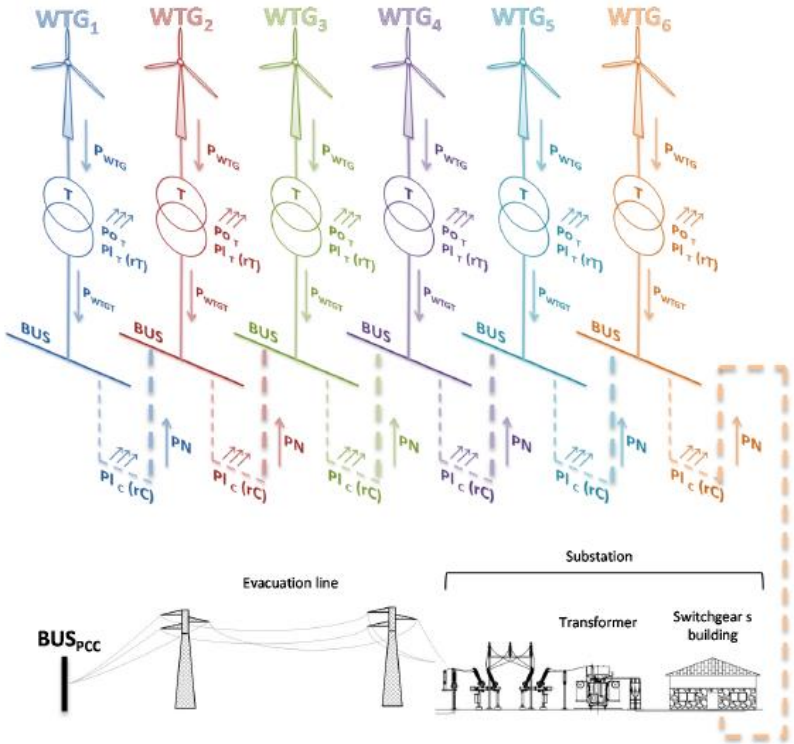
Effects of losses: Electric losses

Electrical power associated with the single bus:

- Active power of the generator
- Reduced by the losses of the transformer (2 - 4%),
- Added by the electrical power output from the previous bus
- Reduced by losses associated with the cable.



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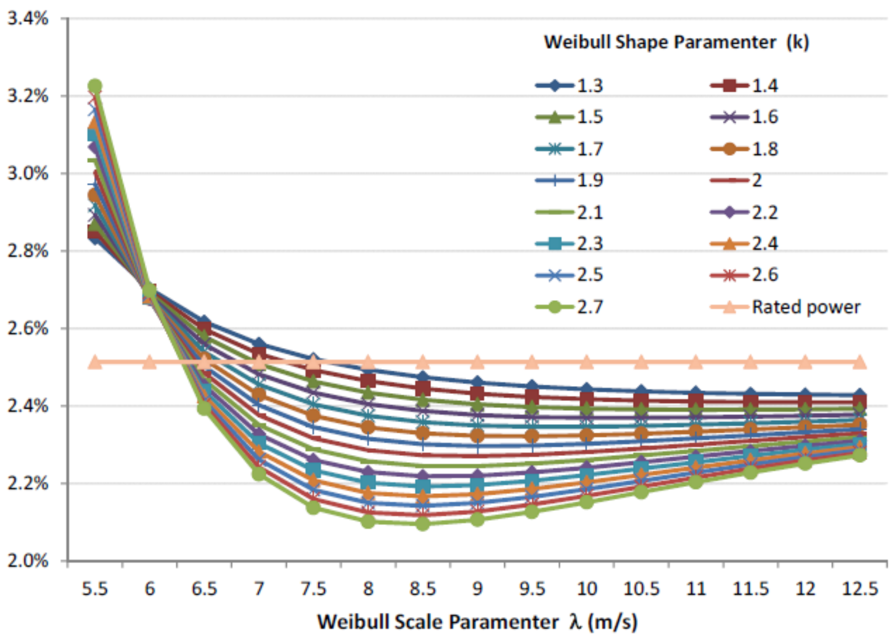
[1]. Colmenar-Santos, Antonio, et al. "Simplified Analysis of the Electric Power Losses for On-Shore Wind Farms Considering Weibull Distribution Parameters." Energies 7.11 (2014): 6856-6885.

Effects of losses: Electric losses

For the total losses of the farm are also considered:

- Losses associated with the transformation station
- Losses associated with the energy evacuation system towards the delivery bus



Energy losses from the Wind Farm

In the preliminary calculation of net production, in the absence of more precise data, an average value of about 2.5% can be considered.

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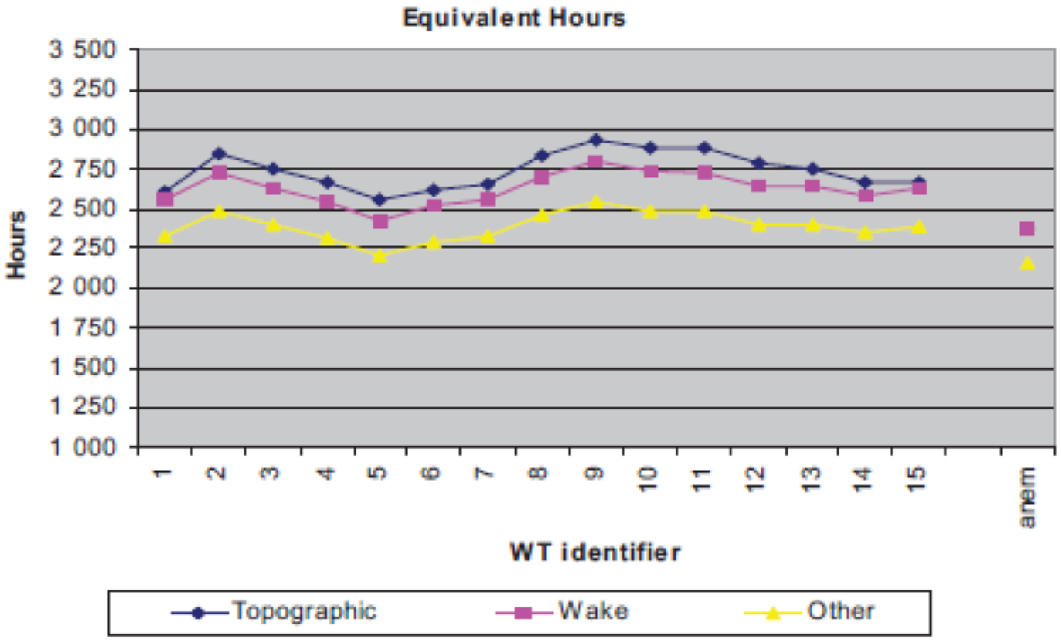
[1]. Colmenar-Santos, Antonio, et al. "Simplified Analysis of the Electric Power Losses for On-Shore Wind Farms Considering Weibull Distribution Parameters." Energies 7.11 (2014): 6856-6885.

Effects of losses: Production evaluation

Equivalent Hours to the Maximum Power and Capacity Factor

- Total production of the wind farm in the year divided by the total nominal power
- They depend on the choice of the wind turbine, the positioning, the wind

A value of about 1900 - 2000 equivalent hours is considered acceptable for the economic sustainability of the project.



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CEI EN 61400-1

The CEI EN 61400-1 is a set of design requirements made to ensure that wind turbines are appropriately engineered against damage from hazards within the planned lifetime.

Wind classes determine which turbine is suitable for the normal wind conditions of a particular site. Turbine classes are determined by three parameters:

1. the average wind speed,
2. extreme 50-year gust,
3. turbulence.

Turbulence intensity quantifies how much the wind varies typically within 10 minutes.

Normally the wind speed increases with increasing height. In flat terrain the wind speed increases logarithmically with height.

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CEI EN 61400-1

Wind Turbine classes determine which turbine is suitable for normal wind conditions of a particular site.

V_{ref}: average wind speed each 10 min with a 50-year recurrence period
I_{ref}: reference turbulence intensity for a wind speed of 15 m/s
IA-IIIC: category for a wind turbine installed for a least 20 years

Wind Turbine classes	I	II	III	S
V_{ref} [m/s]	50	42.5	37.5	Values specified by the designer
A $I_{ref}(-)$	0.16			
B $I_{ref}(-)$	0.14			
C $I_{ref}(-)$	0.12			

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Summary of the provided knowledge

- The power content of the cylindrical column of air is proportional to the square of its diameter D to the cube of its speed V
- The Performance coefficient (power coefficient) is the ratio of the power extracted from the wind and the power available
- N. 3 effects decrease the coefficient of power: rotation of the wake behind the rotor, finite number of blades and a drag force different to zero
- The power delivered by a wind turbine may be subjected to reductions due to altitude (changes in pressure and temperature), ghosting, icing and fouling

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Summary of the provided knowledge

- The energy performance of the wind turbine can be modelled knowing cut-in speed, cut-out speed, nominal speed and control law
- Energy production of wind turbine is affected by Wake losses, blade degradation, electric losses, etc.
- The CEI EN 61400-1 provides a list of wind classes to determine which turbine is suitable for the normal wind conditions of a particular site

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References

Books and Reports:

- CEI EN 61400-1
- Quaderni di Applicazione Tecnica ABB [Translated in English]

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www.weset-project.eu

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Contact: info@weset-project.eu weset.erasmusplus@uva.es

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Wind Farm Layouts grid-connected, off-grid systems, on-shore and off-shore

Lecture 1.4

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Learning outcomes

- Knowledge of the main component of a wind farm
- Understanding the main layout of a wind farm and related issues (transport, civil engineering, …)
- Knowledge of the main features and differences between on-shore and off-shore wind farms
- Knowledge of structure and main components of a off-grid system
- …

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Table of contents

- On-shore wind farms, components and layout
- Off-shore wind farms, components and layout
- Off-grid systems
- …

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ON-SHORE WIND FARM

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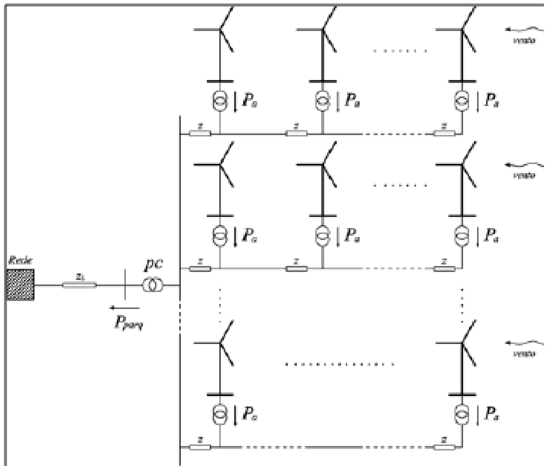
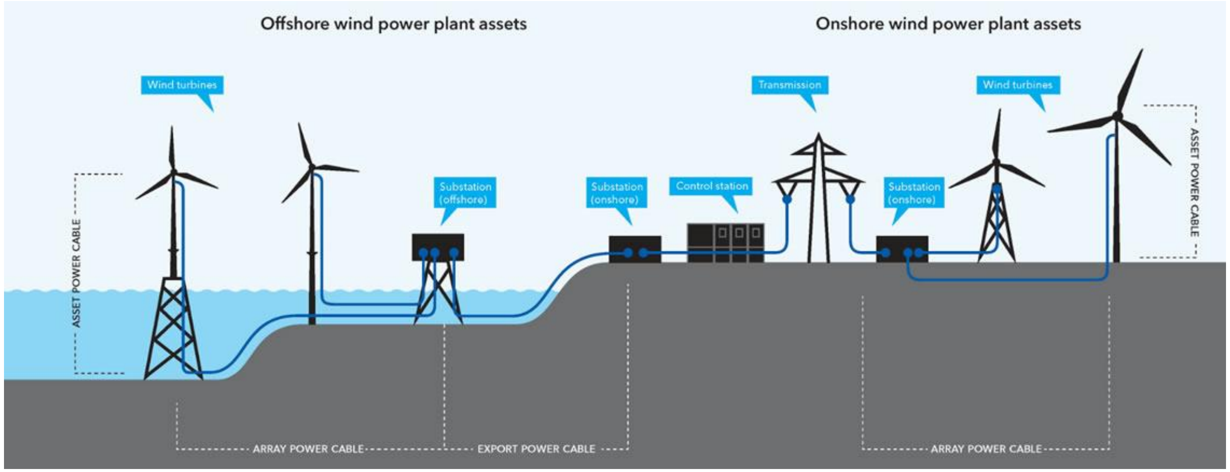
On-shore Wind farm layout



Main elements

- turbines
- pitches
- MT cable ducts
- Internal connections (roads)

- Collection substation
- MT-AT transformation substation
- AT cable ducts
- Network connection substation
- Control centre



Distribution layout of on-shore and off-shore wind farm [Courtesy: googleimages]

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On-shore wind farm layout
Main project aspects

- Project for civil works:
  - roads,
  - assembly sites,
  - foundations

- Project for electrical works:
  - cable ducts,
    - cabins
    - connection to the NTG

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On-shore wind farm layout
Main project aspects

- External road system for access to the site
- Road project inside the park
- Wind turbines foundations project

The road project must include appropriate reports and tables illustrating the adjustment interventions necessary for the transit of vehicles for the transport of wind turbines

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On-shore wind farm layout
Main project aspects: access to the site

Conventional heavy vehicles

- Nacelle
- Hub
- Foundations materials

Exceptional transport with extendable rear platform vehicles

- Blades
- Parts of tower

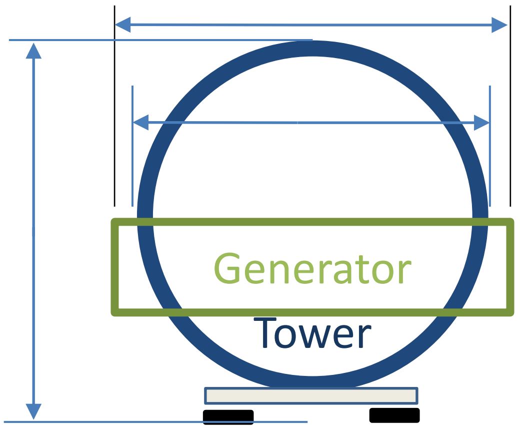
[Courtesy: googleimages]

On-shore wind farm layout
Main project aspects: access to the site

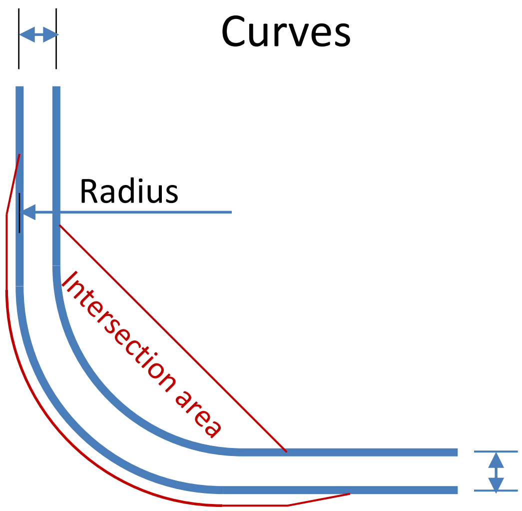
The producers of wind turbines provide indications on slopes and construction characteristics of the roadways that must be made, through specific stratifications, considering the stresses to which they are subjected and the dimensional requirements of the transport route (bends, tunnels, ...)

Typical transport scheme

Generator and tower



Curves



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On-shore wind farm layout
Main project aspects: access to the site

Road project necessary for accessibility to individual project positions and assembly sites

https://www.geograph.org.uk/photo/728835

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On-shore wind farm layout
Civil Works Design: Assembly Places

https://www.flickr.com/photos/portlandgeneralelectric/15813794747/

The storage and assembly pitches are located near the wind turbines and are made in plan, they must contain both an area to allow the unloading of the various elements from the means of transport, and an area for positioning the crane.

The pitches must comply with specific dimensional requirements provided by the wind turbine manufacturers.

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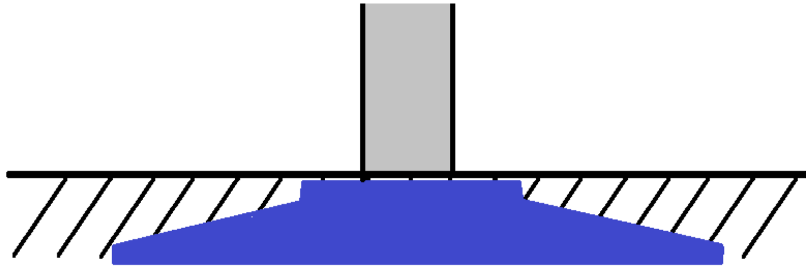
On-shore wind farm layout
Main project aspects: foundations

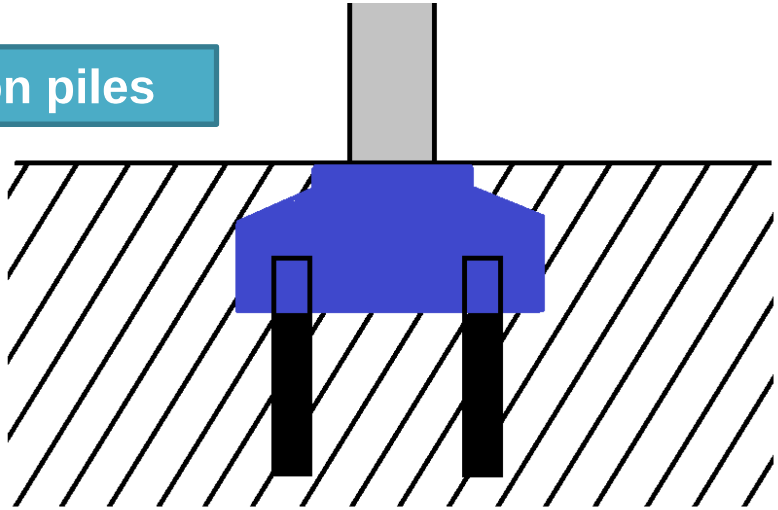
A Geognostic campaign is necessary for the choice of the type of foundation and sizing

Onshore foundations normally consist of a reinforced concrete plate fixed on bored piles of variable diameter and depth depending on the terrain and the specific provided for the machine

Direct foundation



Foundation on piles



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On-shore wind farm layout
Main project aspects: electric components

- MV electric lines inside the park
- Sorting cabin (collector center)
- MV power line outside the park
- Point of connection to the RTN

The project documentation must contain for each system a descriptive and illustrative technical report of the sizing calculations, the performance specification of the technical elements, the maintenance, safety and coordination plans.

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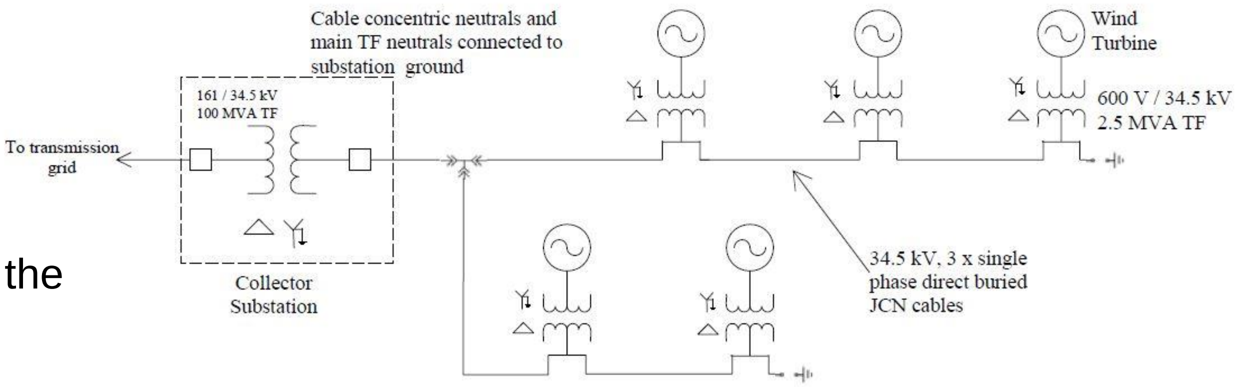
On-shore wind farm layout
Main project aspects: MV power lines



Definition of the layout of the cable lines

- Excavation feasibility
- Expropriation plan
- Disciplinary of existing roads.

[Courtesy: googleimages]

Cable sizing based on the power of the individual generators, the system and the project distances

Summary of single-line wiring diagram with sections and type of cable

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On-shore wind farm layout
Main project aspects: dimensioning of cables

- Electrical criterion of the maximum admissible voltage drop
- Thermal criterion of the maximum allowable heating in the conductors
- Economic criterion of maximum economic profit

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On-shore wind farm layout
Main project aspects: dimensioning of cables

Electrical criterion

- the transmitted power along the conductor,
- the nominal voltage of the plant,
- the length of the conductor.

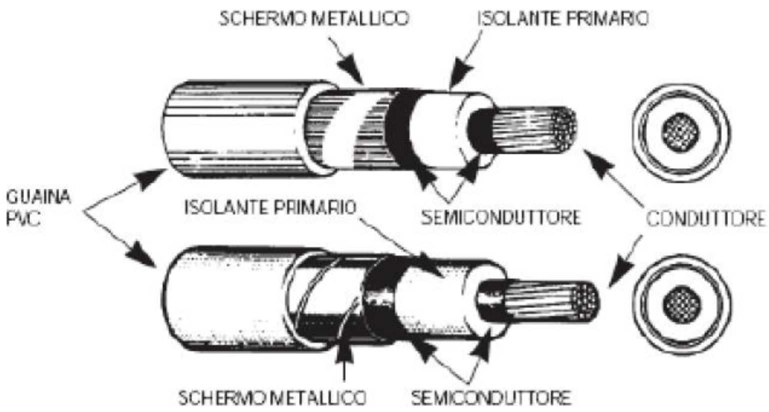
The conductor cross-section is calculated in order to exclude points in the line where the voltage drop reaches the maximum value allowed.

$$\Delta V = \sqrt{3} L I_B (r\cos\varphi + x\sin\varphi)$$ Voltage drop

$$I_B = \frac{P}{\sqrt{3} V \cos\varphi}$$ Operating current

$$\Delta V\% = \frac{\Delta V}{V} 100$$ Percentage voltage drop

$$r = \frac{\rho}{S}$$ Cable resistance



[Courtesy: googleimages]

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On-shore wind farm layout

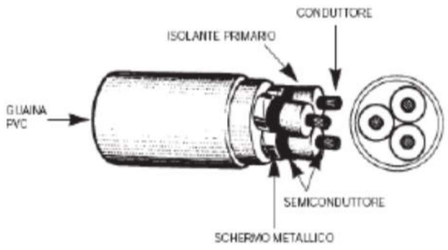
Dimensioning of cables and layout of cable lines

Thermal criterion

- Energy dissipation by Joule effect
- Temperature increase within the conductor
- Reduction of the useful life of the tenant

$$I_Z = I_0 K_1 K_2$$

$$I_Z > I_B$$



The conductor section is determined in such a way that the maximum current density (and therefore the maximum overtemperature with respect to the surrounding environment) does not exceed certain safety values.

Based on the limit values of the current flows (Iz) established by the cable manufacturers, in the various laying conditions, these must be higher than the operating currents (IB) calculated in each section that makes up the electrical circuit.

- Inspection boxes
- Underground cable ducts

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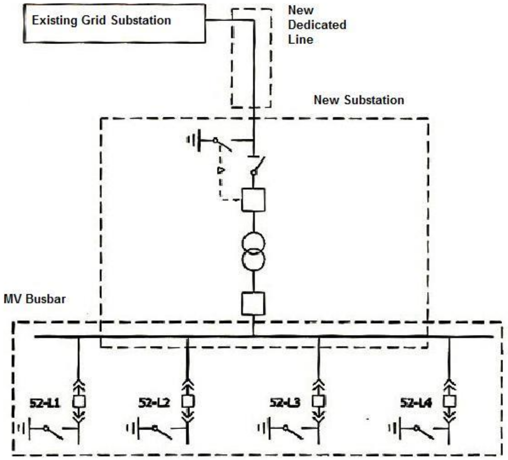
On-shore wind farm layout
Point of Connection to the National Transmission Network

The design of the RTN connection substation depends on the solution assigned by the network manager.

There are tables with plans and sections of:

- User area where the park power line arrives and the MV / HV transformation takes place
- Area of the network operator, where the energy produced is delivered



http://www.windfarmbop.com/wind-farm-substation-an-overview/

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On-shore wind farm layout
SCADA: Supervisory Control And Data Acquisition

Distributed computer system for the electronic monitoring of physical systems

- Sensors, which make measurements of physical quantities of interest on the system in question
- Microcontrollers, PLCs (Programmable Logic Controllers) or microcomputers, which, continuously or at intervals of time, carry out measurements using the sensors to which they are connected and store the measured values in a local memory
- Telecommunications system between the microcontrollers and the supervisor.
  computer network, or a set of serial lines;
- Supervisor computer, which periodically collects data from microcontrollers, processes them to extract useful information, stores data or summary information on disk, eventually triggers an alarm, selects and displays current and past data on screen, possibly in graphic format, and possibly sends selected information to the company information system.

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OFF-SHORE WIND FARM

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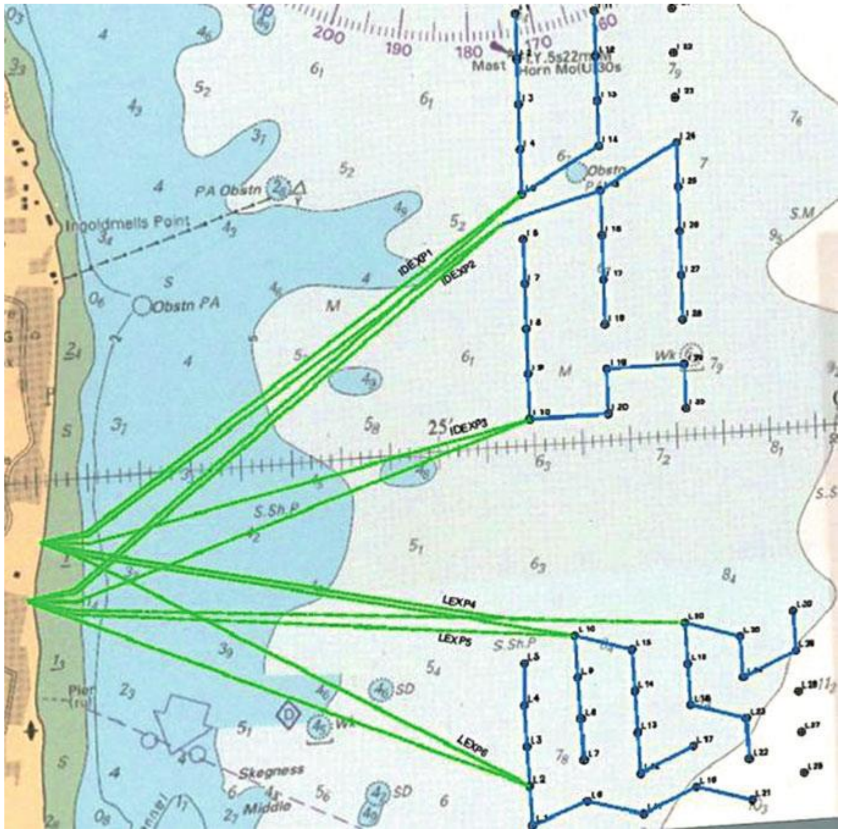
Off-shore Wind farm layout



Source: Siemens

Vattenfall's Horns Rev 1 offshore wind farm, Denmark.
Photograph by Christian Steiness

Middelgrunden, Denmark

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Off-shore Wind turbines

The size of the turbines represents a fundamental node for cutting costs

With the same installed power, the number of structures to be built and transported is reduced

→

- MW technology savings
- Savings on assembly
- Savings on support structures

Maximum size currently installed
P = 6 MW
Height = 120 m
Rotor diameter = 130 m

Maximum size available
P = 8 MW
Height = 130 m
Rotor diameter =160 m

Under development

P > 10 MW
Height > 130 m
Rotor diameter > 180 m

Technological constraints

- Material Weight / Cost
- PMG dimensions
- Nacelle elevation
- New technologies development and industrialization

Repower 6M Series

Vestas V164 8MW

[Courtesy: googleimages]

[Courtesy: googleimages]

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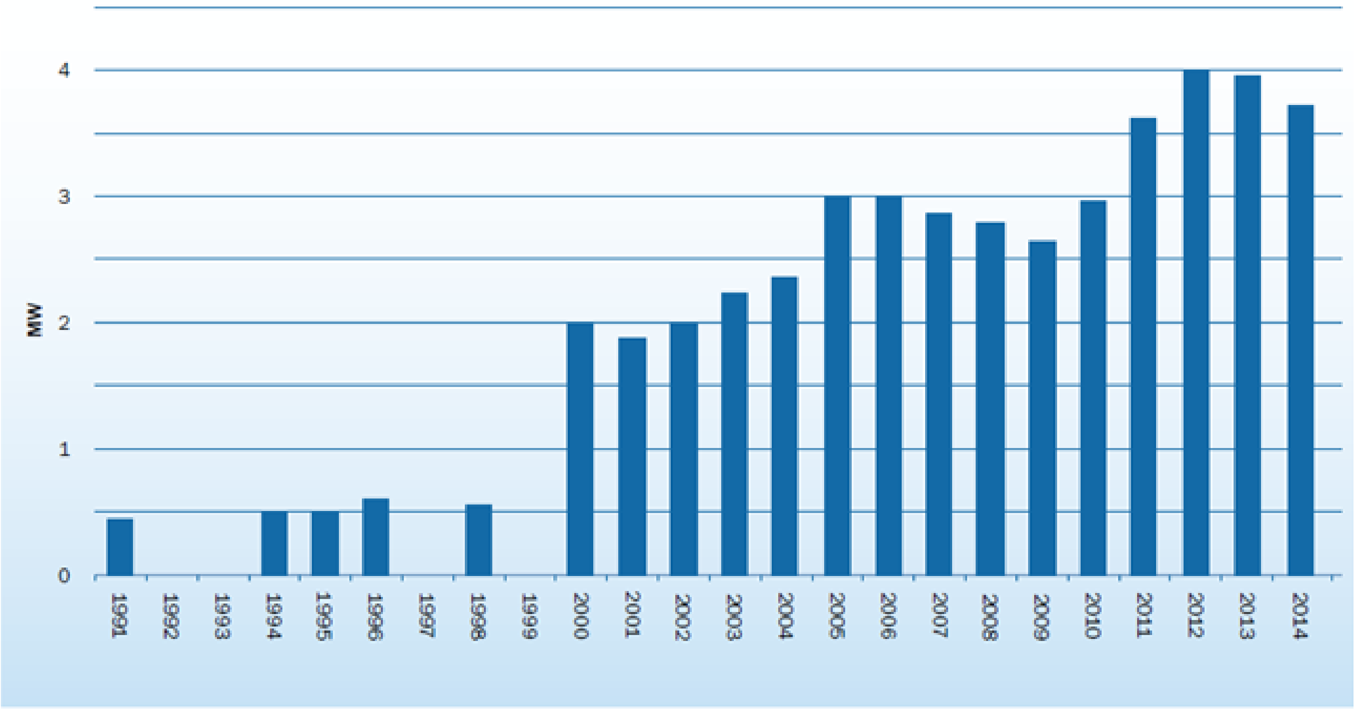
Off-shore Wind turbines

Average Off-Shore wind turbine rated capacity



Source: EWEA 2014

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Off-shore wind technology
Shallow water foundations

The main difference between on-shore and off-shore wind turbines lies in the foundations
The biggest obstacle to the development of offshore wind is in the very expensive foundations and installation activities that must necessarily be carried out offshore.

The characteristics of an adequate foundation structure must be:

- Construction cost compatible with the cost-effectiveness of the plant, considering that the incidence of the foundation cost in sea-side plants rises considerably;
- Ease of construction, transport to the sea and installation;
- Possibility of mass production;
- Adaptability to different depths, and to local conditions;
- Easy assembly with the wind turbine, on site or before launching at sea;
- Easy disposal at the end of the plant's life.

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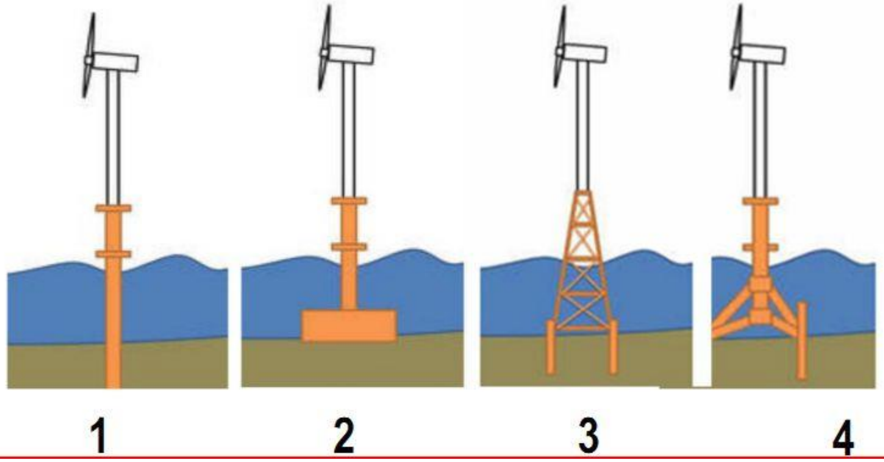
Foundations

	Type	Typical Waterdepth	Typical Size	Typical Weight
1	Monopile	~ 35 m	~ 4 - 5 m Ø	600 - 700 t
2	Gravity	~ 20 m	~ 30 m Ø	1000 - 3000 t
3	Jacket	up to 70 m	~ 25 x 60 m	700 - 900 t
4	Tripod	~ 50 m	~ 35 x 60 m	1000 t



Source: NREL

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Off-shore wind technology
Shallow water foundations

Gravity

Typical usage depth: 10 m
Maximum: 27 m

High-weight cementitious structure and supporting surface

Advantageous in regions where drilling is difficult and in regions with ice formation

Constructively cheaper than the monopile

Higher costs for transport (special vehicles) and preparation of the seabed

[Courtesy: googleimages]

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Off-shore wind technology

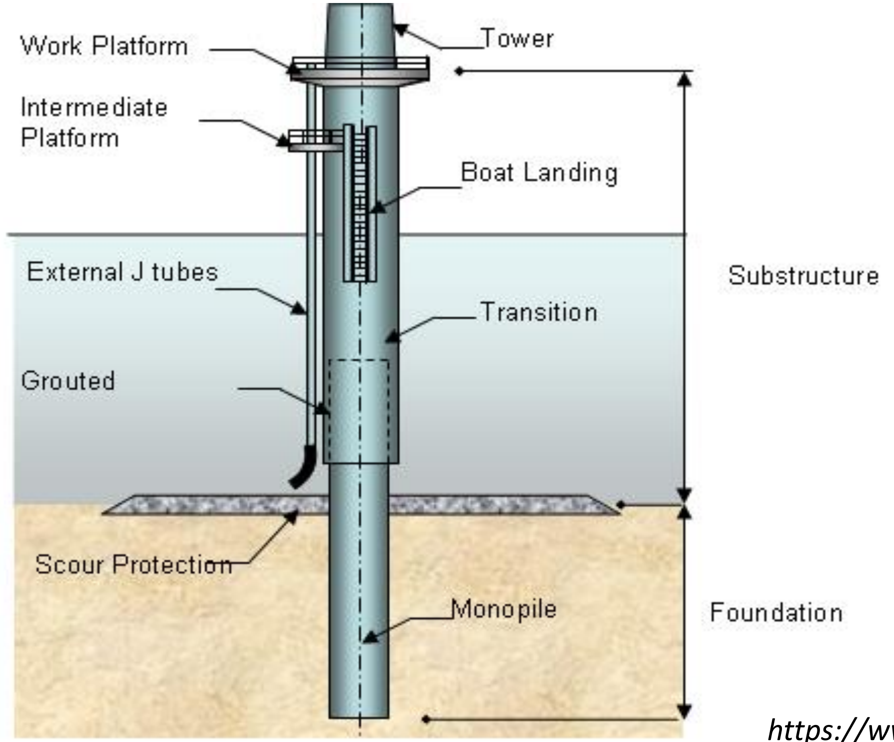
Shallow water foundations

Monopile

Typical usage depth : 10 - 20 m
Maximum: 35 m

Steel pole, inserted in the ground
For the 40 – 50% of its total length

It currently represents the most used type of foundation for shallow water due to its low cost and ease of installation



(The European Wind Energy Association, 2011).

https://www.dillinger.de/dh/aktuelles/presse/00028561/index.shtml

Off-shore wind technology

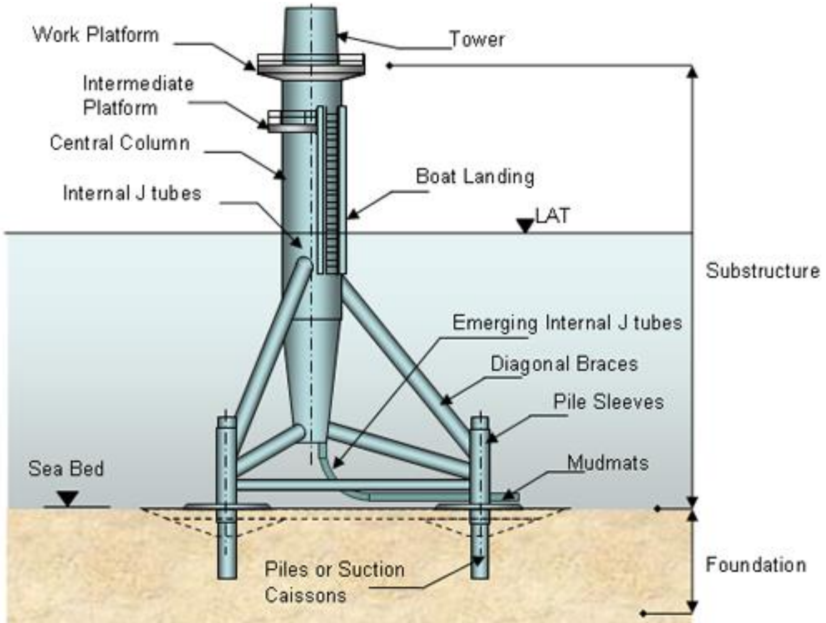
Shallow water foundations

Typical usage depth: 30 – 50 m
Maximum: 50 m

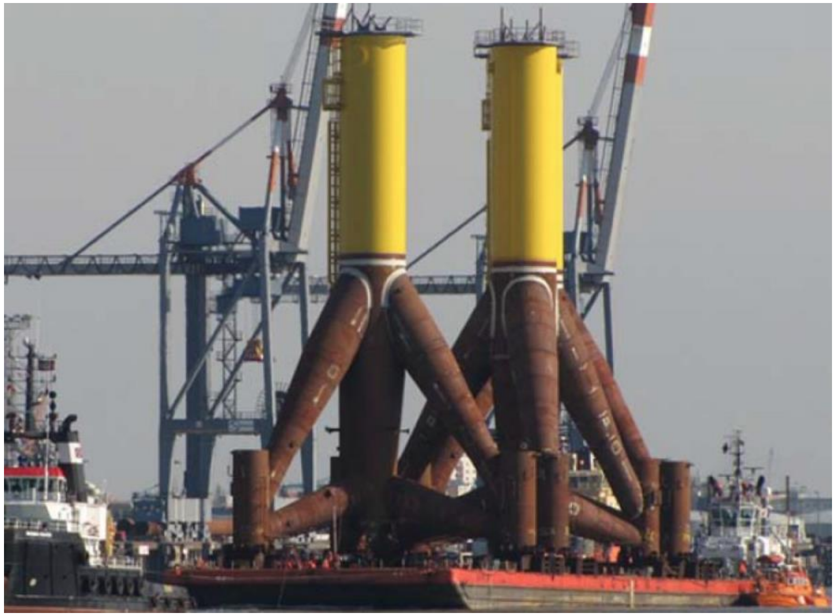
Tripod

Pole supported and fixed by three poles with smaller diameter, that are inserted in the seabed for a depth of about 20 meters.

- Greater resistance to hydrodynamic loads
- More suitable for depths over 30 m



(The European Wind Energy Association, 2011).



[Courtesy: googleimages]

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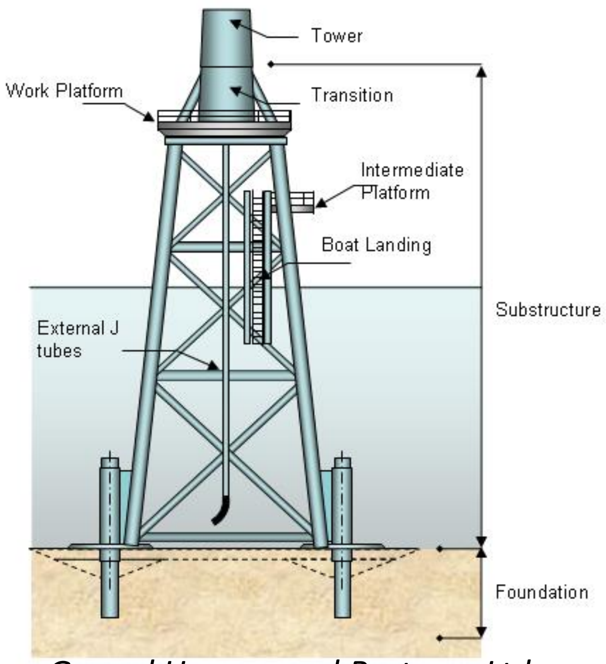
Off-shore wind technology

Shallow water foundations

Typical usage depth : 30 – 70 m
Maximum: 100 m

Jacket

Steel lattice structure fixed to the seabed by means of anchoring piles



Garrad Hassan and Partners Ltd

- Maximum resistance to hydrodynamic loads
- Less specific hydrodynamic force acting on the structure
- Mandatory for depths> 50 m
- High costs and weights

[Courtesy: googleimages]

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Off-shore wind technology

Floating platforms

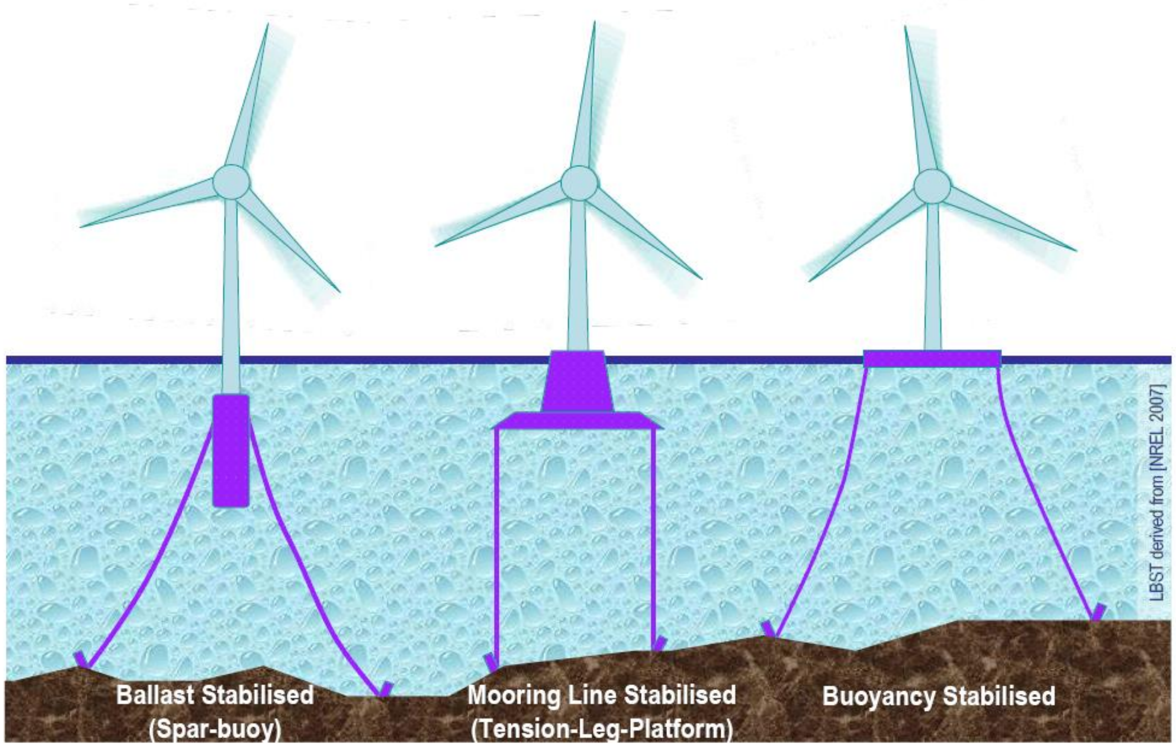
Main components:
- Floating platform
- Mooring lines

- **Ballast Stabilized**, the stabilizing moment is ensured by a large ballast, positioned in the lower end of the floating structure, of vertical and very elongated shape, and anchored by catenary mooring lines to the bottom

- **Boyancy Stabilized,** the moment is obtained from the horizontal shape and extension of a large floating barge, anchored with catenary mooring lines at the seabed.

- **Mooring Line Stabilized" o "Tension Leg Platform"**, the stabilizing moment is obtained with vertical rods anchored to the seabed and acting at the top of the floating structure, equipped with long horizontal arms

Various concepts for floating structures



Source: LBST derived from [NREL 2007]

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TLP - Tension leg platform

Floating platform maintained in position by a vertical anchoring system, kept in tension by the buoyancy of the platform itself.

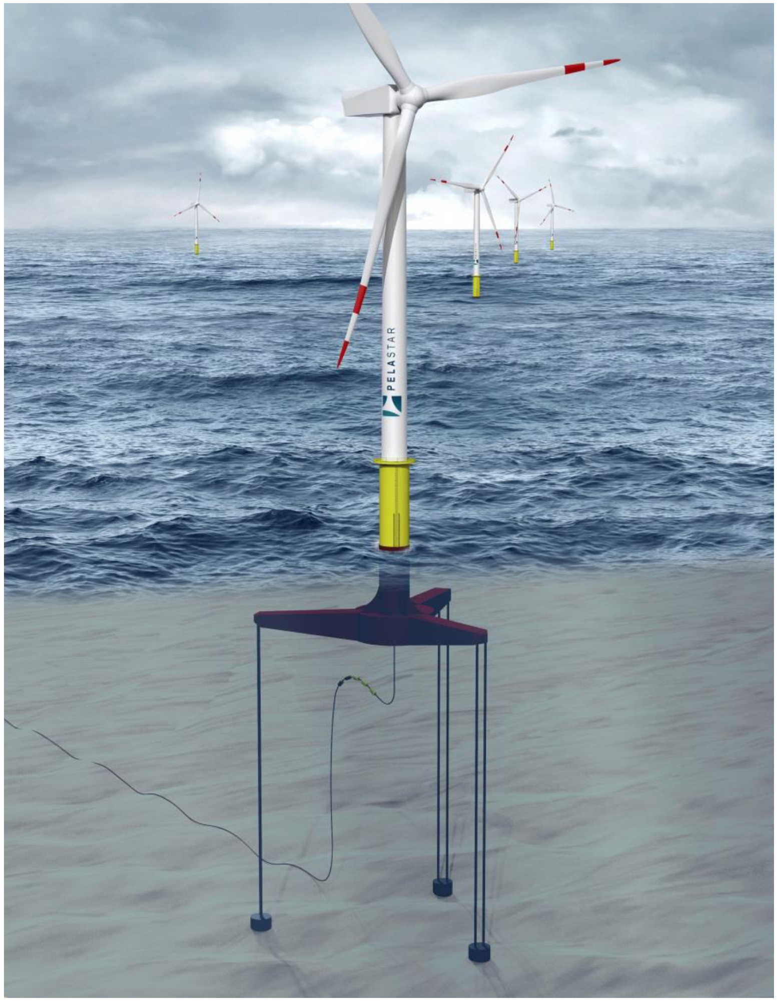
The foundations are anchored by piles driven into the seabed by means of hydraulic pile drivers; alternatively these can be held in place thanks to the gravity foundation

Advantages:

- Good vertical and angular stability
- Assembled on site and easy to transport

Disadvantages:

- Poor stability in the horizontal plane
- Risk of twisting of the tie rods
- Complex anchoring system to ensure safety
- Not suitable for large depths



[Courtesy: googleimages]

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Off-shore wind technology

Floating platforms

Semisubmersible platform

Floating structure composed of at least 3 to 6 floats that form a barge, whose floating stability is ensured by the shape of the float itself

Advantages.

- independence of system stability from moorings and / or tie rods and anchors on the seabed.
- less weight and less immersion in water, therefore minor stresses on the mooring lines, on the anchors and on the structure itself.

Disadvantages:

- tendency of this kind of floating structure to always be positioned parallel to the surface of the water and therefore to rigidly follow the wave motion.
- strong oscillations and relative mechanical stresses on the wind turbine.
- risks of overturning in the event of extreme sea conditions.

[Courtesy: googleimages]

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Off-shore wind technology

Floating platforms

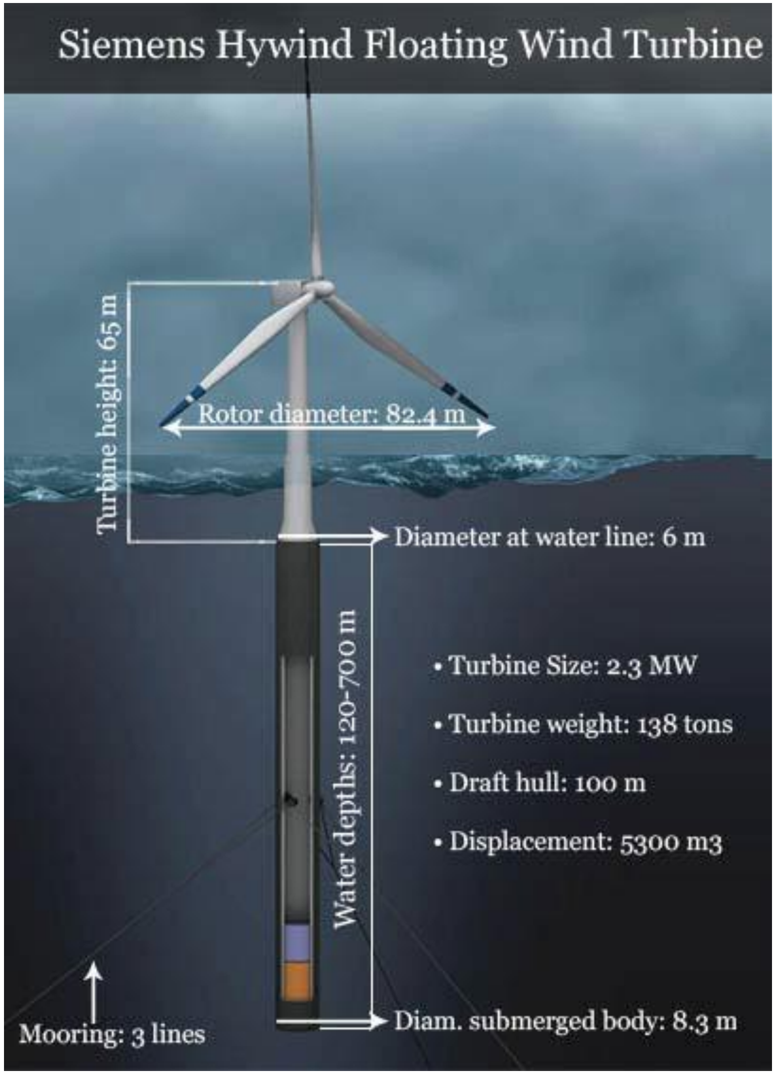
Single spar float

Consisting of a tall, thin tube with a ballasted lower end

Center of gravity is always below the buoyancy center -> Excellent buoyancy stability.

- "**Conventional Spar**", with a floating structure formed by a large cylindrical tank with ballast
- "**Truss Spar**", with a floating structure formed by a large empty upper tank, by a central frame structure, and by a lower tank filled with ballast

From 3 to 20 mooring lines



Source: StatOil

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Single spar float

Advantages:

- Intrinsic and extreme floating stability of this structure
- Stability does not depend on moorings and/or tie rods and anchors on the seabed
- Great inertia and low natural frequency of the structure, which therefore tends to position itself very slowly in a position of stable equilibrium, without following the wave motion.
- Minor mechanical stresses for the wind turbine.

Disadvantages:

- Large weight of the structure consisting largely of the ballast
- Significant mechanical stresses on the moorings and on the anchors caused by the sea currents.

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Off-shore wind technology

Control and transformation buildings

Station for collecting electricity produced by the wind turbines and MV/HV conversion

Depending on the costs and the distance from the shore the transformation station can be:

- Onshore
- In the farm with shallow water foundation
- Floating

Components:

- Transformers
- Switch panel
- Diesel UPS
- Staff hosting facilities
- MV and HV cables
- SCADA and monitoring systems

Source: Offshore Wind Power Marine Services

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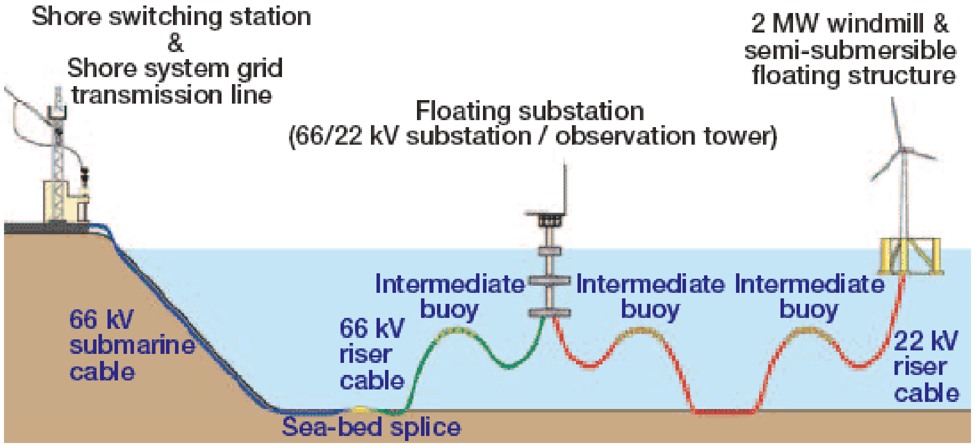
Off-shore wind technology

Main electrical systems

Transmission cables: Internal system

- The internal network cables connect the turbines in the farm connection matrix which is in turn connected to the off-shore collection substation.
- The turbine generates in LV, transforms into MV and is connected to the internal network.
- The internal network in MV is buried 2 - 3 m in the seabed.
- The greater the number of turbines, the greater the power carried by the cables (greater dimensions and voltages).



Transmission cables: external system

- Connection to the land grid
- Underground cables in the seabed using cable-laying ships
- Typically high voltage cables protected by a galvanized steel cover
- The cost and the project related to the operation depends on the seabed, the path, the depth, the environmental conditions

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Summary of the provided knowledge

- On-shore, grid-connected wind farm components, systems and layout
- Off-shore, grid-connected wind farm components, systems and layout
- Off-grid systems
- …

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- Pardalos, Panos M., et al., eds. Handbook of wind power systems. Springer Berlin Heidelberg, 2013.
- Butterfield, Sandy, et al. Engineering challenges for floating offshore wind turbines. No. NREL/CP-500-38776. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2007

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- http://www.windfarmbop.com/

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Feasibility study (logistics, transport and erection)

Lecture 2.1

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Learning outcomes

- To investigate the possible restrictions in a wind farm installation
- To identify obstacles and to find possible alternatives
- To select the correct norms, legislations to be followed for the correct sizing and authorization
- To evaluate visual impacts, using graphical solutions
- To investigate possible national restrictions in the selection of he land for the installation
- To verify the minimum distance from sensible sites in order to make the project in line with local/national laws

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Table of contents

- Feasibility study and selection of suitable site
- Legislations and Norms
  - International
  - European
  - National
  - IEC 61400
- Landscaping Plan

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Feasibility study
Identification of a suitable site

Preliminary study of the wind resource
Does the wind have the right characteristics for the project to be carried out?

Preliminary site evaluation rules:

- Good exposure to winds especially in the main direction
- Checking the gradient of wind intensity in the surrounding space
- Territory verification on onshore sites
- Slope of the promontory (ideal around 17 degrees)
- Vegetation and other obstacles.

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Feasibility study
Identification of a suitable site

Possibility of energy evacuation

Can the site be connected to the distribution network in an economically feasible manner for the size of the project?

Check the proximity of medium and high voltage networks and the economic feasibility of the connection

→

The costs of connection to the high voltage lines could be prohibitive for small projects

Discussion with the electricity distribution and management companies

Maximum installable power and connection costs

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Feasibility study
Identification of a suitable site

Authorizations and restrictions

Is the project accessible to all the permits necessary for its realization?

The restrictions depend on the region and must be evaluated beforehand

Guidelines:

- Avoid areas of landscape, artistic, naturalistic interest
- Reduce visibility with respect to built-up areas
- Avoid sites with population centers within a few hundred meters
  - Noise
  - Shadow flicker
- Check the position of the telecommunication lines and the antennas
  - Interference caused by turbines

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Feasibility study
Identification of a suitable site

Analysis of the territory and the civil works present

Is the site accessible or can it be made within the economic limits given by the size of the project?

Distance from the roads

Complexity of the territory and accessibility to the site

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Feasibility study
Identification of a suitable site

Analysis of the territory and the civil works present

Is the site accessible or can it be made within the economic limits given by the size of the project?

Click on the picture to see the video.

VESTAS – Wind blade transportation [source: Youtube]

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LEGISLATIONS AND NORMS

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Wind Legislations
Global Legislation and Agreement

Global legislation and Agreement

- Kyoto Protocol
- **IEC61400 - serie**

European Legislation: Energy Strategy and Goals

- Renewable energy directive
- Directive 2009/28/EC
- **IEC61400 - serie**

National Energy Strategy and Guidelines

- PEN - National Energy Plan (1988)
- Administrative Guidelines for Renewable Sources (8 July 2010)
- Legislative Decree 28/2011 - guidelines on procedures
- Single Authorization, Authorized Areas, etc.
- Landscaping report – Technical Annex
- …

Regional Operational guidelines

- Regional landscape plan
- …

Municipal Regulation

- Urban Plan
- …

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Wind Legislations
Why?

Standards

Standard (ISO) - a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose.

Benefits:

SOCIETY	BUSINESS
• Reduced technical barriers to trade • Trust in products and services • Increased quality and safety • Dissemination of best practices • Economic growth	• Market penetration • Global availability • Increased sales • Knowledge and sharing best practice • Increased productivity • Frame innovation and reduce development cost • Improved quality/cost balance

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Wind Legislations
International: IEC61400 - serie

IEC = International Electrotechnical Commission

"Standards' purpose is to provide a basis for design, quality assurance and technical aspects for certification"

- Standardization in the field of wind energy generation systems including wind turbines, wind power plants onshore and offshore and interaction with the electrical system(s) to which energy is supplied.
- These standards address site suitability and resource assessment, design requirements, engineering integrity, modeling requirements, measurement techniques, test procedures, operation and maintenance.
- The standards address site-specific conditions, all systems and subsystems of wind turbines and wind power plants, such as mechanical, and electrical systems, support structures, control and protection as well as communication systems for monitoring, centralized and distributed control and evaluation, implementation of grid connection requirements for wind power plants, and environmental aspects of wind power development.

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Wind Legislations
International: IEC61400 - serie

Offshore wind turbine design requirements:
IEC 61400-01 Design requirement
IEC 61400-03 Design requirements for offshore wind turbine

IEC61400-serie

- IEC 61400-01 Design requirement
- IEC 61400-02 Small wind turbines
- IEC 61400-03 Design requirements for offshore wind turbines
- IEC 61400-03-1 Design requirements for offshore wind turbine
- IEC 61400-03-2 Design requirements for floating offshore wind turbines
- IEC 61400-04 Design requirements for wind turbine gearboxes
- IEC 61400-05 Wind Turbine Blades
- IEC 61400-06 Tower and foundation design
- IEC 61400-07 Safety of WTG (Wind Turbine Generator) power converters
- IEC 61400-11 Acoustic noise measurement techniques
- IEC 61400-12-1 Power performance measurements
- IEC 61400-12-2 Power performance based on nacelle anemometry
- IEC 61400-12-3 Wind Farm Power performance testing
- IEC 61400-12-4 Power performance verification of electricity producing wind turbines based on numerical site calibration
- IEC 61400-13 Measurement of mechanical loads

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Wind Legislations
International: IEC61400 - serie

IEC61400-serie

- IEC 61400-14 Declaration of sound power level and tonality
- IEC 61400-15 Assessment of site specific wind conditions for wind power stations
- IEC 61400-21 Measurement and assessment of power quality characteristics of grid connected wind turbine
- IEC 61400-22 Conformity Testing and Certification of wind turbines
- IEC 61400-23 Full-scale structural testing of rotor blades
- IEC 61400-24-TR Lightning protection
- IEC 61400-25 Communication for monitoring and control of wind power plants -
- IEC 61400-26-1: Time based availability for wind turbines
- IEC 61400-26-2: Production-based availability for wind turbines
- IEC 61400-26-3 Ed. 1
- IEC 61400-27-1 Electrical simulation models for wind turbine generation
- IEC 61400-27-2 Electrical simulation models for wind power plant generation
- IEC 61400-30 Safety of the WTGs General principles for Design (EN 50308 Protective measures - Requirements for design, operation and maintenance)
- IEC 61400-40 Electromagnetic Compatibility (EMC)
- IEC 61400-415 Terminology

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Wind Legislations
National and Regional level: Landscaping Plan

“Each intervention must be aimed at an improvement in the quality of the landscape of places, or, at least, must ensure that there is not a decrease in its quality, despite the transformations”

This means that the knowledge of the characteristics and the landscape meanings of the places is the foundation of every project that intends to reach a landscape quality.

- analysis of protection levels
- analysis of the characteristics of the landscape in its various components, both natural and anthropogenic
- analysis of the historical evolution of the territory
- analysis of the inter-visibility of the plant in the landscape

- Regional Landscaping Plan (GIS System) [Only for Italy]

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Wind Legislations
National and Regional level: Landscaping Plan

The inspection

The inspection allows the relief, geometric and photographic, of the current state of the places in their dimensional aspects, materials and use and that allows the immediate confirmation of the knowledge acquired.

The inspection is the first way of relationship with the characteristics of the places object of the project.

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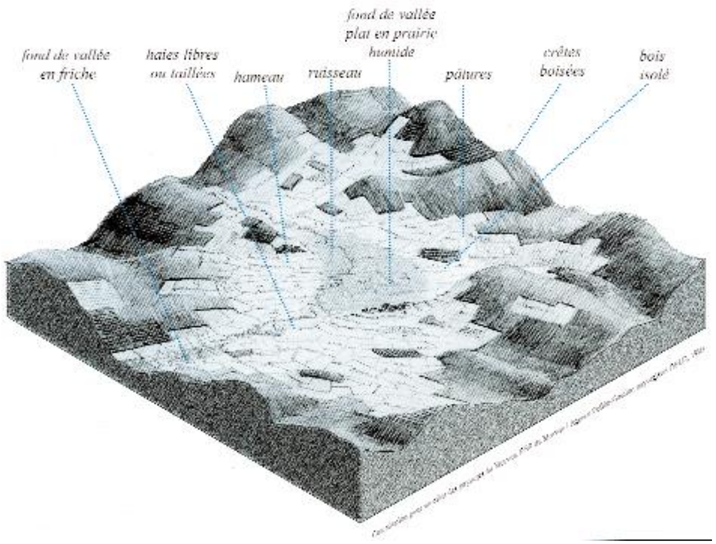
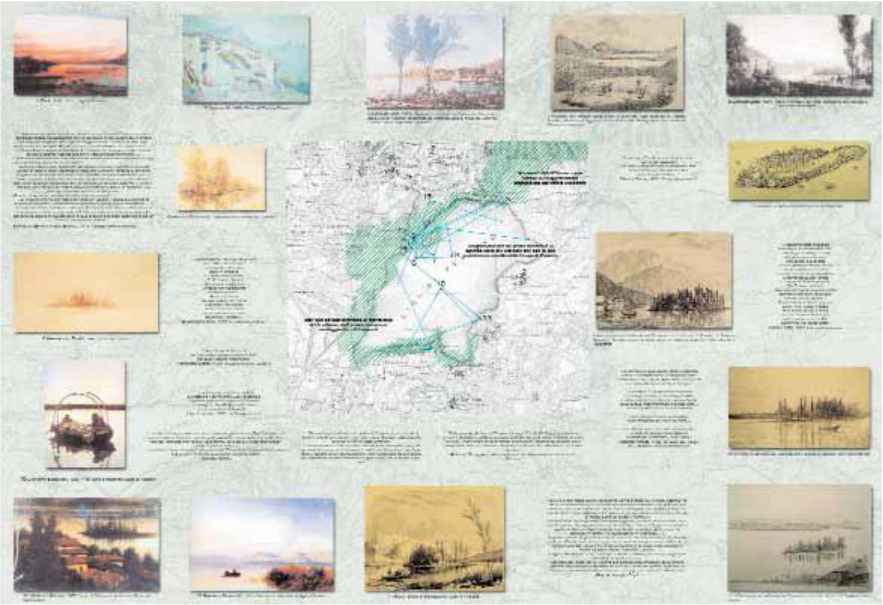
Wind Legislations
National and Regional level: Landscaping Plan



Architecture of places: the visual perception of a place



Historical sites

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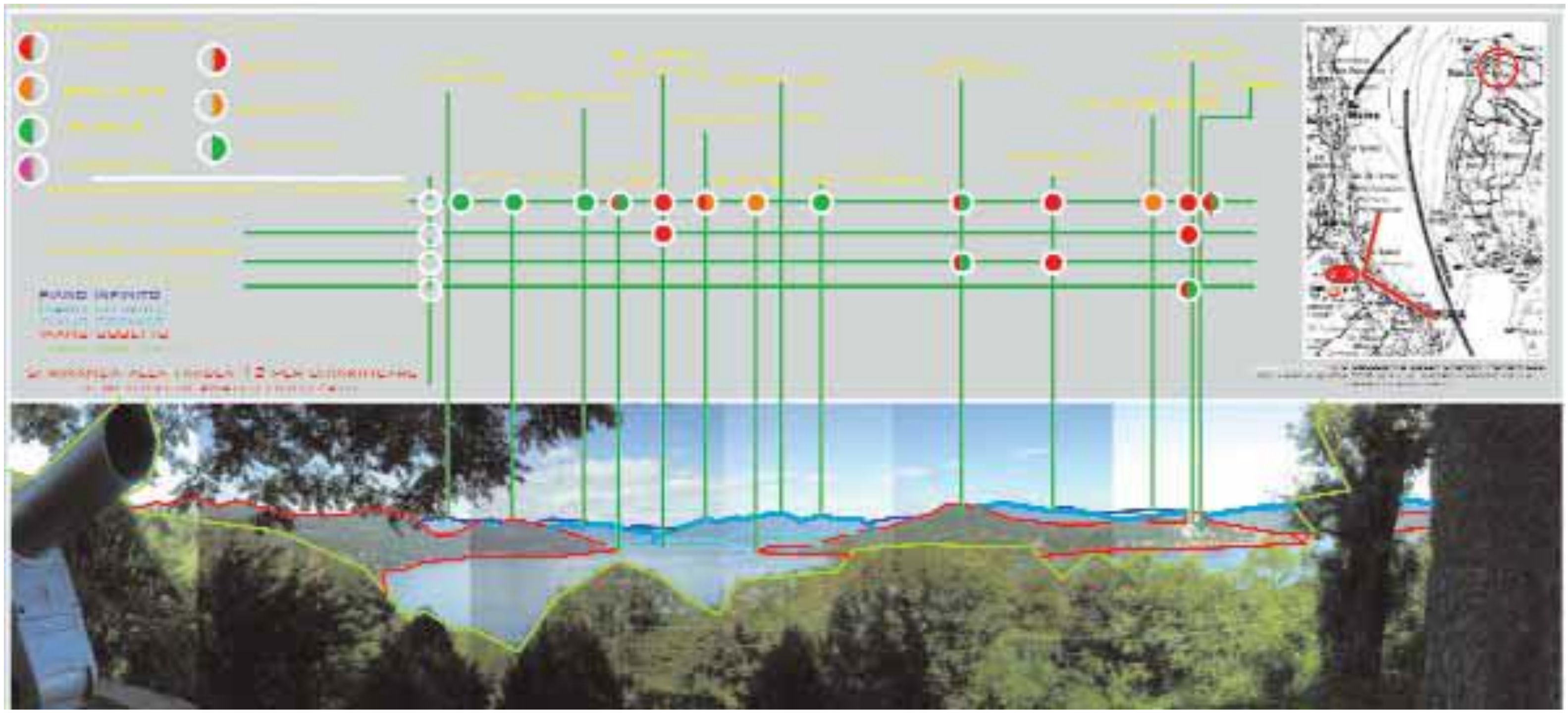
Wind Legislations
National and Regional level: Landscaping Plan



Architecture of places: the visual perception of a place

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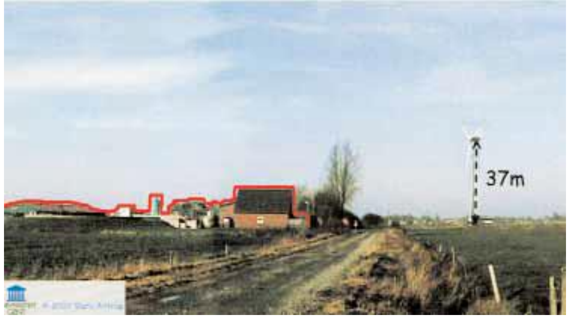
Wind Legislations
National and Regional level: Landscaping Plan

Perception and social acceptance

Visual impact

⇩

Visual effect simulation



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Wind Legislations
National and Regional level: Landscaping Plan

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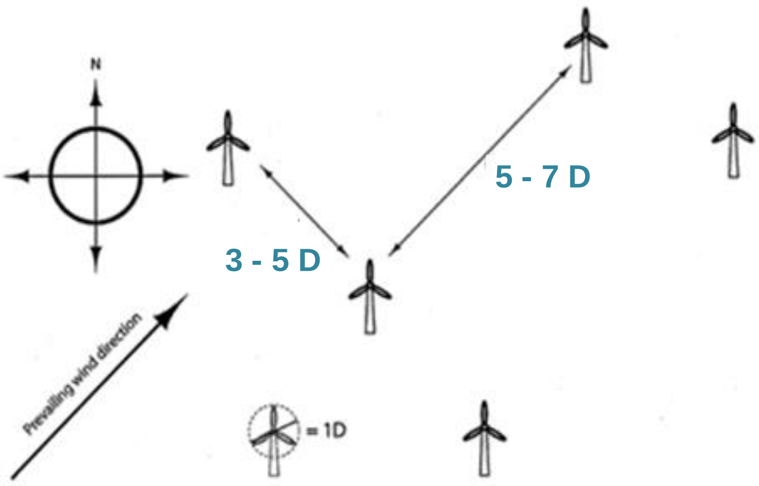
Wind Legislations
National and Regional level

Distance of the turbines from the perimeter of the urban area

Each wind turbine must be at least 15 D (diameter of the turbine) from the boundary of the building area of the urban center; this distance may be not less than 1.00 km.

Distance from the provincial or national roads

The distance of each wind turbine from a provincial or national road must be more than 4 times the diameter of the turbine and in any case not less than 300 m; furthermore, this distance must in any case be greater than the maximum range of the rotating elements in case of accidental breakage.



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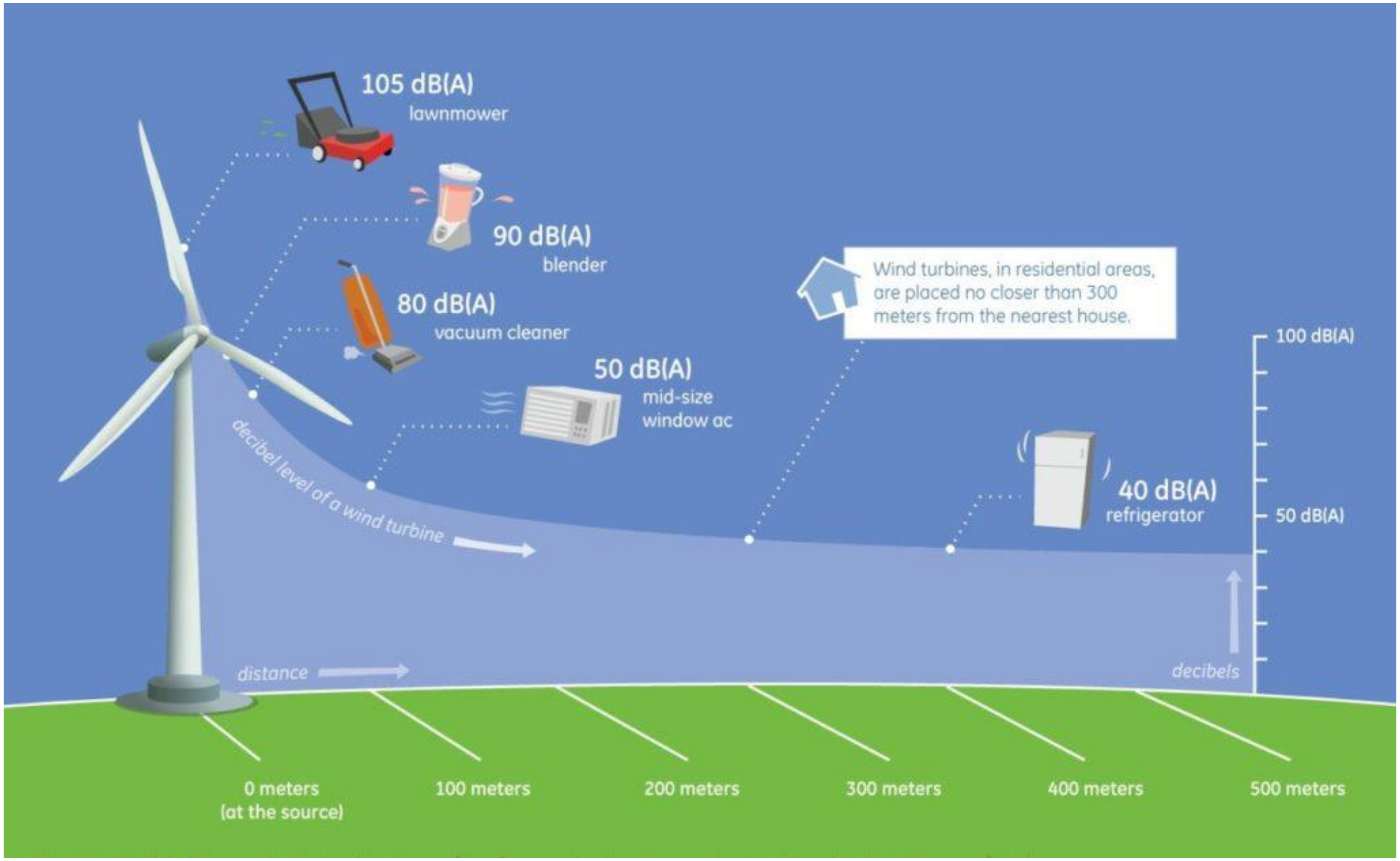
Wind Legislations
National and Regional level



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Wind Legislations
National and Regional level

Noise emissions from wind turbines are a key concern for developers.

All wind turbines emit a faint and periodical noise caused by the blade's movement through the air and by the turbine's machinery.

In most countries environmental noise legislation is based on national regulations.

Allowable environmental noise emission levels are often categorized by area (residential, recreational, medical institutions, industrial and so on) and by timing.

During the day acceptable noise levels vary from 45 db(A) (for hospital, recreational areas) to 70 db(A) (industrial areas) but during the night the values are reduced by approximately 10 to 15 dB(A).

Table I. Overview of Noise Metrics and Threshold Limits.

Governing Jurisdiction	Noise Metric	Rural Area	Residential Area
Belgium – Flanders [1]	L_{Aeq} @ 95% nominal power [dB(A)]	Day: 48 Evening/night: 43	Day: 44 Evening/night: 39
Belgium – Wallonia [2]	L_{Aeq} @ all wind speeds [dB(A)]	45	
Canada	No National Legislation for Wind Turbine Noise		
Canada – Alberta [3]	L_{Aeq} [dB(A)]	40 (basic limit)	40 (basic limit)
Canada - Ontario	L_{Aeq} [dB(A)]	40 @ 4 m/s – 51 @ 10 m/s; 45 @ 8 m/s	45 @ 4 m/s – 51 @ 10 m/s; 45 @ 8 m/s
Canada - Prince Edward Island [4]	No Province Legislation for Wind Turbine Noise, but Setback Distance of 3 Times Total Turbine Height to Neighbouring Residences		
Denmark [5]	L_r [dB(A)] L_r [dB(A)] L_{pALF} (indoors) [dB]	42 @ 6 m/s 44 @ 8 m/s 20 @ 6 and 8 m/s	37 @ 6 m/s 39 @ 8 m/s 20 @ 6 and 8 m/s
Finland [8]	L_{Aeq} [dB(A)]	Day: 45 *(draft)* Night: 40 *(draft)*	
France [6]	L_{Aeq} @ all wind speeds [dB(A)]	Day: increase of 5 dB(A) with reference to background noise level Night: increase of 3 dB(A) with reference to background noise level	
Germany [7]	L_r @ all wind speeds [dB(A)]	Day: 60 Night: 45	Day: 50-55 Night: 35-40
The Netherlands [9]	L_{den} [dB] L_{night} [dB]	L_{den}: 47 L_{night}: 41	
New Zealand [10]	$L_{A90(10min)}$ [dB(A)]	35 or background $L_{A90(10\ min)}$ + 5	40 or background $L_{A90(10\ min)}$ + 5
Norway [11]	L_{den} [dB]	L_{den}: 45	

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Summary of the provided knowledge

- A feasibility study can be divided in four steps:
  - Preliminary study of the wind source
  - Possibility of energy evacuation
  - Authorizations and restrictions
  - Analysis of the territory and the civil works present
- Legislation to be followed is at International, National and Local level
- Project and Wind Turbine components must follow specific standards aim at providing a basis for design, quality assurance and technical aspects for certification
- IEC61400 covers all aspect of wind plant project , design of technology, operational methods

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Summary of the provided knowledge

- One of the most important aspect, also for the social acceptance, is the visual impact of the wind farm, that can be estimated with the analysis of the landscape and the graphical simulation of the wind turbines
- A second important aspects is the noise impacts, strictly regulated at National level.

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References

Books and Reports:

- …

Websites:

- International Electrotechnical Commission - https://www.iec.ch/
- Youtube

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Operation and maintenance issues

Lecture 2.2

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Learning outcomes

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Table of contents

- …
- …
- …
- …
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Module 2.4 Implementation of Wind Energy Systems

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Summary of the provided knowledge

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Social Acceptance

Lecture 2.3

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- Wind energy generally achieve governmental and management support within most of the countries nowadays.
- However, social acceptance is a recurring issue within the regular population.
- Some regions has higher level of social opposition than others due to many reasons but mostly for the ignorance from the population of the positive and negative impacts of this technology on the communities where they are built.

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- Continuing and enhanced knowledge transfer of the impacts of such technology to those living close to the wind farms help in continuous use of this technology with lower opposition.

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What is Social Acceptance?
Social Acceptance Stakeholder

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- What is social acceptance:
  - Socio-political acceptance
  - Market acceptance
  - Community acceptance

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- Socio-political Acceptance
  - Federal Administration
  - Policy Makers
  - State administration
  - Syndicates and technical committees

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- Market Acceptance
  - Utilities
  - Grid Owners/Operators
  - Developers
  - Financial Institutions

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- Community acceptance
  - Original residents
  - Local landowners
  - Local Administration / Authorities
  - Visitors / tourists

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- Community acceptance
  - Local and National NGO’s
  - Opinion Makers
  - Policy Makers
  - Educators
  - Experts
  - Media

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Elements of Social Acceptance

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- Elements of Social Acceptance:
  - Well-being
  - Policy & Strategies
  - Procedural design
  - Distributional justice
  - Implementation strategies

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- Well Being
  - Standard of living
  - Quality of life
  - Health, lights, noise, and shadow
  - Valuation of ecosystems

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- Policy & Strategies
  - Local option for share purchase
  - Fund to support early stage development
  - Wind Turbine administration assist
  - Compensation for loss of property value

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- Procedural design
  - Procedures that are used to design and develop wind farms especially those that create dialogue across stakeholder groups can assist in resolving social implementation issues

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- Distributional justice: Local residents often bear an uneven share of wind energy's impacts
  - Profit margins should be distributed to the community where wind turbines are established
  - Direct and indirect economic returns
    - Project revenues
    - Jobs, general business activity

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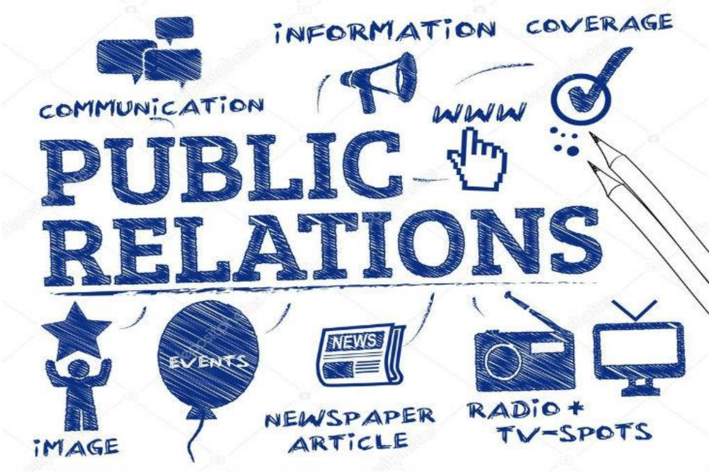
- Implementation strategies: deep opposition may be impossible to overcome; poor project implementation may also affect future success
  - Good planning of Public relations within community could assist
  - Open and transparent communications of pros and cons of projects could help reduce opposition
  - Good education to the community where wind farms are to be built could support implementation



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- Influence of Wind Farms on the main social indicators:
  - Creating new jobs
  - Improve population health
  - Reduce impact on the environment

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- Economic Benefits of the implementation of Wind farms:
  - Cost competitiveness and quick cost break-even in favorable natural conditions.
  - Easy to integrate in (existing) mini-grids fed with diesel. Hybrid wind-diesel systems provide higher quality, lower costs, and are a more reliable and sustainable solution than diesel-only systems.
  - Allow, in combination with such applications as solar to develop a ‘whole-year-round’ solution.
  - The perfect solution not only to generate enough power for feeding and developing small businesses, but also to increase the synergies with growing sectors.

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- Real challenges and opportunities of wind energy sources:
  - Develop knowledge of this technology. Education and training are the key to everything.
  - Encourage local communities and small businesses to use alternative sources of energy. This will increase the reliability of their electricity supply and decrease their electricity bills.
  - Feasibility studies and assessment of wind speed data are missing. This type of study is an easy way to discover new business opportunities and favorable locations.

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- Real challenges and opportunities of wind energy sources:
  - Feasibility studies and assessment of wind speed data are missing. This type of study is an easy way to discover new business opportunities and favorable locations.
  - Integrate, impose and control quality standards and certifications for every new installation. This will ensure the installation of products that will generate reliable electricity over a longer time span.
  - Encourage the development of joint ventures and partnership agreements with expert companies. This will ensure proper installation, operation and maintenance AND will generate local employment.

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Environmental Impact Assessment (EIA)

Lecture 2.4

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Learning outcomes

- To foresee the possible enviromental impacts of wind turbines
- To estimate the incidence of impacts and to evaluate how to reduce them
- …
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Table of contents

- Visual Impact
- Noise Impacts
- Electromagnetic Impact
- Local and migratory birds
- Intermittent shadows
- …

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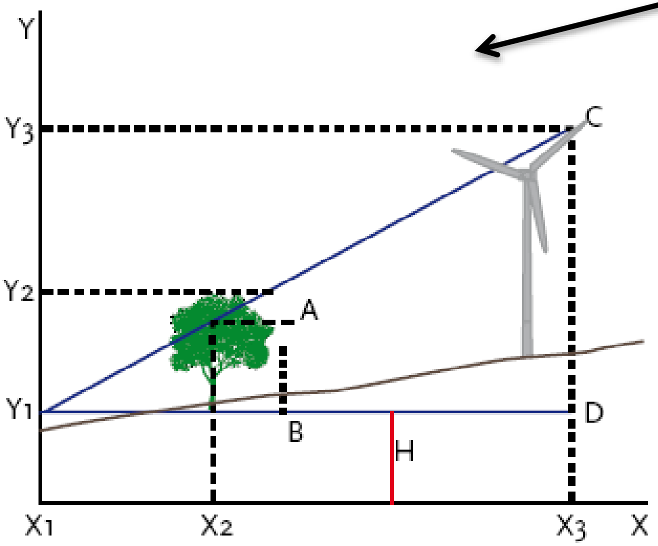
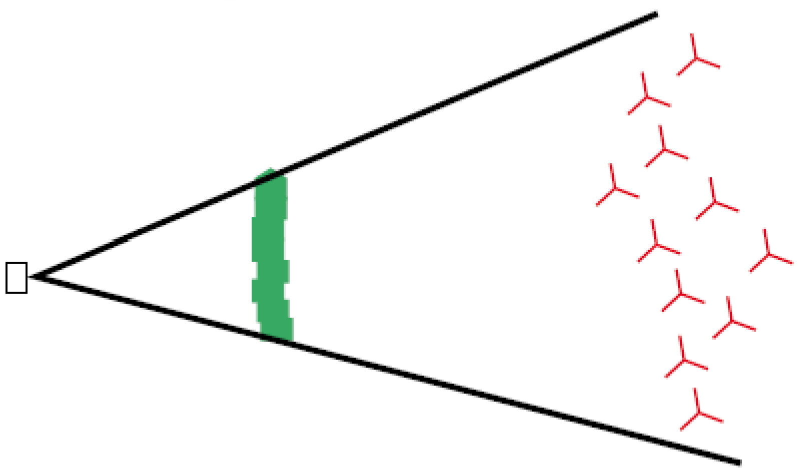
Environmental impacts
Visual impact

The visual emergency, defined as the local variation of the average height of objects visible from the station point on horizon tour of 360 ° (2π) made in each of the directions of the four key domains and including the plant project, the all mediated with a weight identified on the basis of the backgrounds, lighting and the prevailing meteorological conditions.

The station point is made from an observation point coinciding with a place scenically, naturalistically or socially important from the point of view of to safeguard.

Once you have determined the impact index, you can analyze some measures to improve the visual situation: solution shielding and mitigation solution





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Environmental impacts
Noise impact

1. The noise impact of the wind turbines is mainly due to the movement of the rotor , which generates noise , particularly near the periphery of the blades.
   The system of variation of the number of revolutions , which allows to reduce the speed of the rotor when the wind is weak and allows speeds of the ends of the blades more contained , all to the advantage of killing noise .
   When the wind is more intense, the noise associated to the rotor is covered by rustling that the wind itself generates in the surrounding environment , resulting in a minimum acoustic impact of the machine.

2. The equipment within the nacelle also generate noise, in particular the gearbox and the electric generator .
   However, thanks to the use of bases and elastic dampers and sound proofing of the spacecraft , it is possible to reduce considerably the noise and vibrations transmitted outside.
   In high power machines , the spacecraft is positioned at a height to allow a reduction of noise due to the separation between the equipment and the ground.

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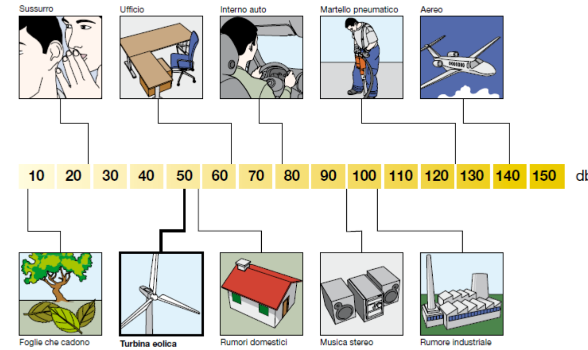
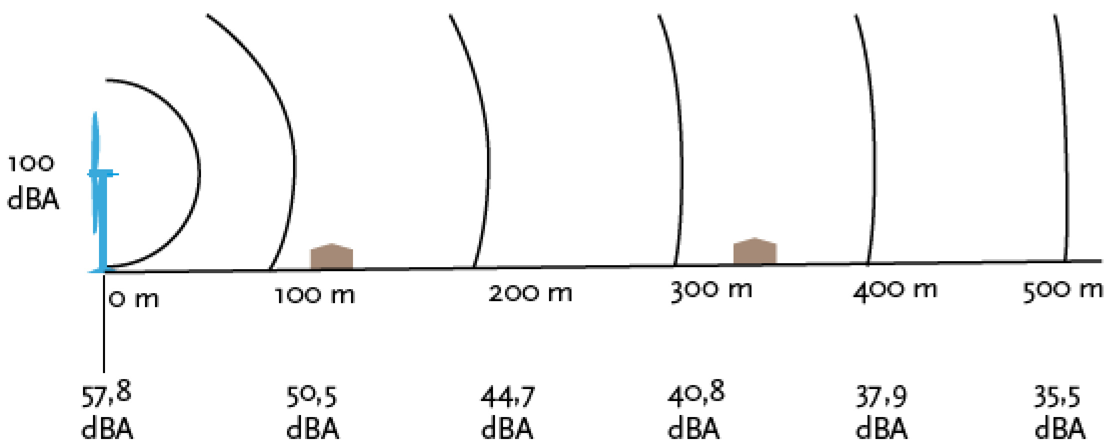
Environmental impacts
Noise impact

If L_a is the intensity of the noise emitted by a wind turbine, considering the atmospheric absorption αa, at a distance R from the machine will be recorded background noise equal to:

$$L_R = L_a - 10\log_{10}\left(2\,\pi\,R^2\right) - \alpha_a \cdot R$$





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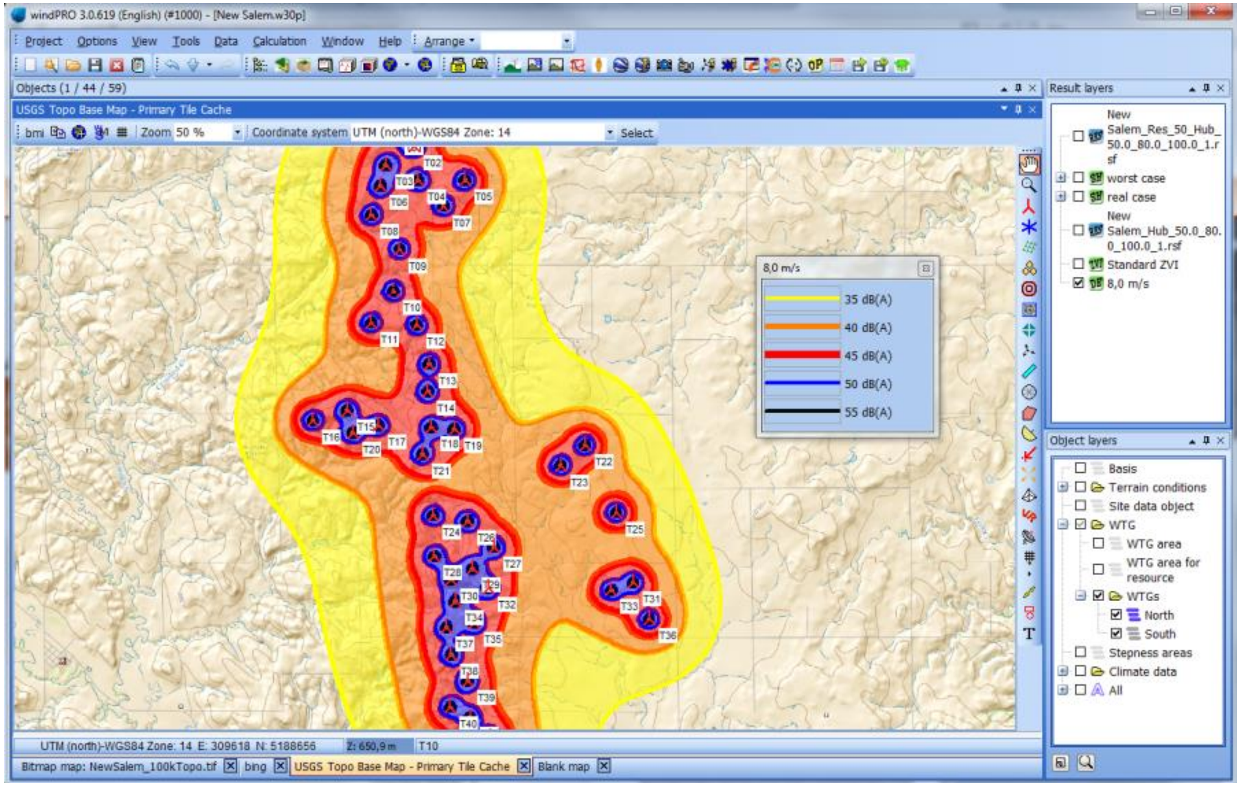
Environmental impacts
Noise impact

In the case of a wind farm must be superimposed on the effects on the individual generators. In the case of wind turbines n we have:

$$L_n = 10 \log \sum_{j=1}^{n} 10^{\left(\frac{L_j}{10}\right)}$$



WindPRO

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Environmental impacts
Electromagnetic impact

Electromagnetic interference is limited to just the area surrounding the wind farm and mainly interference of radio waves. These are local and are not due to the presence, inside the ship, the electrical generator equipped with its auxiliaries. The nacelle is normally screen against this possibility and , moreover , the electrical energy is generated at relatively low voltages .

The interaction with the local and migratory birds is one of the most controversial issues concerning central located in areas with high natural interest. There are numerous species of birds considered as protected, in Italy, many of them are permanent or seasonal retreat right in the Apennine interested eventual development of wind farms . Despite the number of accidents caused by the presence of wind turbines is extremely low , it is good for security exploit areas where it is recognized that there is no migration routes and avoid areas where protected species nest .

The presence of the rotating blades may cause intermittent shadows on the surrounding area during the months when the sun is low on the horizon . This phenomenon can create disturbances near the plant where there are homes. The presence of intermittent shadows, relevance, especially in northern countries.

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Summary of the provided knowledge

- The main environmental impacts are
  - Visual Impact defined as the local variation of the average height of objects visible from the station point on horizon tour of 360°;
  - Noise Impacts mainly due to the movement of the rotor, particularly near the periphery of the blades, and to gearbox and the electric generator in the nacelles;
  - Electromagnetic Impact limited to the area surrounding the wind farm and mainly interferencing with radio waves;
  - Local and migratory birds, mainly when the migratory ways pass through the wind farms;
  - Intermittent shadows cause by the presence of the rotating blades during the months when the sun is low on the horizon.
- …

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References

Books and Reports:

- …

Websites:

- …

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Occupational Health and Safety (OHS&S)

Lecture 2.5

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Wind energy turbines — onshore and offshore

- Wind turbines use wind to generate electricity. The kinetic energy of the wind is first converted into mechanical energy by the rotors of the wind turbines and then into electricity, which is transferred into the grid.
- At present, there is a significant market for distributed power generators, whereby the electricity generated by the turbines is used or stored locally, typically by a private owner.
- Wind turbines tend to be grouped together in wind farms.

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Wind energy turbines — onshore and offshore

- Wind turbines are installed both onshore, including inland and costal installations, and offshore, referring to those installations that are located away from the coast.
- Whether located onshore or offshore, wind turbines consist of similar components

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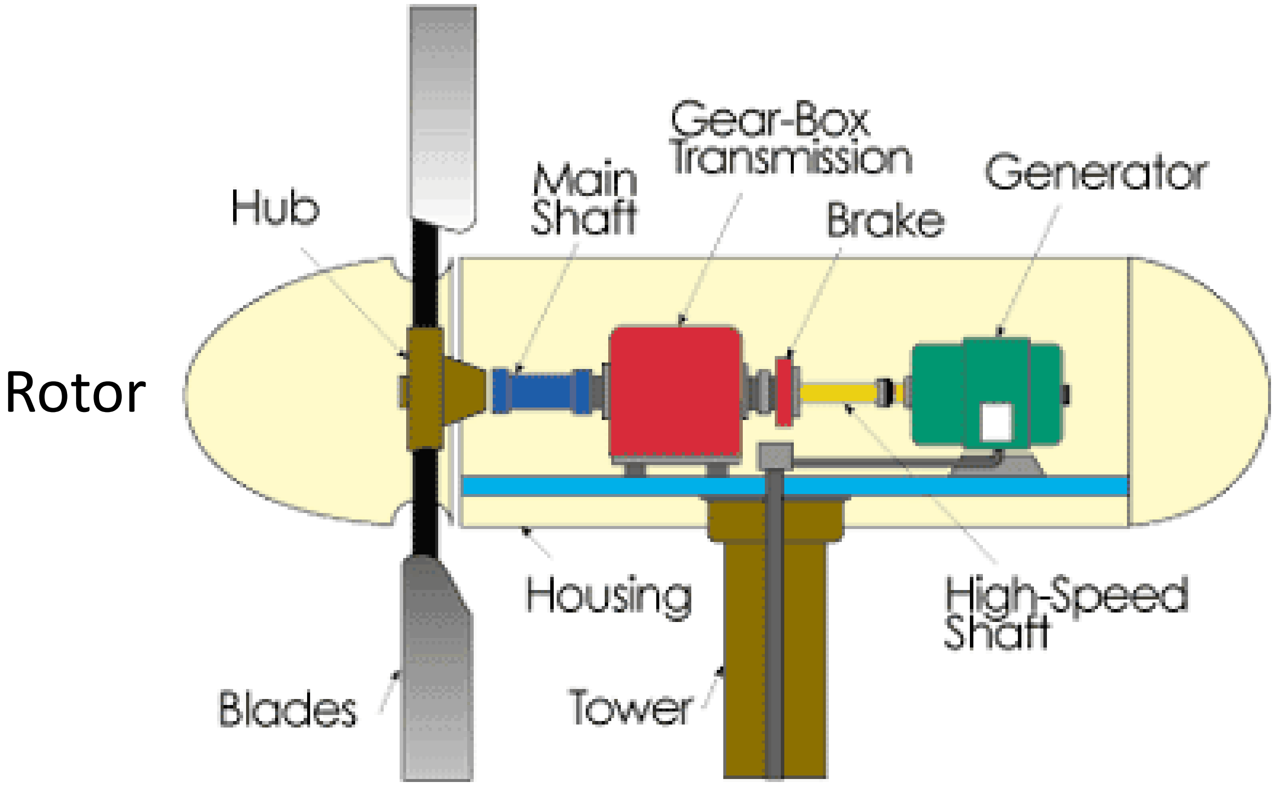
Main components of a Wind Turbine



Wind energy turbines — onshore and offshore

Left: onshore wind turbines

Right offshore wind turbines

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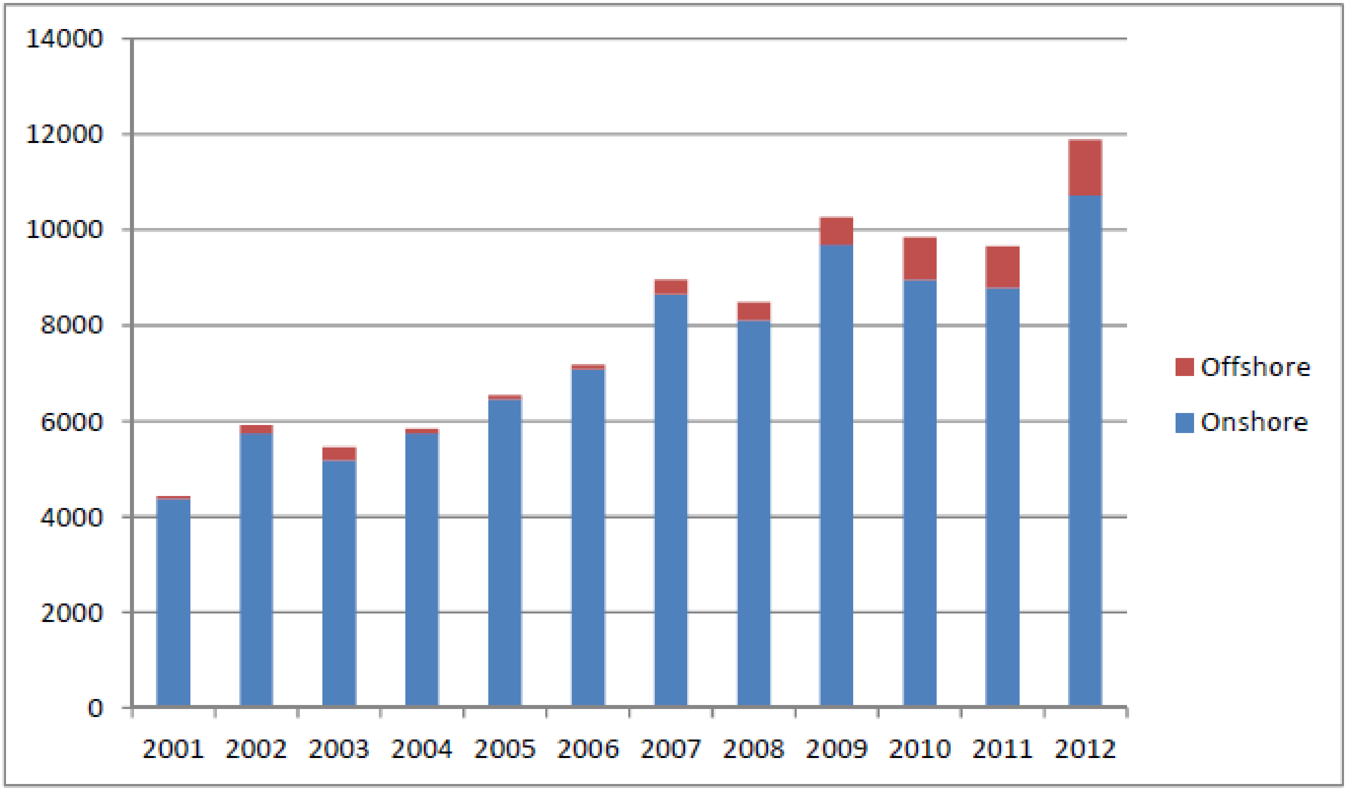
Annual onshore and offshore installations (MW)



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General OSH challenges in the wind energy

- Skills shortage
- Procedures and standards
- Gender aspects in the wind energy sector
- Ageing Workforce
- Work organisation and psychosocial risk factors
- Lack of OSH data and research on the impact of wind energy developments on workers

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Wind Turbines Standards

- IEC 61400-1: Wind turbines — Design requirements
- IEC 61400-2: Wind turbines — Design requirements for small wind turbines
- IEC 61400-3: Wind turbines — Design requirements for offshore wind turbines
- IEC 61400-3-2: Wind turbines — Design requirements for floating offshore wind turbines
- IEC 61400-4: Wind turbines — Design requirements for wind turbine gears
- IEC 61400-5: Wind turbines — Design requirements for wind turbine rotor blades
- IEC 61400-11: Wind turbines — Acoustic noise measurement techniques
- IEC 61400-12: Wind turbines — Wind turbine power performance testing
- IEC 61400-13: Wind turbines — Measurement of mechanical loads
- IEC 61400-14: Wind turbines — Declaration of apparent sound power level and tonality values
- IEC 61400-21: Wind turbines — Measurement and assessment of power quality characteristics of grid connected wind turbines
- IEC 61400-22: Wind turbines — Conformity testing and certification
- IEC 61400-23: Wind turbines — Full-scale structural testing of rotor blades
- IEC 61400-24: Wind turbines — Lightning protection

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Common hazards for both onshore and offshore facilities and those unique to offshore installations

Hazard	Relative risk — offshore versus onshore	Comments
Personal transfers	Higher	For offshore wind farms this would involve the need for helicopter access to offshore facilities, personnel transfers between marine vessels and wind turbines, risk of collisions between vessels and wind turbines or collisions between two or more vessels operating in the same area and falls into water by personnel.
Diving	Higher	Diving operation are unique to offshore wind farms and would include hazards during foundation installation, cable laying and regular turbine inspections, maintenance and, possibly, decommissioning.

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Common hazards for both onshore and offshore facilities and those unique to offshore installations

Hazard	Relative risk — offshore versus onshore	Comments
Emergency evacuations	Higher	Evacuation from offshore wind turbines during a fire, explosion or severe weather conditions are more difficult. In addition, there is also the travel distance to and from shore during emergencies that needs to be considered.
Exposure to weather conditions, heat and cold	Higher	Offshore work is subject to more extreme weather conditions. This may result in time pressure for offshore workers to perform the work, as they have to comply with tight time constraints that can easily be deflected by changes in weather or shipping delays. In addition, offshore facilities have limited possibility for climate-controlled spaces. As a result of changes in weather conditions, workers on offshore facilities can end up stranded on wind turbines for days
Structural	Higher	Structural failures intrinsic to the marine environment, such as wave action, currents and corrosion, will affect components. These are not

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Common hazards for both onshore and offshore facilities and those unique to offshore installations

Crane lifts	Higher	Although the basics of lifting operations are the same onshore and offshore, the following make lifting offshore more difficult: ▪ offshore turbines are larger so entail lifting of larger components (loads); ▪ more extreme weather conditions, e.g. greater wind loads; ▪ movement of the vessel during lifting; ▪ limited working area on the vessel; ▪ motion of the turbine (floaters); ▪ lifting on occasions done over the boat deck.
Falls from heights	Similar	Personnel working in the tower of the nacelle both onshore and offshore are at height and climb ladders many times a day, and they face fall hazards or exposure to dropped objects.
Confined spaces	Similar	For offshore and on land turbines, once the technician is inside the wind turbine, most tasks are exactly the same. Thus, for the majority of tasks inside a wind turbine, the hazards and risks are similar. In a wind turbine, workers encounter confined spaces, with related hazards such as poor ergonomics/awkward postures and exposure to fumes, dust and toxic chemicals and materials.

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Common hazards for both onshore and offshore facilities and those unique to offshore installations

Hazard	Relative risk — offshore versus onshore	Comments
Awkward postures	Similar	Workers confront awkward postures, prolonged kneeling and repetitive upper body movements, often in cramped spaces, which can lead to short-term sprains and fatigue, as well as long-term injuries.
Physical load	Similar	Both facilities require the same amount of climbing, manual handling and physical effort.
Electrical	Similar	Electrical hazards from work being performed inside the turbine are a concern for both types of facility. These would include electrical arcs and electrical shocks that can cause electrical burns and electrocution. The presence of water in offshore wind farms may complicate certain operations such as cable laying and connecting (usually done remotely).

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Example of hazards encountered during the construction phase of wind farms

- Falling structures, loads or objects during lifting operations.
- Falls from heights.
- Noise
- Mechanical hazards, such as contact with moving parts.
- Offshore — marine operations and transportation, for example ship collisions or man overboard.
- Electrical — short circuits, overcharge, electrostatic phenomena or falls due to shock.
- Fire or explosion of turbine (use of combustible materials) or vessel.
- Manual handling.
- Ergonomics — physiological effects as a result of heavy lifting and repeated movements, fatigue from climbing ladders or working in confined spaces.
- Working with dangerous substances.
- Working in confined spaces — the configuration of all nacelles will classify them as confined spaces.
- Environmental effects — wind, wave and currents, or lightning.
- Organisational — time pressure, insufficient or lack of safety equipment, lack of competence or skills for wind energy sector, different actors/companies all involved in the same operation.
- Exposure to noise and vibration.
- Evacuation of persons from wind turbines as a result of changing weather conditions and locations may be challenging.

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Wind Energy Hazards

- Falls
- Confined Spaces
- Lockout/Tagout
- Crane, Derrick and Hoist Safety
- Electrical
- Machine Guarding
- Other Typical Workplace Hazards

Picture Source: http://simplifiedsafety.com/solutions/application/wind-turbine/

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NORDEX

Wind Turbine Blade Manufacturing

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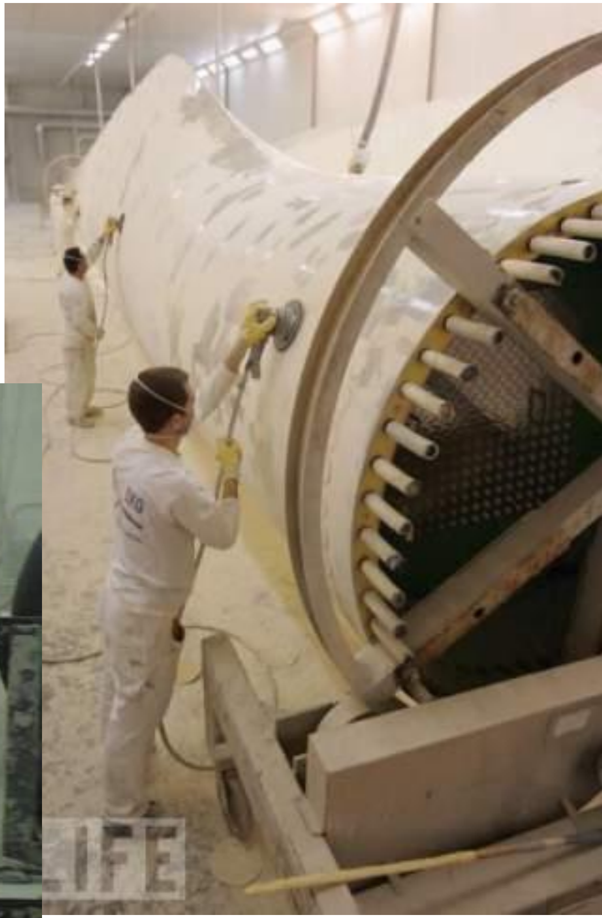
Sanding & Grinding



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Wind Energy Hazards (contd.)

- Fire Hazards
- Medical and First Aid

Source: http://www.windaction.org/pictures/1054

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Weatherization and Insulation Hazards

- Use of Spray Polyurethane Foam (SPF)
- Chemical Hazards - Isocyanates
- Confined Space Hazards
- Fall Hazards
- Fire Hazards
- Medical and First Aid
- Electrical Hazards

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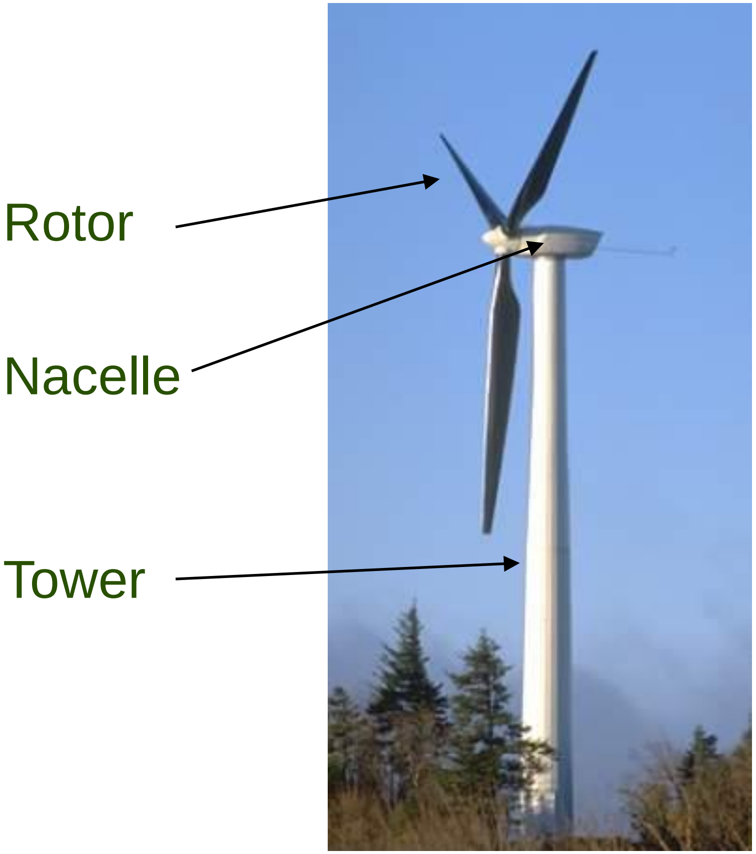
Turbine subsystems include:

- A rotor, or blades, which convert the wind's energy into rotational shaft energy
- A nacelle (enclosure) containing a drive train, usually including a gearbox and a generator
- A tower, to support the rotor and drive train; and electronic equipment such as controls, electrical cables, ground support equipment, and interconnection equipment.



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Occupational Safety and Health = Core Value

- Improve Worker Safety and Health
- Support of Continuous Education and Training of Employers and Employees in the Wind Industry
- Work Cooperatively with Regulating Agencies to Ensure the Safety and Health for All Workers

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AWEA Safety and Health Committee

- AWEA Safety and Health Committee
  - Created 3 years ago
  - Over 450 members participating
  - 9 subcommittees and task forces
    - 20-50 participants on each subcommittee
    - Monthly conference calls
  - Address the most pressing issues within the industry

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- Education and Understanding the Intricacies of Development and the Sustainability of Wind Generation Plants

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Safety and Health Initiatives

- Empowering Workers to be Engaged and Take Ownership in Worker Safety and Health Programs

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Safety and Health Initiatives

- Collect and Monitor Injury, Illness, and Fatality Data
  - Leading Indicators
  - Injuries, Illness, and Fatalities
  - What are the Causes
  - Where are the Accidents
- Identify the High Hazard Areas
- Develop Solutions to Eliminate or Significantly Reduce Hazards

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Operational failure modes for a wind turbine

- Tower collapse
- Blade failure
- Tower strike

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Operational failure modes for a wind turbine

- Fire
- Lightning strike

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Medical fitness to work for wind turbine projects

- Vision: Visual acuity must be adequate for safe work and will normally be at least a visual acuity of 6/9 in the better eye and 6/12 in the worse eye (with correction if worn).
- Hearing: Hearing should be assessed using a practical test.
- Cardiovascular system: Significant abnormalities of the cardiovascular system, should be avoided.
- Respiratory system: Climbing vertical ladders within turbine towers requires good respiratory function.
- Musculoskeletal system: A full range of movement of the back, neck and all four limbs is necessary for safety when climbing vertical ladders and working in confined spaces.

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Medical fitness to work for wind turbine projects

- Nervous system: Any current or recent history of unexplained loss of consciousness, seizures, or vertigo requires assessment.
- Diabetes: Well-controlled diabetic workers who do not suffer hypoglycaemic attacks may be considered fit, but should have a full medical assessment by the physician.
- Mental state: Mental illness involving severe anxiety and depression is usually incompatible with work offshore as it may put workers' lives at risk.
- Drugs and alcohol: Workers' physical and mental fitness must not be impaired through the abuse of alcohol or drugs

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Medical fitness to work for wind turbine projects

- Skin: Additional precautions are needed for sun-sensitive skin conditions when working outdoors.
- Obesity: Obesity is not a contraindication per se, but agility and mobility must not be significantly impaired.
- Physical fitness to climb: Good cardiorespiratory physical fitness is necessary for the climbing aspect of work on wind turbine towers.

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- Safety and Health Outlook: Wind Energy, presentation of the American Wind Energy Association

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Economical Sustainability

Lecture 2.6

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Learning outcomes

- To identify the different costs incurred in the design and installation of a wind farm
- To estimate the incidence of different costs according with the wind farm type (onshore or offshore) and the location of energy plant
- To develop an analysis of total costs and an evaluation of return of investment
- …
- …
- …

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Table of contents

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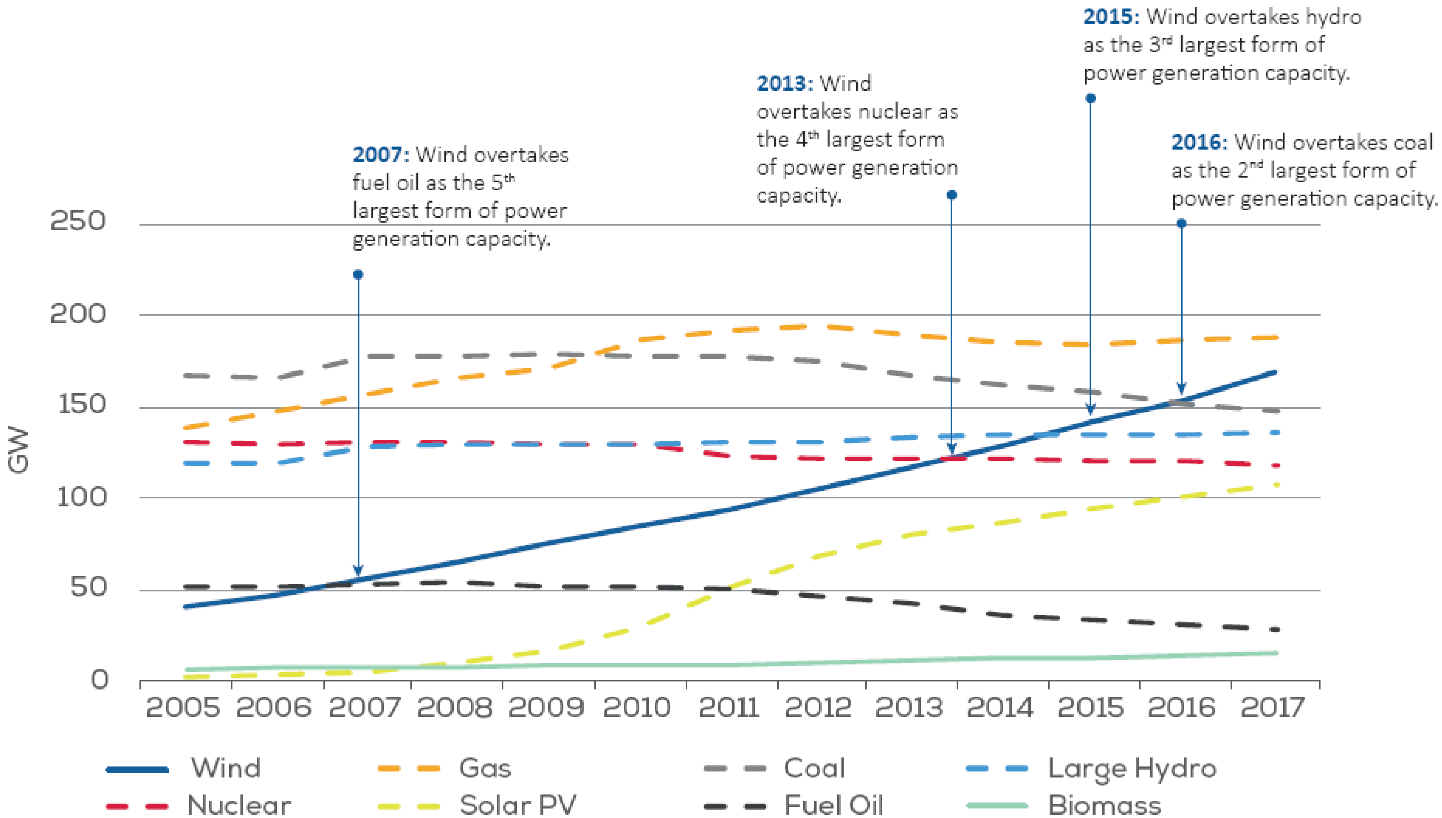
Total power generation capacity in the EU 2005-2017

Europe installed 16.8 GW (15.6 GW in the EU) of gross additional wind power capacity in 2017. Total net installed capacity is 168.7 GW.



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Cost Analysis - Indicators

The three indicators that have been selected are:

1. Equipment cost (factory gate FOB and delivered at site CIF);
2. Total installed project cost, including fixed financing costs;
3. The levelised cost of electricity LCOE.

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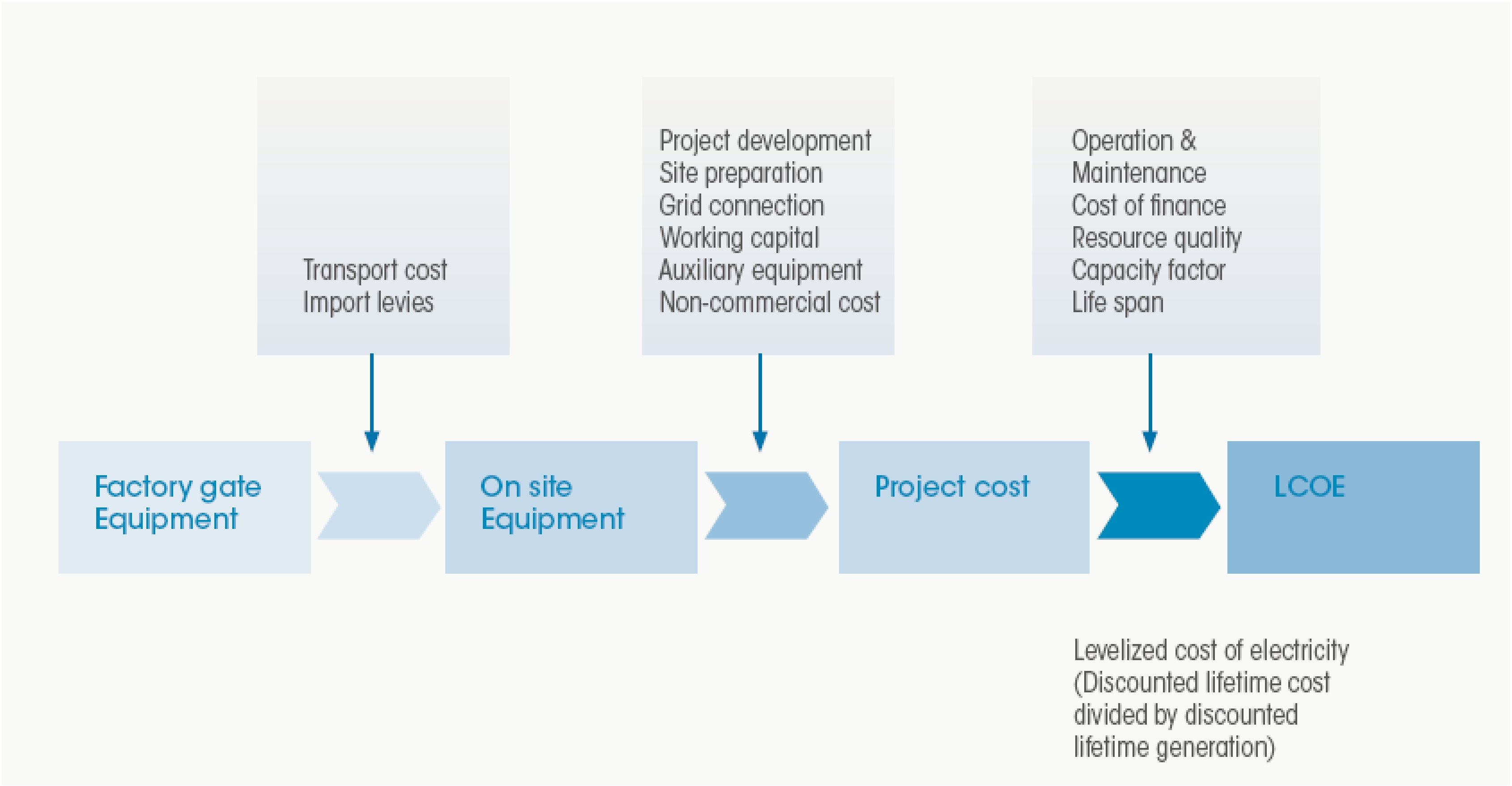
Cost Analysis - Indicators



Renewable Power Generation Cost Indicators and Boundaries

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Cost Analysis - Indicators

The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate.

An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss.

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

LCOE = the average lifetime levelised cost of electricity generation;

I_t = investment expenditures in the year **t**;

M_t = operations and maintenance expenditures in the year **t**;

F_t = fuel expenditures in the year **t**;

E_t = electricity generation in the year **t**;

r = discount rate; and

n = economic life of the system.

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Cost Analysis - Indicators

Like other renewable energy technologies, wind is capital intensive, but has no fuel costs.

The key parameters governing wind power economics are the:

1. Investment costs (including those associated with project financing);
2. Operation and maintenance costs (fixed and variable);
3. Capacity factor (based on wind speeds and turbine availability factor);
4. Economic lifetime;
5. Cost of capital.

Although capital intensive, wind energy is one of the most cost-effective renewable technologies in terms of the cost per kWh of electricity generated.

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Cost Analysis - Indicators

The installed cost of a wind power project is dominated by the upfront capital cost (often referred to as CAPEX) for the wind turbines (including towers and installation) and this can be as much as 84% of the total installed cost.

Similarly to other renewable technologies, the high upfront costs of wind power can be a barrier to their uptake, despite the fact there is no fuel price risk once the wind farm is built.

The capital costs of a wind power project can be broken down into the following major categories:

- The turbine cost: including blades, tower and transformer;
- Civil works: including construction costs for site preparation and the foundations for the towers;
- Grid connection costs: This can include transformers and sub-stations, as well as the connection to the local distribution or transmission network; and
- Other capital costs: these can include the construction of buildings, control systems, project consultancy costs, etc.

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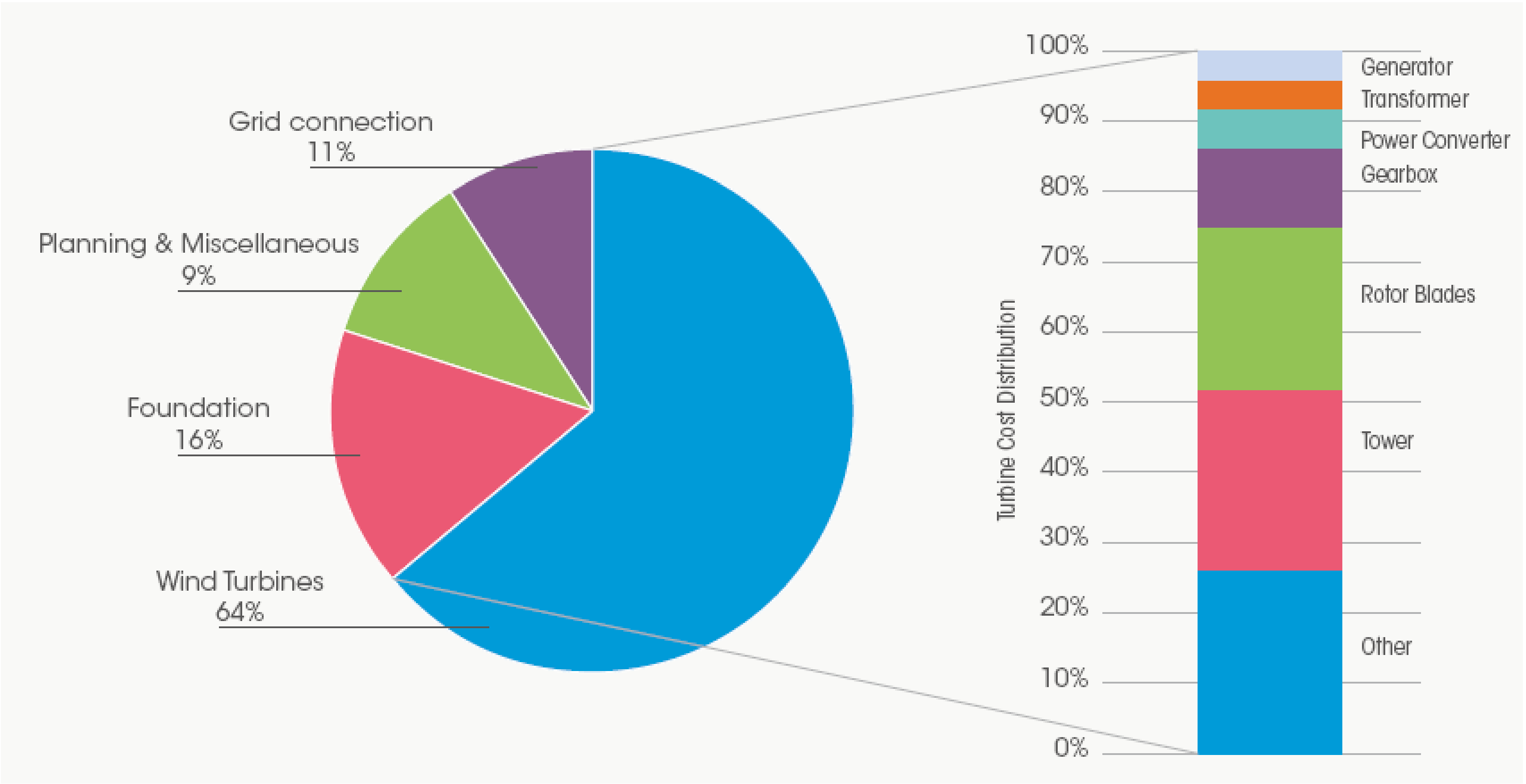
Cost Analysis - Indicators



Capital Cost Breakdown for a Typical Onshore Wind Power System And Turbine

Cost Analysis - Indicators

	Onshore	Offshore
Capital investment costs (USD/kW)	1 700-2 450	3 300-5 000
Wind turbine cost share (%)[1]	65-84	30-50
Grid connection cost share (%) [2]	9-14	15-30
Construction cost share (%) [3]	4-16	15-25
Other capital cost share (%) [4]	4-10	8-30

1. Wind turbine costs includes the turbine production, transportation and installation of the turbine.
2. Grid connection costs include cabling, substations and buildings.
3. The construction costs include transportation and installation of wind turbine and tower, construction wind turbine foundation (tower), and building roads and other related infrastructure required for installation of wind turbines.
4. Other capital cost here include development and engineering costs, licensing procedures, consultancy and permits, SCADA (Supervisory, Control and Data Acquisition) and monitoring systems.

Comparison of capital cost breakdown for typical onshore and offshore wind power systems in developed countries, 2011

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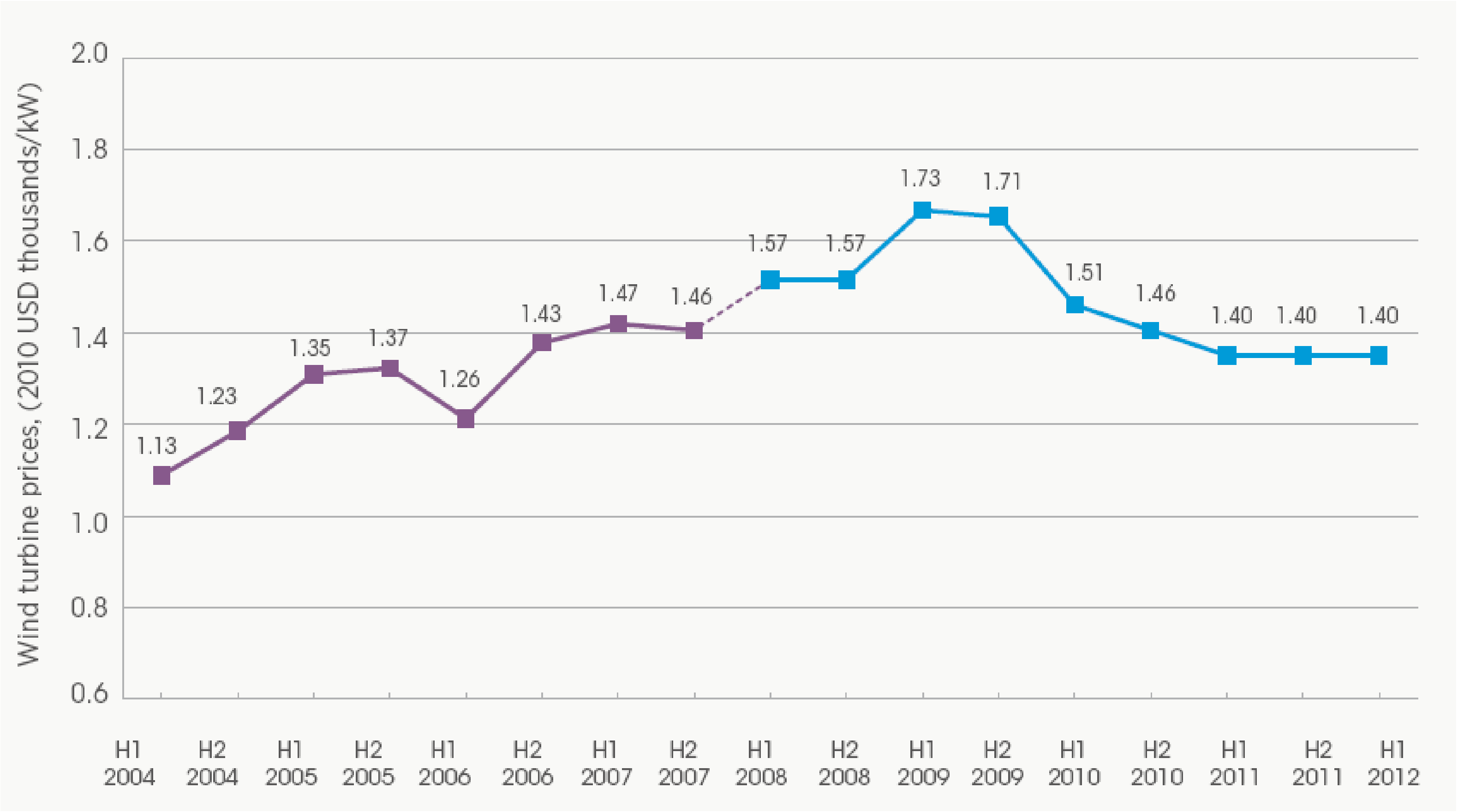
Cost Analysis - Indicators



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Cost Analysis - Indicators

Average wind Turbine prices (real) by Country, 2006 to 2010

Wind Turbine Price					
	2006	2007	2008	2009	2010
	2010 USD/kW				
Australia	–	–	–	1 635	1 725
Austria	–	–	2 384	2 053	2 123
Canada	–	–	–	1 685	–
China	885	928	911	864	644
Denmark	1 147	–	–	–	–
Germany	1 333	–	1 699	–	–
Greece	–	–	–	–	–
India	–	–	–	–	–
Ireland	–	1 730	1 639	1 380	1 460
Italy	1 290	1 874	1 892	1 798	1 592
Japan	865	1 652	1 713	2 123	1 991
Mexico	–	–	–	1 557	1 526
Netherlands	–	–	–		–
Norway	1 238	–	–		–
Portugal	1 086	1 478	1 581	1 593	1 261
Spain	–	–	–	1 317	–
Sweden	–	–	–	1 607	1 858
Switzerland	–	–	2 160	2 053	1 924
United Kingdom	–	–	--		–
United States	1 183	1 224	1 456	1 339	1 234

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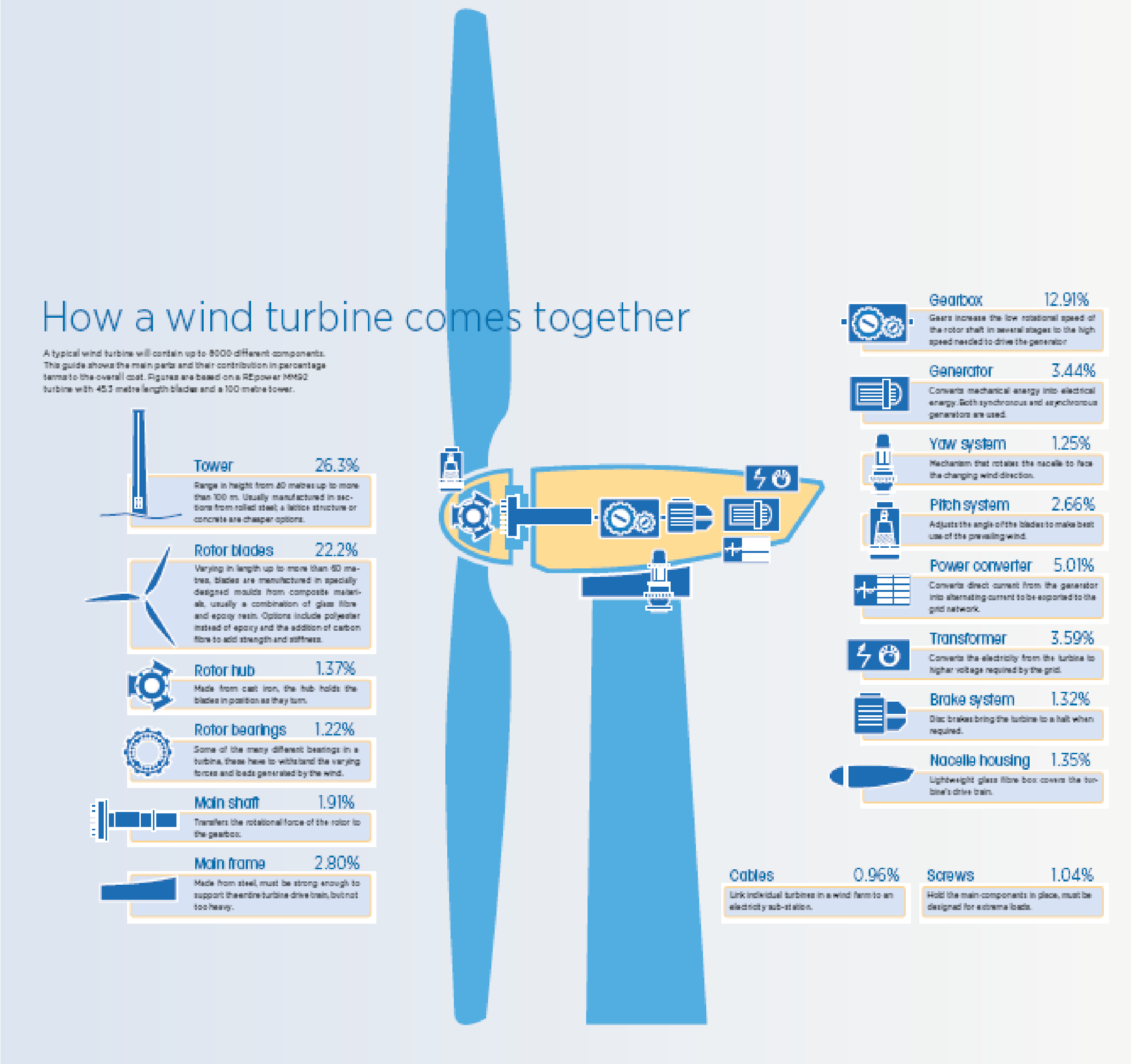
Cost Analysis - Indicators

Wind turbine cost breakdown
(5 MW offshore wind turbine)



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Summary of the provided knowledge

- In the estimation of the total cost of a wind farm, the following indicators should be taken in consideration:
    1. Equipment cost (technologies, transport costs and import);
    2. Project cost (project development, site preparation, auxiliary equipment, financing costs);
    3. The levelised cost of electricity LCOE (including in the evaluation maintenance and operational costs)
- The LCOE is the price of electricity required for a project where revenues would equal costs
- Wind turbine's price can have a considerable difference per Countries
- The incidence of the turbine's cost on the total cost of the energy plant can go from the 30-50% for offshore wind farm to 65-84 % for onshore solutions

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Managing wind farm project implementation and operation

Lecture 2.7

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1. Projects in Modern Organizations

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The Definition of a "Project"

- In discussions of project management, it is sometimes useful to make a distinction between project, program, task, and work packages
- The term program refer to an exceptionally large, long-range objective that is broken down into a set of projects.
- These projects are further divided into tasks which in-turn split into work packages that are themselves composed of work units
- Project is a specific, finite task to be accomplished

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Purpose

- A project is usually a one time activity with a well-defined set of desired end results
- It can be divided into subtasks that must be accomplished in order to achieve the project goals
- The subtasks require careful coordination and control in terms of timing, precedence, cost and performance
- The project itself must be coordinated with other projects carried out by the same parent organization

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Interdependencies

- Within any project, tasks are interacting and depend on each others
- Some tasks can never be started unless another tasks are performed
- The project manager must keep all these interactions clear and maintain the appropriate interrelationships with all groups

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Uniqueness

- Each project has some elements that are unique
- No two construction projects are precisely alike

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Conflict

- More than any other managers, the project manager lives in a world characterized by conflict
- Projects compete with functional departments for resources and personnel in case of multi-project organizations
- The members of the project team are in almost constant conflict for the project's resources

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Introduction to Project Management

- Some of the ancient projects include:
  - The construction of the Egyptian pyramids
  - The building of the Temple in Jerusalem.
- Todays examples of projects include:
  - Construction of Wind Turbine Farm
  - Building a Reservoir
  - Launching a satellite
  - Transportation of American forces in Operation Iraqi Freedom,
  - The pursuit of new treatments for AIDS,
  - The development of the joint U.S.-Russian space station are with which most of us are familiar.

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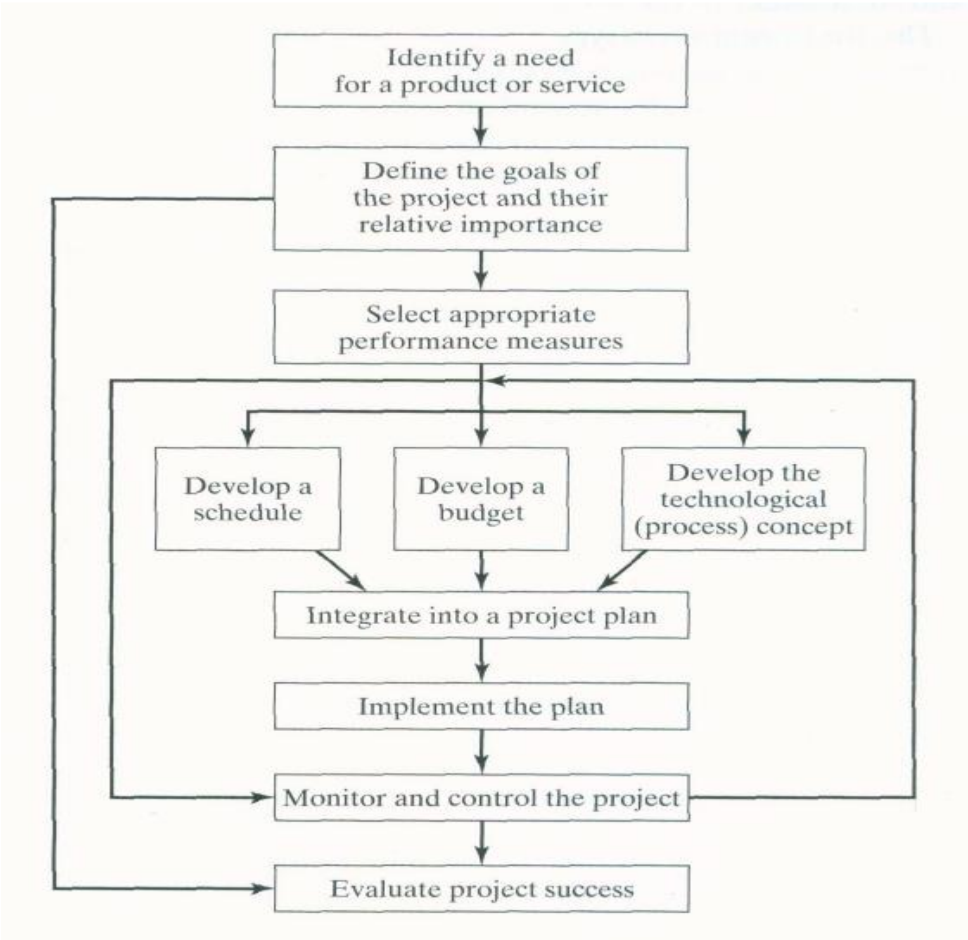
Project Management Processes



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Risk and Uncertainty

- In project management, it is common to refer to very high levels of uncertainty as sources of risk.
- Risk is present in most projects, especially in the R&D environment. Why?
- Without trying to sound too pessimistic, it is wise to assume that what can go wrong will go wrong.

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Principal sources of uncertainty

- Random variations in component and subsystem performance
- Inaccurate or inadequate data
- Inability to forecast satisfactorily as a result of lack of experience
- Specifically they may be:
  - Uncertainty in scheduling
  - Uncertainty in cost
  - Technological Uncertainty

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Laws of Project Management

1. No major project is ever installed on time, within budget, or with the same staff that started it. Yours will not be the first.
2. Projects progress quickly until they become 90% complete, then they remain at 90% complete forever.
3. A carelessly planned project will take three times longer to complete than expected; a carefully planned project will take only twice as long.
4. Project teams hate progress reporting because it vividly manifests their lack of progress.

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Project Life Cycle

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Project Personnel

- A project manager
- An assistant project manager (if necessary)
- A project (home) office
- A project team

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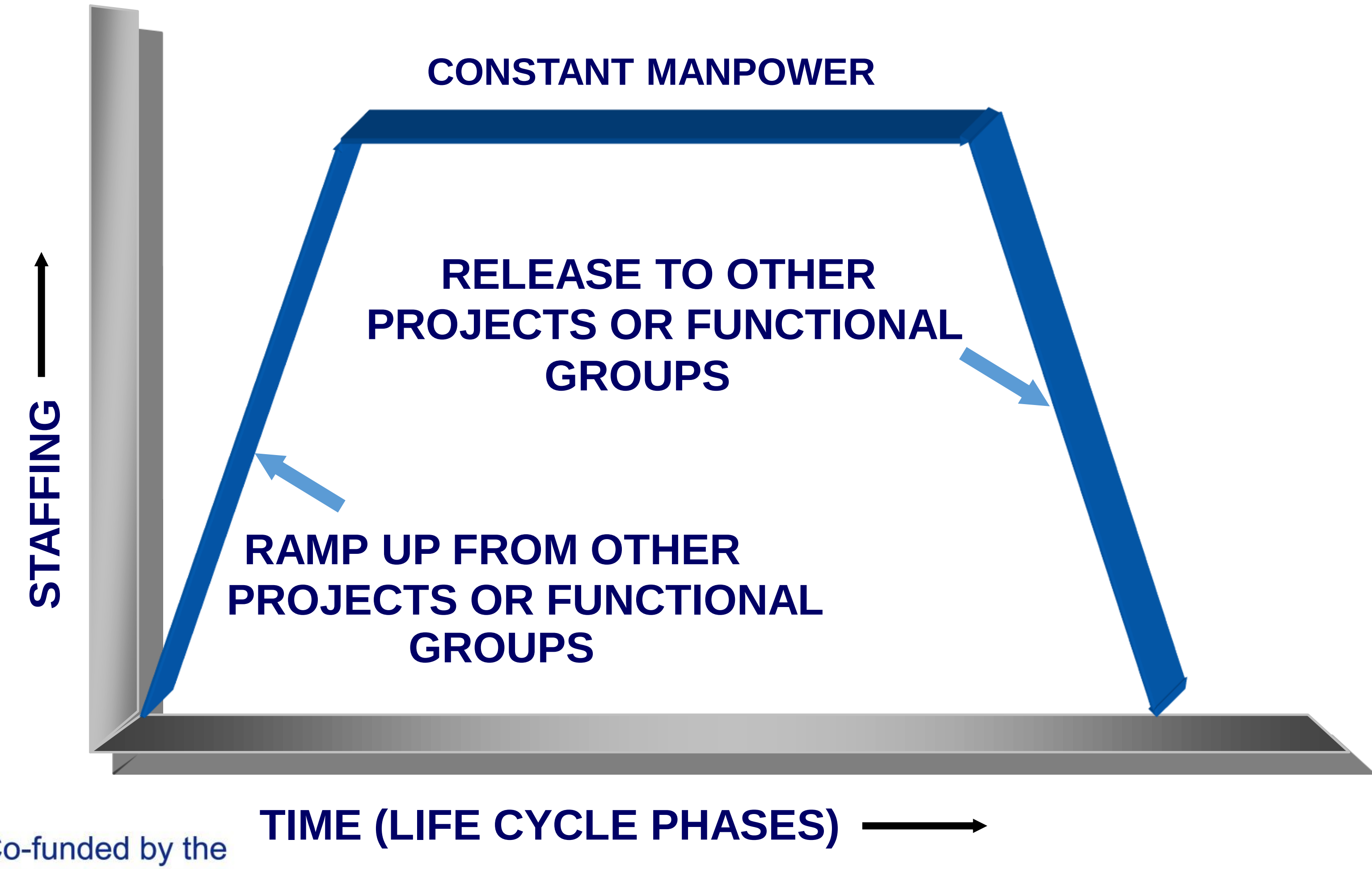
Staffing Pattern Versus Time



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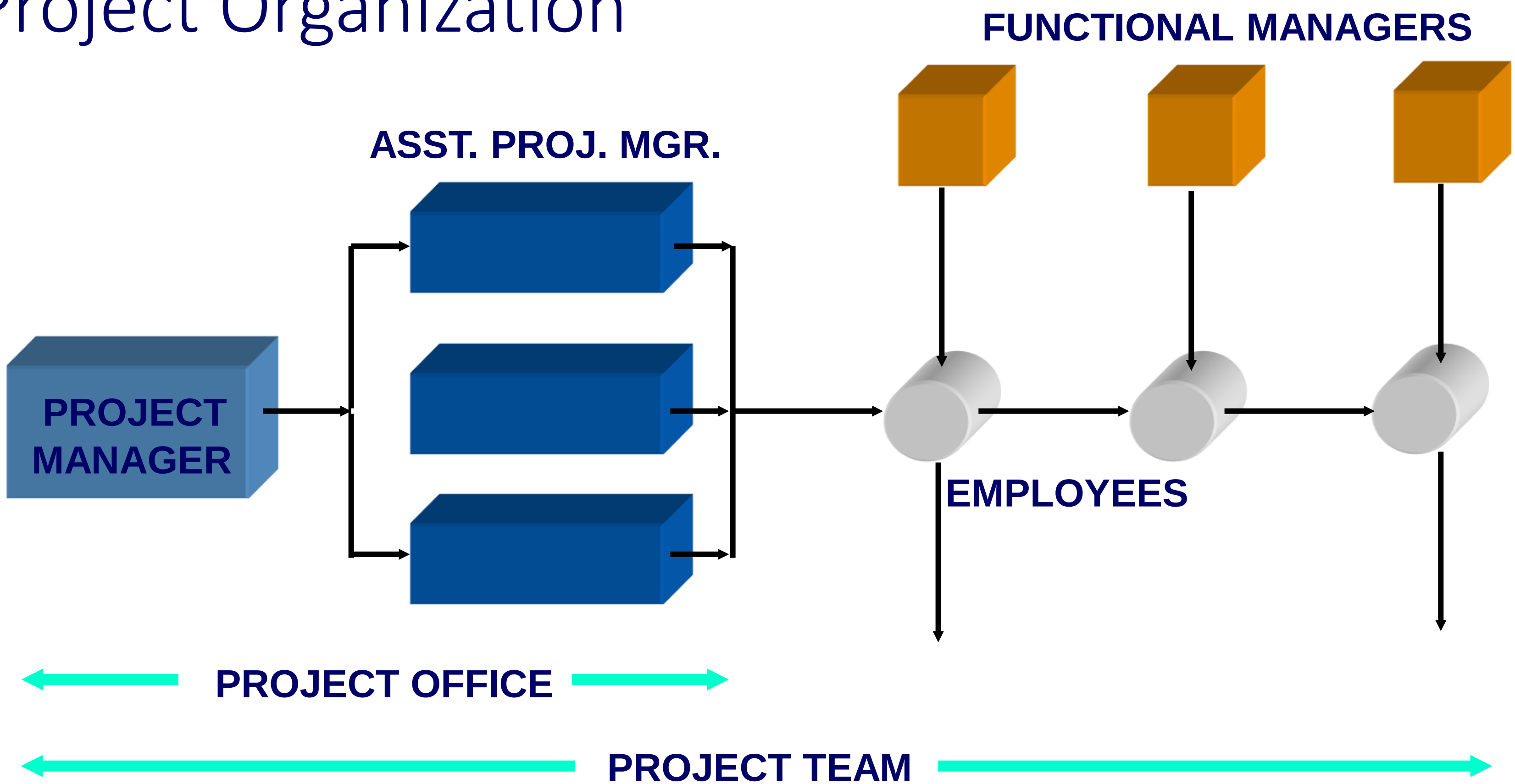
Project Organization



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Project Planning

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Most Managers Do Not Like Planning Due To The Following:

- It takes time.
- They have to think.
- It involves paper work.
- They are committed to achieve a specific result within a specified time period.

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"If You Don't Know Where You Are Going, You Will Probably End Up Somewhere Else"

–Lourence Peters

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Reasons for Planning

- To eliminate or reduce uncertainty
- To improve efficiency of the operation
- To obtain a better understanding of the objectives
- To provide a basis for monitoring and controlling work

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Planning Requirements

- The statement of work (SOW)
- The project specifications
- The milestone schedule
- The work breakdown structure (WBS)

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Statement of Work (SOW)

- The statement of work (SOW) is a narrative description of the work to be accomplished.

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Statement of Work Elements

- General scope of the work
- Objectives and related background
- Contractor’s tasks with its specifications
- Contractor end-item performance requirements
- Reference to related studies, documentation, and specifications
- Data items (documentation)
- Support equipment for contract end-item

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Project Specification

Description	Specification Number
Civil	**100 (index)**
▪Concrete	101
▪Field Equipment	102
▪Piling	121
▪Roofing and Siding	122
▪Soil Testing	123
▪Structural Design	124
HVAC	**200 (index)**
▪Hazardous Environment	201
▪Insulation	202
▪Refrigeration piping	210

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Milestone Schedule

- Project Milestone schedule contain such information as:
  - Project Start Date
  - Project End Date
  - Other Major Milestone
  - Schedule for Data Items (Deliverables or Reports)

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Work Breakdown Structure

- In planning a project, the project manager must structure the work into small elements that are
  - Manageable, in that specific authority and responsibility can be assigned
  - Measurable in terms of progress
- WBS is a project-oriented family tree subdivision of the hardware, services, and data required to produce the end product
- WBS is structured in accordance with the way the work will be performed

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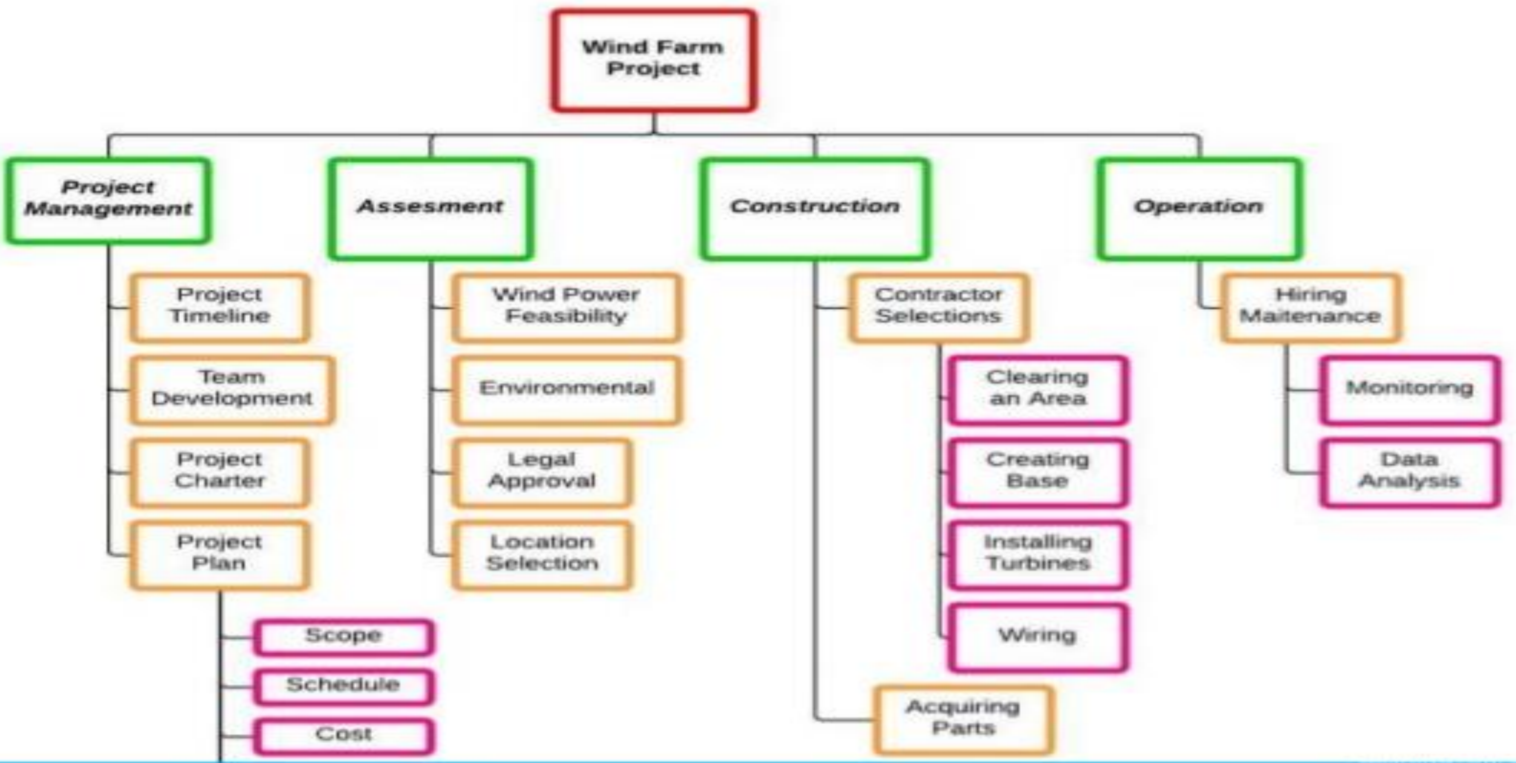
Work Breakdown Structure



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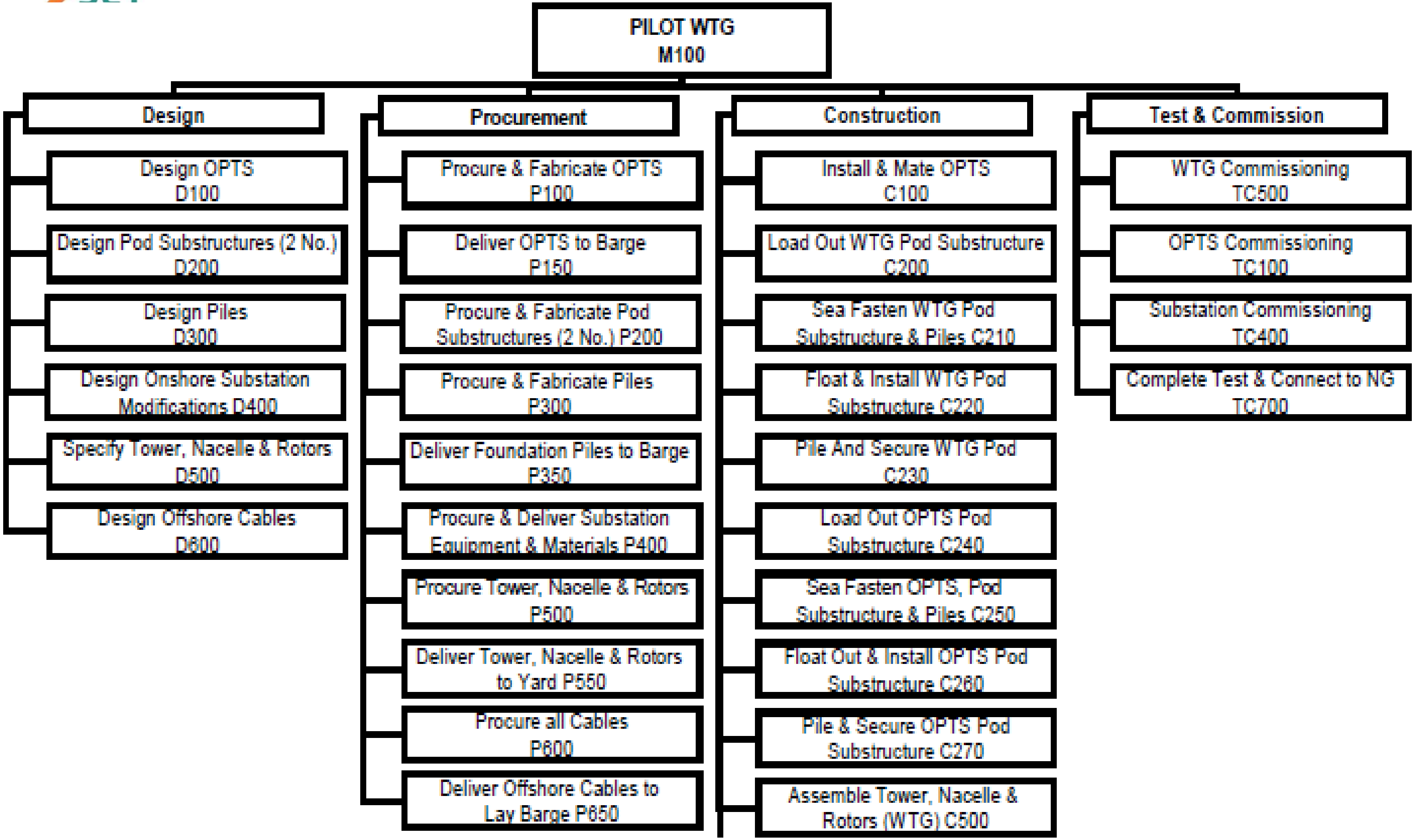

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Project Scheduling Techniques

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Introduction

- Project scheduling deals with:
  - Establishment of timetables and dates during activities required to complete the project are performed.
- Schedules are the cornerstone of the planning and control system
- Due to High importance, they are written into the contract
- The scheduling include information like:
  - The estimated duration of activities
  - The technological precedence relations among activities
  - Constraints imposed by the availability of resources and the budget
  - Due-date requirements

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Network Techniques

- The basic approach to all project scheduling is to form a network that graphically portrays the relationships between the tasks and milestones in the project.
- Several techniques evolved in the late 1950s for organizing and representing this basic information.
- Best known today are:
  - The program evaluation and review technique (PERT)
  - The critical path method (CPM).

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CPM

- The major difference between the two:
  - CPM assumes that activity times are deterministic,
  - PERT/CPM is based on a diagram that represents the entire project as a network of arrows and nodes
  - The two most popular approaches are either to place the activities on the arrows (AOA) and have the nodes signify milestones or to place activities on the nodes (AON) and let the arrows show precedence relations among activities

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Precedence Relations Among Activities

- The schedule of activities is constrained by the availability of resources and technological constraints known as precedence.
- Four general types of precedence relations exist:
    - A "finish to start," requires that an activity can start only after its predecessor has been completed.
        - For example, it is possible to lift a piece of equipment by a crane only after the equipment is secured to the hoist.

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Precedence Relations Among Activities

- A "start to start" relationship exists when an activity can start only after a specified activity has already begun.
  - For example, in projects in which concurrent engineering is applied, logistic support analysis starts as soon as the detailed design phase begins.

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Precedence Relations Among Activities

- The "start to finish" connection occurs when an activity cannot end until another activity has begun.
  - This would be the case in a project of building a nuclear reactor and charging it with fuel, in which one industrial robot transfers radioactive material to another.
  - The first robot can release the material only after the second robot achieves a tight enough grip.

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Precedence Relations Among Activities

- The "finish to finish" connection is used when an activity cannot terminate unless another activity is completed.
    - Quality control efforts, for example, cannot terminate before production ceases, although the two activities can be performed at the same time.

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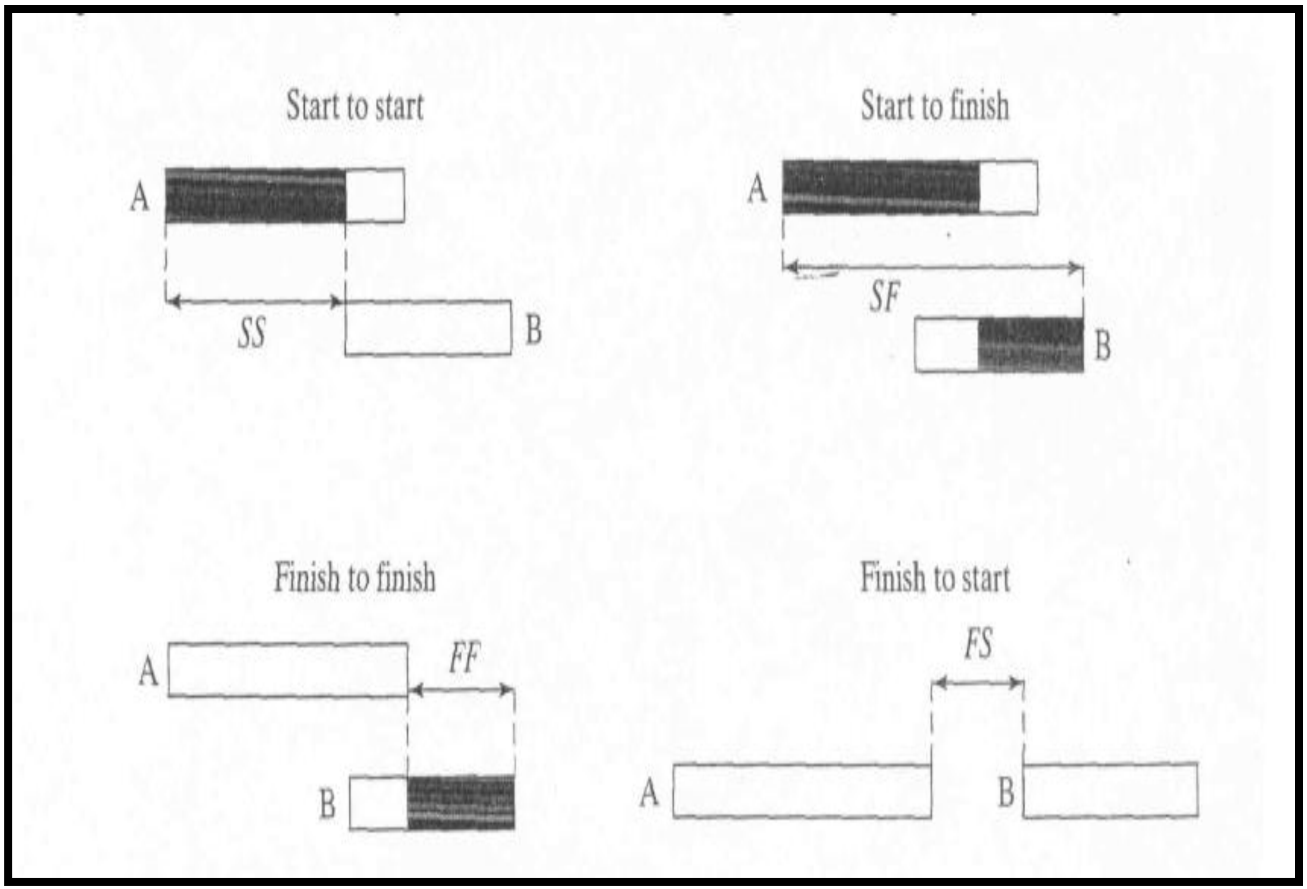

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Precedence Relations Among Activities

- In the following sections, we concentrate on the analysis of "finish to start" connections, the most common.
- The following table contains the relevant activity data.

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Example

Data for Example Project

Activity	Immediate predecessors	Duration (weeks)
A	-	5
B	-	3
C	A	8
D	A, B	7
E	-	7
F	C, E, D	4
G	F	5

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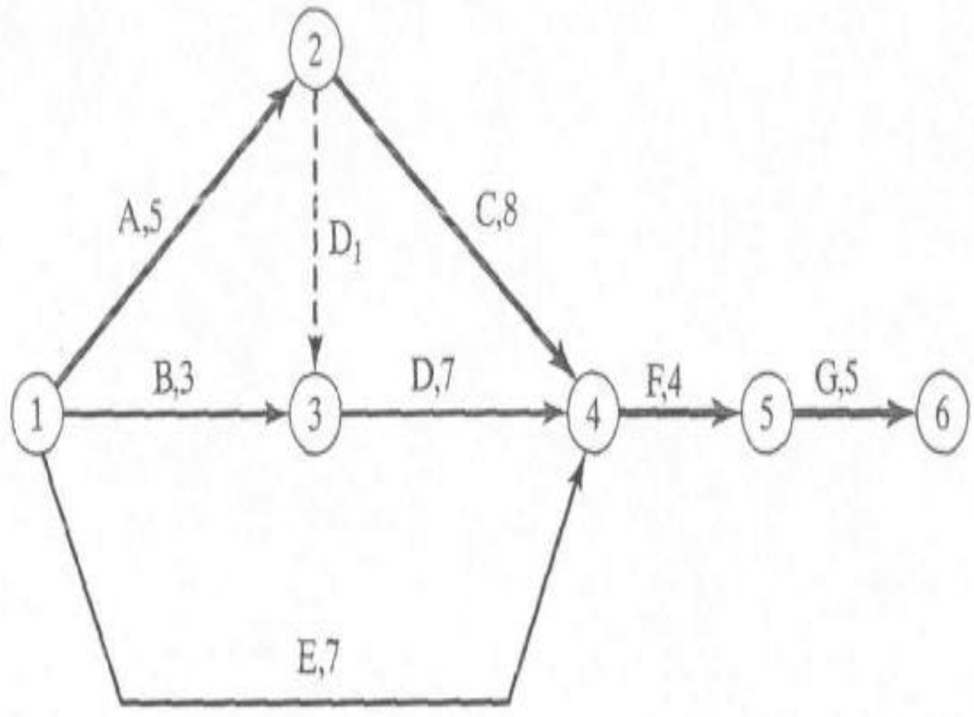

Figure VI.d Complete AOA project network.

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Example

- In this example network, there are four sequences of activities connecting the start and finish nodes. Each is listed in the following Table.

TABLE 9.3 Sequences in the Network

Sequence number	Events in the sequence	Activities in the sequence	Sum of activity times
1	1-2-4-5-6	A, C, F, G	22
2	1-2-3-4-5-6	A, D_1, D, F, G	21
3	1-3-4-5-6	B, D, F, G	19
4	1-4-5-6	E, F, G	16

Project Budget

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Techniques for Managing The Budgets

- The project budget represents scheduled expenditures as a function of time.
- The simplest approach to budgeting is to estimate the expected costs associated with each activity, task, and milestone.
- Based on the project schedule, these costs are assigned specific dates and a budget is generated
- The development of project budgets based on schedule and resource considerations is the first step in an iterative approach
- The next step is to integrate the individual project budgets into an acceptable organizational budget

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- Rescheduling activities makes the integration of single-project budgets into an acceptable organizational budget easier.
- To illustrate the relationship between a project's cash flow and its schedule, let us return to the example project. The length of the critical path in the project is 22 weeks.

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Project Activity Durations and Costs		
Activity	**Duration (weeks)**	**Cost ($1000)**
A	5	1.5
B	3	3.0
C	8	3.3
D	7	4.2
E	7	5.7
F	4	6.1
G	5	7.2
		31.0

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Slack Management

- Critical activities are A, C, F and G, whereas activities B, E and D have either free or total slack that can be used for budget planning.
- An early-start schedule results in relatively high expenditures in the project's earlier stages, whereas a late-start schedule results in relatively high expenditures in the later stages.
- Assume for budgeting purposes, that the cost of each activity is evenly distributed throughout its duration.

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TABLE 11.4 Cash Flow of an Early Start Schedule

Week	Activity A	B	C	D	E	F	G	Weekly cost, $	Cumulative cost, $
1	300	1000			814.3			2,114	2,114
2	300	1000			814.3			2,114	4,229
3	300	1000			814.3			2,114	6,343
4	300				814.3			1,114	7,457
5	300				814.3			1,114	8,571
6			412.5	600	814.3			1,827	10,398
7			412.5	600	814.3			827	12,225
8			412.5	600				1,013	13,238
9			412.5	600				1,013	14,250
10			412.5	600				1,013	15,263
11			412.5	600				1,013	16,275
12			412.5	600				1,013	17,288
13			412.5					412	17,700
14						1,525		1,525	19,225
15						1,525		1,525	20,750
16						1,525		1,525	22,275
17						1,525		1,525	23,800
18							1,440	1,440	25,240
19							1,440	1,440	26,680
20							1,440	1,440	28,120
21							1,440	1,440	29,560
22							1,440	1,440	31,000
Total	1,500	3,000	3,300	4,200	5,700	6,100	7,200	31,000	

TABLE 11.5 Cash Flow of the Late Start Schedule

	Activity								
Week	A	B	C	D	E	F	G	Weekly cost, $	Cumulative cost, $
1	300							300	300
2	300							300	600
3	300	1000						1,300	1,900
4	300	1000						1,300	3,200
5	300	1000						1,300	4,500
6			412.5					412	4,913
7			412.5	600	814.3			1,827	6,739
8			412.5	600	814.3			1,827	8,566
9			412.5	600	814.3			1,827	10,393
10			412.5	600	814.3			1,827	12,220
11			412.5	600	814.3			1,827	14,046
12			412.5	600	814.3			1,827	15,873
13			412.5	600	814.3			1,827	17,700
14						1,525		1,525	19,225
15						1,525		1,525	20,750
16						1,525		1,525	22,275
17						1,525		1,525	23,800
18							1,440	1,440	25,240
19							1,440	1,440	26,680
20							1,440	1,440	28,120
21							1,440	1,440	29,560
22							1,440	1,440	31,000
Total	1,500	3,000	3,300	4,200	5,700	6,100	7,200	31,000	

Slack Management

- The Following Figures depicts the cash flows for the early- and late-start schedules, and their cumulative cash flows.
- From the cumulative cash flows we can see that if the strategic long-range organizational budget allocates only $4,500 to the project for weeks 1 through 5, then during this period, only a late-start schedule is feasible.

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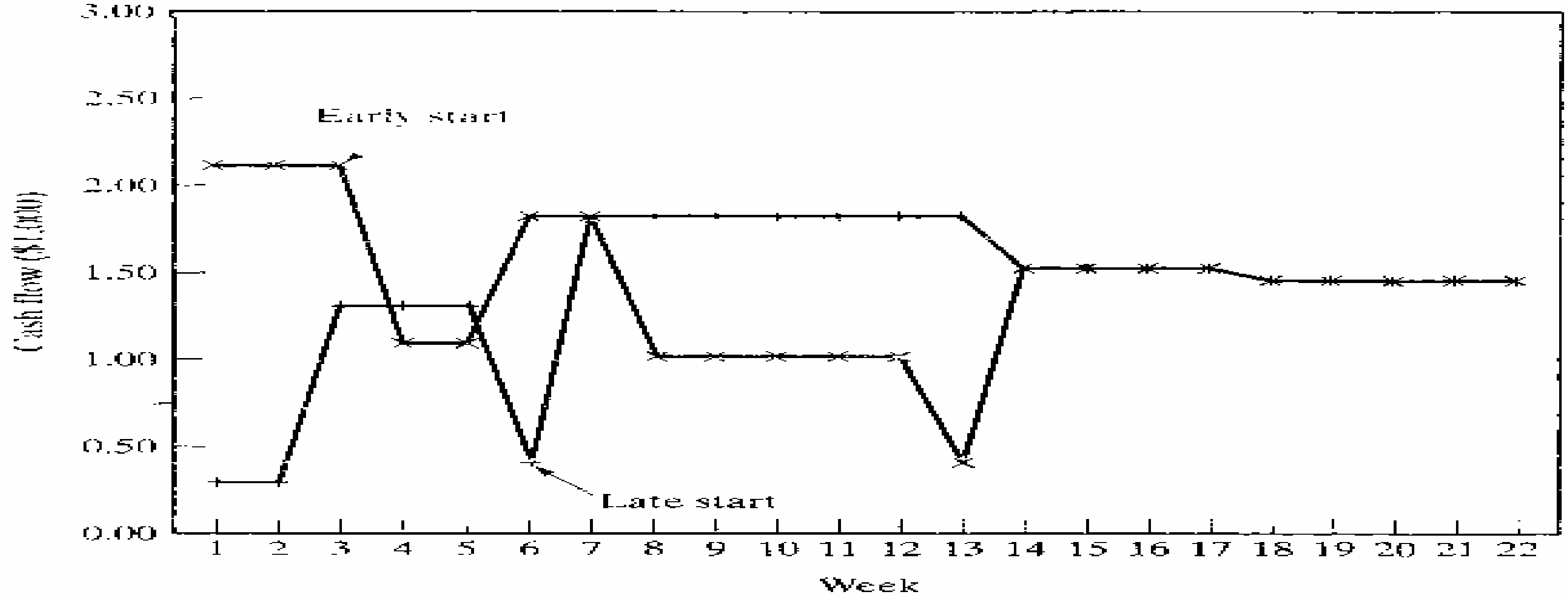
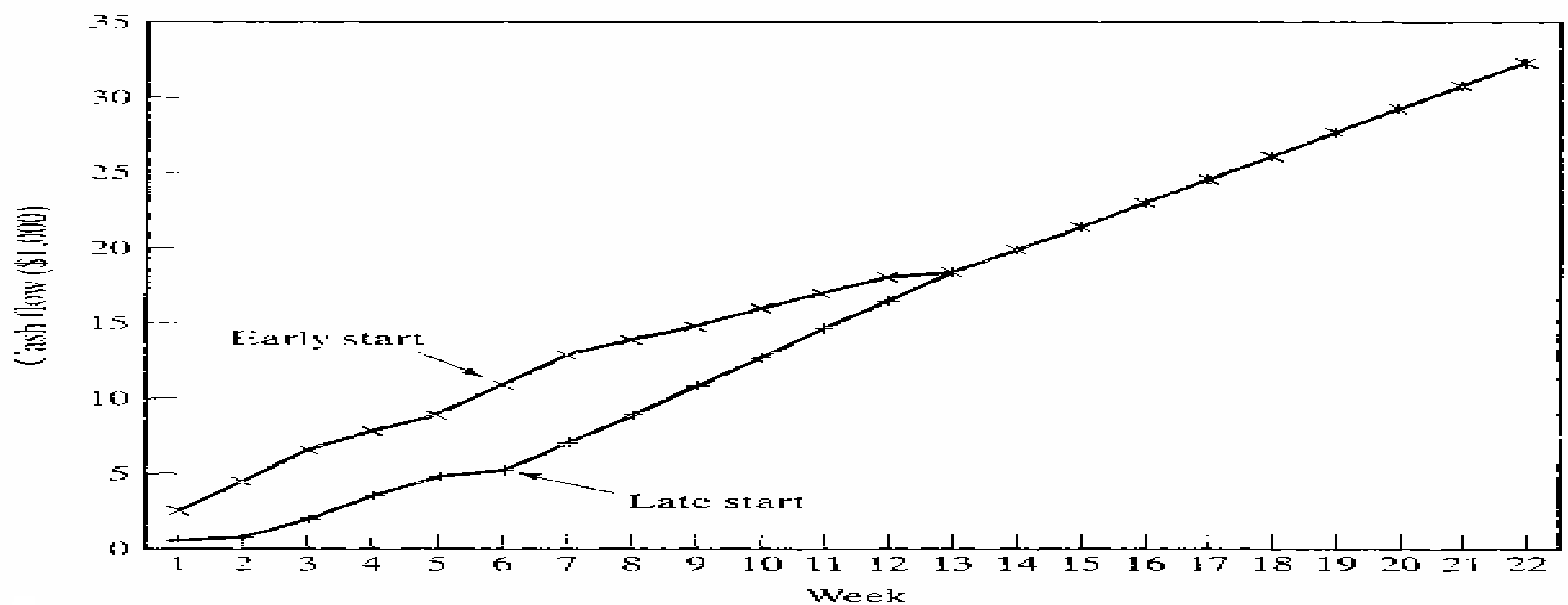


Cash flow for early-start and late-start schedules.



Cumulative cash flow for early-start and late-star schedules.

Project Time Crashing

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Crashing

- Change the duration of an activity by changing the technologies used to perform it and add or delete the necessary resources.
- So far we have assumed that each activity is performed in the most economical way, which was defined as the normal mode. That is, the combination of resources assigned to each activity was selected to minimize the cost of completing it.
- However, in many cases, it is possible to reduce an activity's duration by spending more money.

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Crashing

- Crashing is the procedure whereby an activity's duration is shortened by adding resources and paying extra direct costs,
- This implies that tradeoffs exist between cost and time
- The emphasis is achieved by constructing a time-cost curve for each activity, such as the one shown in the following figure.
- This curve plots the relationship between the direct cost for the activity and its resulting duration.

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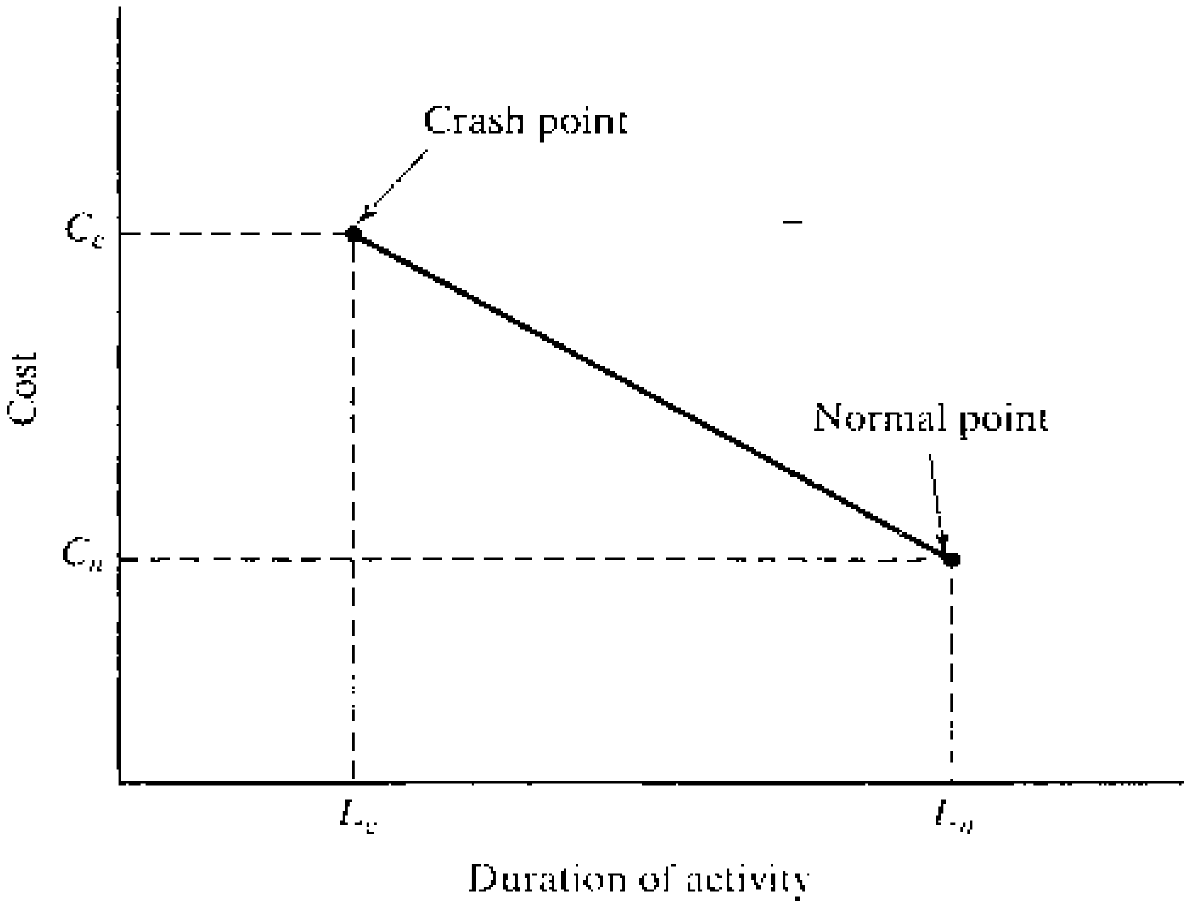

Typical Time-Cost Tradeoff Curve

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Crashing

- For example, a manual painting operation that requires 4 days at $400 per day.
- With a special compressed airflow system, however, two workers can complete the job in 2 days for $1,000 per day. Thus, the activity can be performed in 4 days for
- $400 x 4 = $1.600 or in 2 days for $1,000 X 2 = $2.000.
- The normal duration is associated with the lowest-cost option for the activity.
- This value is used in a CPM analysis and in the preparation of the initial budget.

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Crashing

- A crashed program includes activities performed more quickly than they normally would be as a result of the allocation of additional resources.
- To plan a crashed program, management must decide which activities to crash and by how much. To illustrate this point, consider the crashing costs and durations list in the following Table for the example project.
- In this table, the normal duration and the normal cost of each activity are those used in the basic schedule. Each activity can be crashed at least once. Five of the activities (A, C, D, F, G) can be crashed twice.

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Example

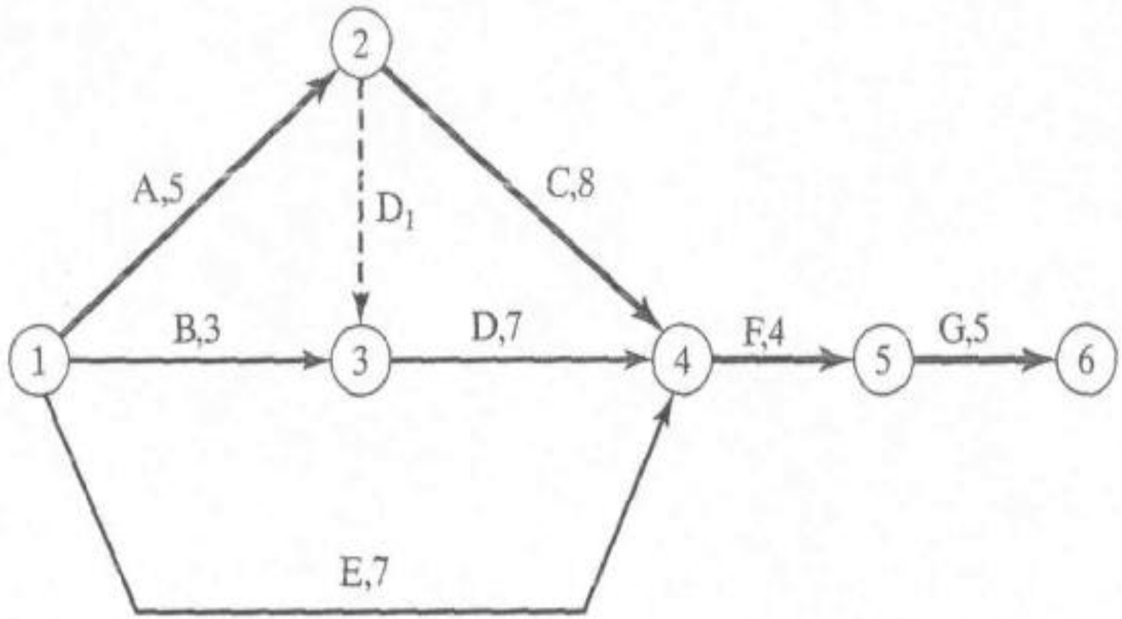

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TABLE 11.6 Duration and Cost for Normal and Crashed Activities

	Normal		Crashing activity the first time		Crashing activity a second time	
Activity	Cost	Duration (weeks)	Additional cost	Duration (weeks)	Additional cost	Duration (weeks)
A	$1,500	5	$2,000	4	$1,000	3
B	$3,000	3	$2,000	2	—	—
C	$3,300	8	$2,000	7	$1,000	6
D	$4,200	7	$2,000	6	$2,000	5
E	$5,700	7	$1,000	6	—	—
F	$6,100	4	$1,000	3	$2,000	2
G	$7,200	5	$1,000	4	$1,000	3

Example

- To illustrate this heuristic process, the project's normal duration is 22 weeks, and the critical activities are A, C, F, G. Reducing the project's length requires crashing one critical activity. At this stage, the cost of crashing each critical activity is as follows:

Activity	Cost to crash
A	$2,000
C	$2,000
F	$1,000
G	$1,000

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TABLE 11.7 Crashing the Project (Cost in $1,000, Duration in Weeks)

	22 weeks		21 weeks		20 weeks		19 weeks		18 weeks		17 weeks		16 weeks		15 weeks		14 weeks	
Activity	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur
A	1.5	5	1.5	5	1.5	5	1.5	5	1.5	5	3.5*	4	4.5*	3	4.5	3	4.5	3
B	3.0	3	3.0	3	3.0	3	3.0	3	3.0	3	3.0	3	3.0	3	3.0	3	3.0	3
C	3.3	8	3.3	8	3.3	8	3.3	8	3.3	8	3.3	8	3.3	8	5.3*	7	5.3	6
D	4.2	7	4.2	7	4.2	7	4.2	7	4.2	7	4.2	7	4.2	7	4.2	7	6.2	6
E	5.7	7	5.7	7	5.7	7	5.7	7	5.7	7	5.7	7	5.7	7	5.7	7	5.7	7
F	6.1	4	7.1*	3	7.1	3	7.1	3	9.1*	2	9.1	2	9.1	2	9.1	2	9.1	2
G	7.2	5	7.2	5	8.2*	4	9.2*	3	9.2	3	9.2	3	9.2	3	9.2	3	9.2	3
Total cost of activities	31		32		33		34		36		38		39		41		44	

* Crashed activity

Project Resource Management

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Effect of Resources on Project Planning

- So far, the precedence relations among activities are the sole constraints (finish to start).
- This assumes that there are enough resources available to permit any number of activities to be scheduled simultaneously.
- As we will see. this is rarely the case.

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- To discuss the relationship between resource requirements and the scheduling of activities, consider the example project that was introduced in the following table.

TABLE 9.2 Data for Example Project

Activity	Immediate predecessors	Duration (weeks)
A	–	5
B	–	3
C	A	8
D	A, B	7
E	–	7
F	C, E, D	4
G	F	5

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Resource Requirements for the Example Project

Activity	Duration (weeks)	Required labor (days per week)	Total labor (days required)
A	5	8	40
B	3	4	12
C	8	3	24
D	7	2	14
E	7	5	35
F	4	9	36
G	5	7	35

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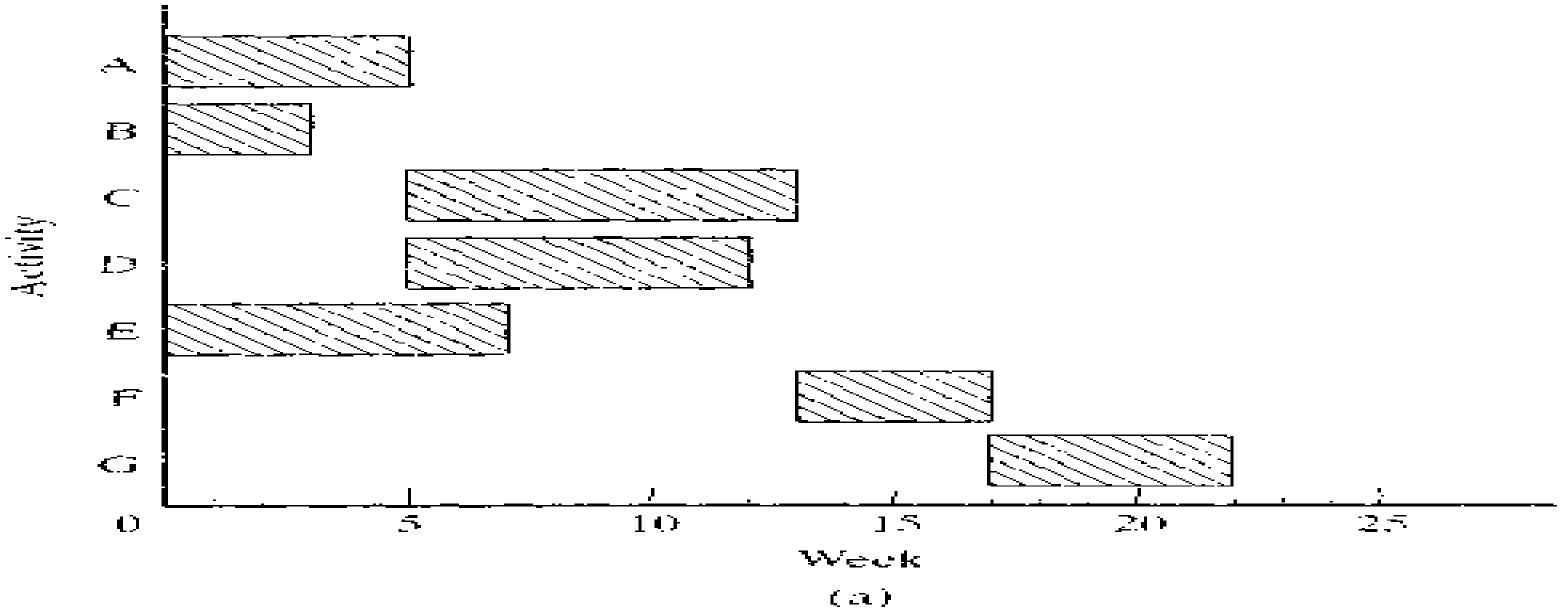

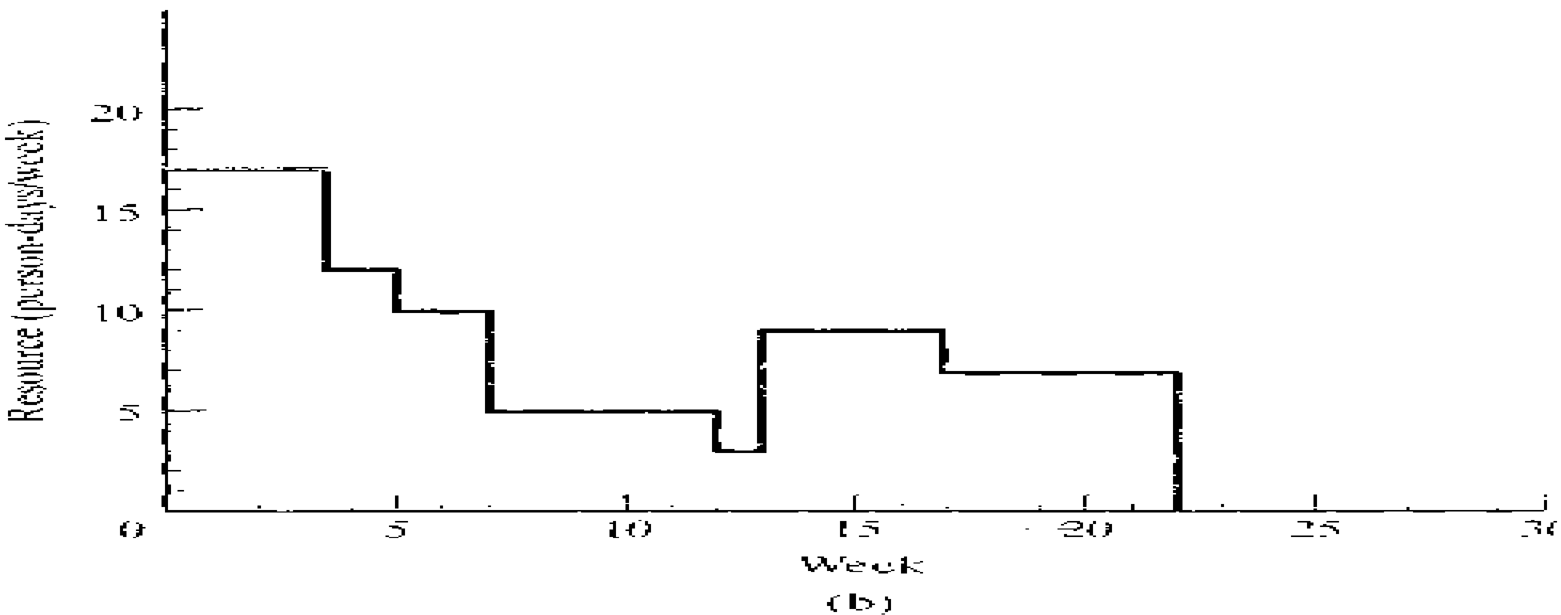

Figure 10.2 (a) Gantt chart and (b) resource profile for the early-start schedule.

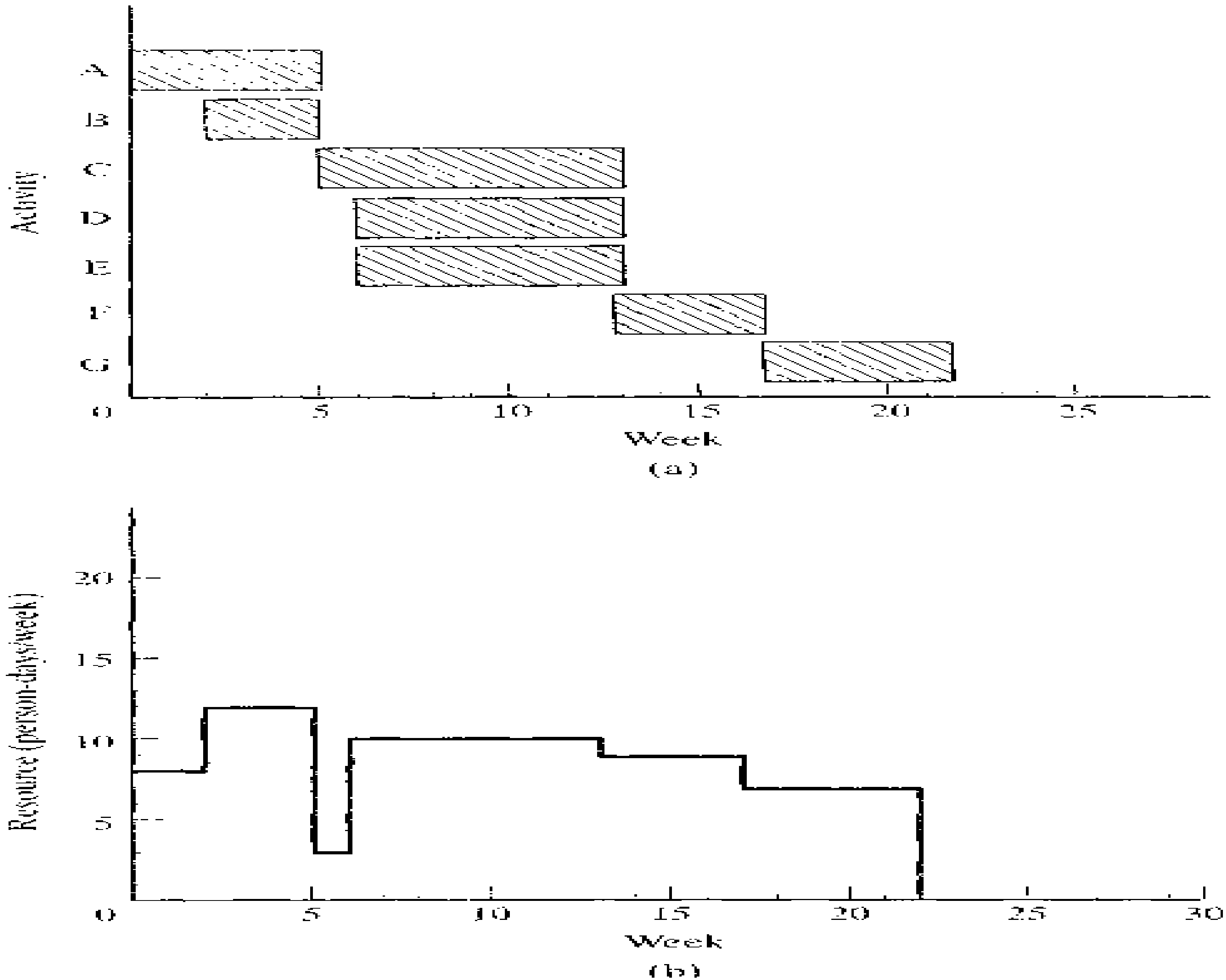

Figure 10.3 (a) Gantt chart and (b) resource profile for the late-start schedule.

Project Termination

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Reasons Why Plans Fail

- Corporate goals not understood lower down in the organization/company
- Plans include too much in too little time
- Poor financial estimates
- Plans based upon insufficient data
- Project estimates are best guesses and are not based on any standards, or history
- Insufficient time allocated for project estimating

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Stopping Projects

- Final achievement of the objectives
- Poor initial planning and market forecast
- A better alternative is found
- A change in the company interest and strategy
- Allocated time is exceeded
- Key people leave the organization
- Problem too complex for the resources available

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Tutorial

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Case Study (1)

- Given the elements of a maintenance job (bearing overhaul) for a wind turbine in the following table.
  - Develop AOA network diagram for the job
  - Find the CP
  - Put the schedule on a Gantt Chart
  - Reduce the overall maintenance duration by 50 days

Job (Activity)	Description	Time (Minutes) Normal	Time (Minutes) Crash	Costs ($) Normal	Costs ($) Crash	Immediate Precedence Relationship
A	Dismantling	50	30	100	150	0
B	Repairing bolster pockets	67	50	120	150	A
C	Repairing side frame rotation stop legs	90	60	150	200	A
D	Checking friction blocks and all springs	35	25	50	75	A
E	Repairing bolster rotation stop gibs	80	25	140	170	B
F	Repairing side frame column wear plates	55	40	100	130	C
G	Repairing bolster pivot	210	150	250	300	E
H	Assembling	65	45	120	150	D, F, and G
I	Painting	40	30	80	100	H

Co-funded by the
Erasmus+ Programme
of the European Union

References and Acknowledgements

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of the European Union

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Thank You for Your Attention!

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

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Co-funded by the Erasmus+ Programme of the European Union