Implementation of Wind Energy Systems

Module 2.4

Module Presentation
Lecture 0

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Objectives

The main objective of this module is to enhance the design capabilities of students interested in commercialization and implementation of wind energy systems.

The module includes topics like placement selection, sizing, connection to the grid, business administration of wind farms, logistics and occupational safety.

ECTS: 3

EQF level: 7

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Learning Outcomes

Intellectual Skills

The students will be able to have a good understanding of the:

O1. Physical quantities characterizing the operation of the wind energy technology;

O2. Principles of economic feasibility;

O3. Sizing and selection of wind turbines;

O4. Micro-siting and layout of wind farms;

O5. Principles of environmental impact assessments.

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Learning Outcomes

Professional Skills

The students will be able to:

O1. Perform basic economic feasibility of wind energy projects;

O2. Practice basic negotiation of wind energy projects with respect to national regulations and/or international norms;

O3. Use the necessary tools for the design and modeling of wind farms;

O4. Develop a good understanding regarding the current situation of the technology, the market;

O5. Perform basic environmental impact assessment;

O6. Debate/compare/elect wind energy options out of other renewable/conventional resources.

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Technical Contents

FIRST PART: TECHNICS

1. **Test and measurements; Wind data analysis**
2. ***Exercise1: Collection and processing of Wind Data (Wind Maps)***
3. **Selection of Location and Sizing**
4. **Analysis and design of wind farms, predictions of energy production**
5. ***Exercise2: Optimal Turbine choice***
6. **Wind Farm Layouts: grid-connected, off-grid systems, on-shore and off-shore**
7. **Exercise3: Simulation of Project**

SECOND PART: PROJECT MANAGEMENT

1. **Feasibility study (preparation, analysis, evaluation, and social acceptance)**
2. **Operation and maintenance issues**
3. **Managing wind farm project implementation and operation**
4. **Environmental Impact Assessment (EIA)**
5. **Occupational Health and Safety (OHS&S)**
6. **Economical Sustainability.**
7. ***Project Work with the use of selected software for the Wind Farm Design***

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Recommended literature

Books:

1. [Christopher A. Simon, Alternative Energy: Political, Economic, and Social Feasibility, Rowman & Littlefield Publishers, Inc.]
2. [Occupational safety and health in the wind energy sector, European Agency for Safety and Health at Work, 2013]
3. [Mathew Sathyajith, Wind Energy: Fundamentals, Resource Analysis and Economics, Springer]
4. [Chong Ng and Li Ran, Offshore Wind Farms-Technologies, Design and Operation, Elsevier Ltd., 2016]

Open resources:

1. [Feasibility Study of Economics and Performance of Wind Turbine Generators at the Newport Indiana Chemical Depot Site Joseph Owen Roberts and Gail Mosey Produced under direction of U.S. Environmental Protection Agency (EPA) by the National Renewable Energy Laboratory (NREL) under Interagency Agreement IAG-09-1750 and Task No. WFD3.1001.]

Review articles:

1. [Marllen Santos, Mario González, “Factors that influence the performance of wind farms”, Renewable Energy, May 2019, 643-651]
2. [Mert Satir, Fionnuala Murphy, and Kevin McDonnell, “Feasibility study of an offshore wind farm in the Aegean Sea, Turkey”, Renewable and Sustainable Energy Reviews, 2018, 2552-2562]

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Recommended literature

Web links:

https://globalwindatlas.info/

http://www.windustry.org/community_wind_toolbox

https://www.initiafy.com/blog/wind-turbine-safety/

https://www.windpowerengineering.com/operations-maintenance/safety/what-are-the-safety-precautions-for-wind-turbine-workers/

Software:

Commercial software used by Industries: design and simulation of Wind Farm

WindFarm: http://www.resoft.co.uk/English/index.htm

WindFarmer: https://www.dnvgl.com/energy/generation/software/windfarmer/windfarmer-analyst.html

WASPs: http://www.wasp.dk/products

Software Open Source:

RETScreen http://www.nrcan.gc.ca/energy/software-tools/7465

Exercises and Tutorial in MathLab/SciLab environment on:

1. **Wind farm sizing and calculation of energy production (Basic approach)**
2. **Costs of Wind farm installation and repowering (Basic approach)**

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Module 2.4

Further information:

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Implementation of Wind Energy Systems

Module 2.4

Test and measurements; Wind data analysis

Lecture 1.1

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of wind source for Master Students in Engineering, focusing on the prediction of the wind potential, the analysis of main direction, frequency and speed.

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Evaluate the different wind sources;

O2. Estimate the wind speed and the influence of external parameters like temperature, pressure, density, etc.;

O3. Estimate numerically the influence of site's characteristics and orography;

O4. Graph wind speed in value, frequency, direction;

O5. Have confidence with the main tools for the estimation of the wind sources.

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Technical Contents

1. *The main wind sources*
2. *Measurement systems and methodology*
3. *Data gathering and elaboration*
4. *Numerical models*

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The wind source and formation

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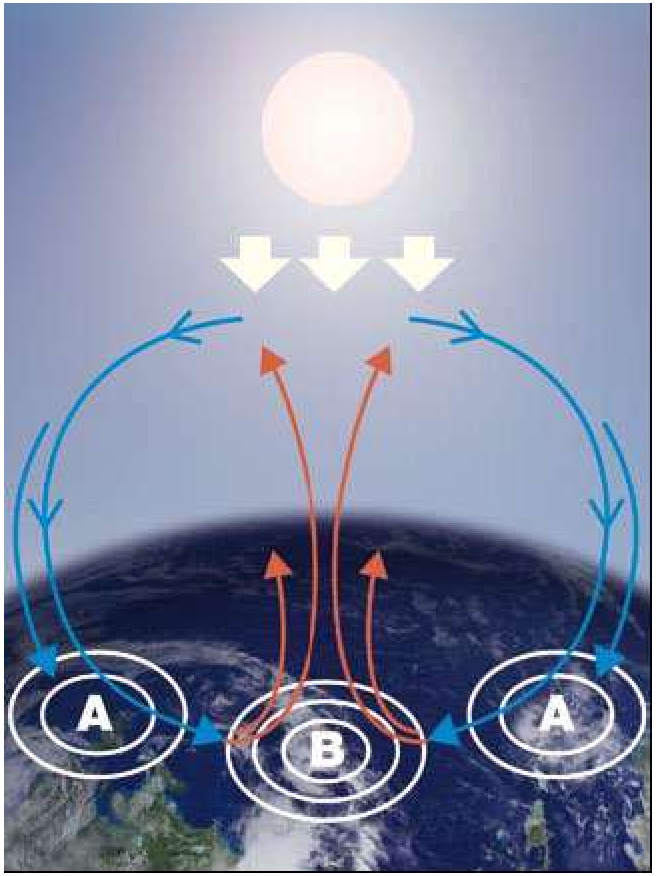

Source: 1

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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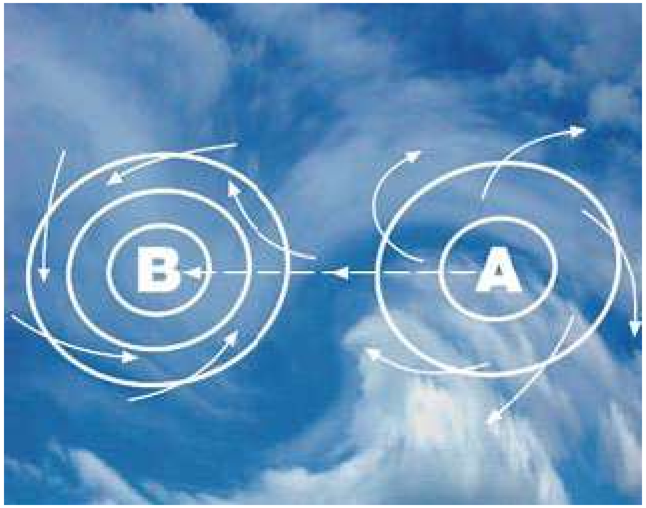
The wind source and formation



Source: 1

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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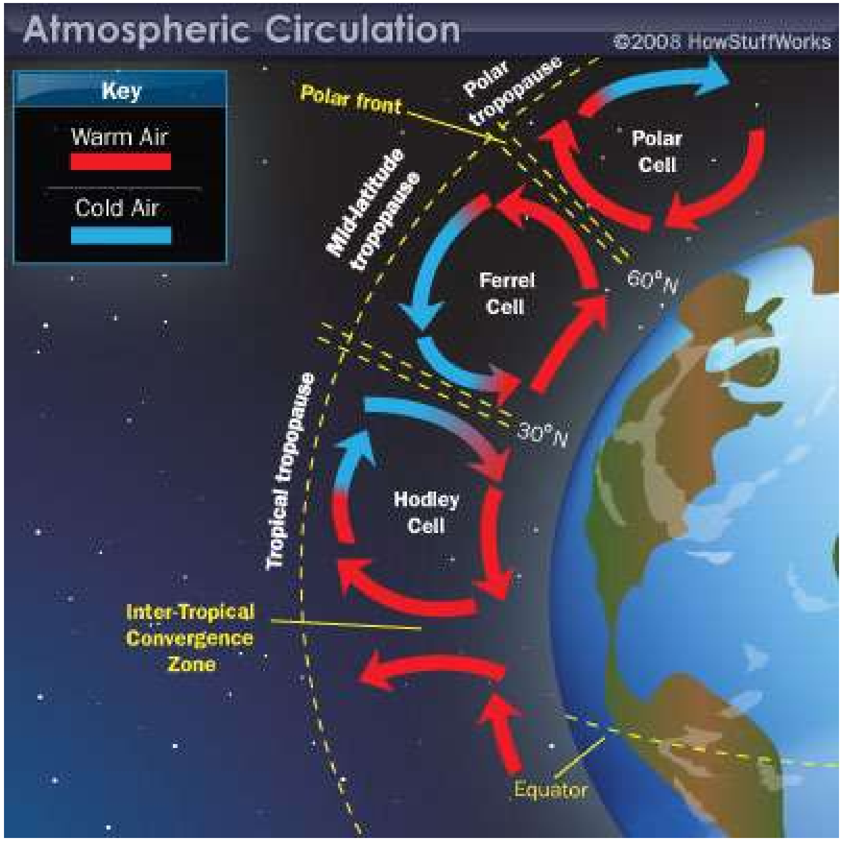
The wind source and formation

Types of wind:

✓ Global wind

✓ Local wind



Source: [1]

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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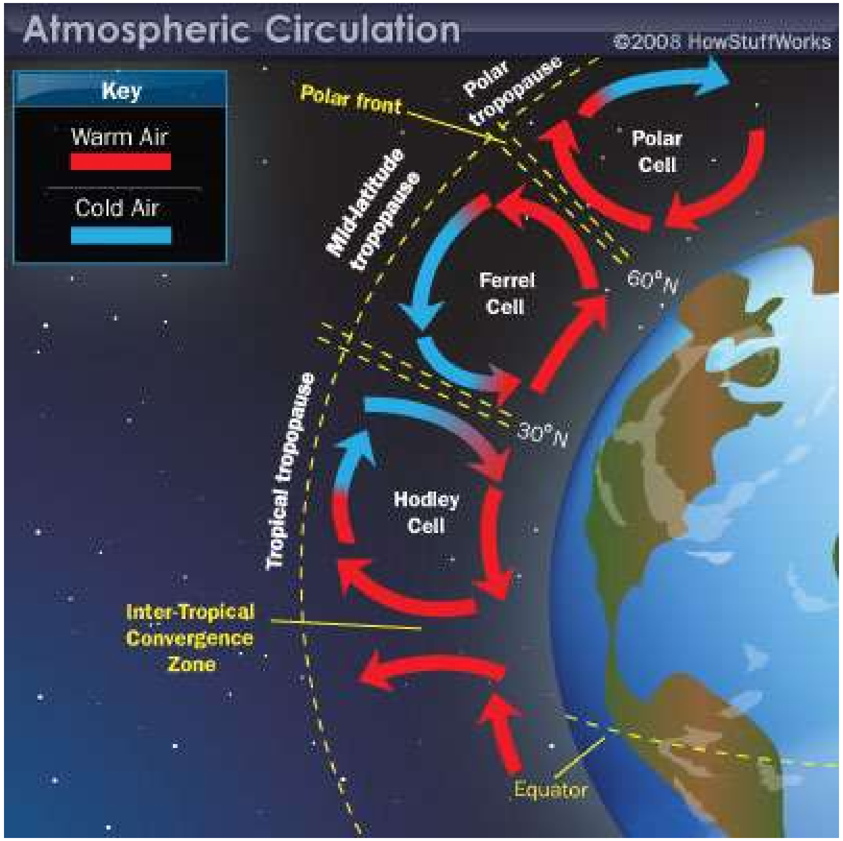
The wind source and formation

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



Source: [1]

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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

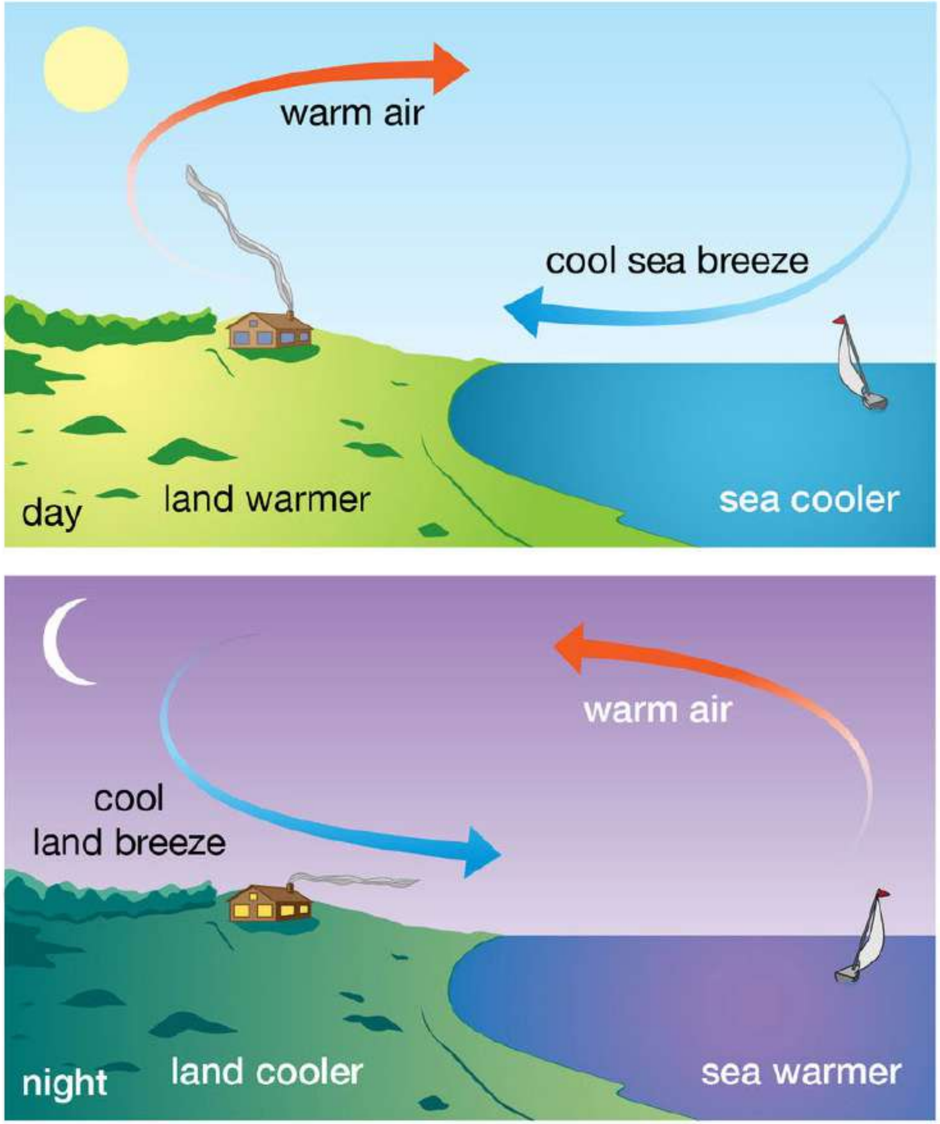
During the Daytime:

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: 2

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The wind source and formation

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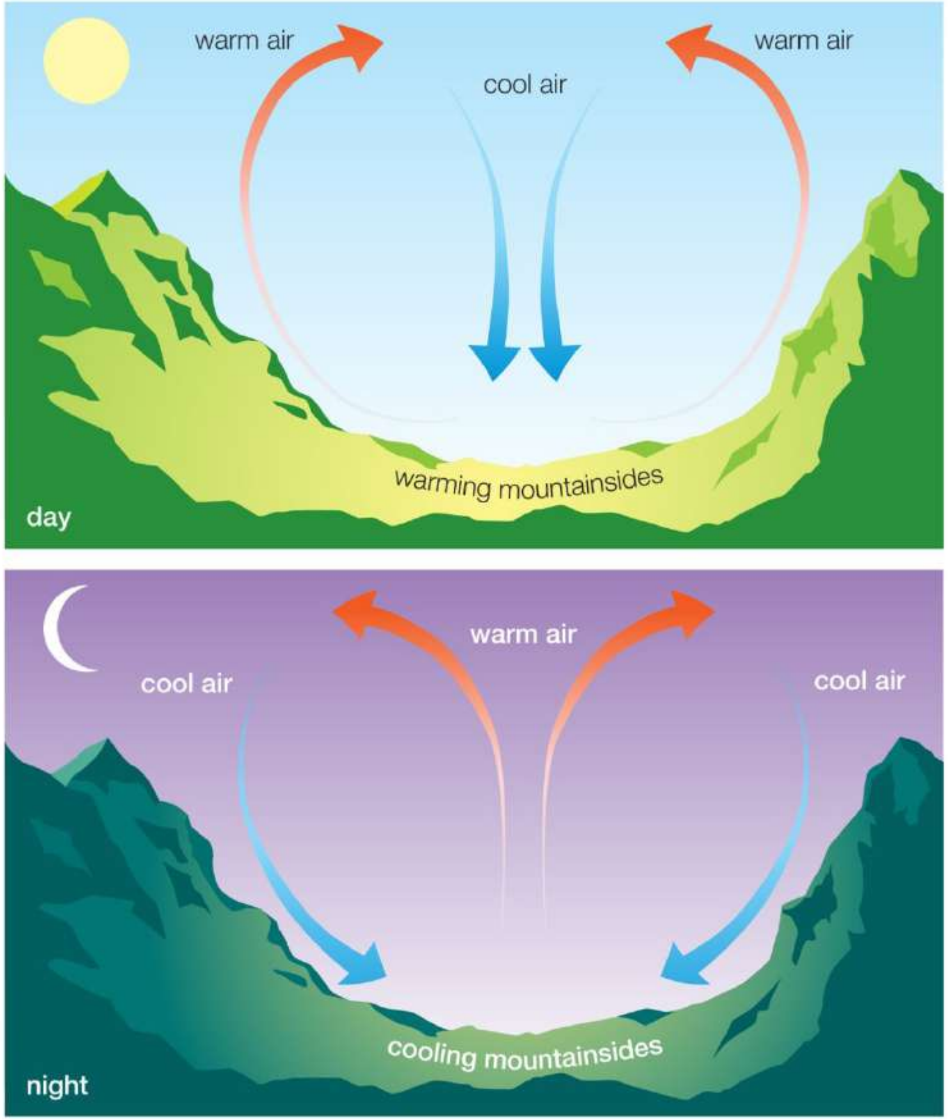
Mountain areas

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.



Source: Encyclopedia Britannica, Inc.

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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.

Source: Photo by Spencer Roberts.

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Windiness of a site - measurement

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

They are normally fitted with two anemometers at different heights.

Cup anemometer. Source: Vector Instruments

Ultrasonic anemometers. Source: Campbell Scientific

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Windiness of a site - measurement

The measurement campaign takes at least one year

Installation of the meteorological 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

Measurement towers → Anemometer and Wind Vane (velocity and direction measurement)
Measurement towers → Pole and guy-wires (20 – 100 m)
Measurement towers → Data acquisition system

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

Anemometric tower.
Source: Universidad Complutense Madrid

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Windiness of a site - measurement

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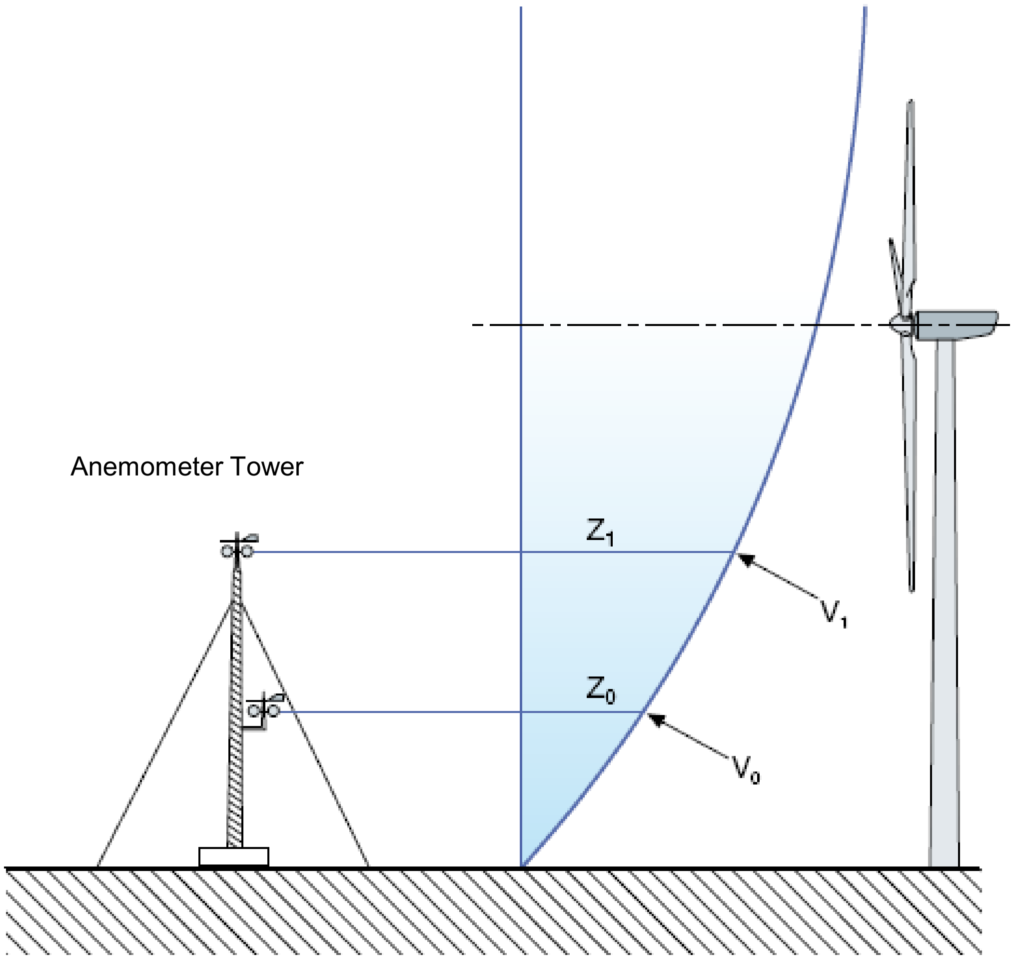

Source: 1

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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.

Source: [3]

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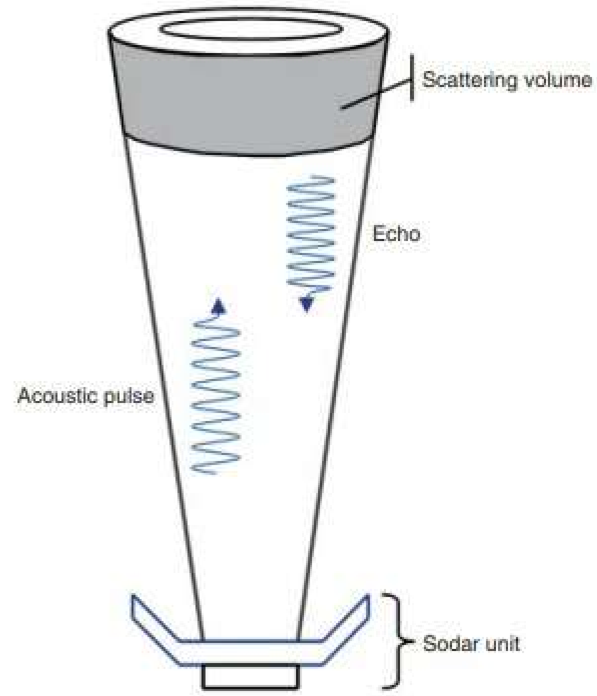
Windiness of a site - measurement

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.



Source: AWS Truepower

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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

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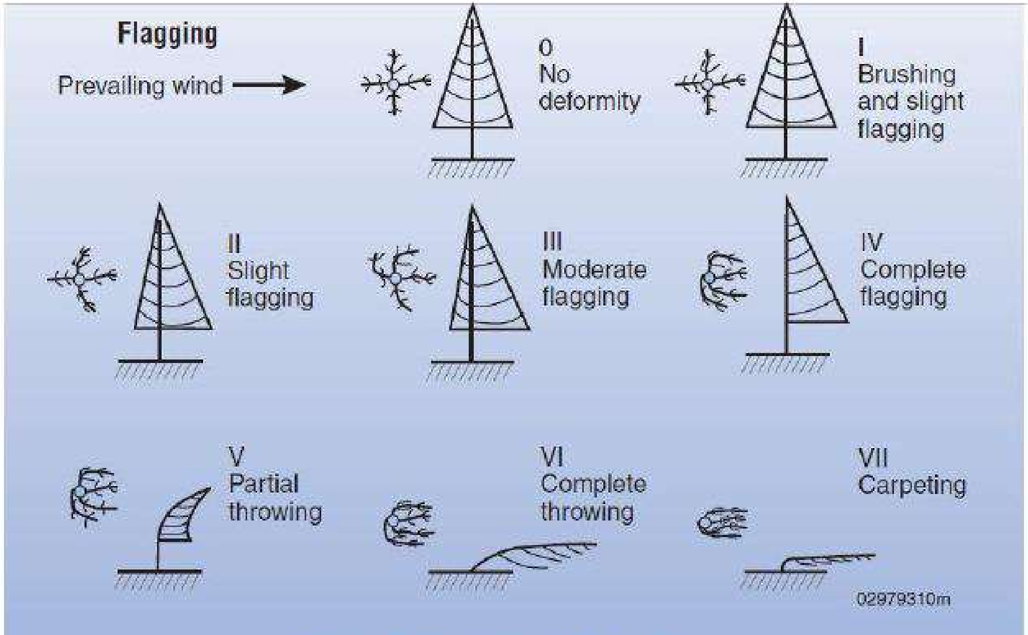
The vegetation on the ground is also a good indicator of the prevailing winds.

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



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

Source:3

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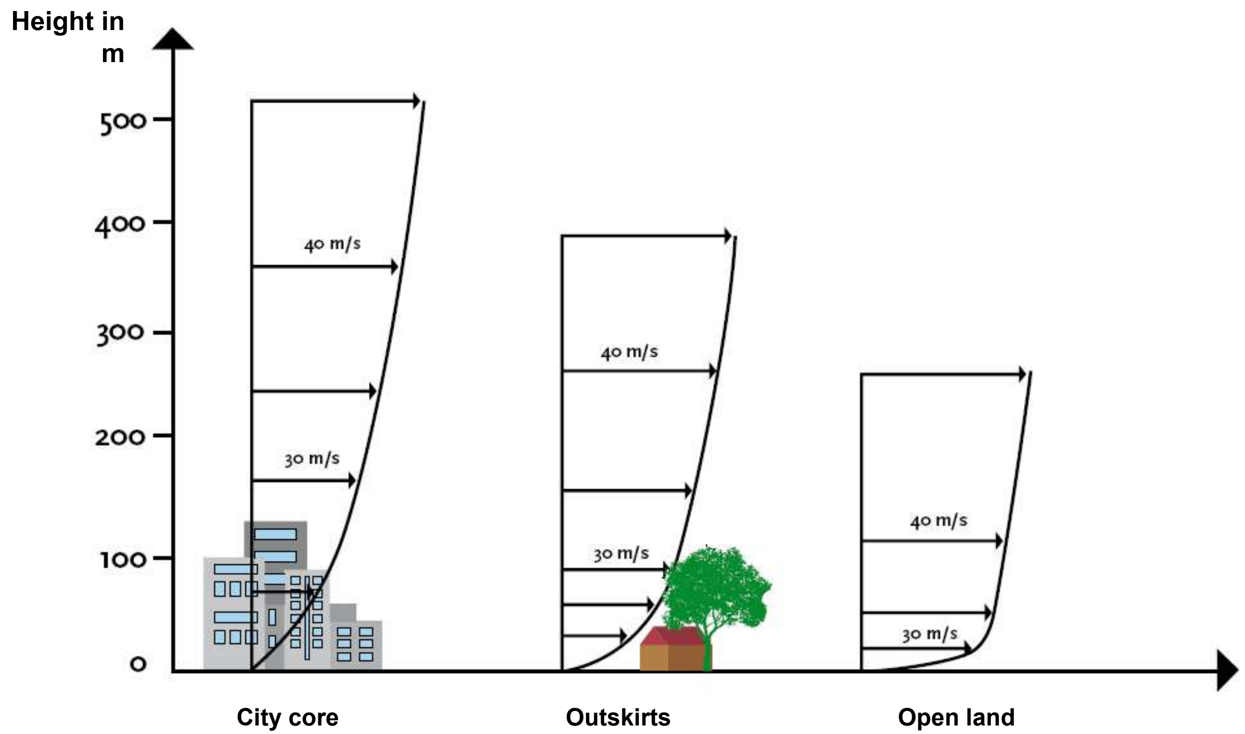
Windiness of a site - Randomness

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).



Source: 1

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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

Source: Data collected by the author

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Windiness of a site – Data gathering

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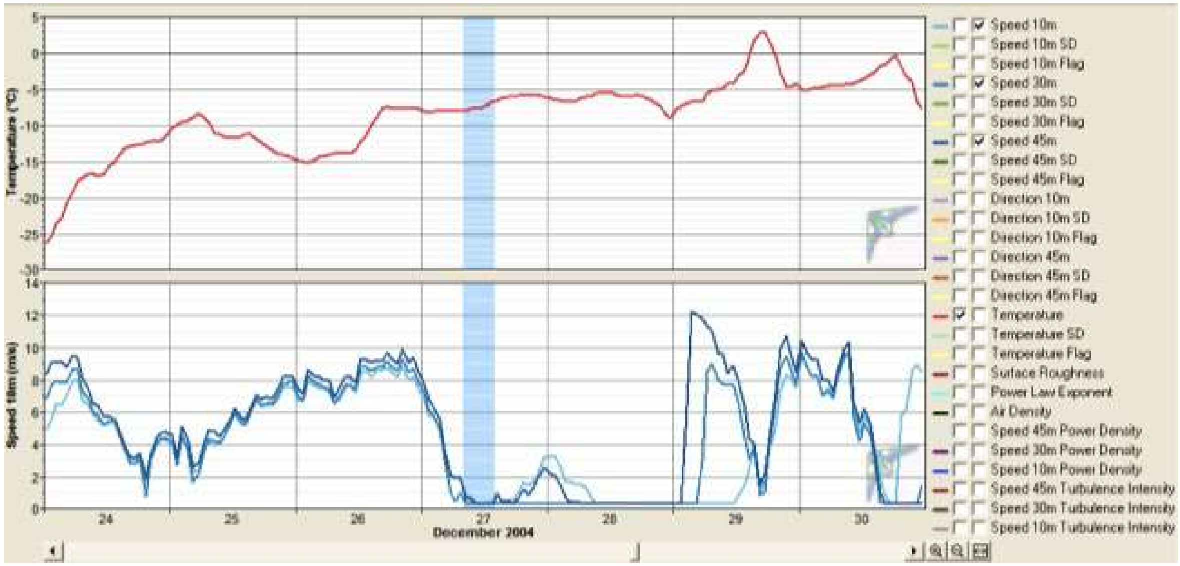
- Wind data are usually gathered in daily temporal series
- The acquisition trigger depends on the instrument (in general is 1 second)
- The data are averaged and collected in periods of 10 minutes
  - Average value
  - Maximum
  - Minimum
  - Standard deviation



Source: screenshot by the author

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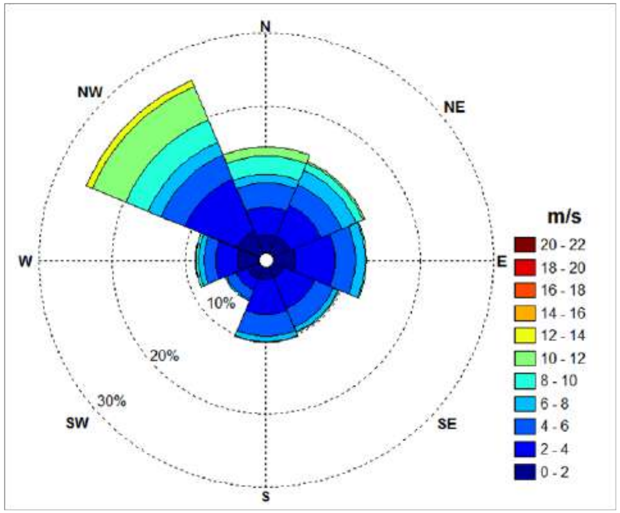
Windiness of a site – Data elaboration

- 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)

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

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



Source: by the author

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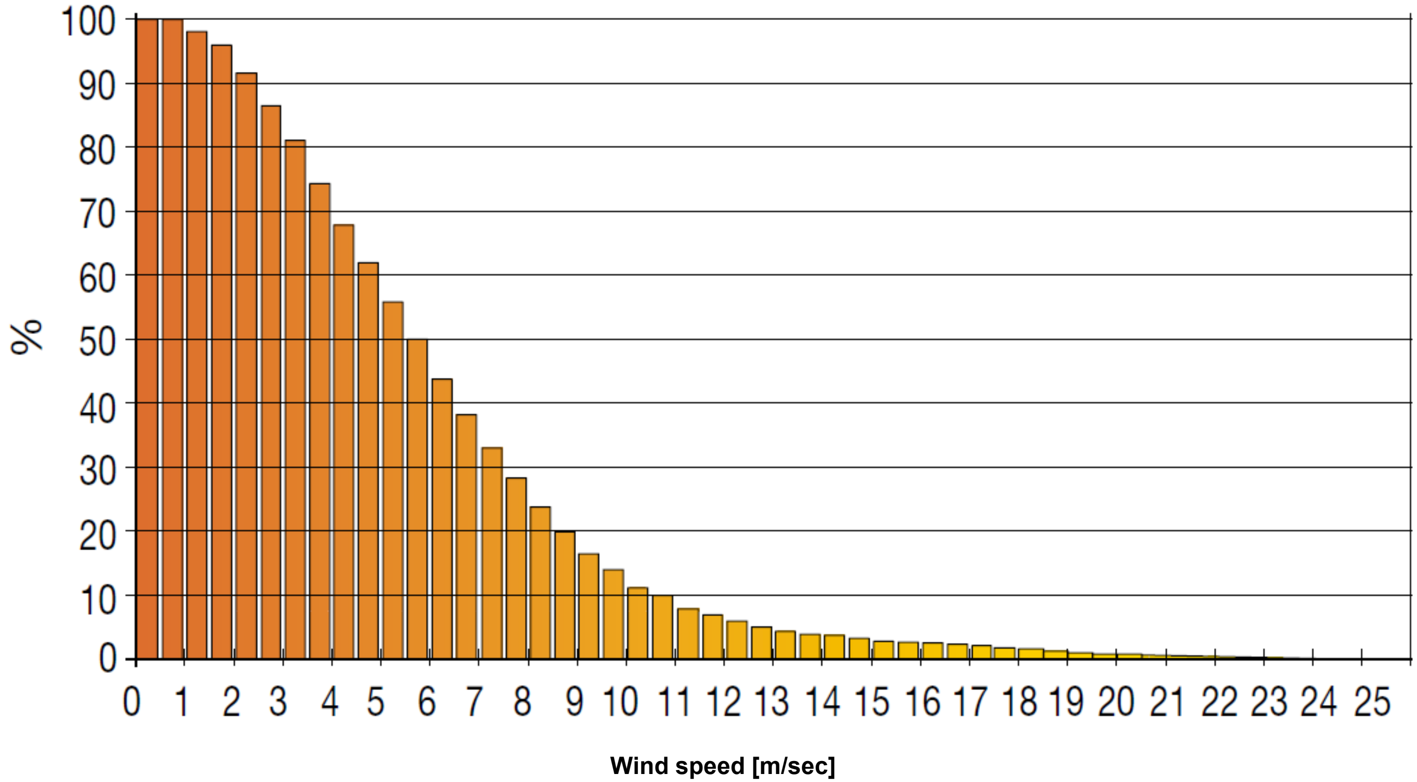
Windiness of a site - the frequency

Histogram of the percentage duration of wind speeds



Source: 1

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Windiness of a site - the frequency

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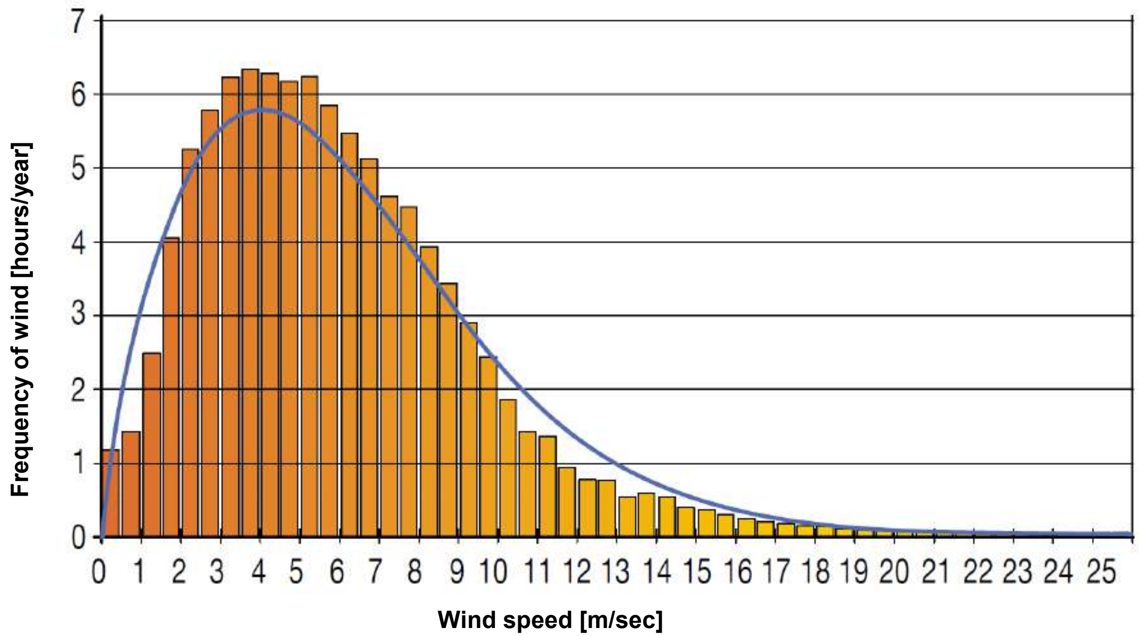
The measurements obtained with the surveys are organized into classes of speed given amplitude. Each class is defined by a average value of the wind speed belongs to the same class, which is associated with the corresponding number of hours / year of persistence of the wind speed within the respective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



Source: 1

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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 :

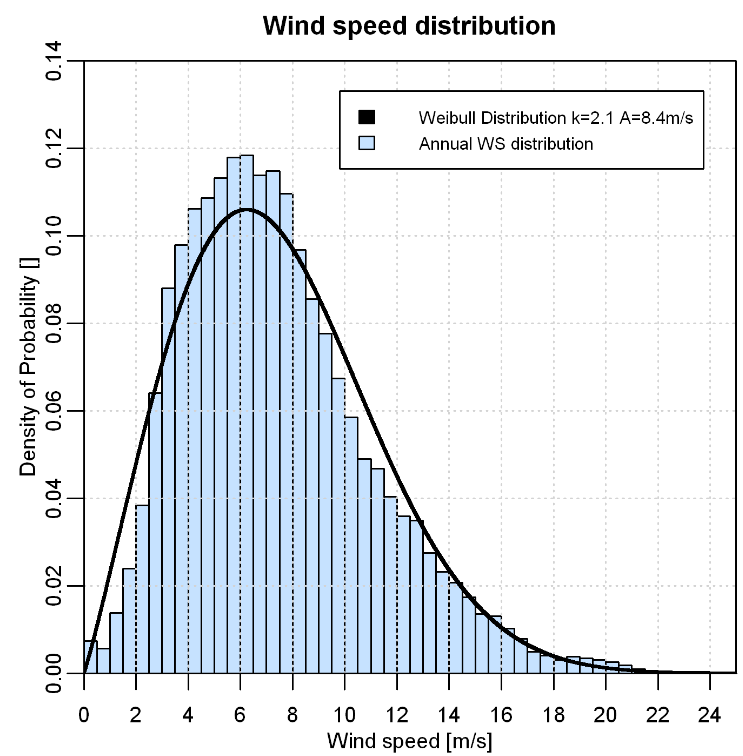
Shape parameter(k)

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

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.



Source: [4]

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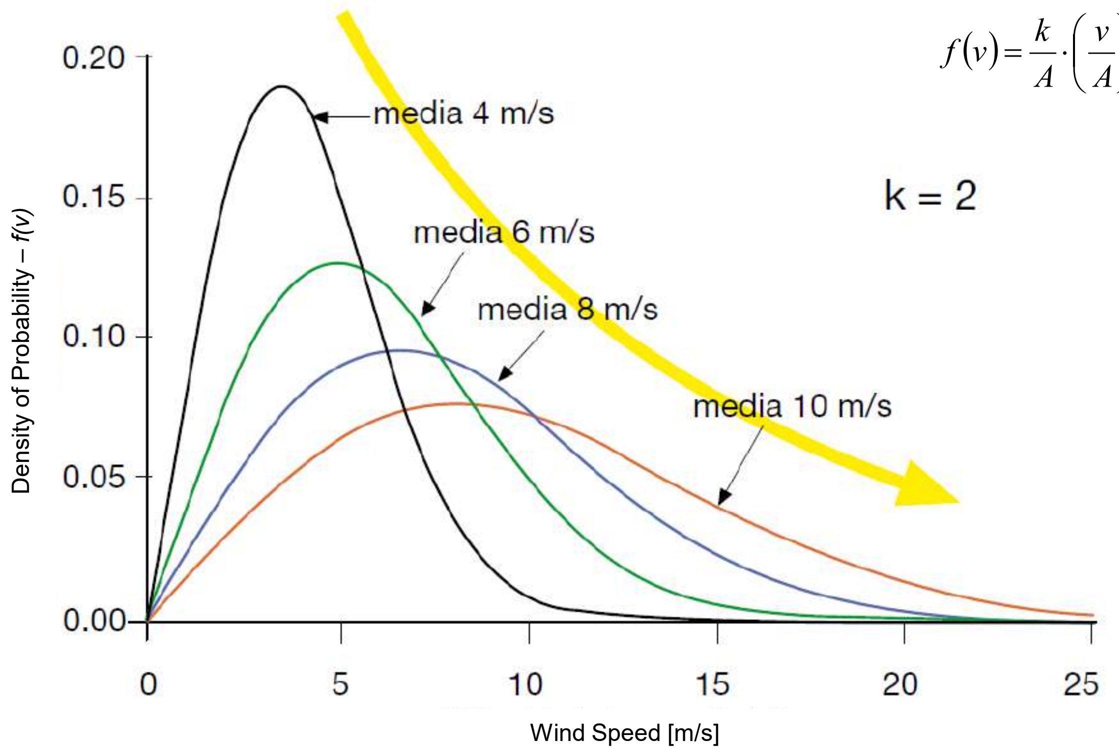
Windiness of a site - the frequency

Weibull distribution:

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)



* Media = Average

Source: 1

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Windiness of a site - the frequency

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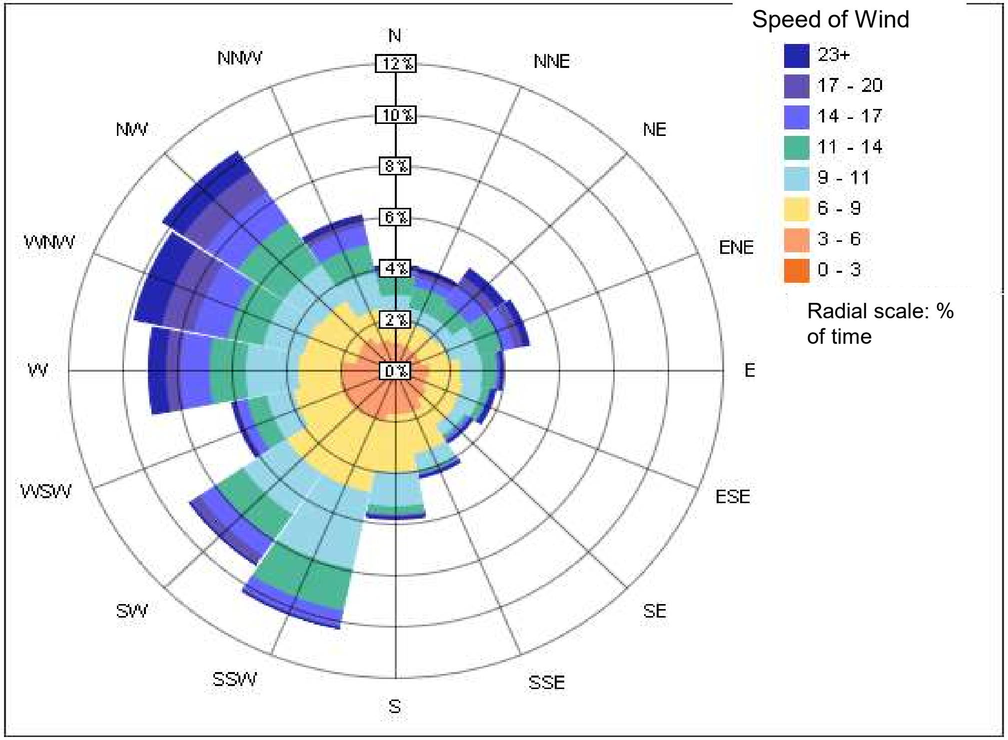
To plot the information on the distribution of the speed and frequency of the main directions using the compass rose.

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.



Source: [5]

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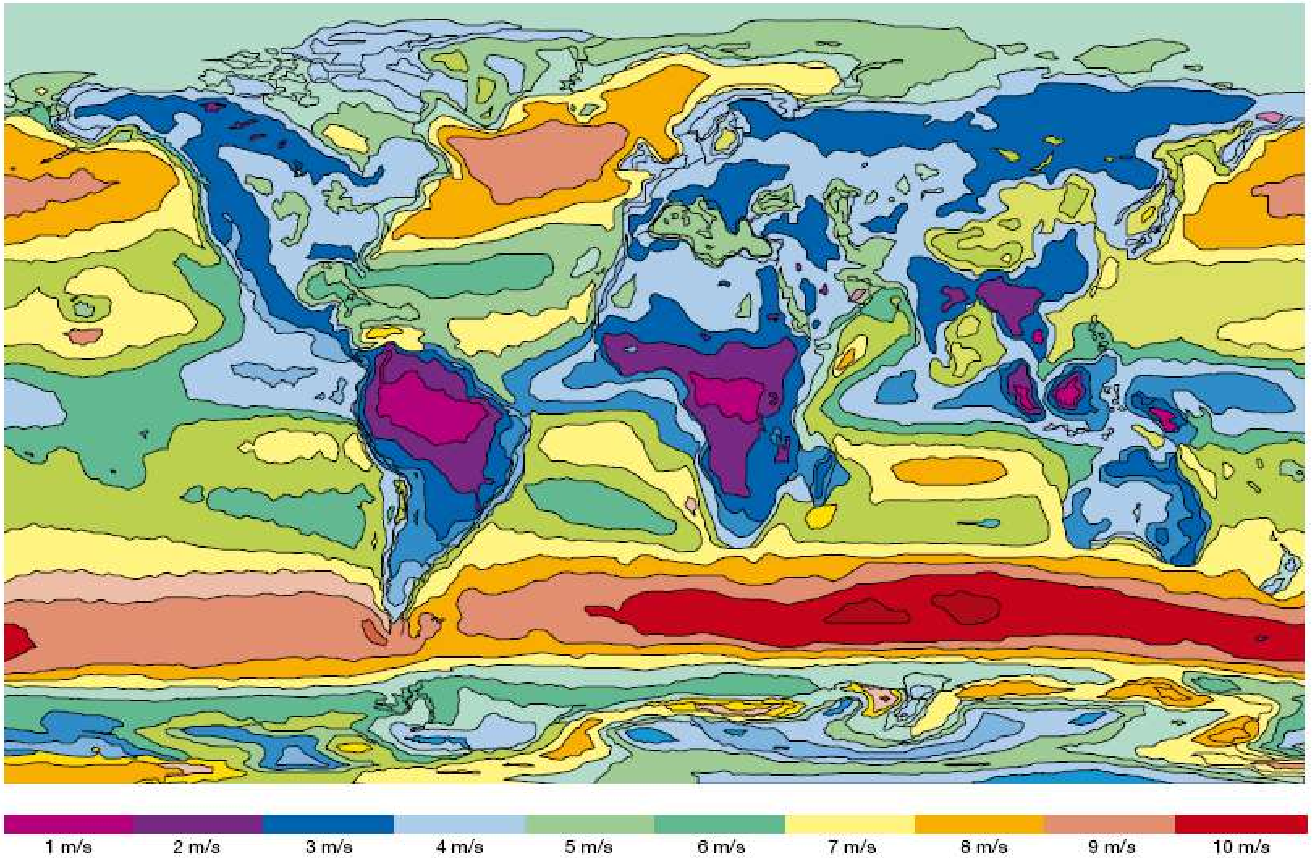
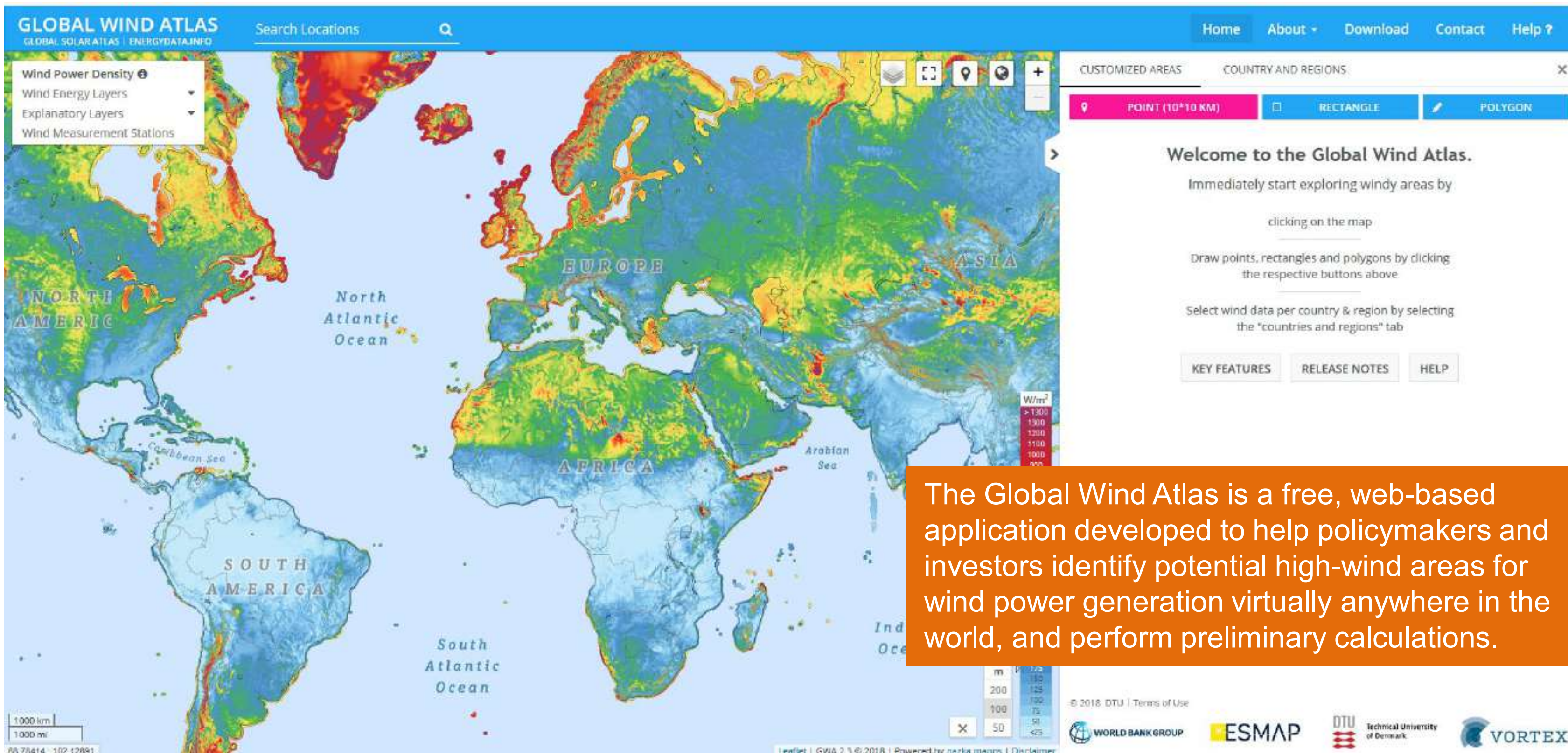
Wind Maps



World wind map: average wind speed in m/s at 10m of height. Source: 1

Tools and Software



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.

Source: https://globalwindatlas.info/

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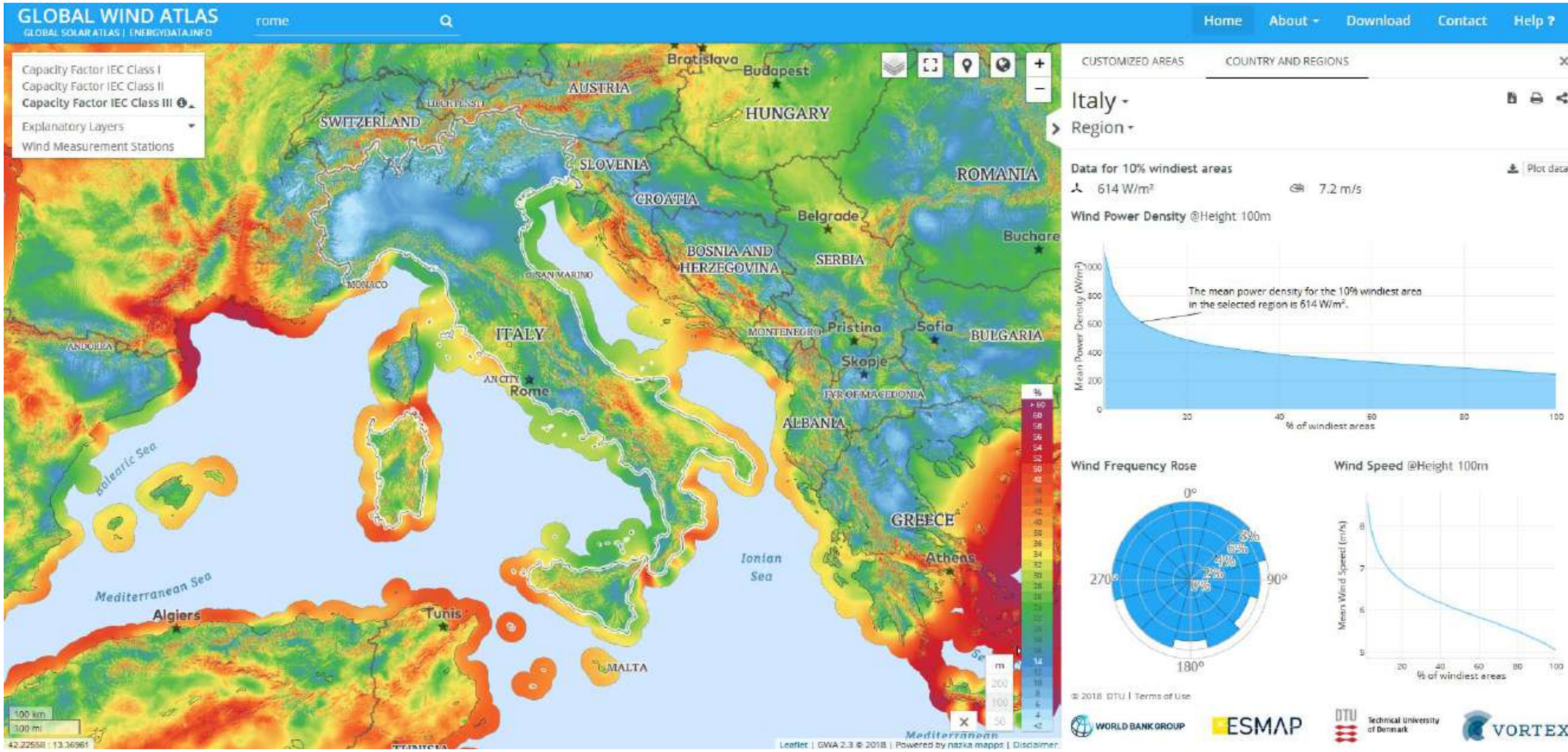
Tools and Software



Source: https://globalwindatlas.info/

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Recommended literature

Books:

1. **Quaderni di Applicazione Tecnica ABB [Translated in English]**
2. **Garrison, T., 1993. Oceanography: An invitation to Marine Science, Belmont, Wadsworth Publishing Company**
3. **A Siting Handbook for Small Wind Energy Conversion Systems, WindBooks (January 1, 1980), ASIN : B002VY1BSI**

Web links:

[1] https://science.howstuffworks.com **Howstuffworks**
[2] https://globalwindatlas.info/ **Global Wind Atlas**
[3] https://www.physics-and-radio-electronics.com/blog/sodar-sonic-detection-ranging**/ Physics and Radio-Electronics**
[4] http://emmanuel.branlard.free.fr/work/papers/html/2008ecn/node36#fig:**Wind_speed_distribution**
[5] https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2015/ENU/Revit-Analyze/files/GUID-2AACFEA1-16BD-4A01-BD75-81B12E56A57C-htm.html

Introduction to Wind Energy

Module 2.1

Further information:

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Implementation of Wind Energy Systems

Module 2.4

Selection of Location and Sizing

Lecture 1.2

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of data collection, the measurement tools and the micro-siting method for the analysis of wind potential in a specific site.

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Evaluate the main characteristics of selected site;

O2. Recognize the different simulation models micro-siting;

O3. Identify local effects due to the orography;

O4. Identify the main site's characteristics must be considered for a correct dimensioning of a wind farm.

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Technical Contents

1. *Micro-siting*
2. *Digital Elevation Model*
3. *Wind maps*
4. *Site's characteristics*

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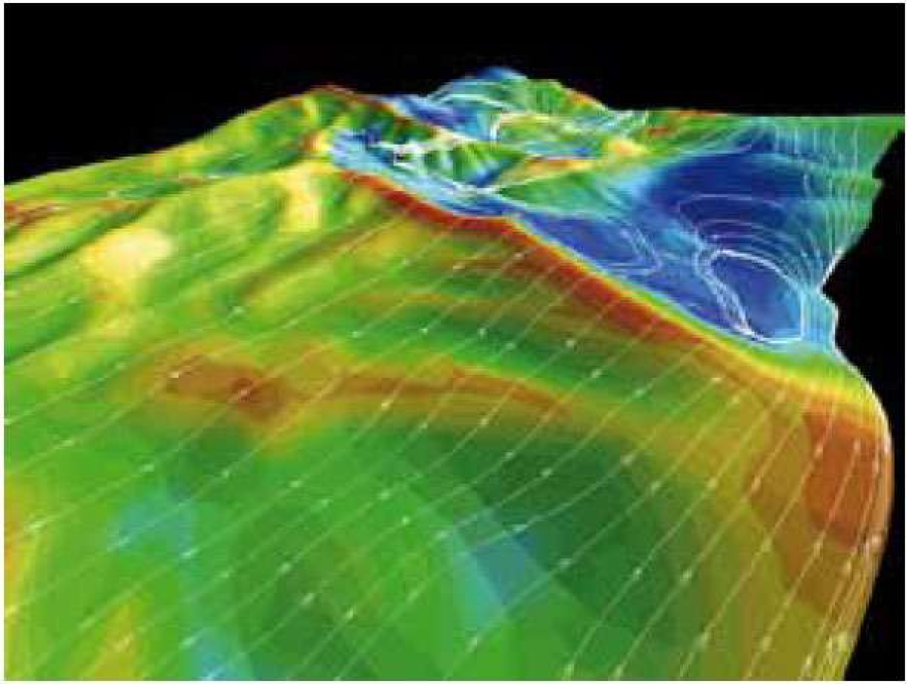
Windiness of a site - micro-siting

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



Source: [2]

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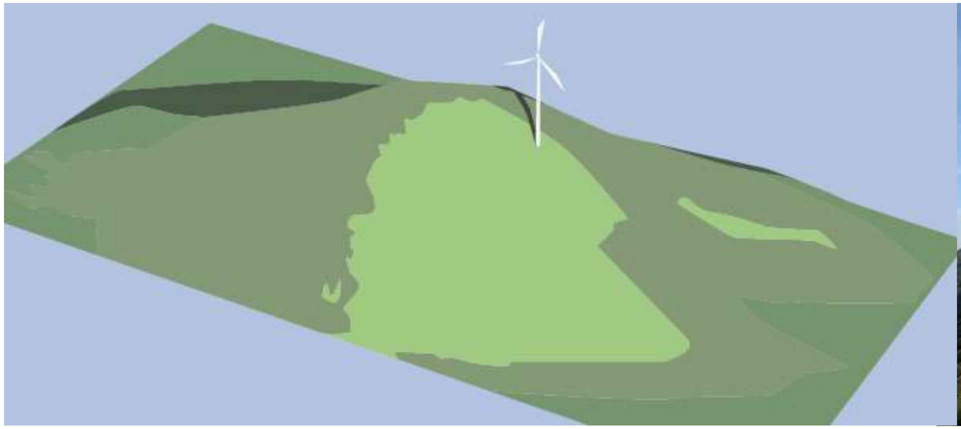
Windiness of a site - micro-siting

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.



Source: Danish Wind Industry Association

Source: [3]

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Windiness of a site - micro-siting

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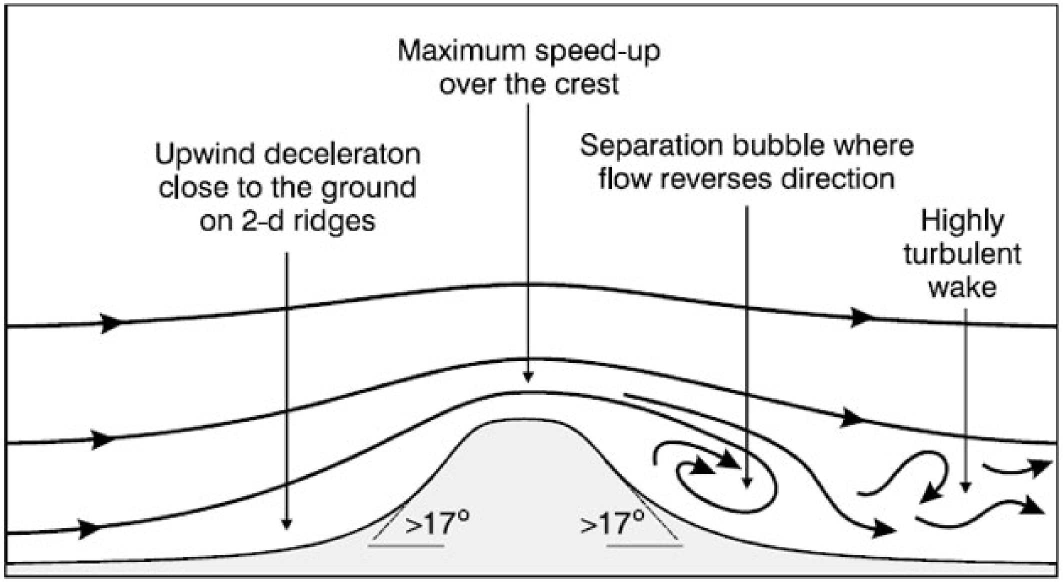
Hill effect, for low slope hills, the stream pipe get compressed by the rising of the ground surfaces and the pressure of the atmospheric stratification, generating a sort of venture effect on the wind which is then expanded and accelerated on the top of the hill (momentum conservation law)



Source: www.ecocitizenaustralia.com.au

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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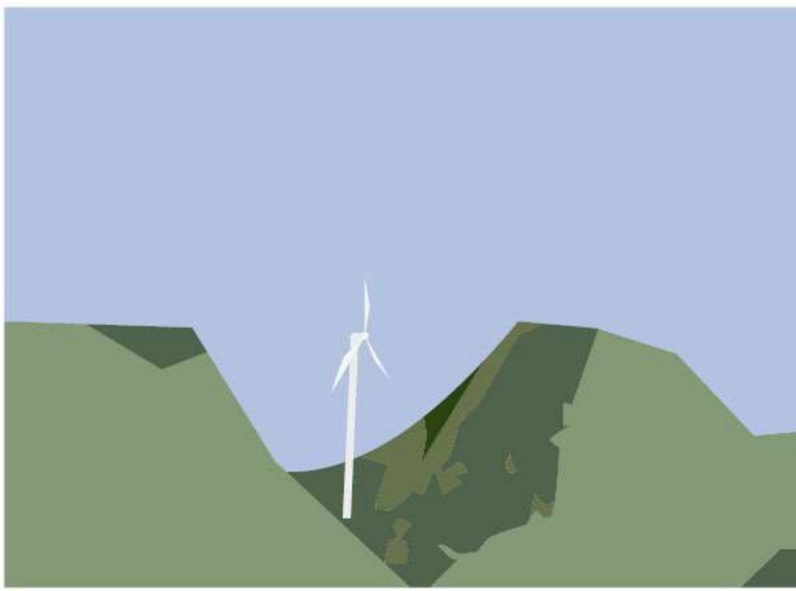
Windiness of a site - micro-siting

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.



Source: Danish Wind Industry Association

Source: [4]

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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

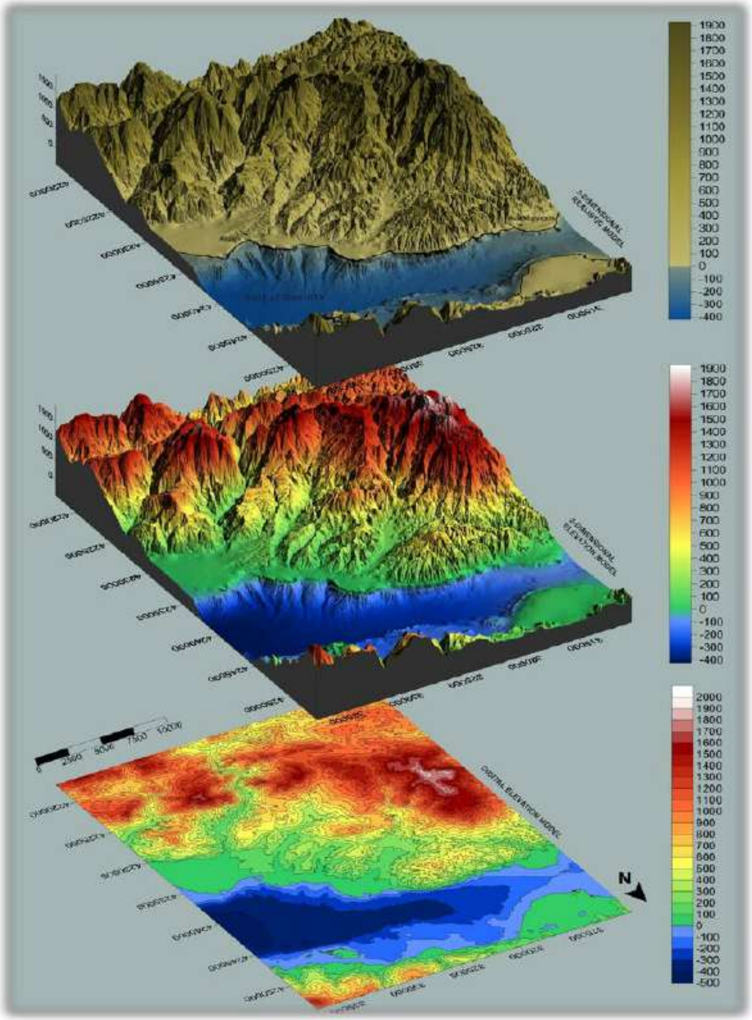
Ground roughness map

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

Source: Data collected by the author



Source: ResearchGate by Paraskevi Nomikou

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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)

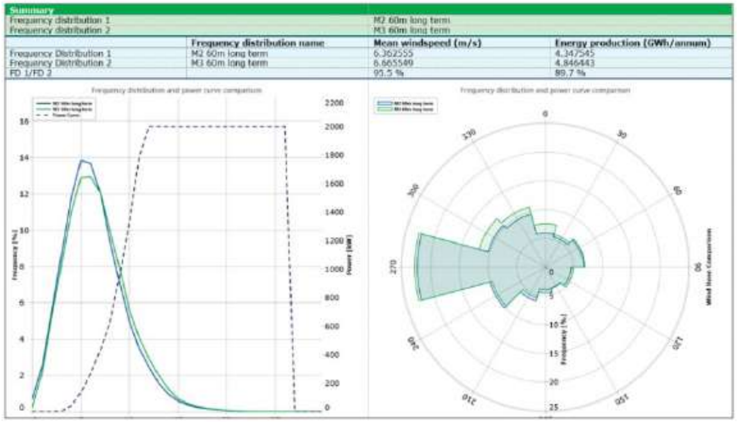
Some software

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)

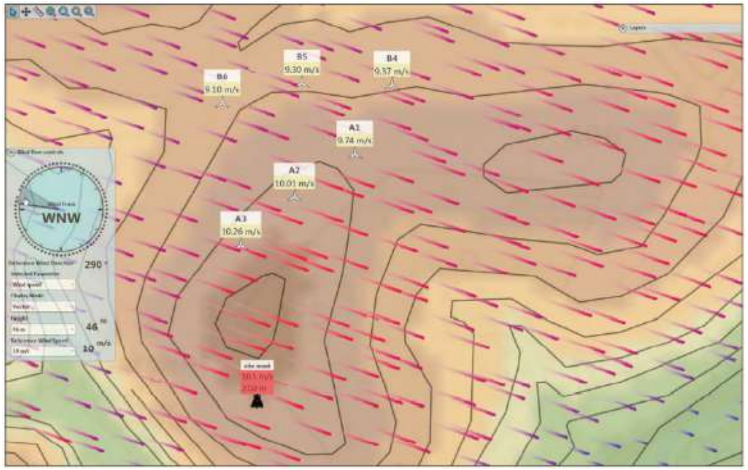
- WAsP
- Wind Pro
- Wind Farmer
- Wind Farm

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

- WindSim
- MeteoDyn



Source: WindFarmer (Analyst flyer)



Source: WindFarmer (Analyst flyer)

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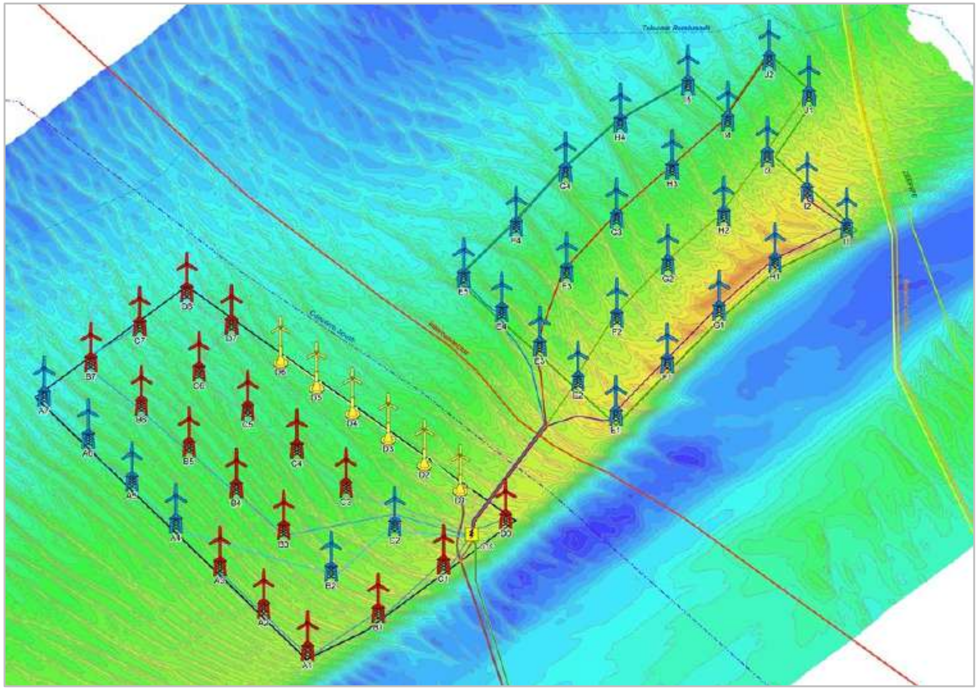
Windiness of a site - micro-siting

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

Definition and optimization 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



Wind Farm Layout. Source: http://www.c-power.be

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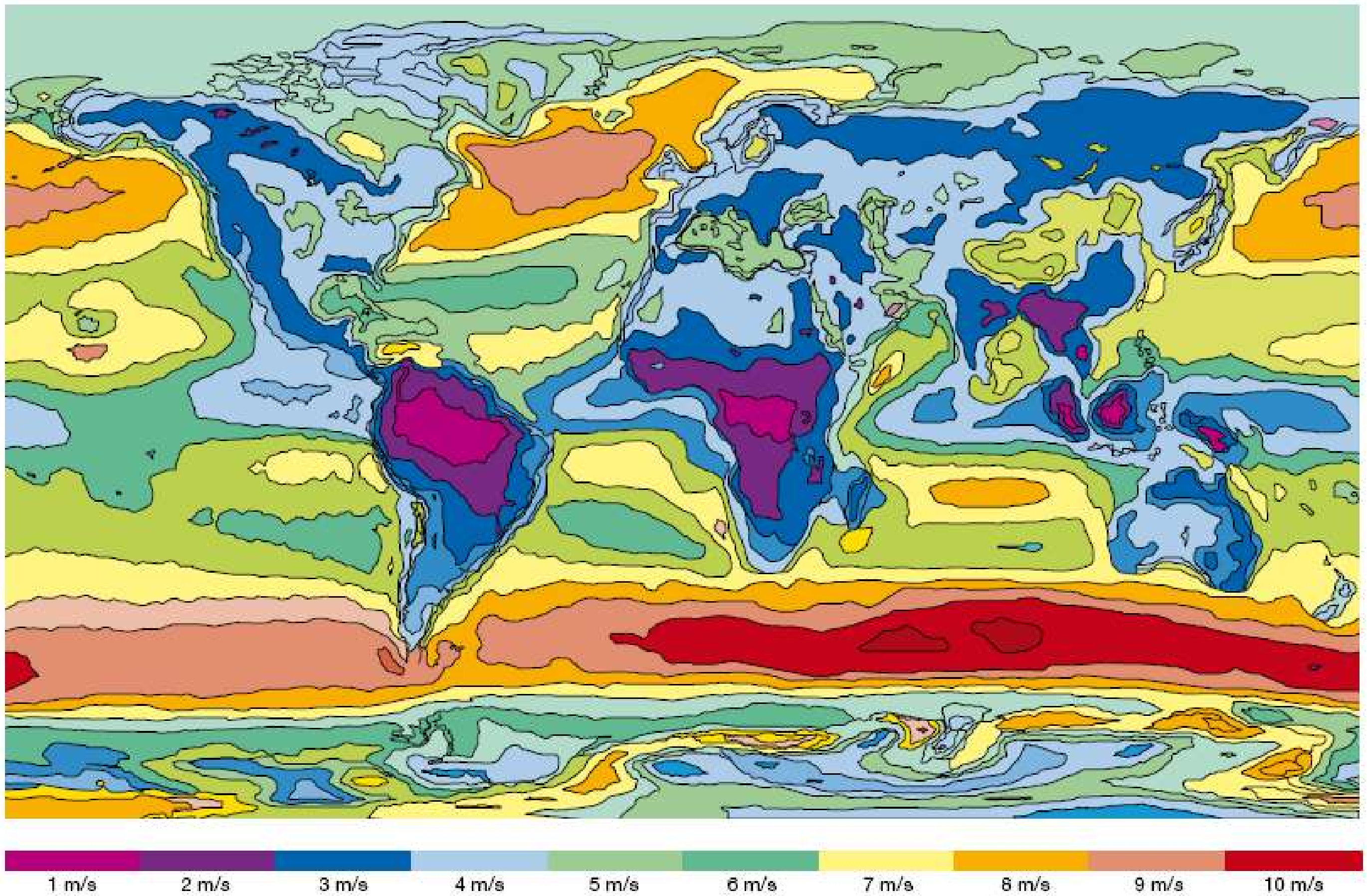
Wind maps



World wind map: average wind speed in m/s at 10m of height. Source: 1

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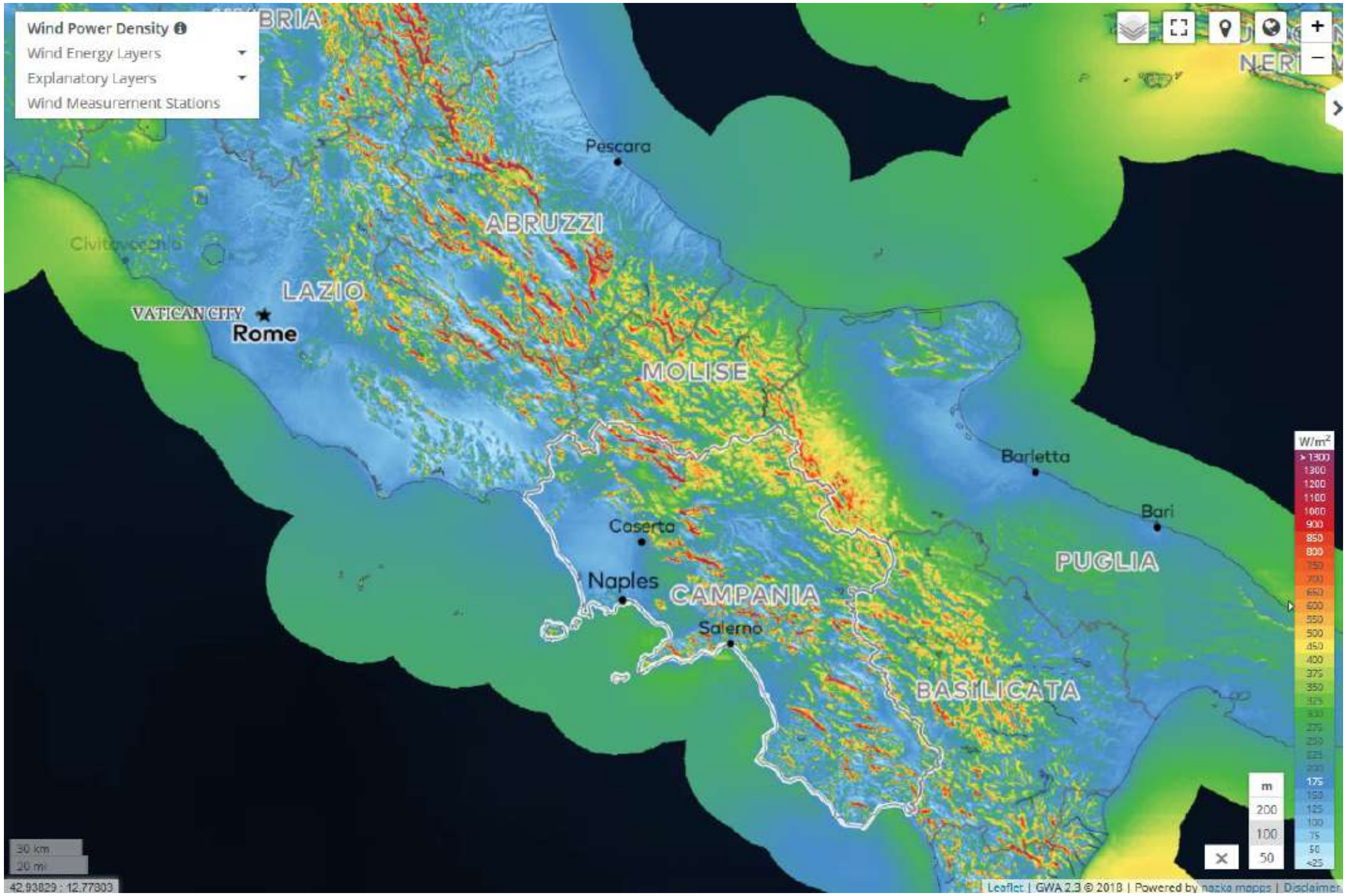
Wind Power Density



Wind Power Density. Source: [1]

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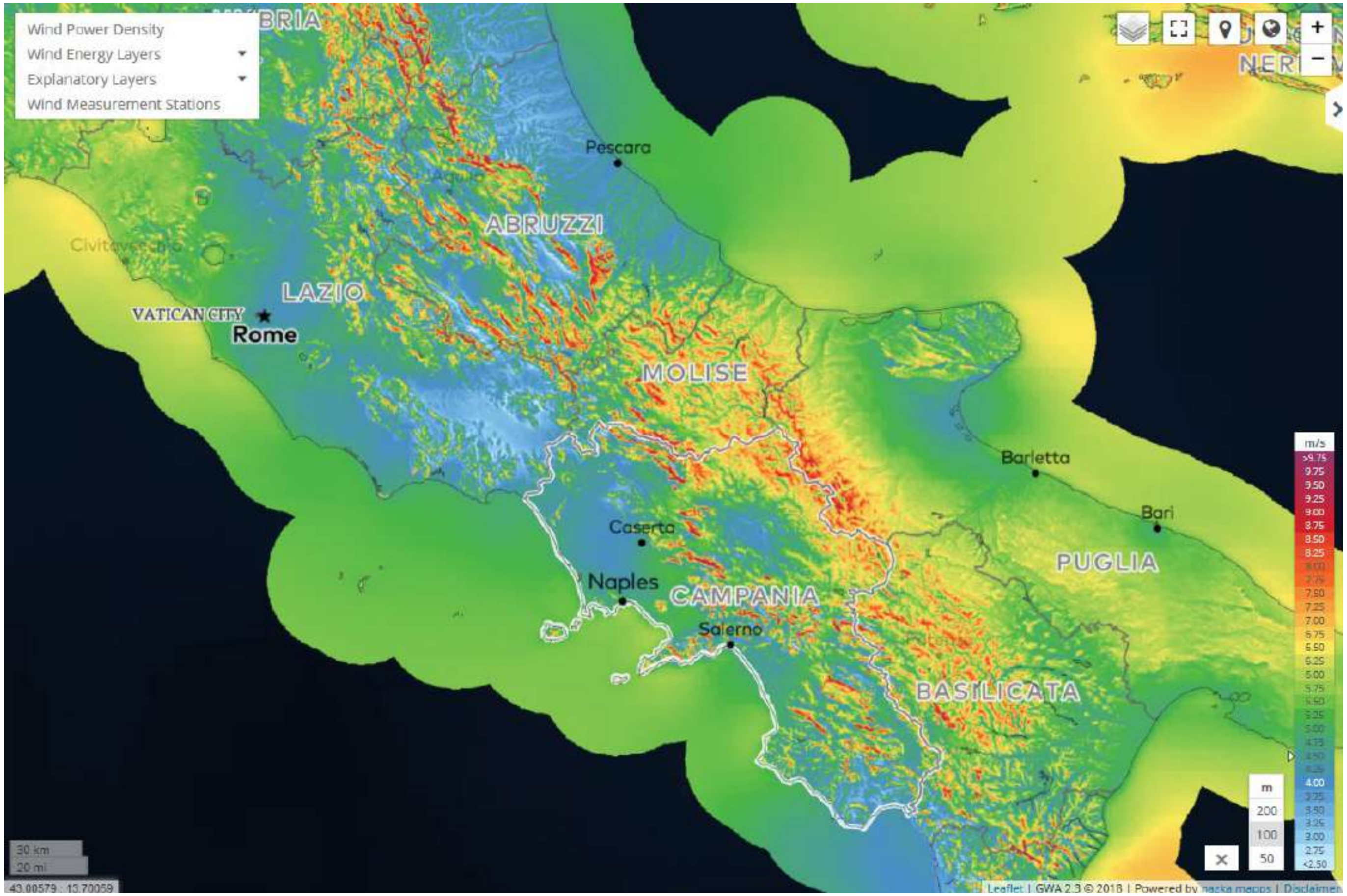
Wind Speed



Wind Speed. Source: [1]

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Orography

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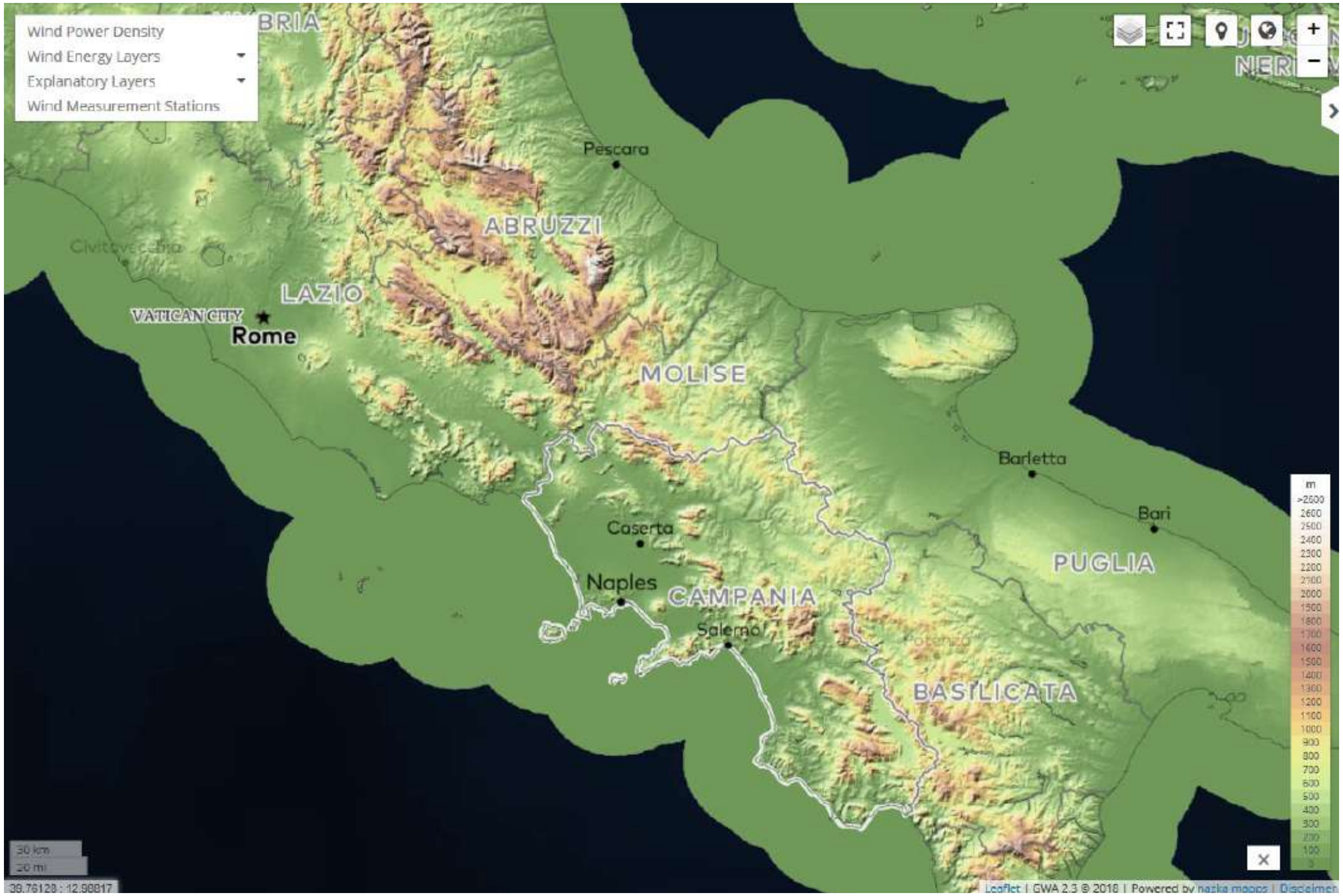

Orography. Source: [1]

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Roughness

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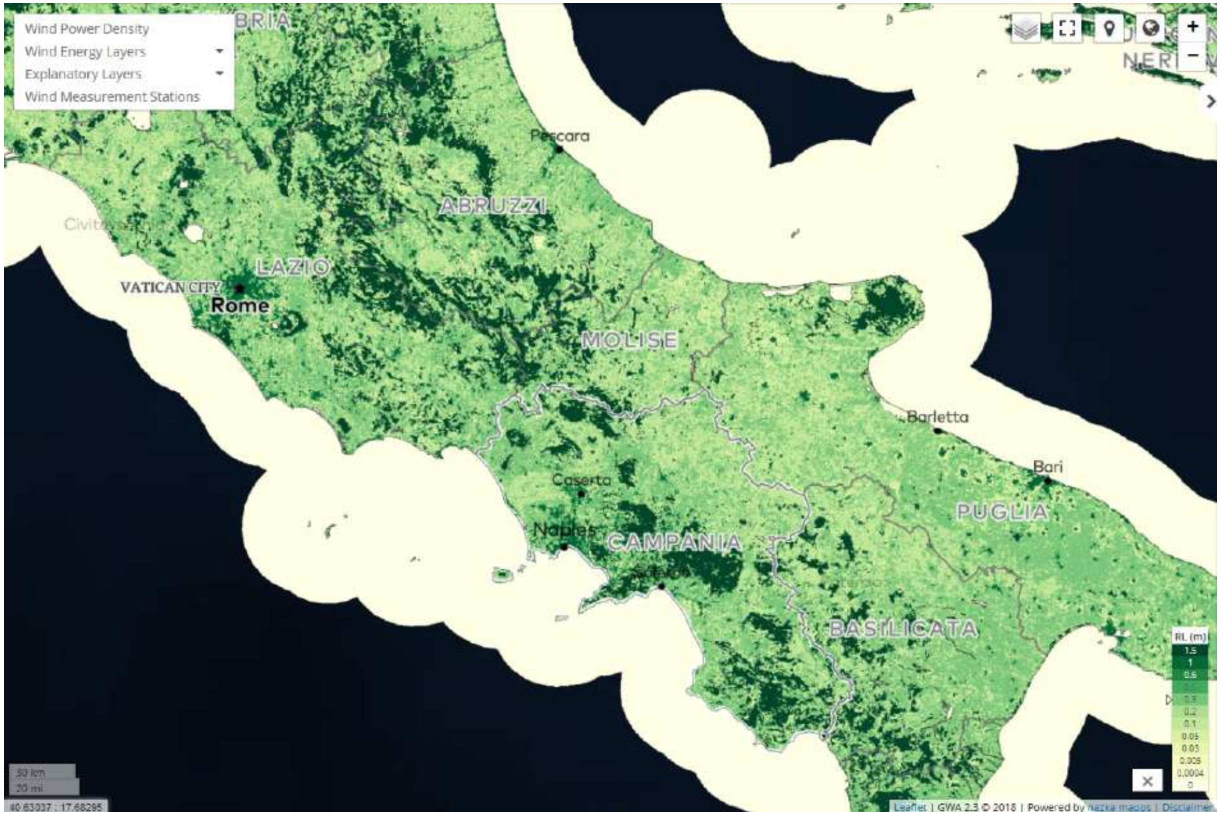
The ruggedness index (RIX) is a measure of the steepness or ruggedness of a terrain.

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.



Roughness. Source: [1]

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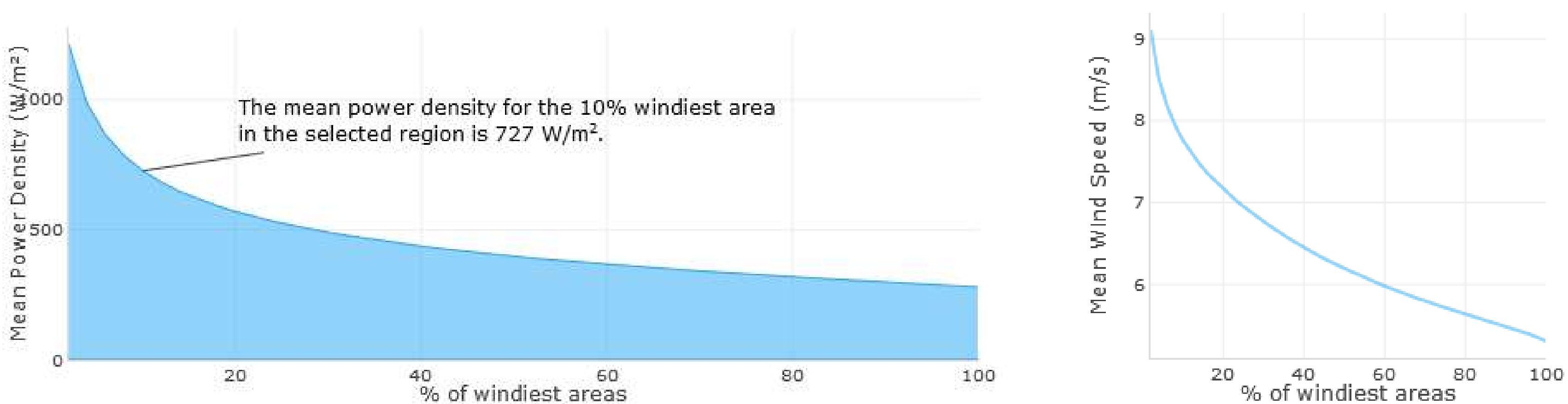
Wind Power Density @Height 100m

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.



Power density and Mean Wind Speed. Source: [1]

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Recommended literature

Books:

1. **Quaderni di Applicazione Tecnica ABB [Translated in English]**

Web links:

[1] https://globalwindatlas.info/ **Global Wind Atlas**
[2] MEGAJOULE Inovação presents Windie™
[3] www.pinterest.it
[4] https://eu.desertsun.com

Module 2.4

Further information:

www.weset-project.eu

info@weset-project.eu

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Implementation of Wind Energy Systems

Module 2.4

Analysis and design of wind farms, predictions of energy production

Lesson 1.3

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on aerodynamic potential of the wind and the main coefficients for the evaluation of the performances of the wind turbines.

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Evaluate the power extractable from the wind source;

O2. Estimate the relation among power, diameter and wind speed;

O3. Evaluate the total energy efficiency of a wind system;

O4. Select the more appropriate turbine looking at the cut-in, cut-out and nominal speeds;

O5. Identify the main energy losses associated to the wind turbine operation.

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Technical Contents

1. *Power contents of wind source*
2. *Performance coefficient*
3. *Total efficiency of a wind system*
4. *Selection of the turbine*
5. *Effects of energy losses*

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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:

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

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

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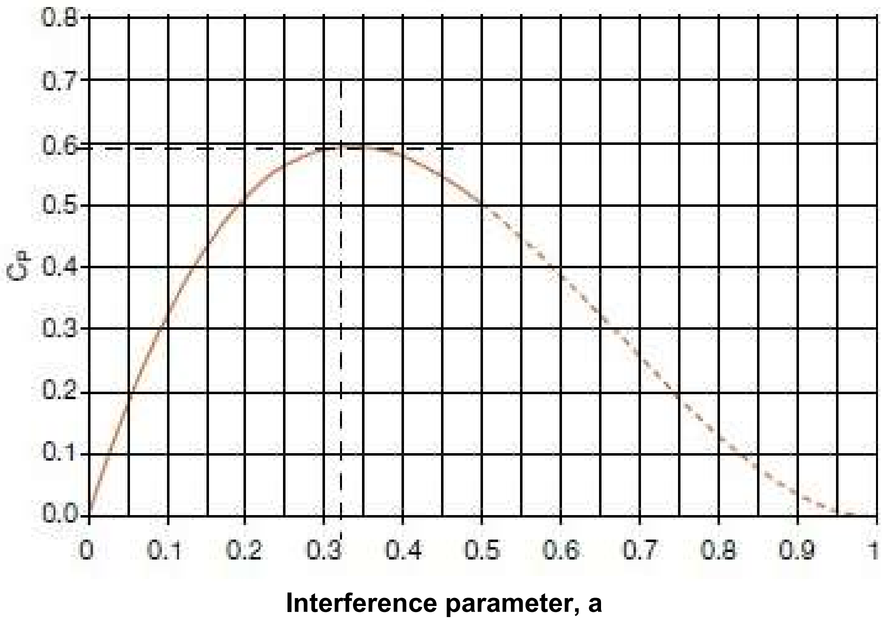
Define the Performance coefficient (power coefficient) as the ratio of the power extracted from the wind and the power available.

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

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

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.

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



Source: 2

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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

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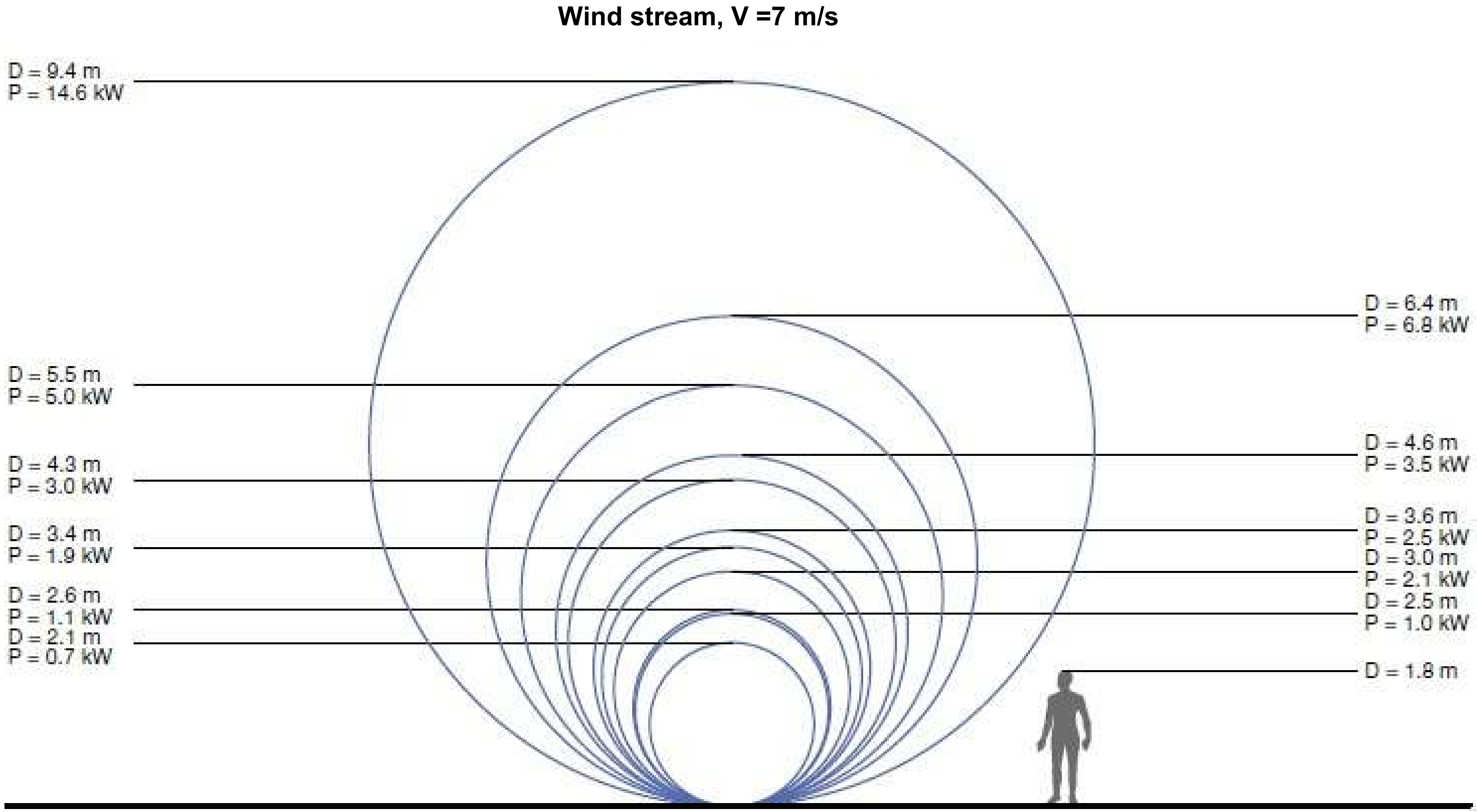
The power depends on the cube of the wind speed.



Source: 2

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Total efficiency of Wind system

The energy available from the wind is:

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

con $E_{d,s} = E_d / A$

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

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

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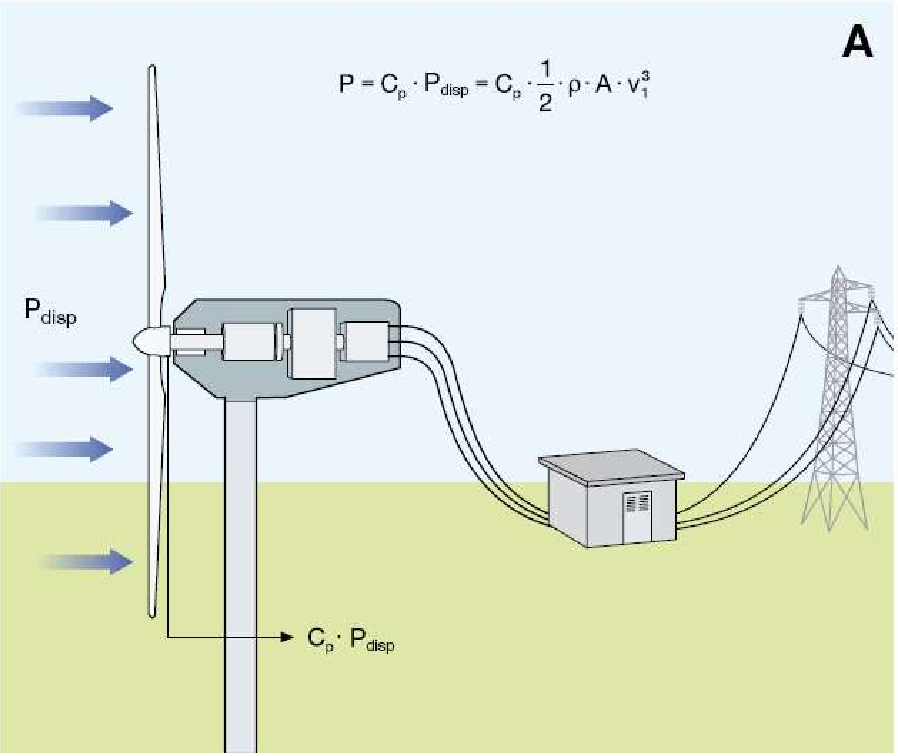

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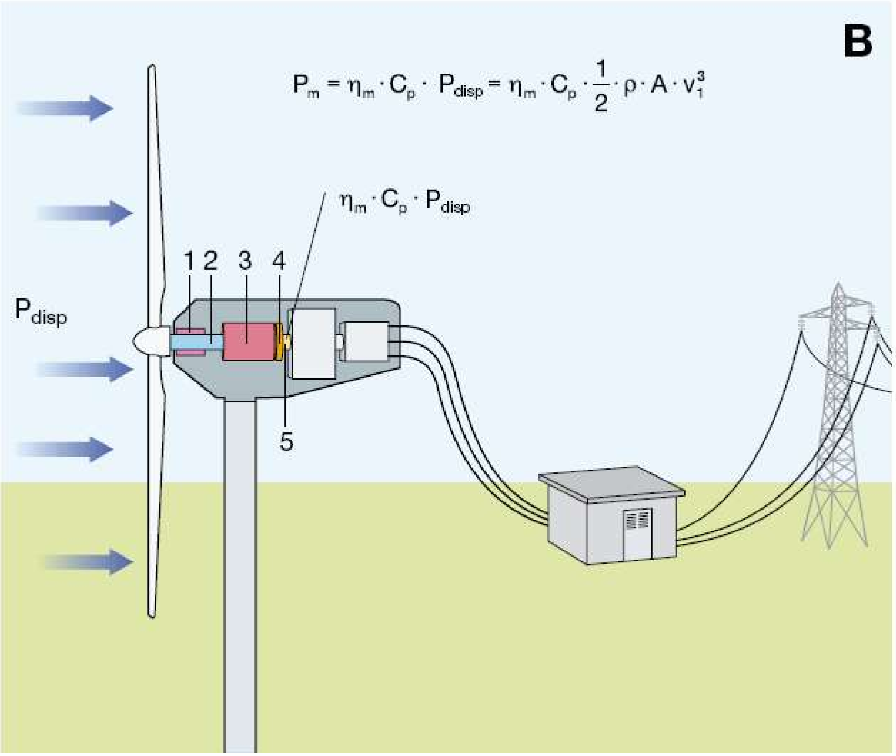

Source: 2

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

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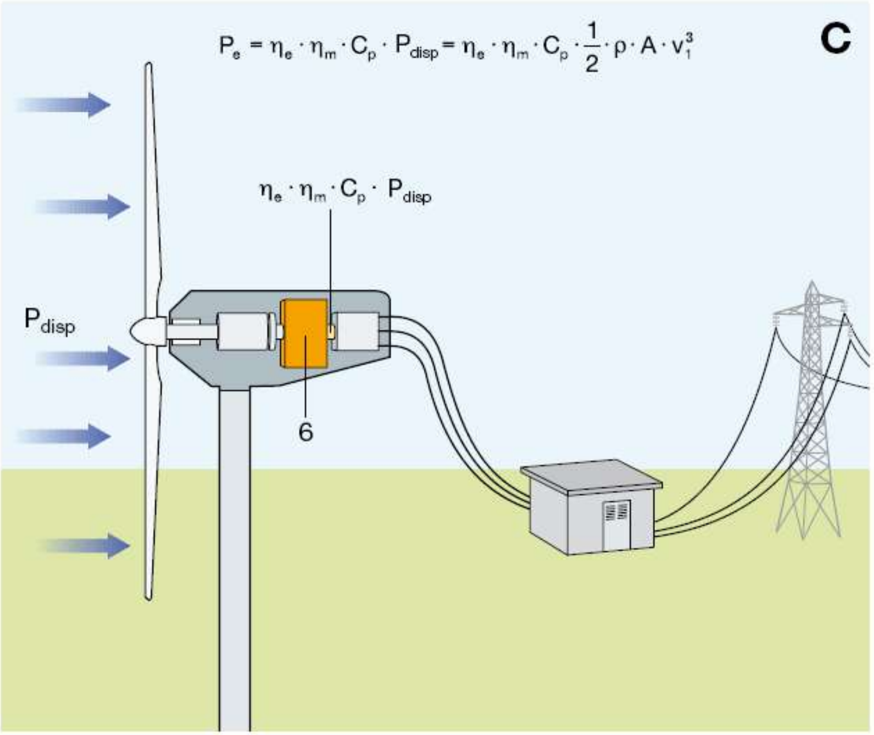

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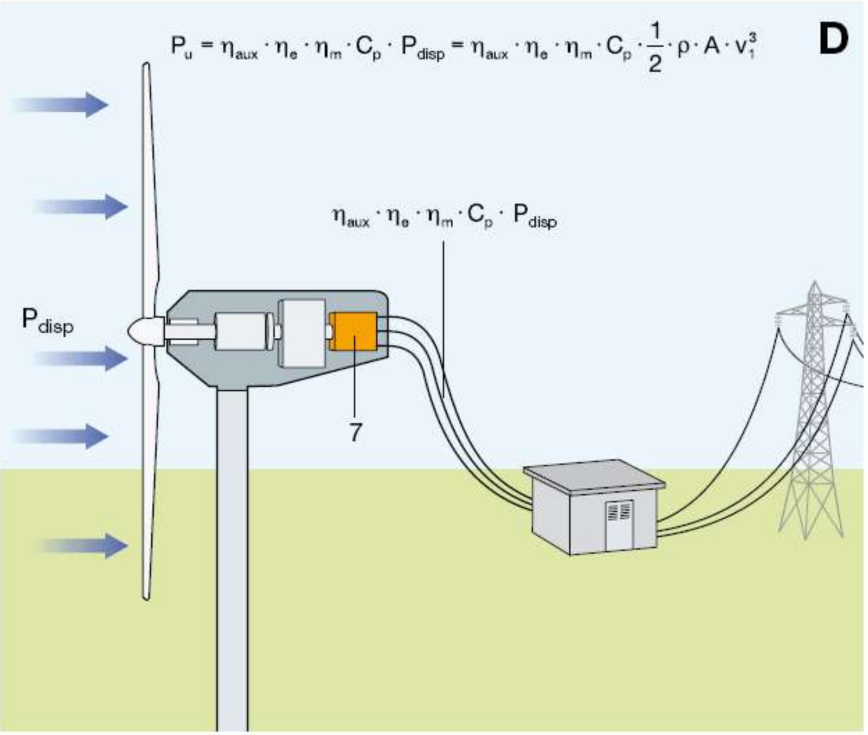

Source: 2

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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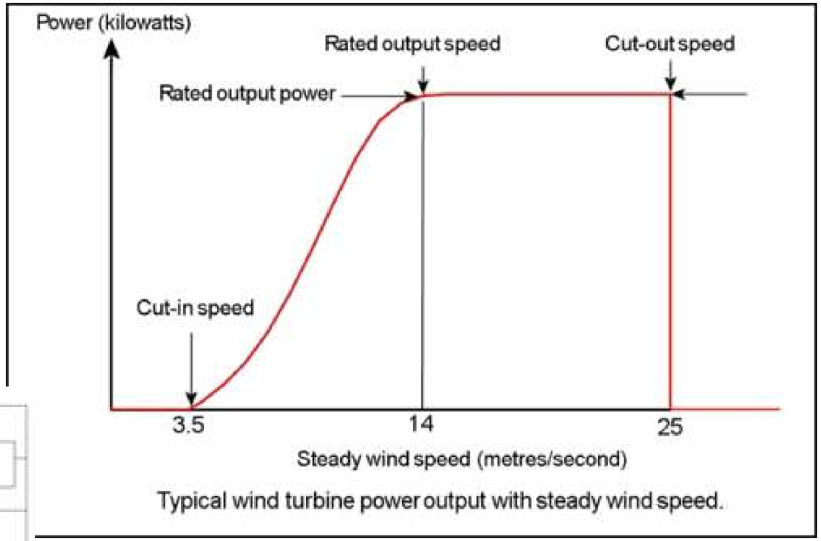
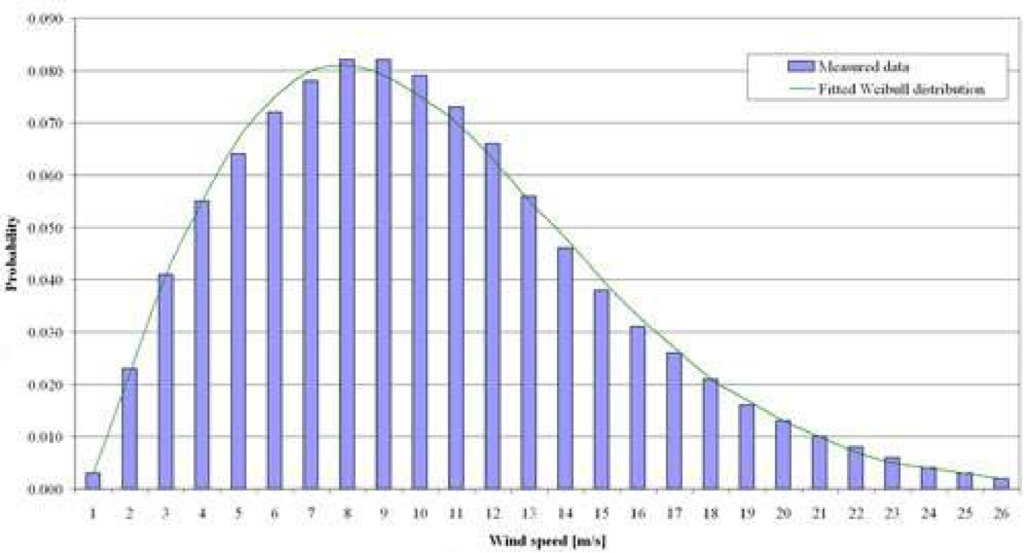
Selection of the turbine

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

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



Source: Wind Power Engineering Development



Source: Garrad Hassan

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

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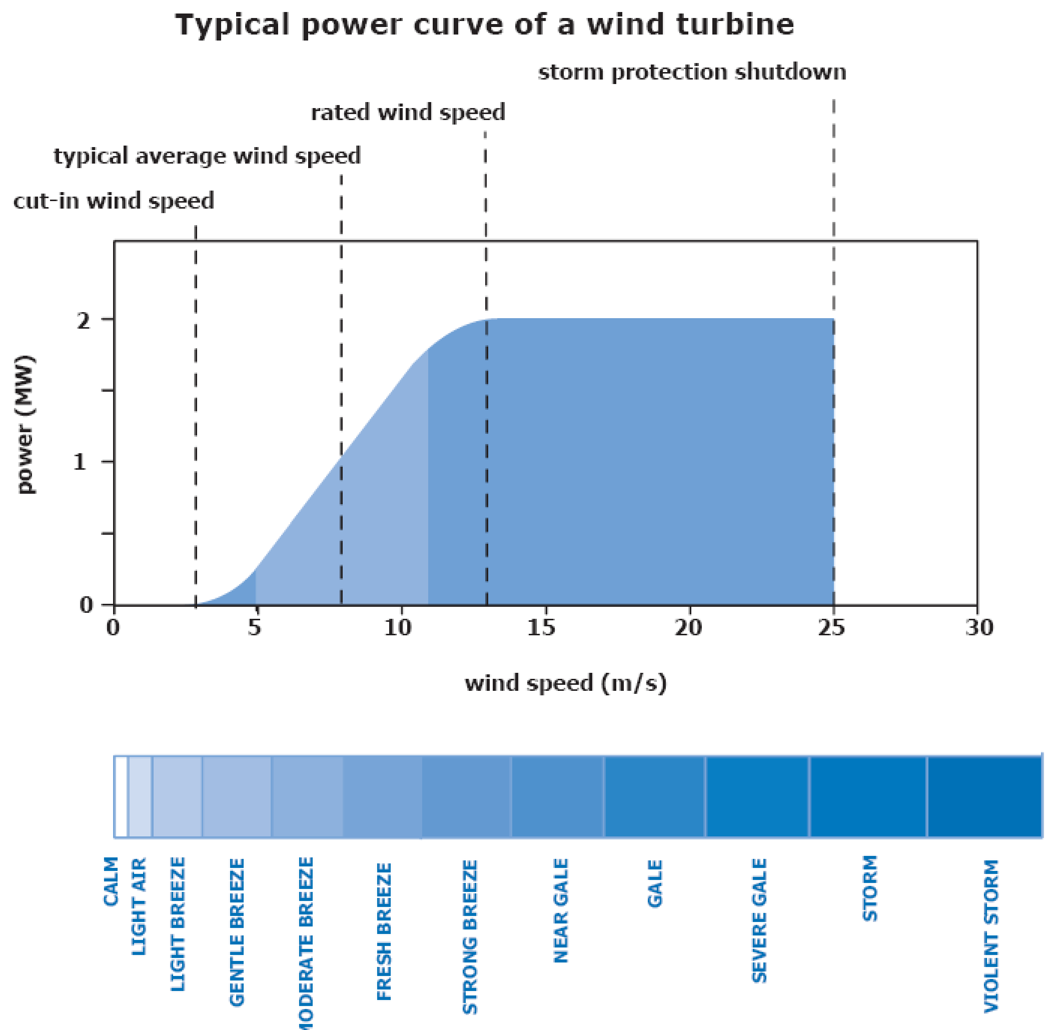
Selection of the turbine



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.

Source: 3

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Selection of the turbine

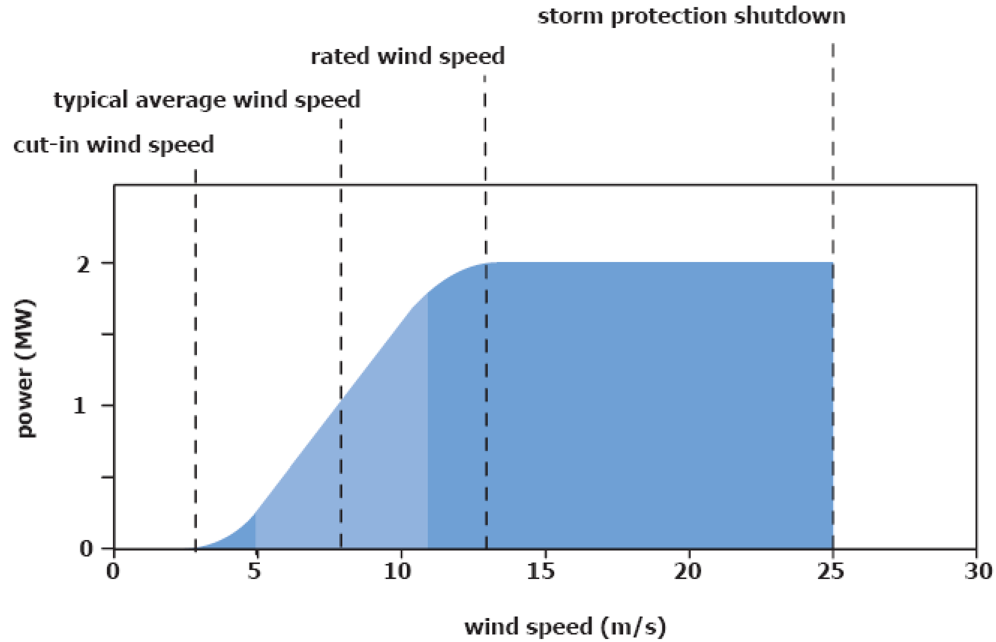
Rated output power and rate wind speed

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 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.

Typical power curve of a wind turbine



Source: 3

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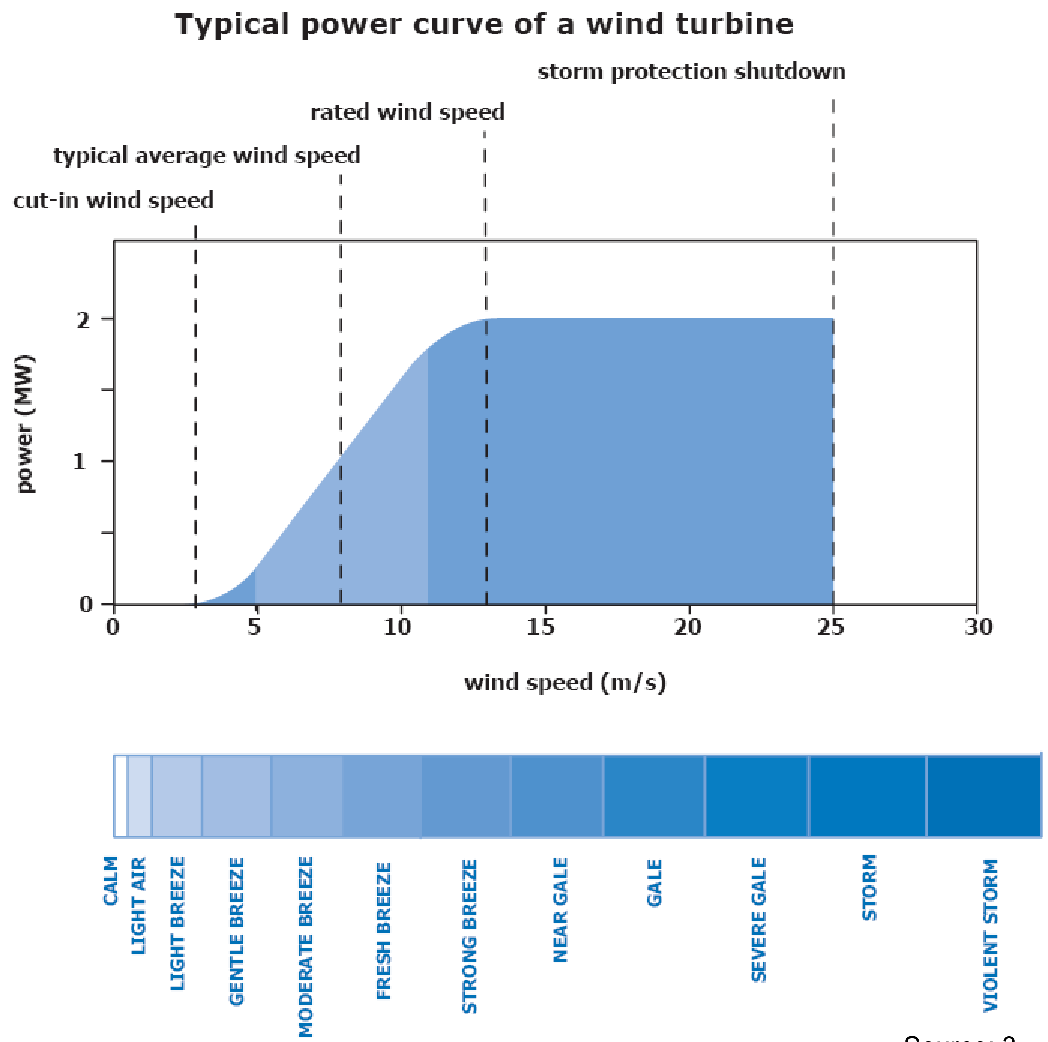
Selection of the turbine



Cut-out speed

As the speed increases above the rate 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.

Source: 3

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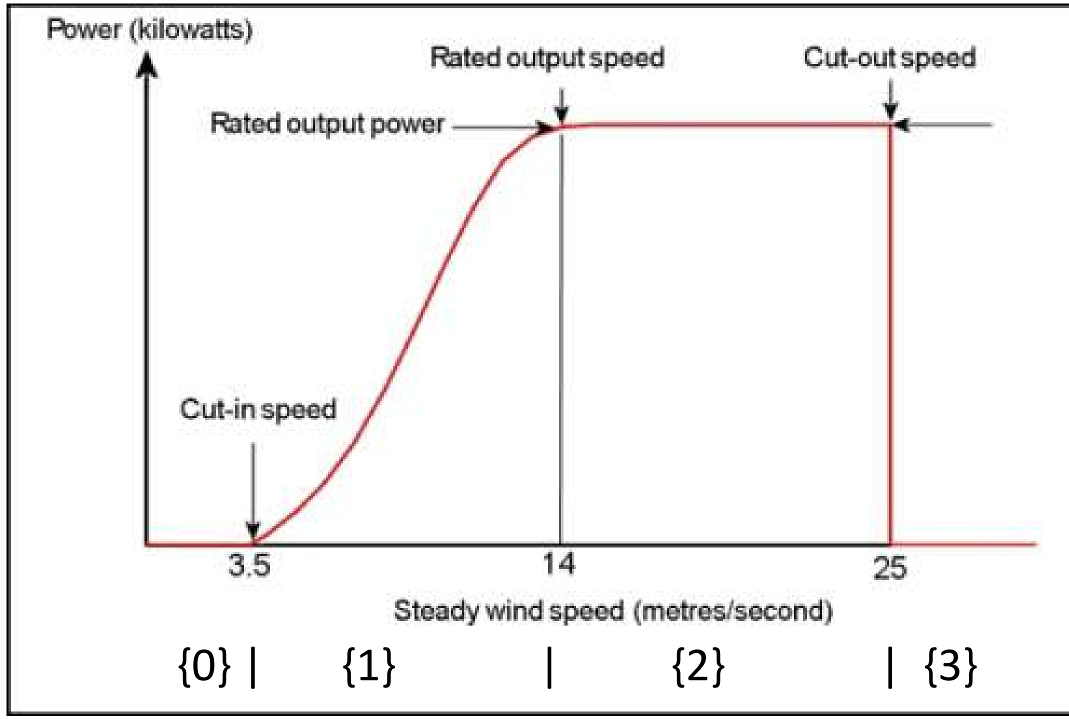
Selection of the turbine

Three characteristic velocities:

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

V_D Design

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



Source: 2)

P_D *Design power*

$P(V_1)$ model law

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

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

$\left.\begin{matrix} \\ \\ \end{matrix}\right\} P = 0$

Range [1] $\left(V_{cut\,in} \div V_D\right)$ Approximated to a 2nd order poly $P = P_D \dfrac{V_1^2 - V_{cut\,in}^2}{V_D^2 - V_{cut\,in}^2}$

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 and 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 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

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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

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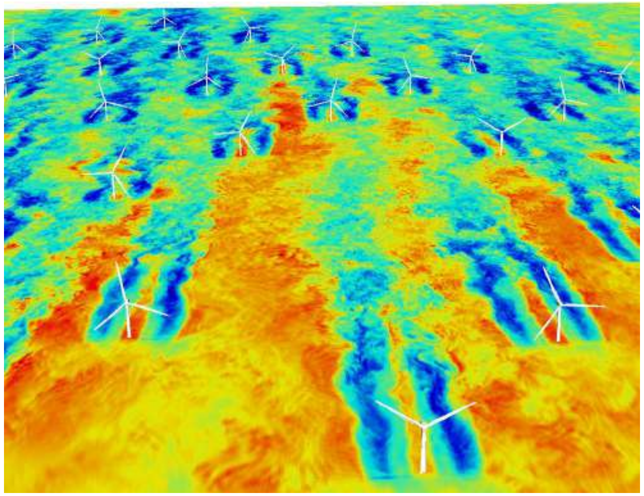
A turbulent wake is generated downstream of the rotor which modifies the wind entering the next rotor

- Loss of power
- Vibrating loads

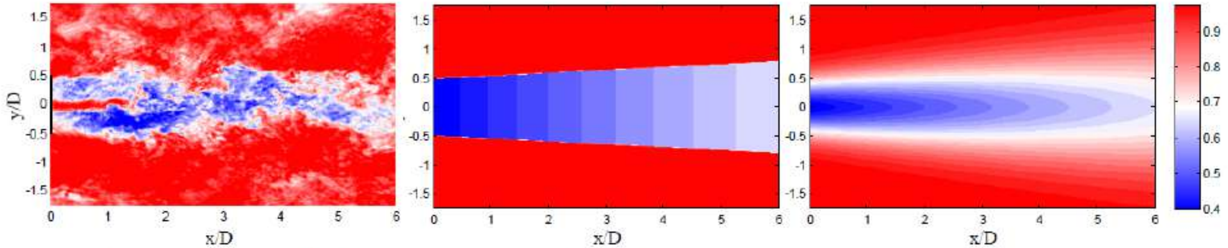
Manufacturers provide safety distances to minimize losses.

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



Source: [1]

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



Source: [1]

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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

Source: http://www.windaction.org

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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

Source: https://core.ac.uk

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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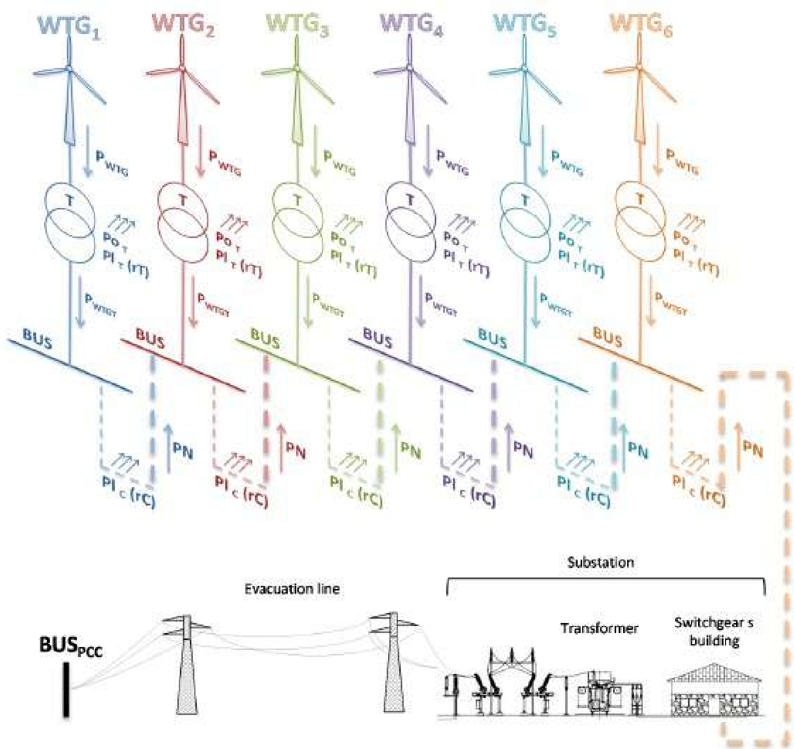
Effects of losses: Electric losses

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.



Source: 1)

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Effects of losses: Electric losses

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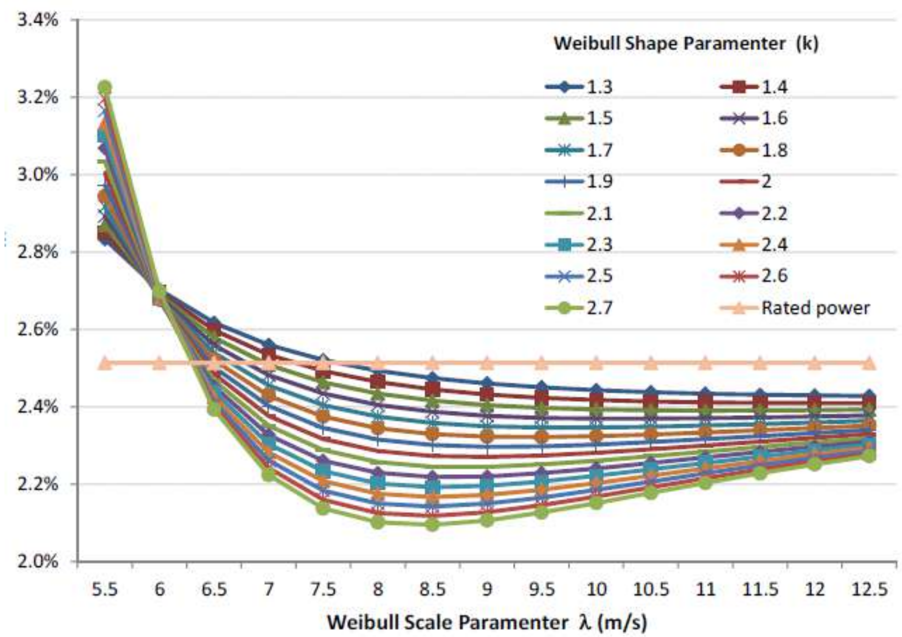
For the total losses of the farm are also considered:

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

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



Energy losses from the Wind Farm. Source: 1)

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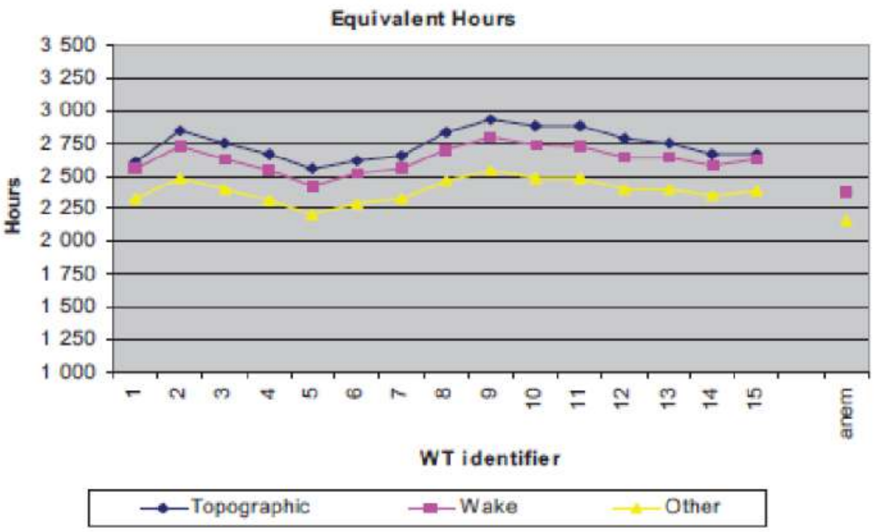
Effects of losses: Production evaluation

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.



Equivalent hours. Source: 1)

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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		

Source: 1.

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Recommended literature

Books:

1. **CEI EN 61400-1**
2. **Quaderni di Applicazione Tecnica ABB [Translated in English]**
3. **BWEA Briefi ng Sheet, Wind Turbine Technology**

Review articles:

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.**
2) **Optimizing a Distributed Wind-Storage System Under Critical Uncertainties Using Benders Decomposition, IEEE Access, June 2019**

Web links:

[1] https://www.nrel.gov/ **NREL**

Module 2.4

Further information:

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info@weset-project.eu

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Module 2.4

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

Lesson 1.4

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on On-shore and Off-shore wind farms (components, systems and layout) and Off-grid solutions.

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Know the main component of a wind farm;

O2. Understand the main layout of a wind farm and related issues (transport, civil engineering, …);

O3. Know the main features and differences between on-shore and off-shore wind farms;

O4. Know the structure and main components of a off-grid system.

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ON-SHORE WIND FARM

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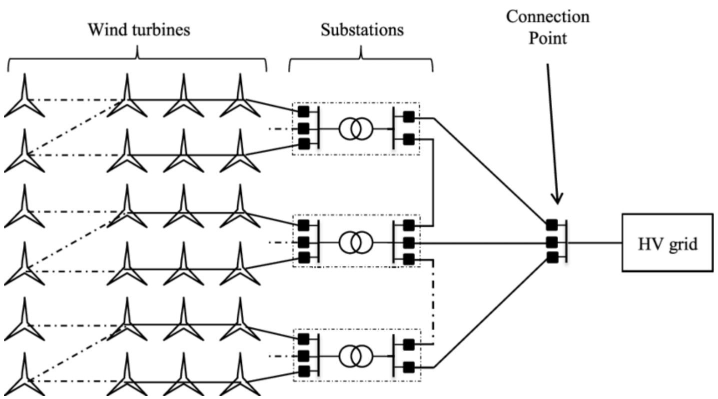
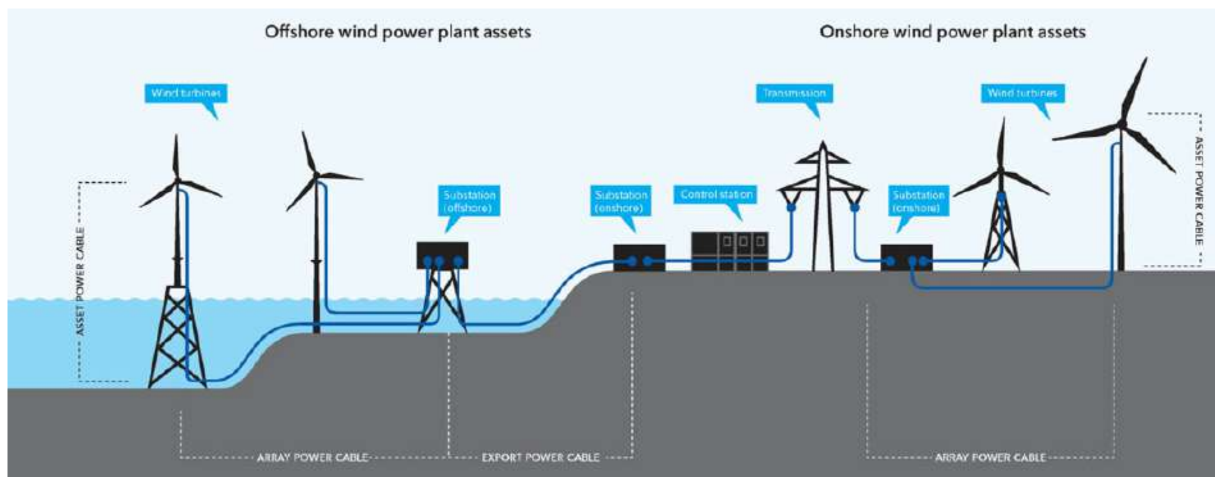
On-shore Wind farm layout



Source: [3)]

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. Source: [2)]

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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

Source: [11]

Source: [12]

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

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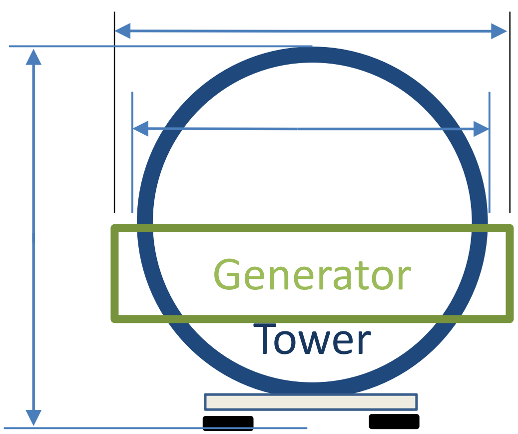
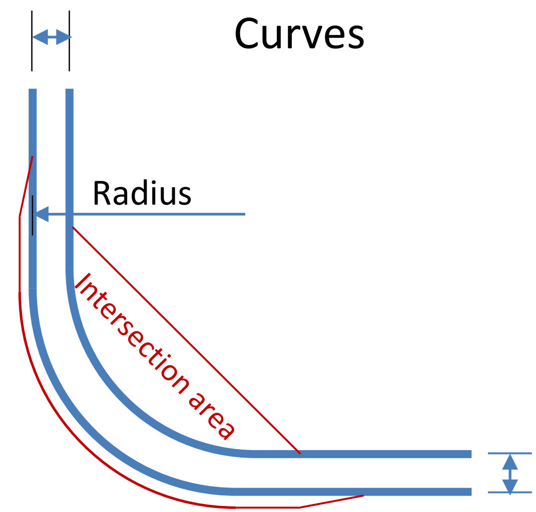
The producers of wind turbines provide indications on slopes and construction characteristics of the roadways that must be made, through specific stratifications, considering the stresses to which they are subjected and the dimensional requirements of the transport route (bends, tunnels, ...)

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

Source: [4]

Source: [4]

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

Source: [5]

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

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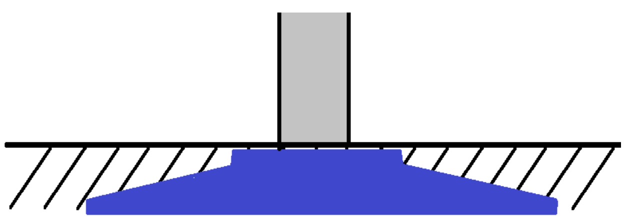
A Geognostic campaign is necessary for the choice of the type of foundation and sizing

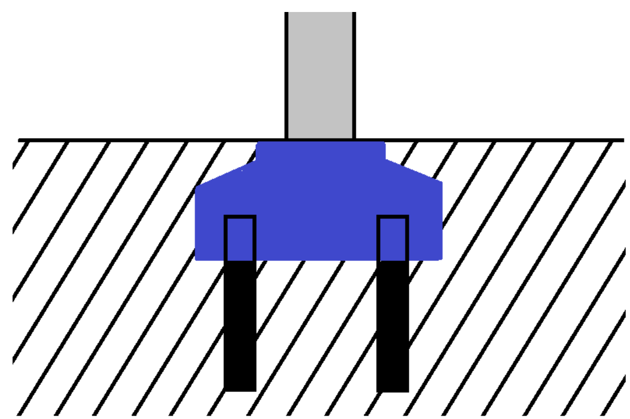
Onshore foundations normally consist of a reinforced concrete plate fixed on bored piles of variable diameter and depth depending on the terrain and the specific provided for the machine

Direct foundation



Source: designed by the author

Foundation on piles



Source: designed by the author

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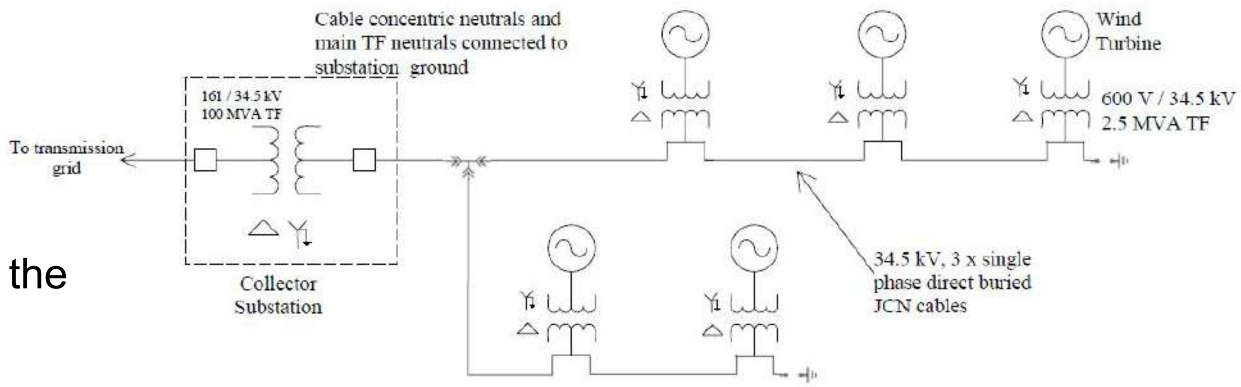
On-shore wind farm layout
Main project aspects: MV power lines



Source: [15]

Definition of the layout of the cable lines
- Excavation feasibility
- Expropriation plan
- Disciplinary of existing roads.

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

Source: [14]

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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

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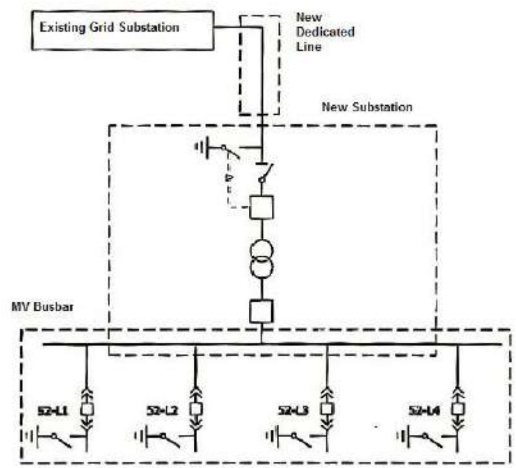
The design of the RTN connection substation depends on the solution assigned by the network manager.

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

Source: [15]



Source: [6]

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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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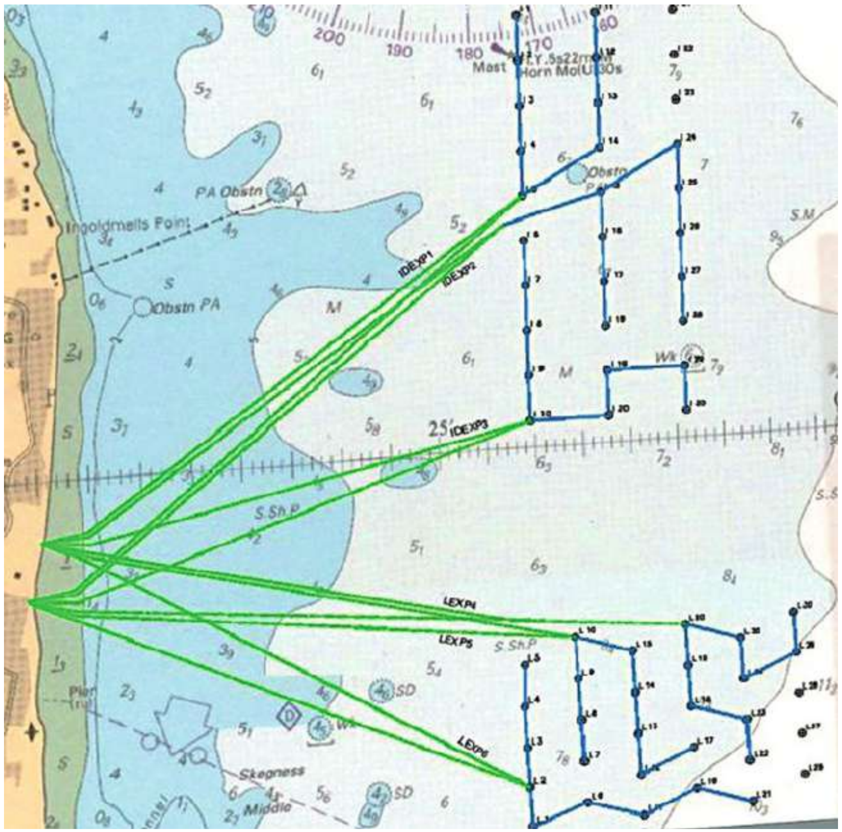
Off-shore Wind farm layout



Source: [7]

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

Source [16]

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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

[Source: Google images]

[Source: Google images]

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Off-shore Wind turbines

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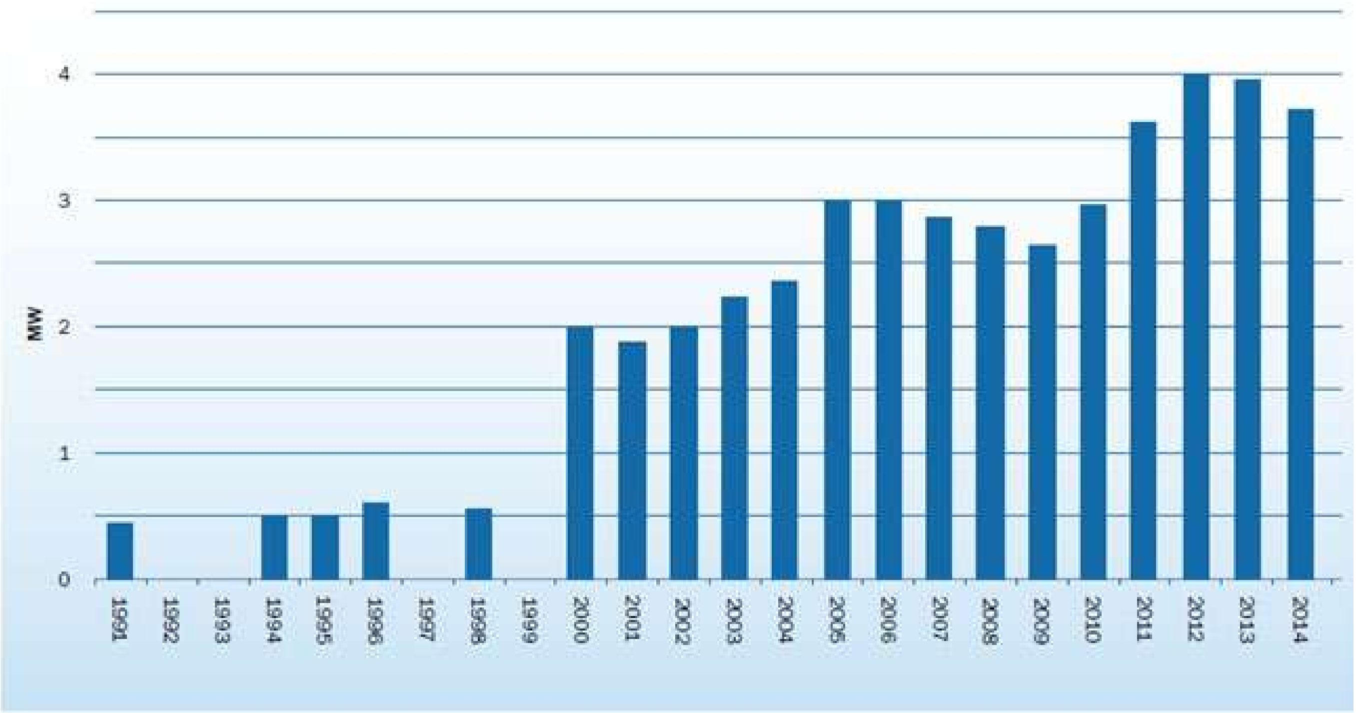
Average Off-Shore wind turbine rated capacity



Source: [1]

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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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Off-shore wind technology Shallow water foundations

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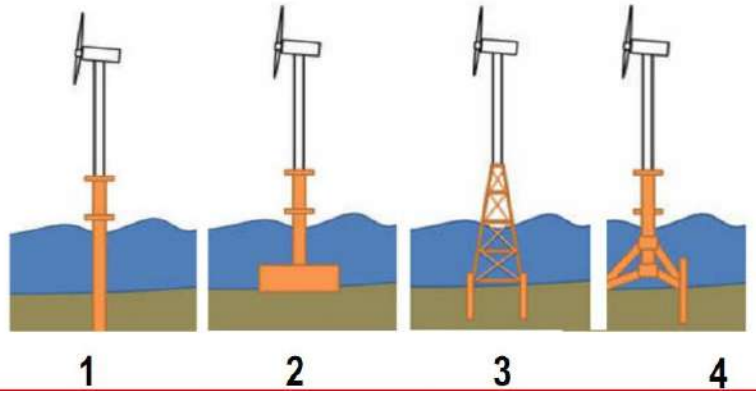
Foundations

	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: [2]

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Off-shore wind technology
Shallow water foundations

Gravity

Typical usage depth: 10 m
Maximum: 27 m

Constructively cheaper than the monopile
Higher costs for transport (special vehicles) and preparation of the seabed

High-weight cementitious structure and supporting surface

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

Source: [17]

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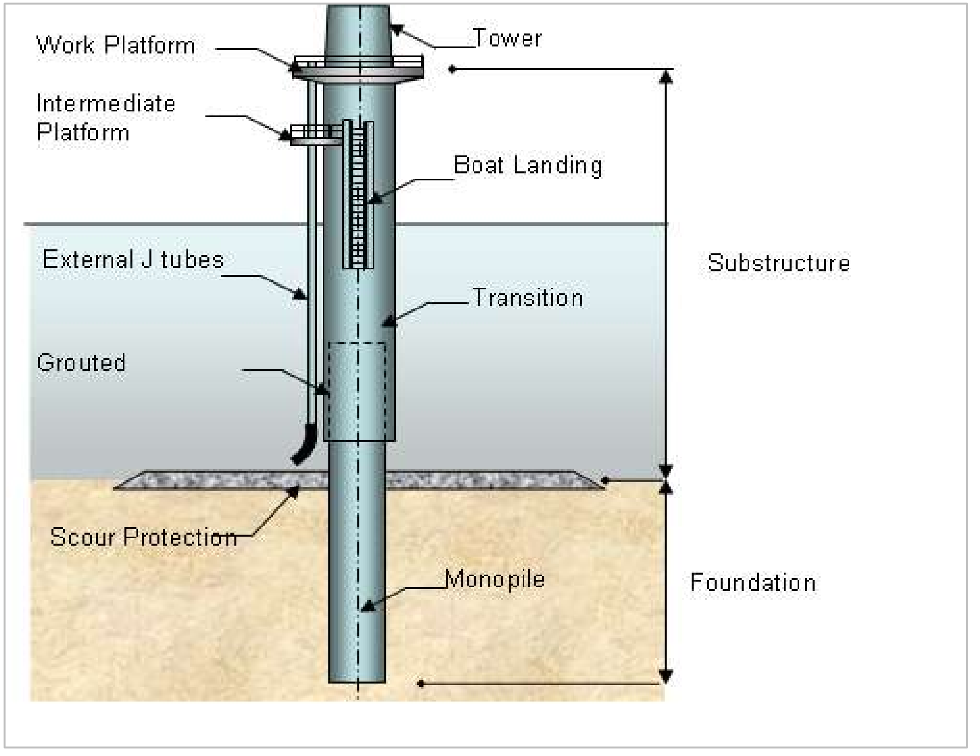
Off-shore wind technology
Shallow water foundations

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



Source: [1]

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Off-shore wind technology
Shallow water foundations

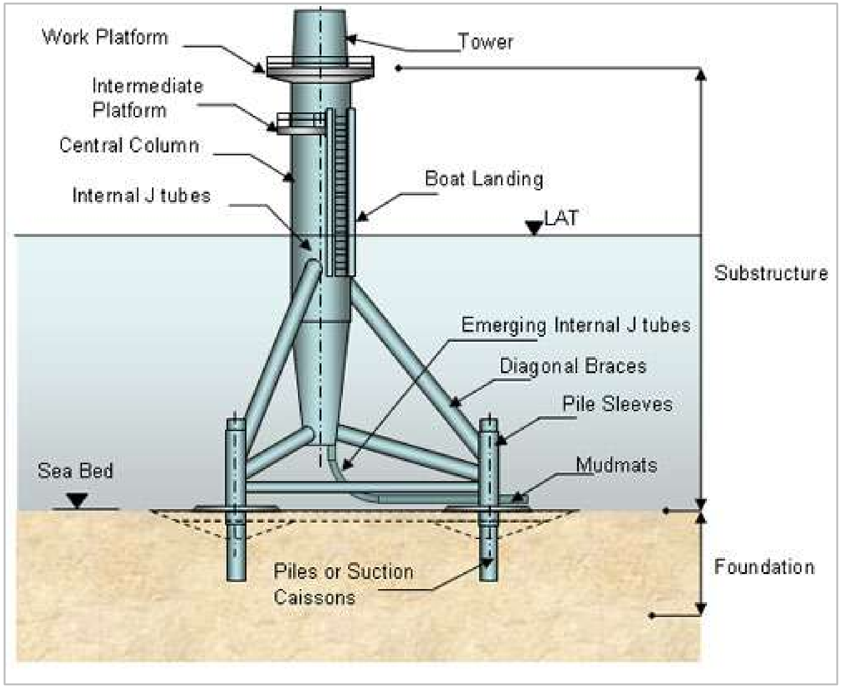
Tripod

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

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

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

Source: Google Images



Source: [1]

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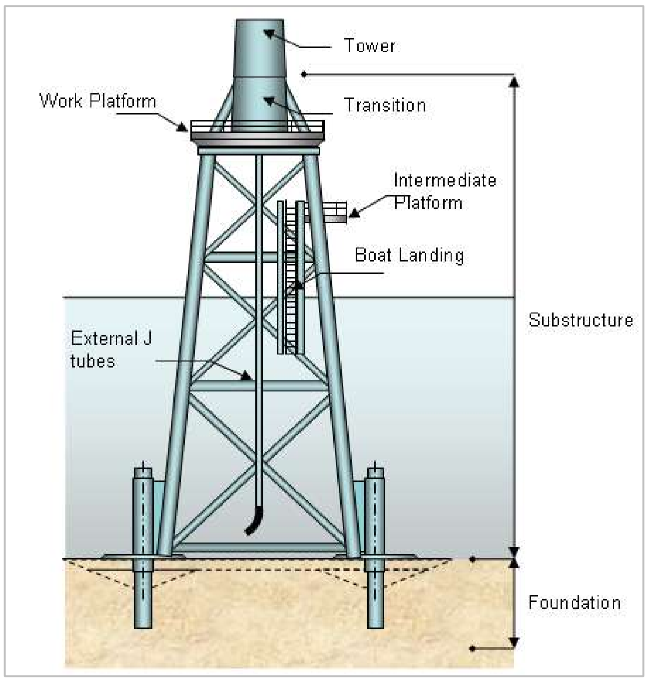
Off-shore wind technology
Shallow water foundations

Jacket

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

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



Source: [8]

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

Source: [18]

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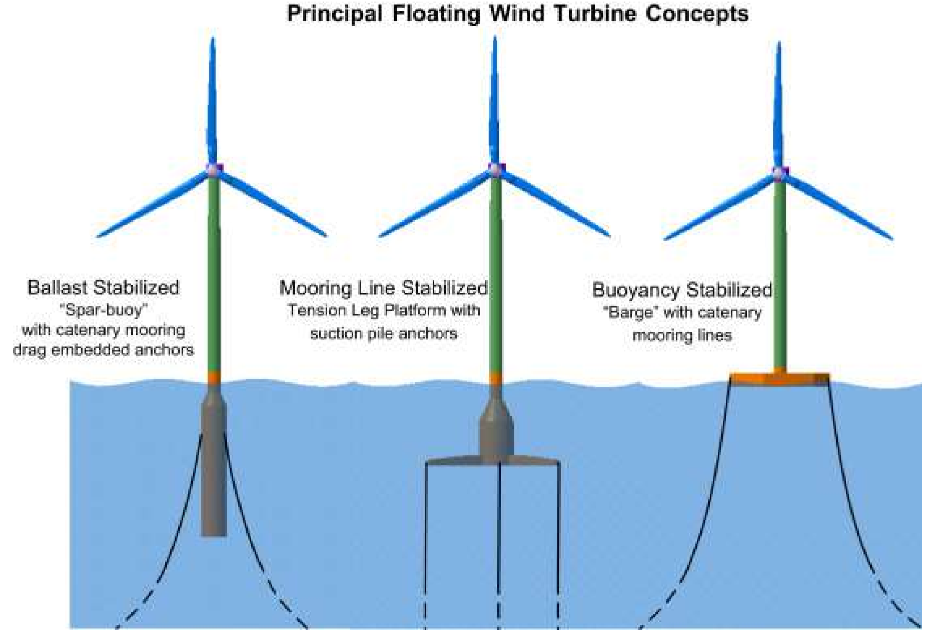
Off-shore wind technology
Floating platforms

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



Source: 1)

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Off-shore wind technology
Floating platforms

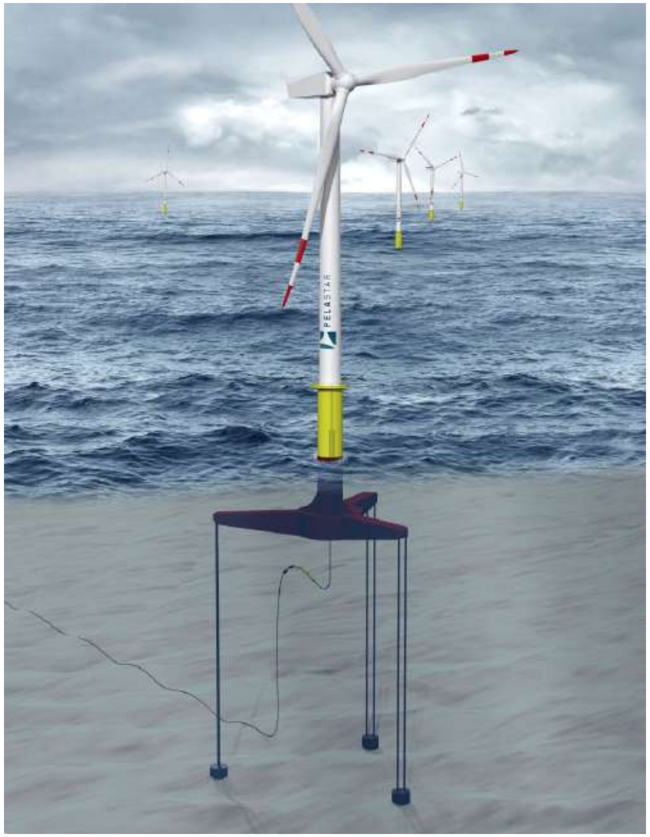
TLP - Tension leg platform

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



Source: Lynn Porter, Daily Journal of Commerce, August 29, 2011.

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Off-shore wind technology Floating platforms

Semisubmersible platform

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.

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

Source: [10]

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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: [9]

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Off-shore wind technology
Floating platforms

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

Offshore Wind Power Marine Services. Source: dapd

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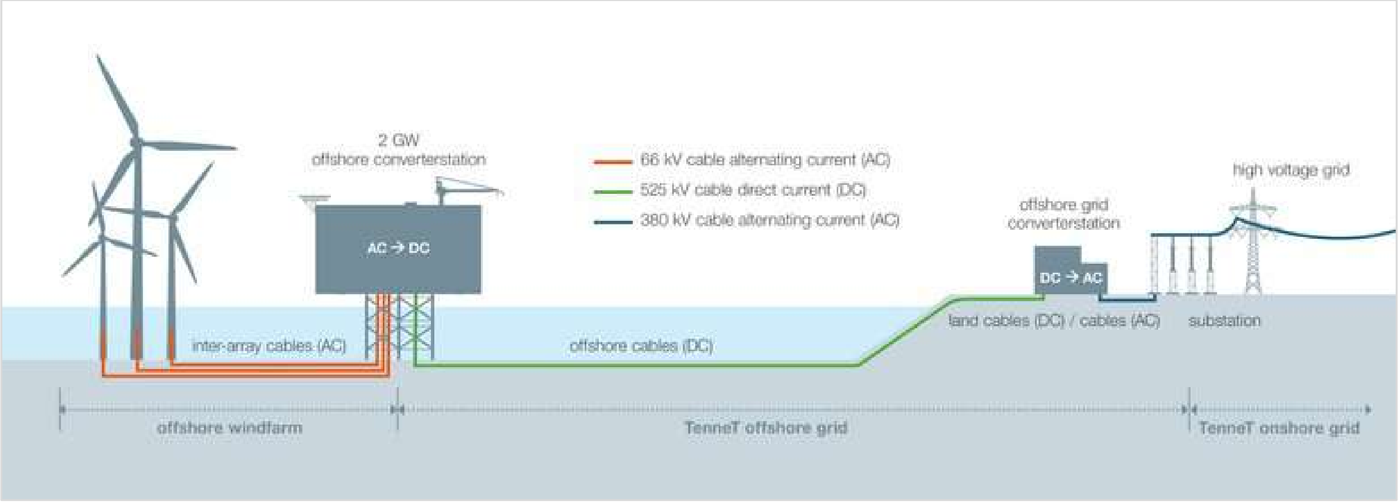
Off-shore wind technology Main electrical systems

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).



Source: [10]

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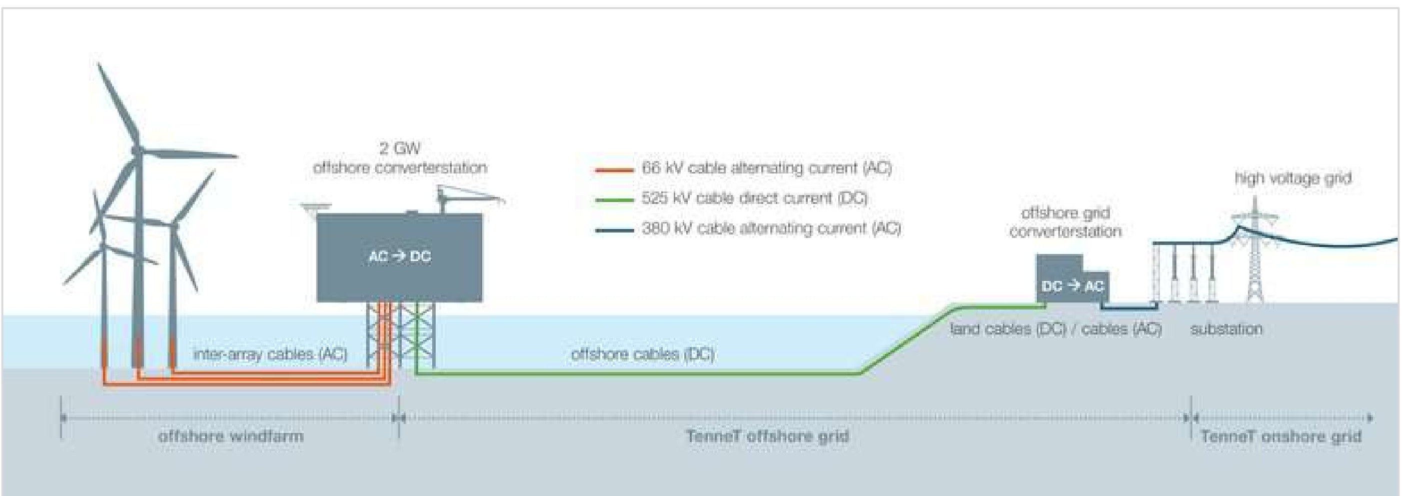
Off-shore wind technology
Main electrical systems

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



Source: [10]

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Recommended literature

Books:

1. Pardalos, Panos M., et al., eds. Handbook of wind power systems. Springer Berlin Heidelberg, 2013.
2. 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

Review articles:

1) Thanh-ToanTranDong-HyunKim, (2015). The platform pitching motion of floating offshore wind turbine: A preliminary unsteady aerodynamic analysis. Journal of Wind Engineering and Industrial Aerodynamics, Volume 142, Pages 65-81.
2) Standardization, certification and training needs in Taiwan, A European perspective, Per Enggaard Haahr, 25 April 2019
3) Optimal design of the electric connection of a wind farm, Energy, Elsevier, 165 (2018), 972-983

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Recommended literature

Web links:

[1] www.ewea.org/ **EWEA**
[2] https://www.nrel.gov/wind/ **NREL**
[3] http://www.windfarmbop.com/ **Wind Farm Bop**
[4] https://www.geograph.org.uk/photo/728835 **Geograph**
[5] https://www.flickr.com/photos/portlandgeneralelectric/15813794747/ **Flick**
[6] http://www.windfarmbop.com/wind-farm-substation-an-overview/ **Wind Farm bop**
[7] https://www.siemensgamesa.com **Siemens Gamesa**
[8] www.garradhassan.com **Garrad Hassan & Partners Ltd**
[9] www.modernpowersystems.com **Modern Power System**
[10] https://www.offshorewind.biz **Offshore Wind**
[11] https://www.cbc.ca/news/canada/windsor/wind-turbine-delivery-to-shut-down-belle-river-intersection-1.4194098
[12] https://www.nrel.gov/news/features/2009/1927.html
[13] https://www.windfarmbop.com/cable-trenches-layout-design/mv-cable-single-line-diagram/
[14] http://lsvinacable.vn/electric-power-cable
[15] https://www.windfarmbop.com/wind-farm-substation-an-overview/mv-hv-wind-farm-substation-transformer/
[16] https://www.saipem.com/en/media/news/2020-08-25/saipem-protagonist-offshore-wind-will-develop-wind-farm-italy
[17] http://www.steelwindtower.com/wind-turbine-foundation-5-foundation-types-explained-for-onshore-wind-turbine/
[18] https://www.titanndt.co.uk/?lightbox=dataItem-jcthj4w4

Module 2.4

Further information:

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info@weset-project.eu

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

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Module 2.4

Feasibility study (logistics, transport and erection)

Lesson 2.1

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on the international standards and regulations as IEC61400.

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Investigate the possible restrictions in a wind farm installation

O2. Identify obstacles and to find possible alternatives

O3. Select the correct norms, legislations to be followed for the correct sizing and authorization

O4. Evaluate visual impacts, using graphical solutions

O5. Investigate possible national restrictions in the selection of he land for the installation

O6. 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
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

Source: [4]

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
Identification of a suitable study site

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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

Source: [5]

Source: [6]

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 - series**

European Legislation: Energy Strategy and Goals

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

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

Source: done by the author

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Wind Legislations
Why?

Benefits:

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.

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 - series

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 - series

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 - series

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.

Source: 1.

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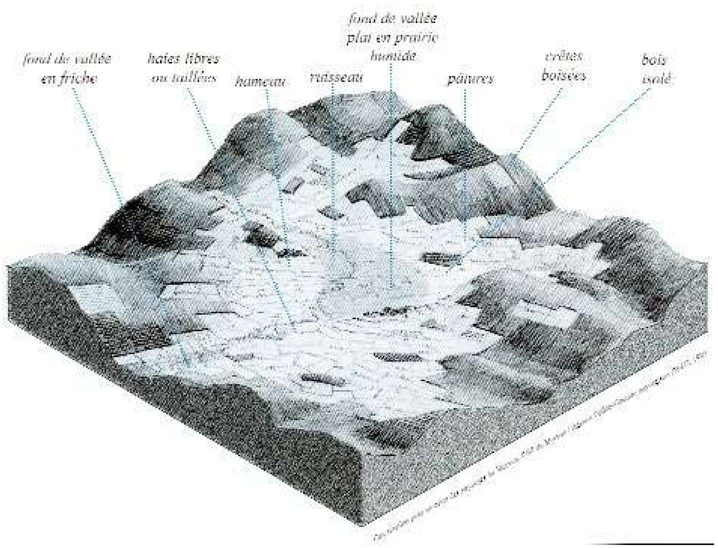
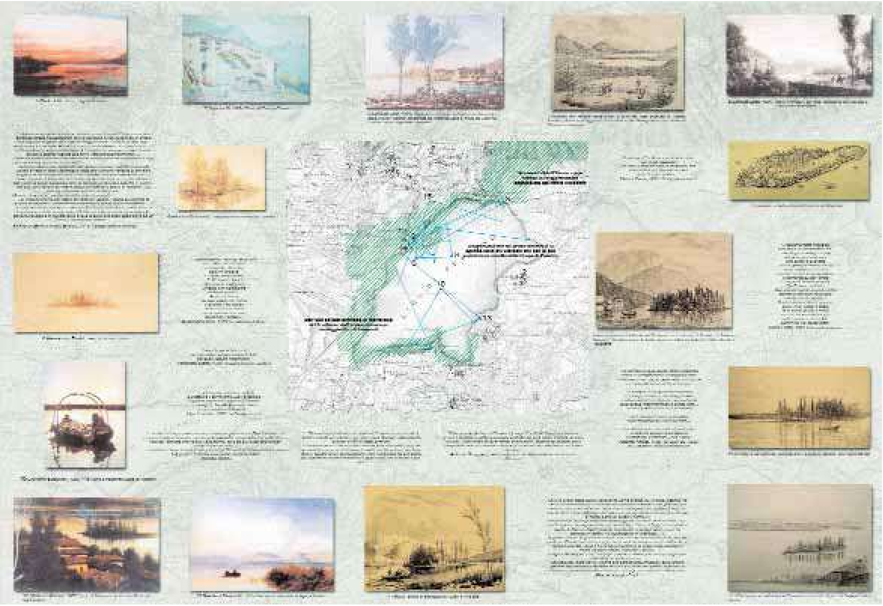
Wind Legislations
National and Regional level: Landscaping Plan



Architecture of places: the visual perception of a place. Source: 1.



Historical sites. Source 1.

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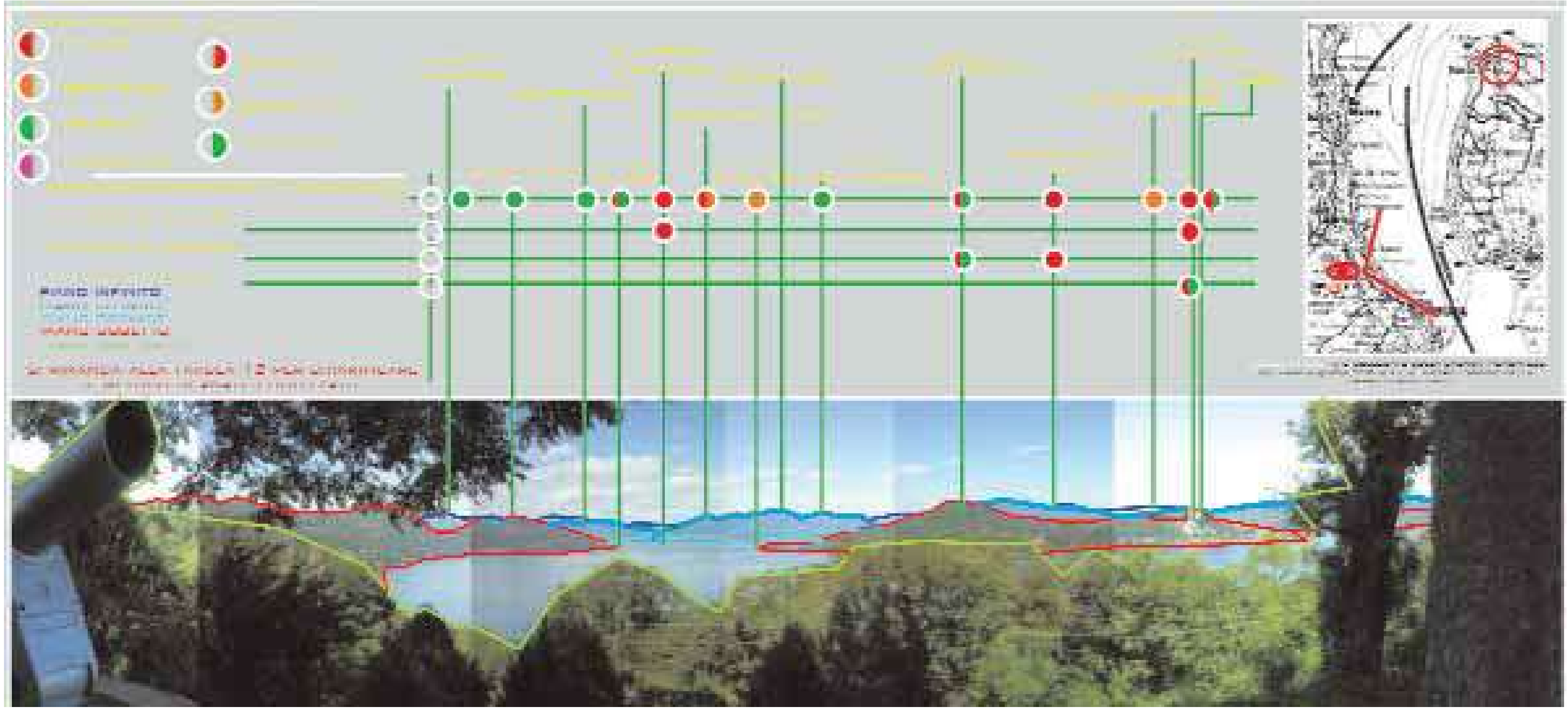
Wind Legislations
National and Regional level: Landscaping Plan



Architecture of places: the visual perception of a place. Source: 1.

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Wind Legislations National and Regional level: Landscaping Plan

Perception and social acceptance

Visual impact

⇩

Visual effect simulation

Source: 1.

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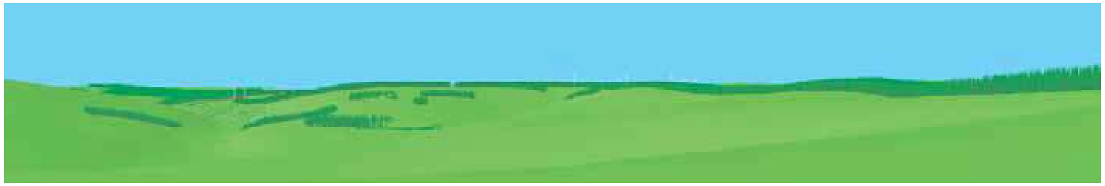
Wind Legislations
National and Regional level: Landscaping Plan



Source: 1.

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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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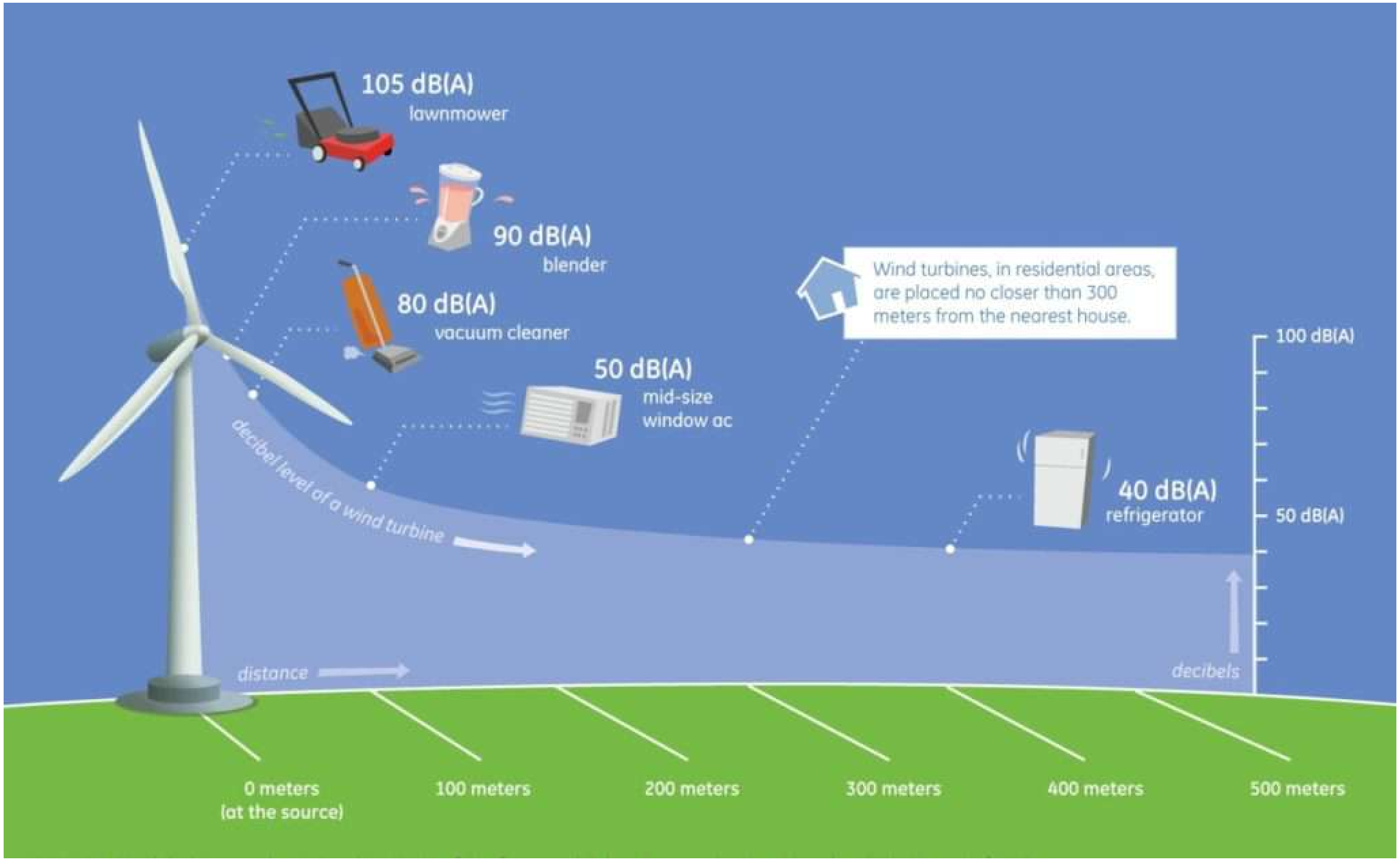
Wind Legislations
National and Regional level



Source: [3]

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Wind Legislations
National and Regional level

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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	

Source: WTN 2013 International legislation and regulations for wind turbine noise

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Recommended literature

Books:

1. **Gli impianti eolici: suggerimenti per la progettazione e la valutazione paesaggistica, MIBAC (Italy)**

Review articles:

1) **Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. Renewable and sustainable energy Reviews, 11(6), 1117-1145.**

Web links:

[1] https://www.iec.ch/ **International Electrotechnical Commission**
[2] Youtube
[3] https://www.ge.com **General Electric**
[4] https://www.tuv.com/world/en/power-grid-modelling-and-simulation.html
[5] https://californiawolves.wordpress.com/tag/or-7/
[6] https://www.mammoet.com/news/record-breaking-transport-of-wind-turbine-blade/

Module 2.4

Further information:

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Operation and maintenance issues

Lecture 2.2

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Learning outcomes

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Module 2.4 Implementation of Wind Energy Systems

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References and Acknowledgements

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Summary of the provided knowledge

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Books and Reports:

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Websites:

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Operation and Maintenance issues

Lecture 2.2

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Learning outcomes

- Fundamental Aspects of Wind Turbine Operation
- Condition Monitoring and its importance in Wind Turbine Operation and Maintenance activities.
- Technical Condition Monitoring and its importance in Maintenance activities.
- Operation of Wind Turbines Within a Wind Farm Compared to Stand Alone Operating Units.

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Table of contents

- Operation of Wind Turbines
- Operation within a Wind Farm
- Condition Monitoring and Data Acquisition Systems
- Technical Condition Monitoring and Maintenance activities Plan.
- Maintenance and Repair activities

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Operation of Wind Turbines

- Wind turbines are designed for automatic operation. It is a must for commercial applications.
- Considering power output of a few megawatts at the most, labour costs for permanent operating staff would be economically prohibitive.
- Although a certain amount of operator intervention is still required, e.g. for the commissioning, for monitoring and for maintenance purposes, the automatic monitoring systems are of special importance

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- With respect to operational reliability, wind turbines are normally being run without operating personnel and rely on automatic condition monitoring.
- They are equipped with a control and monitoring unit with operating keys and a small display screen which is normally mounted in the tower base and is easily accessible.
- The data collected is primarily used by the maintenance personnel in order to characterise the instantaneous operating status, and for the retrieval of measurement values about the status of the most important units.
- In addition, certain operations required for maintenance can be performed "manually".

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- In principle, this information can also be accessed by the operator.
- However, numerous internal data concerning the technical state of the units and error messages are encrypted so that only limited information is available to the operator.
- Usually, the information from the monitoring units of the individual wind turbines can be sent to any other location so that remote monitoring is possible.

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Operation within a Wind Farm

- In the case of wind farms containing a number of turbines, the data must be combined and transmitted serially.
- They can then be interrogated individually by the remote monitoring station.
- Certain operations can also be performed from these stations. Thus it is possible, for example, to isolate the turbines from the grid and to start them again.
- This type of remote monitoring is standard practice today with all modern wind turbines. The corresponding software package is included in the turbine delivery.
- In the case of large wind farms, higher-level operating data are now often being fed into the Internet and can be retrieved from there.

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- The technical monitoring requires an appropriate data acquisition system in the turbine and, if possible, also the acquisition of data from the environment
- For example wind and weather information from an external anemometer station or the acquisition of certain parameters from the grid.
- In the wind turbine, the required measurement data are acquired from sensors on the mechanical and electrical components (Fig. 1).

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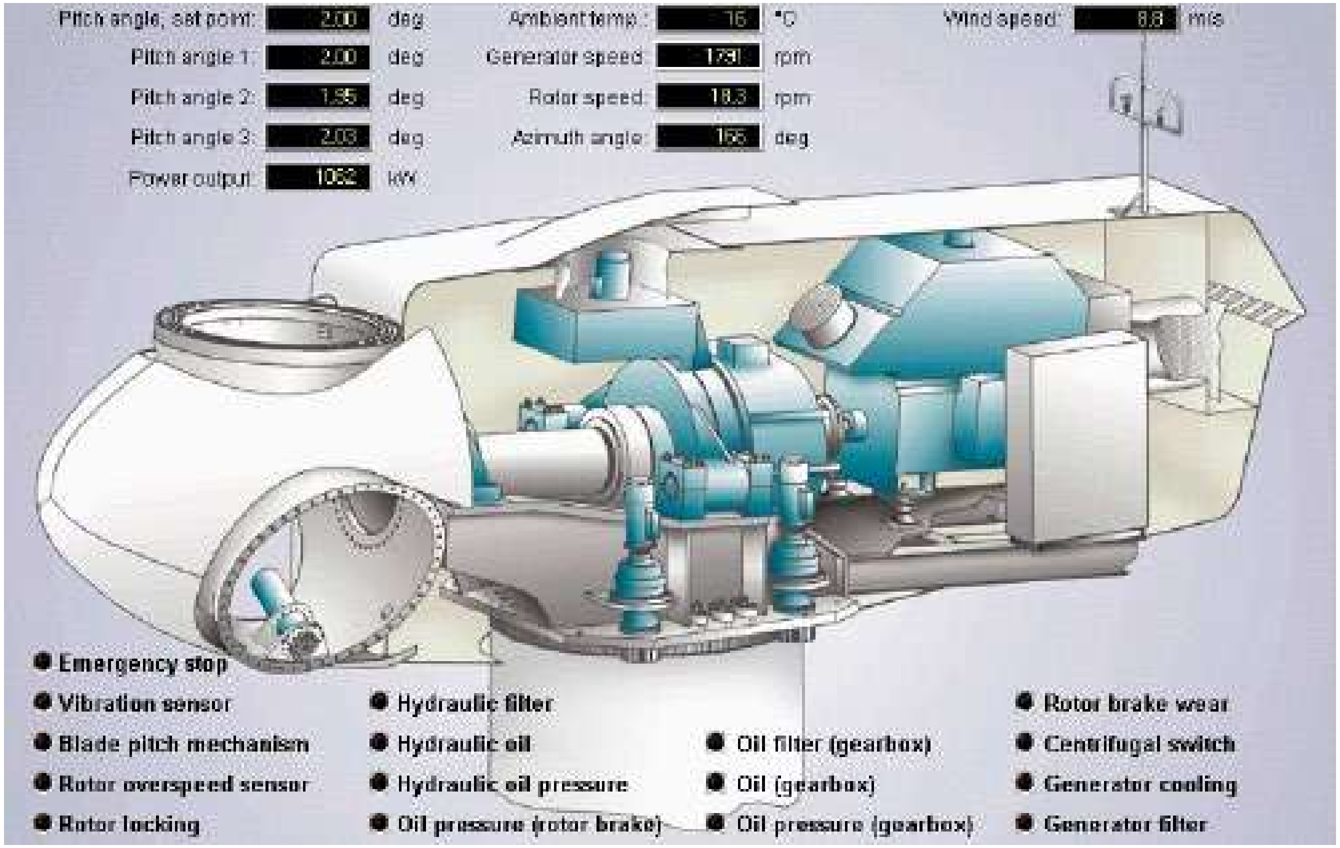

Fig. 1 - Data acquisition in the nacelle of a GE-1.5S turbine for monitoring its mechanical components (GE)

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- The electrical data and information about the operating state are taken from the data flow from the control system.
- Naturally, this data acquisition system must not interact with the control system if there is an error in the monitoring system.
- The data are stored over relatively long periods and can be evaluated from the most varied aspects and edited in table form or graphics.

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- Depending on the degree of user friendliness of the software, this information can be retrieved directly on the turbine or on-line by remote monitoring, or it will have to be stored on a data medium and evaluated by using special computer programmes.
- The turbine monitoring system commonly has a menu-structure with different levels and options.

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Operational data Collection

- Besides the wind turbine identification data and general operational information, the main menu shows, for example, the following parameters are shown on the display (see Fig. 2):
  - Wind velocity,
  - Electric power output,
  - Generator speed,
  - Rotor speed,
  - Pitch angle,
  - Voltage,
  - Frequency,
  - Current intensity.

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Module 2.4 Implementation of Wind Energy Systems

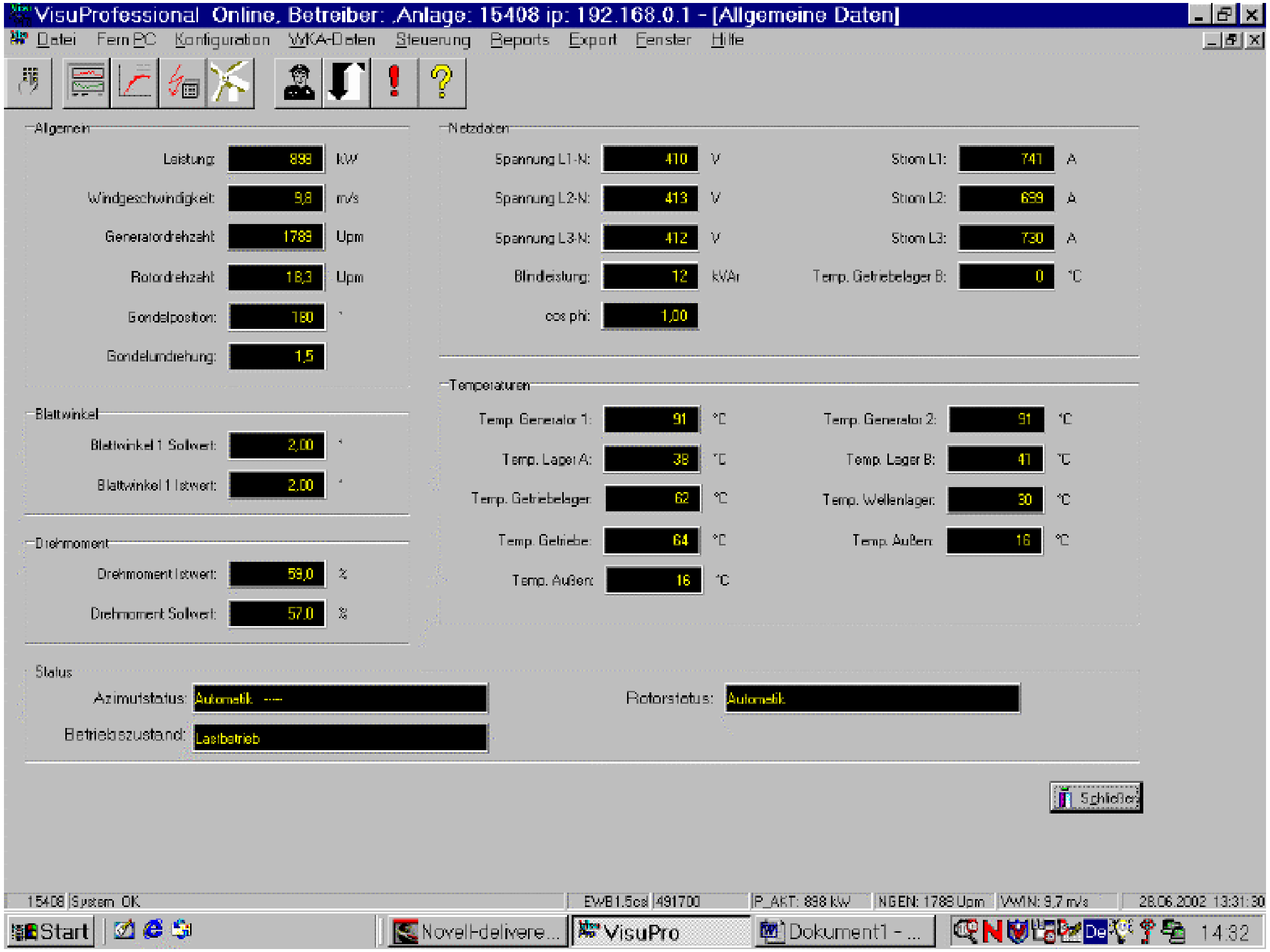

Fig. 2 - Main remote monitoring menu of a GE-1.5S turbine (GE)

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- Below this level there is a level of sub-menu options, for example referring to the complete wind and weather data or to a more detailed overview of the electrical parameters such as cos ϕ current and voltage for all three phases etc.
- Apart from this instantaneous information relating to the operating conditions, the monitoring parameters provide the possibility of calling up and/or printing out long-term data evaluations in a statistical or graphical form.

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- For example power and availability statistics of the current operating year, or also as a "short-time graph" of the variation of wind speed, rotor speed and electrical power over the period of some minutes (Fig. 3).
- The software also provides for a statistical analysis of the electrical output power in dependence on wind velocity over a relatively long period.

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- However, the "power curve“ thus generated must be treated with caution. In most cases, the wind velocity used as a basis in this case is not correct.
- When the rotor is running, the wind speed measurement taken on the nacelle is incorrect and must be corrected in dependence on power in order to obtain the true, unaffected wind speed as a reference basis.
- These relationships should be accurately known before drawing conclusions related to such power statistics.

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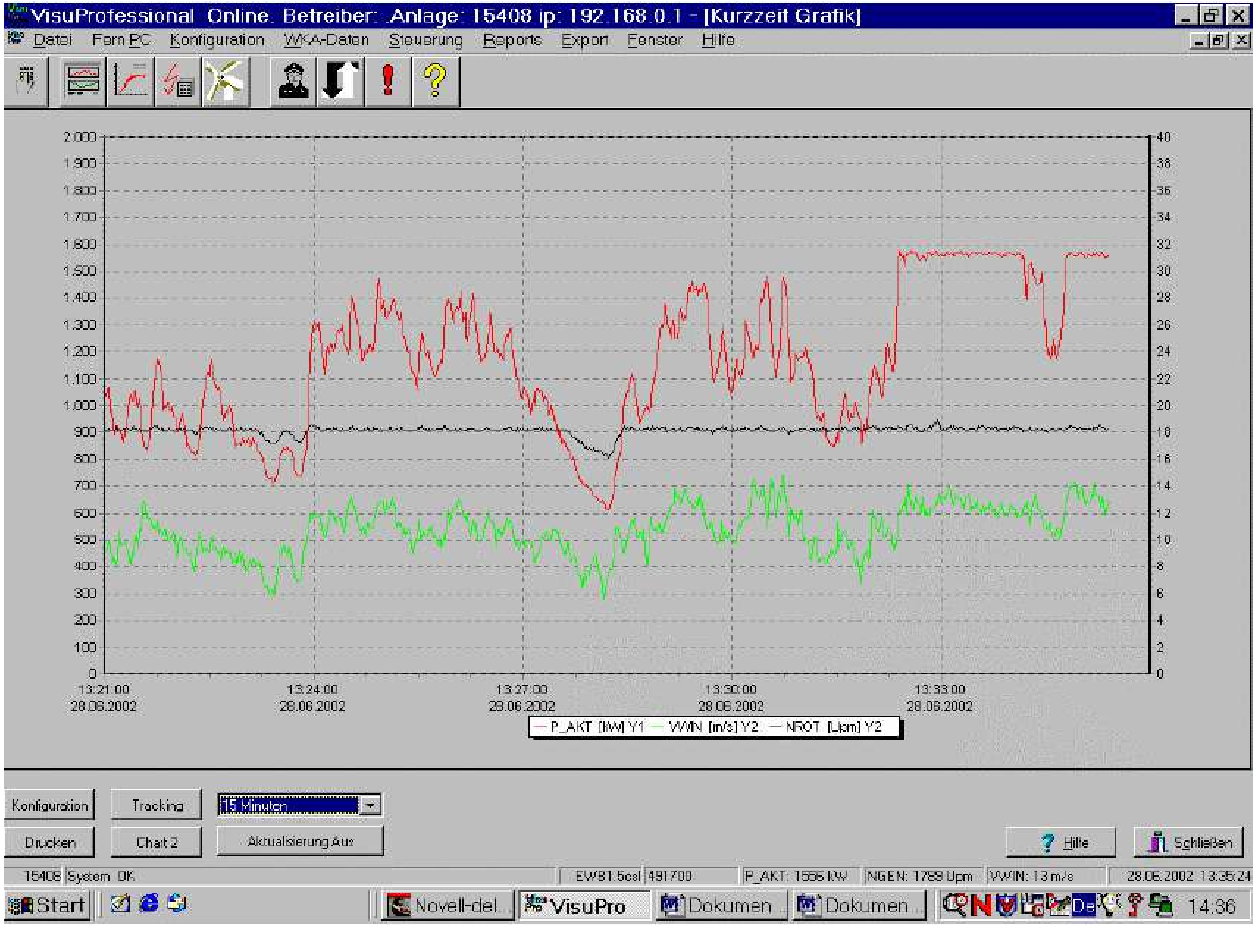

Fig. 3 - Short-time graph (15 minutes) of wind velocity, rotor speed and electrical power output of a TW-1.5S turbine (GE).

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- For some time, *early fault detection* methods have been developed which use so called *condition monitoring systems*. The aim is to predict from certain criteria the occurrence of damage in order to avoid unexpected stoppages.
- This is of particular importance in offshore installation of wind turbines.
- These systems are based on the acquisition of certain properties of the components, for example their vibration behaviour, the structural sound radiation or the analysis of the power output.

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- The analysis of these data reveal damage which has already occurred (cracks or abnormal wear phenomena) in early stages. These systems are particularly important for offshore wind turbines.

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Monitoring of Large Wind Farms

- Operating a large wind farms imposes additional requirements on the operational organisation, apart from the functioning of the individual turbines.
- If all turbines are operated in parallel with the grid, an overall monitoring system is not required. Just like a stand-alone wind turbine, each individual turbine, with its autonomous control and monitoring system, is capable of automatically stepping through the entire operating cycle, involving all required operating conditions without any overall control system.

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- Economic reasons, however, suggest a central monitoring where there is a larger number of turbines involved.
- In a wind farm comprising fifty wind turbines, it is not rare to find that distances of up to ten kilometres must be overcome from the first to the last wind turbine due to the minimum distances between turbines required for aerodynamic reasons.
- A central monitoring system is extremely useful under such circumstances.

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- To monitor and control the operational sequence of large wind farms, special monitoring and data evaluation systems were developed which combine the data of individual turbines in a suitable manner.
- This makes it possible to display the power characteristics of the entire wind farm, and also to exercise a type of higher-level sequence control.
- The aim is to optimise the power generation and energy delivery of the entire wind farm under various external boundary conditions, for example due to restrictions with regard to grid infeeding.

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- On the other hand, the individual control systems of the wind turbines are becoming more and more "intelligent" so that the wind turbines themselves can respond to external events or states of the grid without any central control system.

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Technical Condition Monitoring

- Replacing components in wind turbines is relatively expensive if these are the large and heavy parts.
- On the one hand, the access routes to the sites are long and require costly logistic measures for the transportation of, e.g. rotor blades, every time. In addition, disassembly and assembly are no less costly since large cranes have to be procured. Not least, accessibility is frequently delayed for days because of poor weather conditions, e.g. "too much wind".

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Technical Condition Monitoring

- Special type of technical condition monitoring for wind turbines has been developed in recent years which is increasingly being used. Using strain gauges, these data acquisition and evaluating systems measure critical parameters. Mainly vibrations and frequency spectra, measured using accelerometers, can be transmitted to the service organisation via the internet.
- Vibration and frequency analyses, in particular, have been found to be an effective measure for recognizing indications of probable damage and premature wear phenomena of mechanical components.

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Technical Condition Monitoring

- Damage on roller bearings, gear wheels, shafts and similar components becomes apparent very early as changes in the typical frequency spectra of the components.
- In the example of Fig. 4, these frequency spectra are automatically analysed and from these, so-called "traffic light spectra" which have yellow and red areas and indicate the state of danger.
- When the yellow areas are reached, E-mails are automatically sent to the service organisations of the manufacturers.

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Technical Condition Monitoring

- The service specialists are able to increase the intensity of monitoring and activate further detailed analyses. If the changes reach the red area, an alarm message is issued and repair measures are initiated.
- Condition monitoring is therefore considered to be indispensable, especially for wind turbines which are installed offshore. A variety of different systems and procedures have already been developed and are in most cases offered by the manufacturers of the wind turbines.

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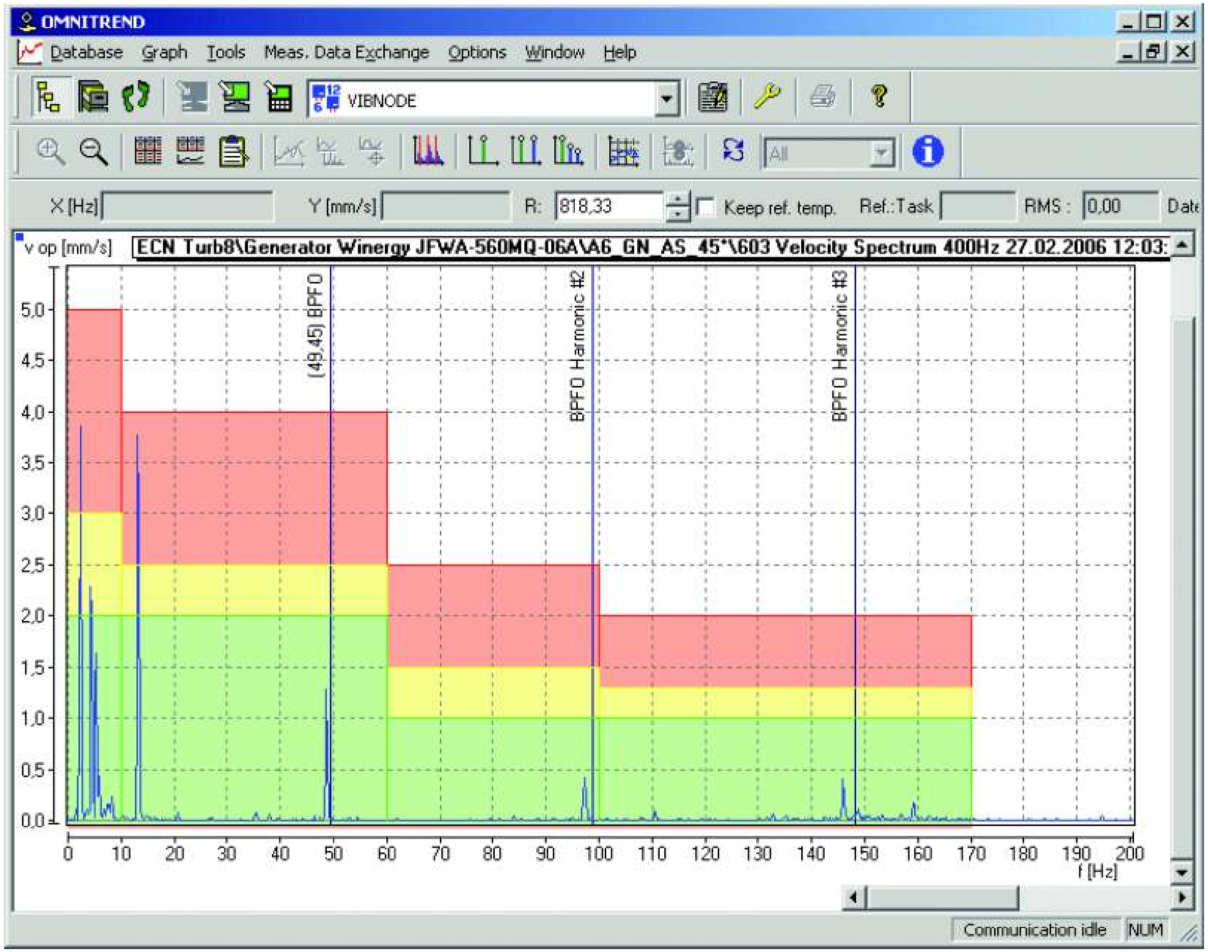

Fig. 4 - Frequency spectrum and associated "traffic light spectrum" from a technical condition monitoring system.

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Maintenance and Repair activities

- Just like any other technical system, wind turbines must be serviced regularly and, in the case of defects, repaired.
- In wind turbines the conventional components of mechanical- electrical energy conversion such as shafts, bearings, gears and generator require maintenance similar to that with other technical systems.
- The type and interval of maintenance work required should be contained in the turbine manual.

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Maintenance and Repair activities

- The general question is whether wind turbines require an extraordinary level of maintenance or whether they are often in need of repair.
- There are two reasons why this could be so:
  - The ambient conditions of a wind turbine are unusually tough. Not only are wind turbines exposed to "wind and weather" over a service life of at least 20 years, but their preferred sites close to the coast where the air is salty also provide ideal conditions for corrosion on all metal components.

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Maintenance and Repair activities

- Another reason is the high number of operating hours achieved by a wind turbine over the period of its service life. The effective operating period of a wind turbine at a good site is about 5000 hours per year corresponding to a full-load operating time of 2500 hours. This amounts to 100 000 hours running time over the turbine's design life of 20 years.

- The extremely high dynamic loading on the components is of special significance.
- The load fluctuations by themselves already lead to high cyclic loads on the components. Combined with the high number of operating hours, load alternations of an order of magnitude of 10^7 to 10^8 are obtained over the service life of the turbine.

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Maintenance and Repair activities

- Material fatigue, therefore, requires special attention and there is also corrosion to be dealt with.
- For many materials, there are no verified empirical values available about the fatigue strength with 10^7 to 10^8 load alternations.

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Summary of the provided knowledge

- Basics of Wind Turbine Operation
- Condition Monitoring for wind Turbines
- Operation of Wind Turbines within a Wind farm
- Maintenance and Repair Activities Related Issues.

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Social Acceptance

Lecture 2.3

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Learning outcomes

- Understanding issues in Social Acceptance of Wind Farms projects
- Learning measures to improve Social Acceptance

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- Motivation
- Social Acceptance

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- Wind energy generally achieve governmental and management support within most countries.
- However, social acceptance is a recurring issue within the population.
- Some regions have high level of social opposition than others mostly due to the lack of knowledge from the population of the positive and negative impacts 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 help in the adoption of this technology, and lower opposition.

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What is Social Acceptance?
Social Acceptance Stakeholder

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Why is Social Acceptance important?

- Social acceptance is a key challenge for the deployment of wind energy and could limit the overall wind resource we are able to exploit to meet climate change targets.
- Social acceptance can be influenced by a very wide range of factors, including project characteristics, perception of the distribution of costs and benefits, degree of public participation.
- Perceived impacts of projects on landscapes, property values, health and biodiversity also influence social acceptance.

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- What is Social Acceptance?

  It includes the following:
  - Socio-political acceptance
  - Market acceptance
  - Community acceptance

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- Socio-political Acceptance

It includes the following stakeholders:

  - Federal Administration
  - Policy Makers
  - State administration
  - Syndicates and technical committees

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- Market Acceptance

This includes the following stakeholders:

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

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- Community acceptance

In terms of community stakeholders, these are the following:

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

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- Community acceptance

Community also includes the following:

  - 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, light, 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 assistance
  - 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 the 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 adequate locations.
  - Easy to integrate in (existing) mini-grids fed with diesel. Hybrid wind-diesel systems provide higher quality, lower costs, and are more reliable and sustainable.
  - Allow, in combination with such applications as solar to develop a ‘whole-year-round’ solution.
  - Solution to generate power for and developing small businesses, and 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.
  - 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 facilitate to discover new business opportunities and favorable locations to install wind farms.

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- Real challenges and opportunities of wind energy sources:
  - Integrate, impose and control quality standards and certifications for every new installation. This will ensure the installation of products that 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 opportunities.

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Module 2.4

Environmental Impact Assessment (EIA)

Lesson 2.4

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on the main environmental impacts.

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Learning outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Foresee the possible environmental impacts of wind turbines;

O2. Estimate the incidence of impacts and to evaluate how to reduce them.

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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

Source: [3]

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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

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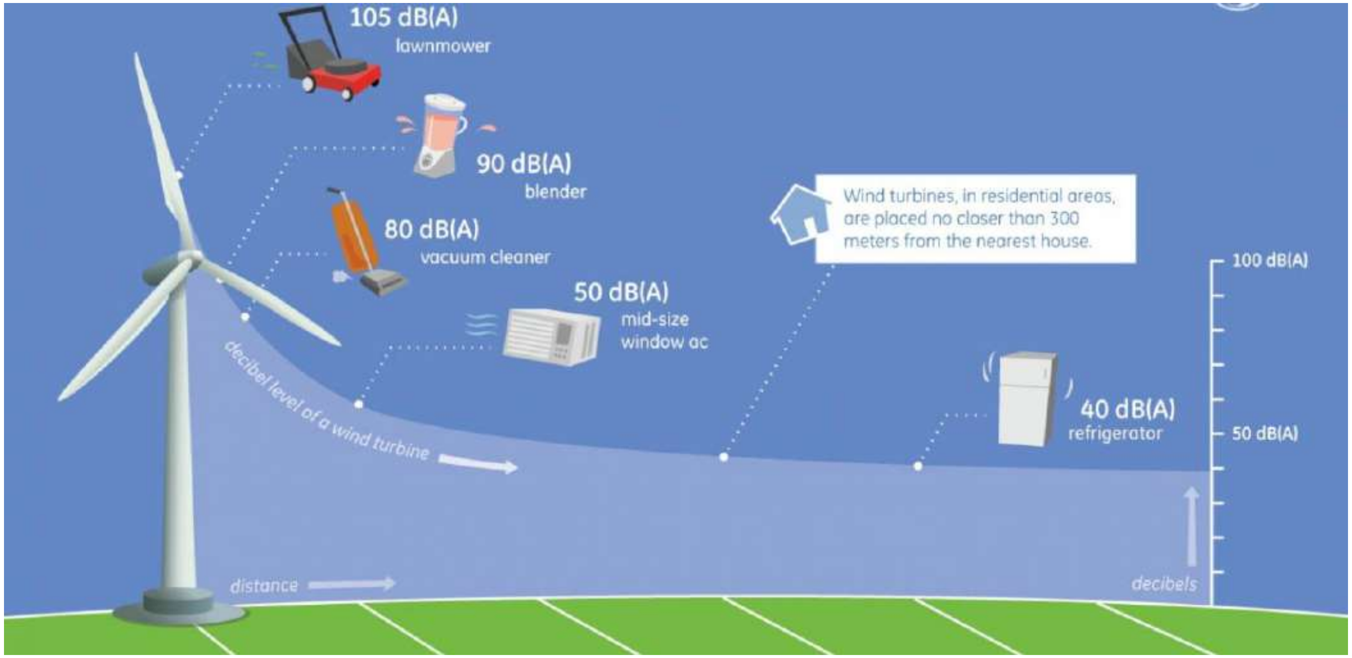
If L_a is the intensity of the noise emitted by a wind turbine, considering the atmospheric absorption αa, at a distance R from the machine will be recorded background noise equal to:

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



Source: [1]

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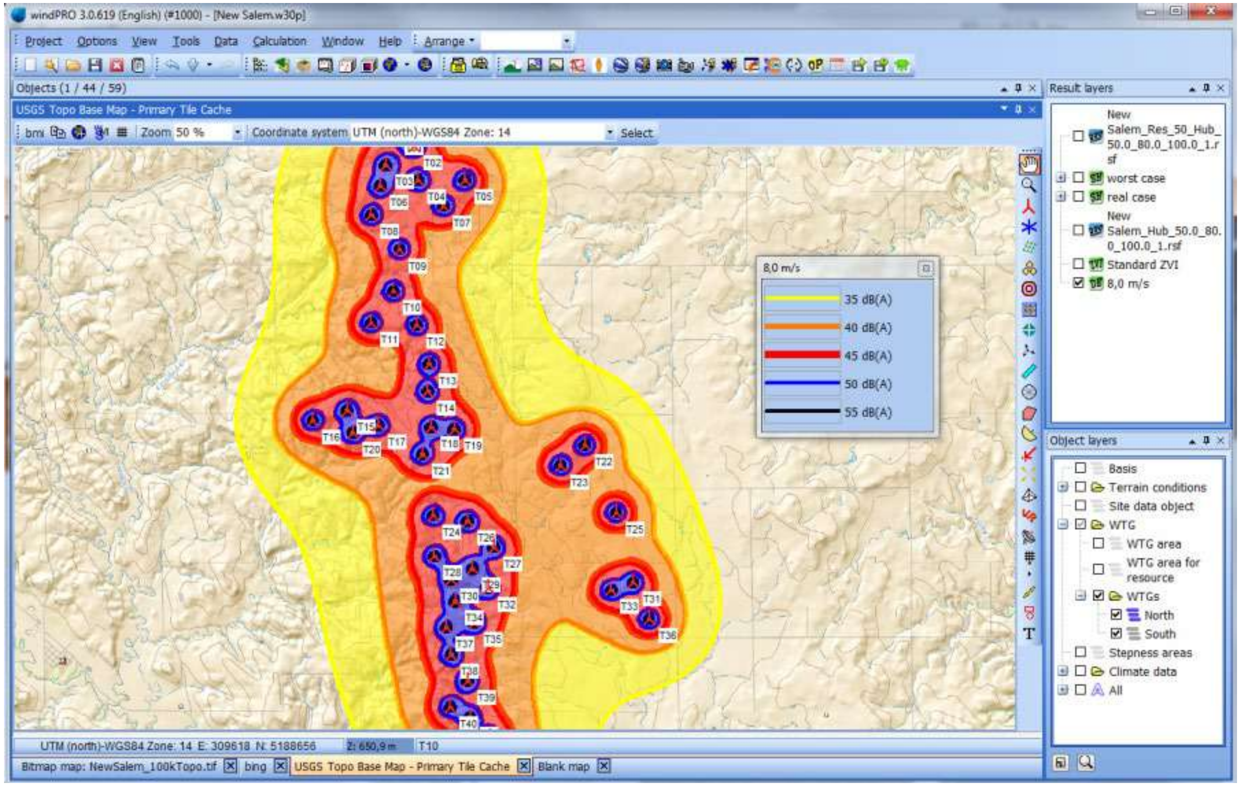
Environmental impacts
Noise impact

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. Source: [2]

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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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Recommended literature

Web links:
[1] https://www.ge.com **General Electric**
[2] https://www.emd.dk/windpro **WindPro**
[3] www.greenrhinoenergy.com **Green Rhino Energy**

Module 2.4

Further information:

www.weset-project.eu

info@weset-project.eu

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Occupational Health and Safety (OHS&S)

Lecture 2.5

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Learning outcomes

- Understanding hazards for both onshore and offshore facilities
- Implementing Safety and Health Initiatives

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Table of contents

- Recall of main wind farms relevant to OSH
- General OSH challenges in the wind energy sector
- Wind Turbines Standards
- Medical fitness to work for wind turbine projects
- Hazards during the construction phase

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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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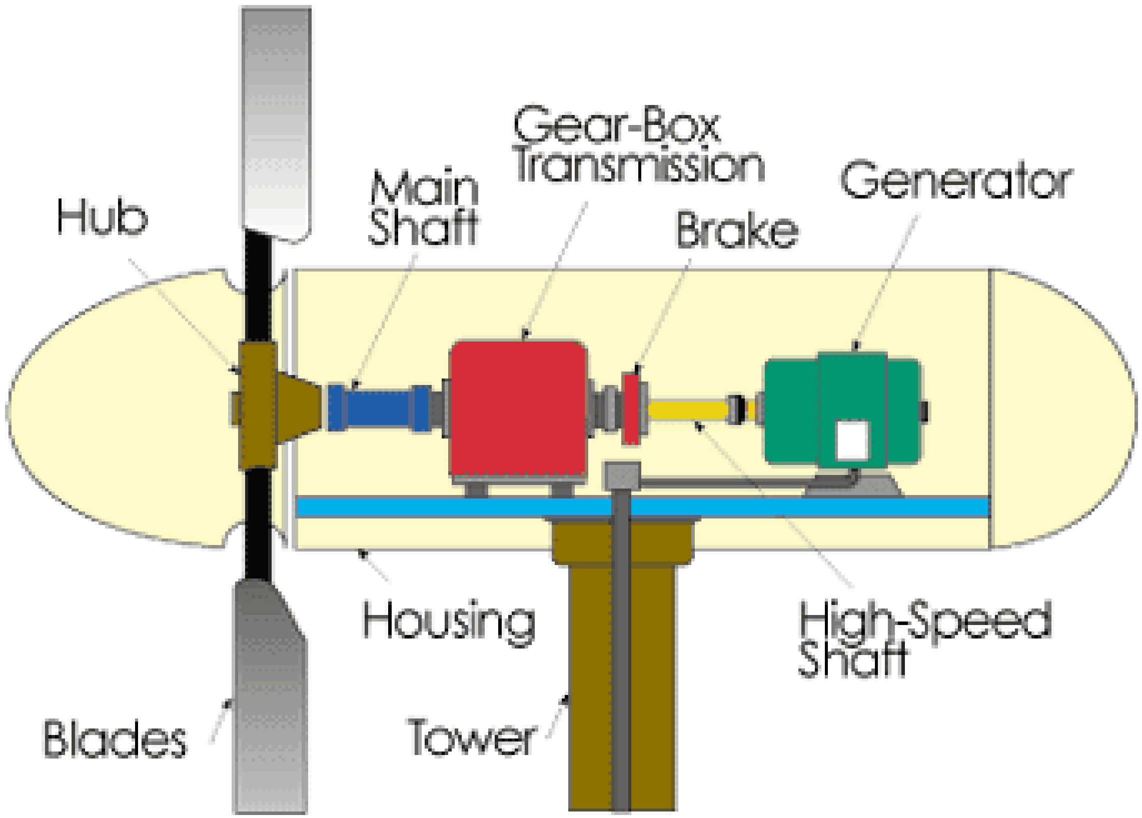
Main components of a Wind Turbine

Rotor



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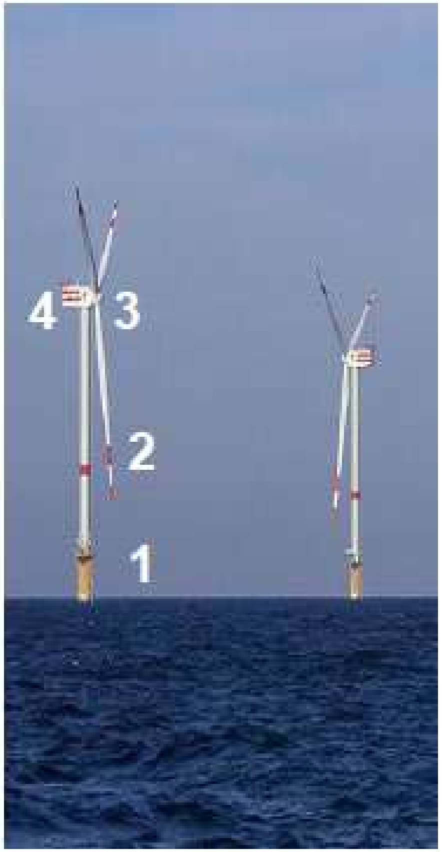
Onshore and Offshore Wind turbines

Left: onshore wind turbines

Right offshore wind turbines



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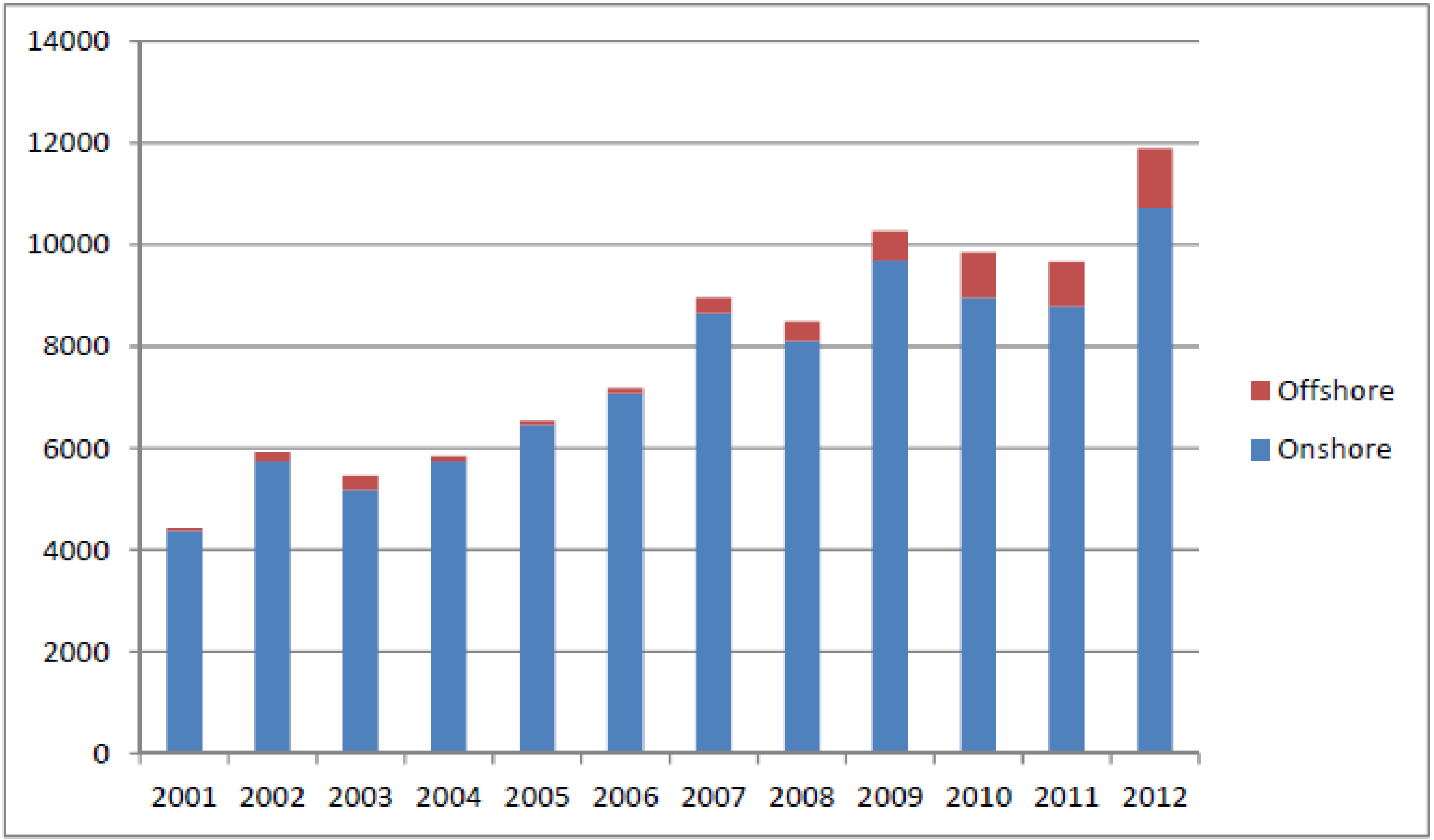
Annual onshore and offshore installations (MW)



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General OSH challenges in the wind energy sector

- 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

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

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

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

- 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.

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Example of hazards encountered during the construction phase (contd)

- 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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Wind Turbine Blade Manufacturing

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Sanding & Grinding Activities

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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

They include the following:

- 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 hypoglycemic 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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1. European Risk Observatory Report, Occupational safety and health in the wind energy sector, 2013, ISSN: 1831-9343.
2. Safety and Health Outlook: Wind Energy, presentation of the American Wind Energy Association.
3. Onshore Wind Health & Safety Guidelines, Renewable UK- The voice of wind and marine energy, Issue 1, 2015.

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Implementation of Wind Energy Systems

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Module 2.4

Economical Sustainability

Lesson 2.6

2.1 L4 v3

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Objectives

The purpose of this module is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on the estimation of the total cost of a wind farm and the main indicators.

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to:

O1. Identify the different costs incurred in the design and installation of a wind farm;

O2. Estimate the incidence of different costs according with the wind farm type (onshore or offshore) and the location of energy plant;

O3. Develop an analysis of total costs and an evaluation of return of investment.

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Technical Contents

1. *Costs analysis – Main indicators*
2. *LCOE*
3. *key parameters*
4. *Capital costs*
5. *Turbine prices*
6. *Breakdown costs per turbine's components*

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Total power generation capacity in the EU 2005-2017

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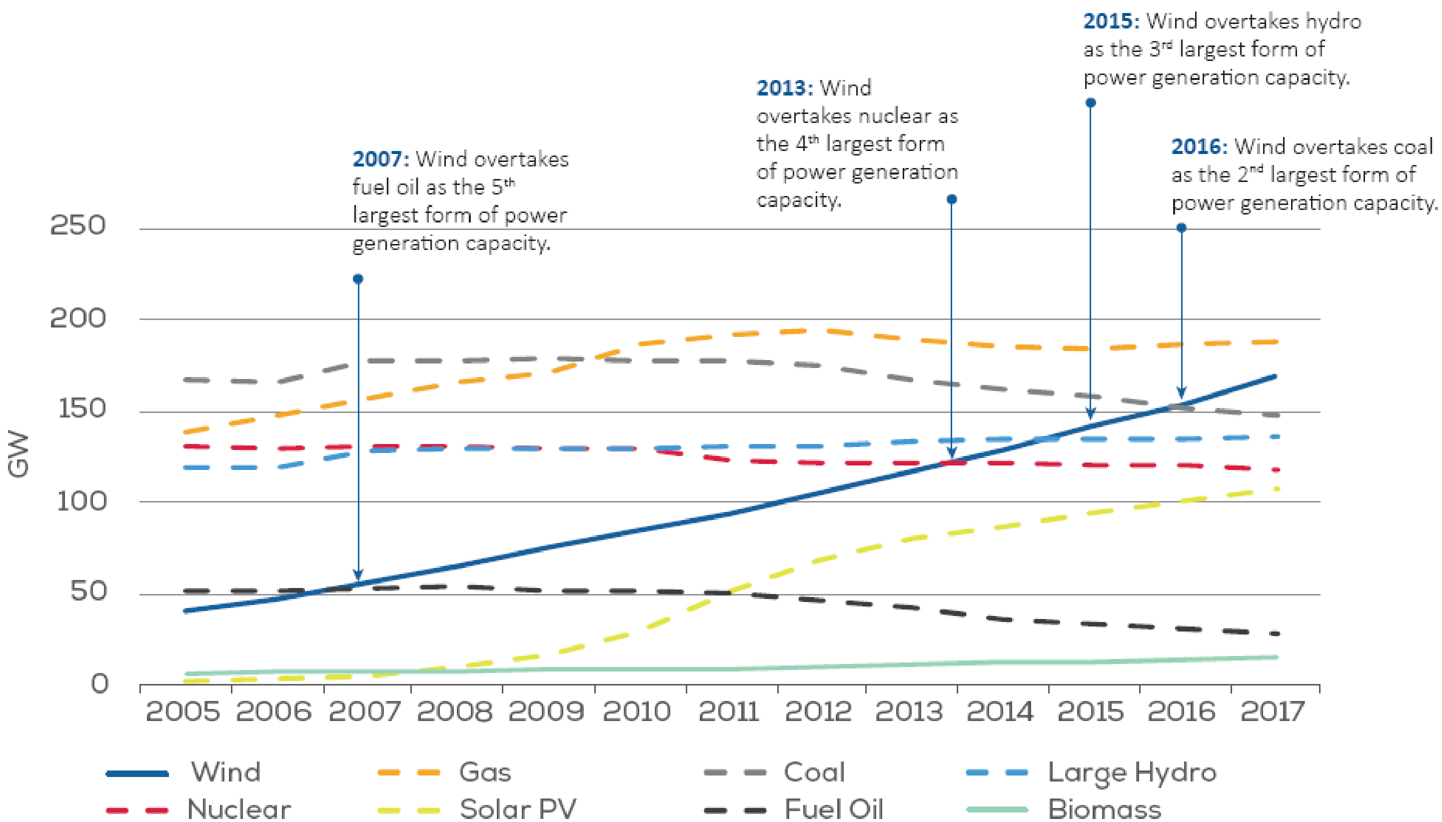
Europe installed 16.8 GW (15.6 GW in the EU) of gross additional wind power capacity in 2017.
Total net installed capacity is 168.7 GW.



Source: 1.

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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

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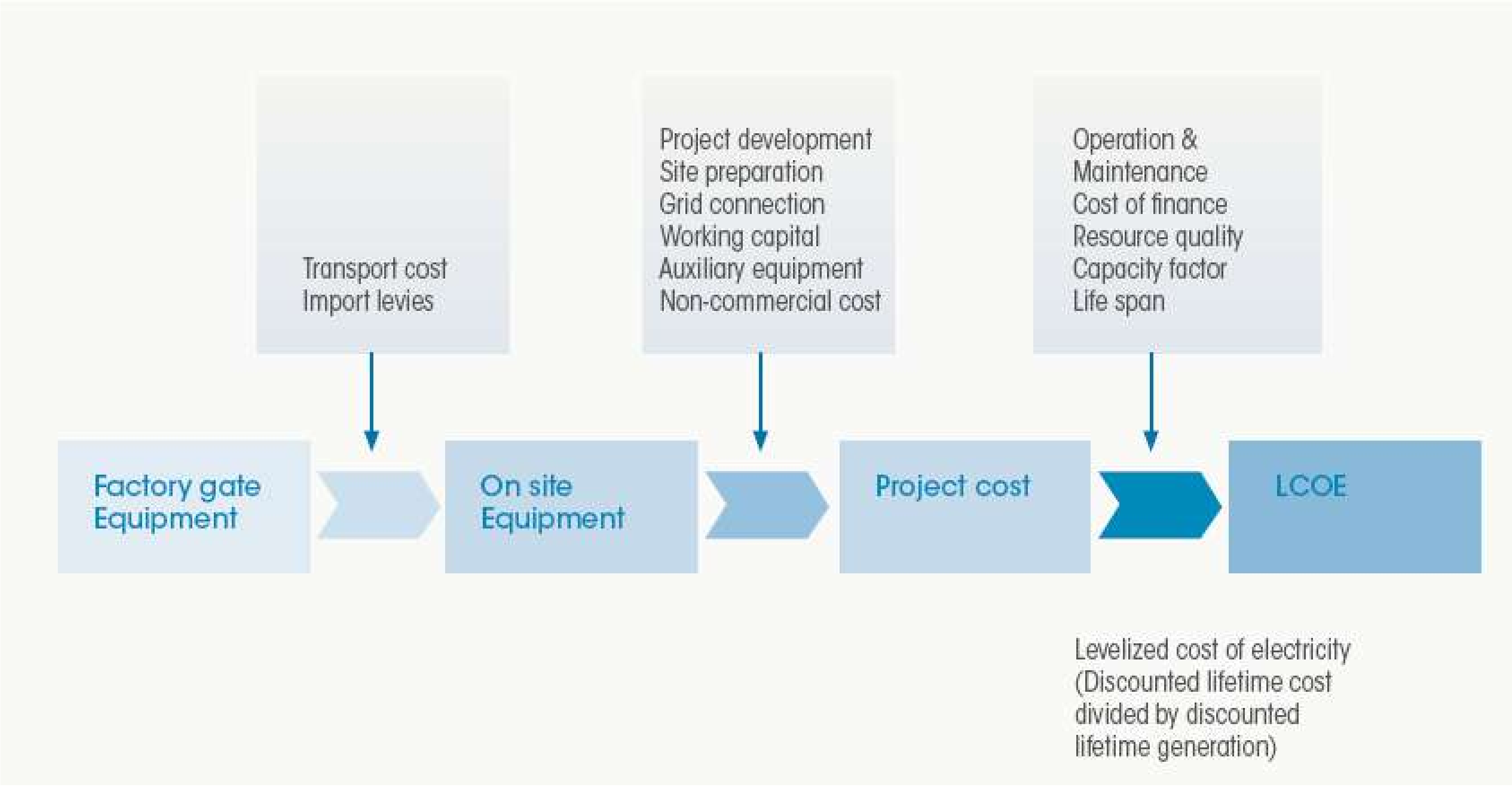

Renewable Power Generation Cost Indicators and Boundaries. Source: 2.

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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.

LCOE:

- Measures lifetime costs divided by energy production
- Calculates present value of the total cost of building and operating a power plant over an assumed lifetime
- Allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities

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

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.

Source: 2.

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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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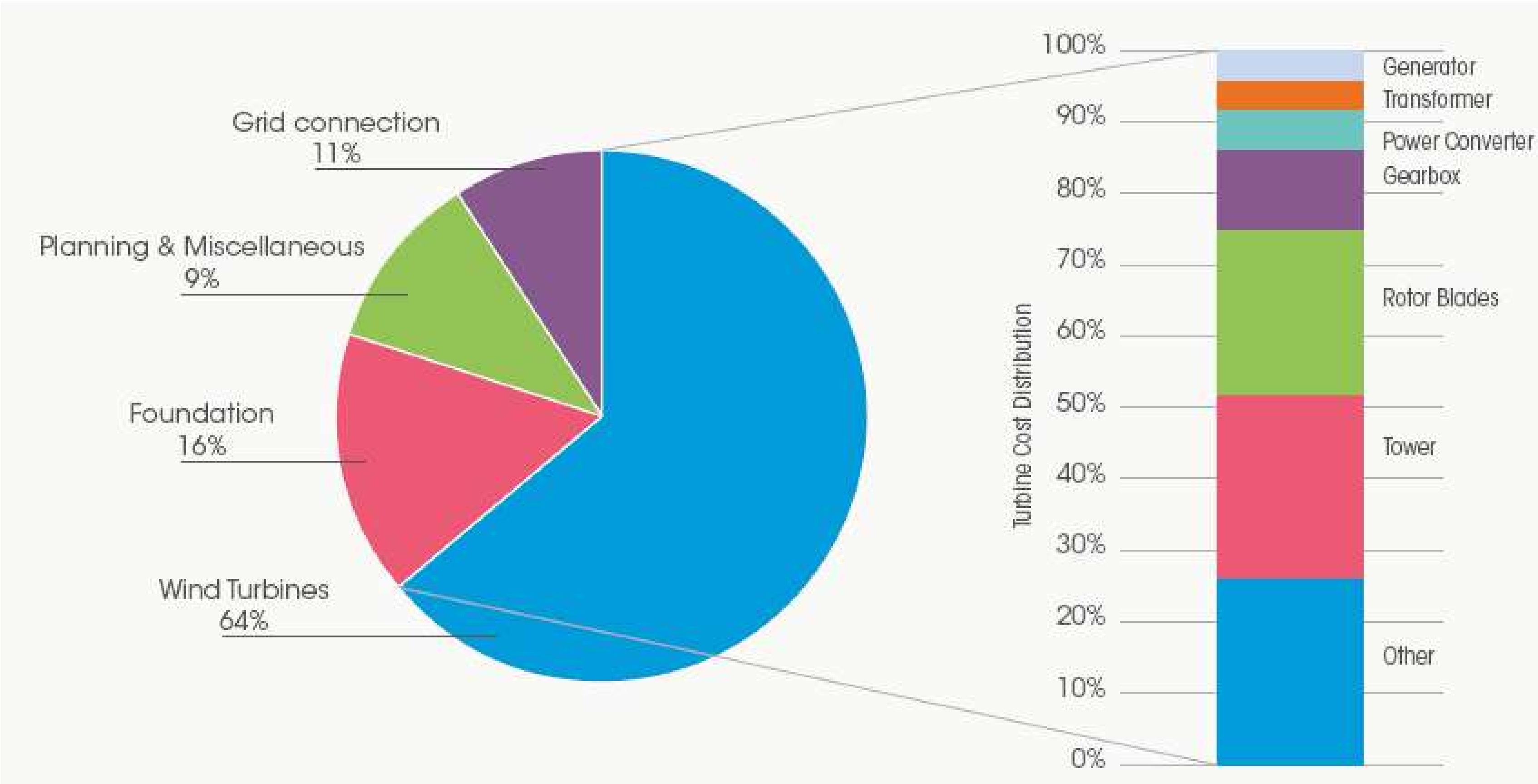
Cost Analysis - Indicators



Capital Cost Breakdown for a Typical Onshore Wind Power System And Turbine. Source: 2.

www.weset-project.eu

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

Source: 2.

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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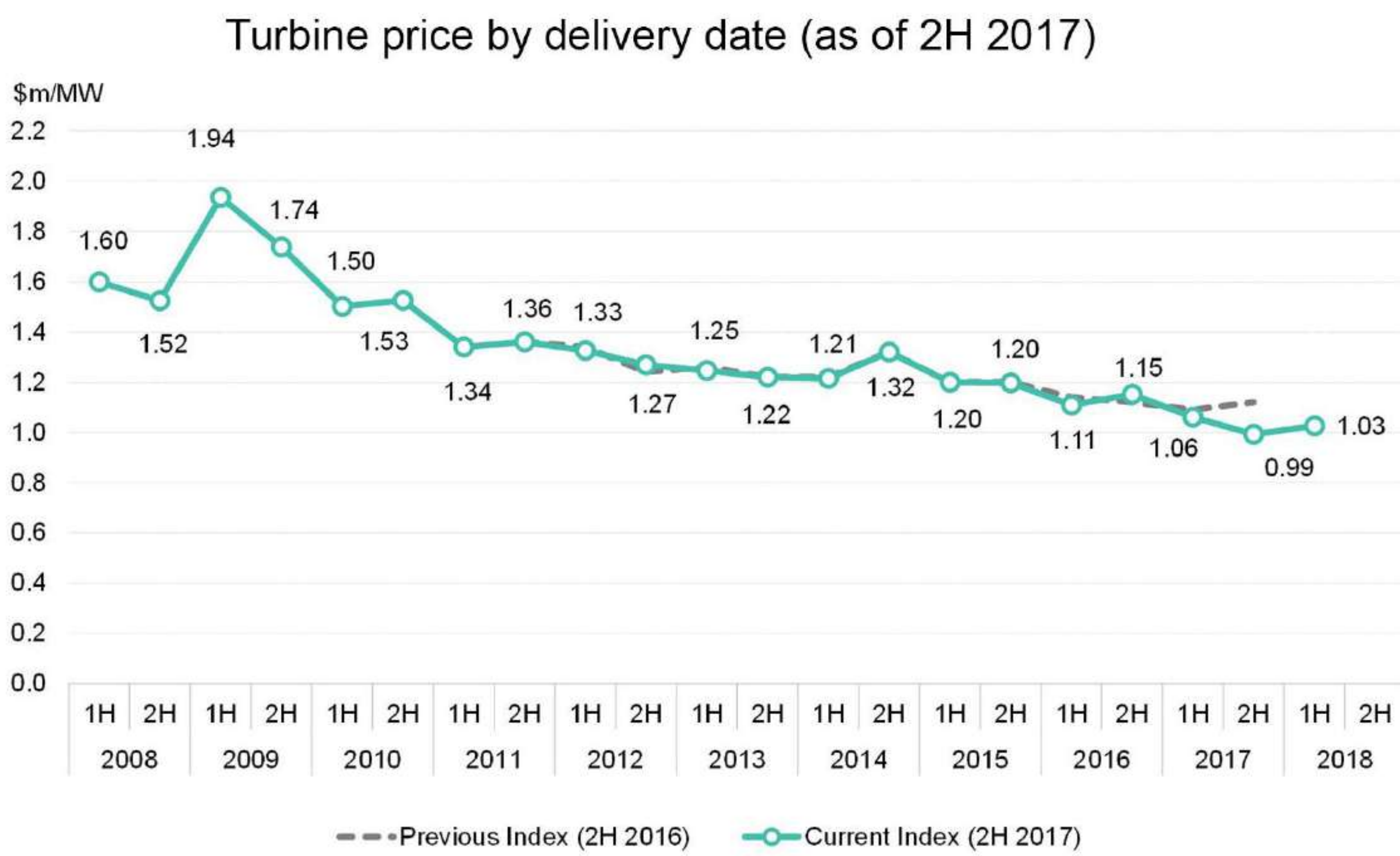

Source: [1]

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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

Source: 2.

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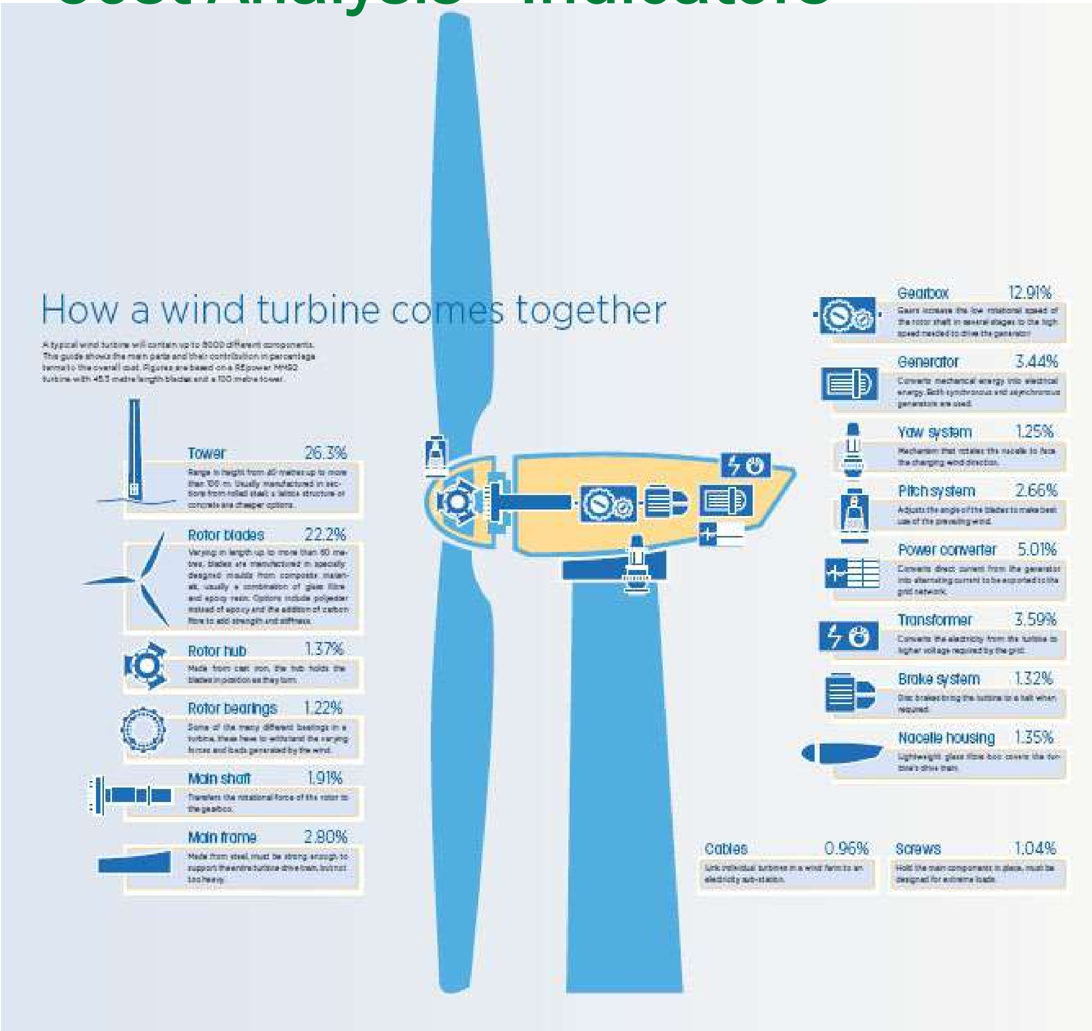
Cost Analysis - Indicators

Wind turbine cost breakdown
(5 MW offshore wind turbine)



Source: 2.

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Recommended literature

Books:

1. **Wind in power 2017. Annual combined onshore and offshore wind energy statistics, Wind Europe**
2. **Renewable Energy Technologies: Cost Analysis Series. Wind Power, IRENA - International Renewable Energy Agency, 2012**

Web links:

[1] https://about.bnef.com **Bloomberg New Energy Finance**

Implementation of Wind Energy Systems

Module 2.4

Further information:

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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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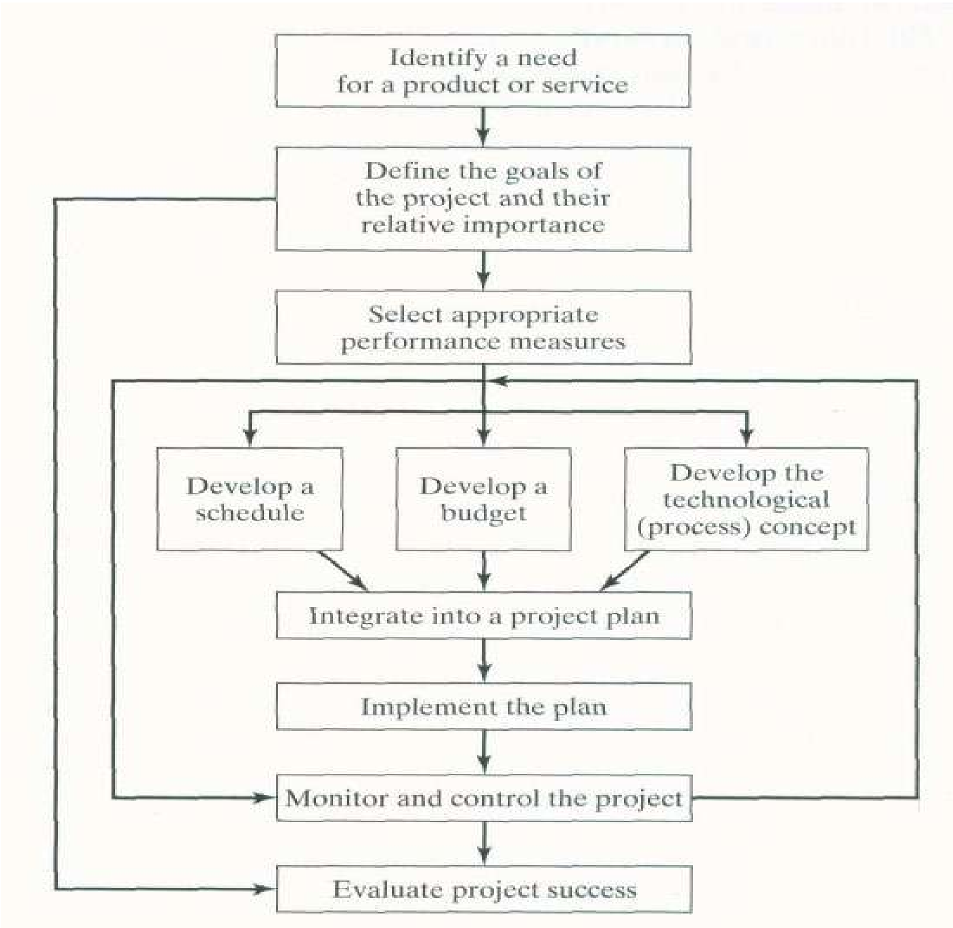
Project Management Processes



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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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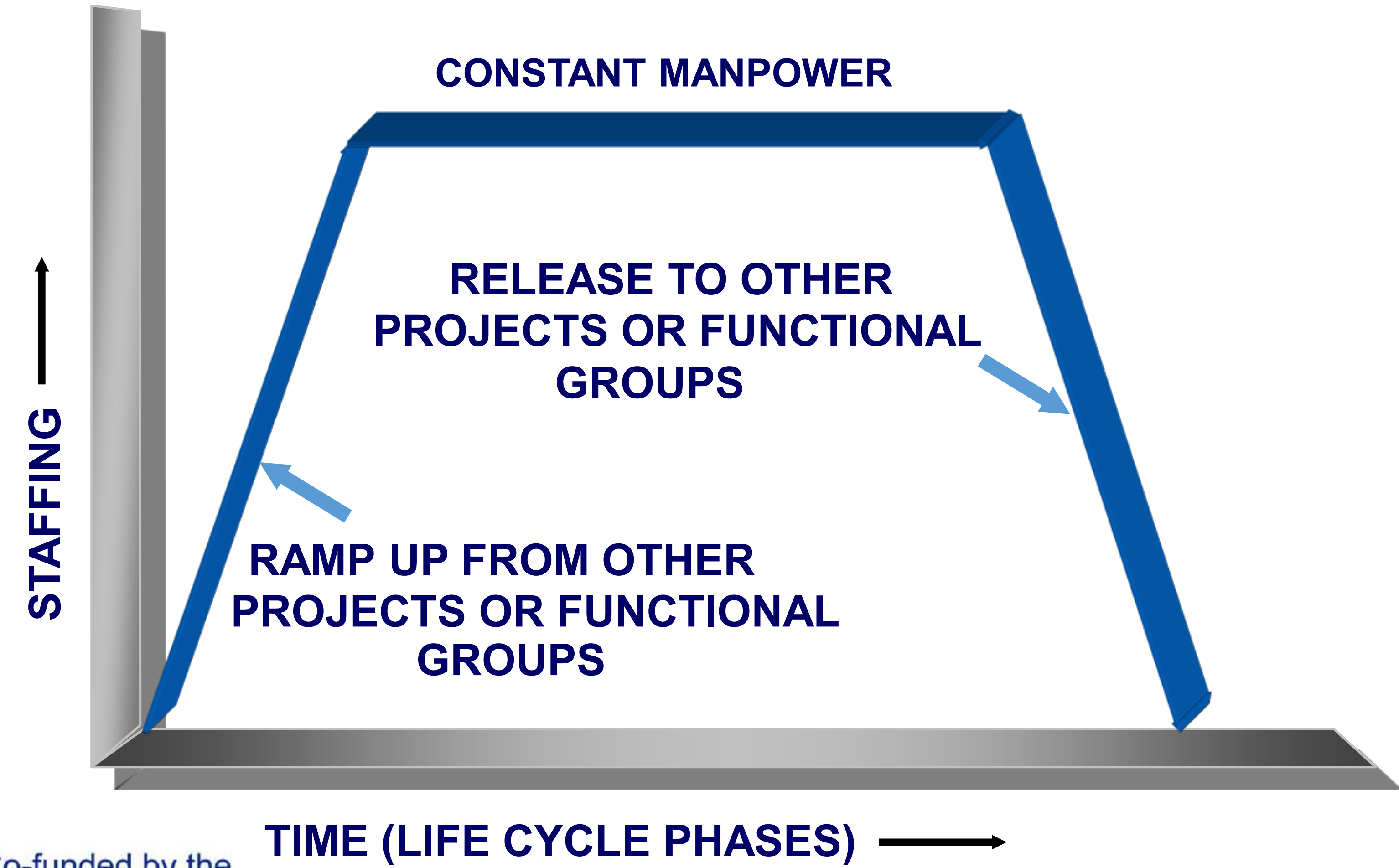
Staffing Pattern Versus Time



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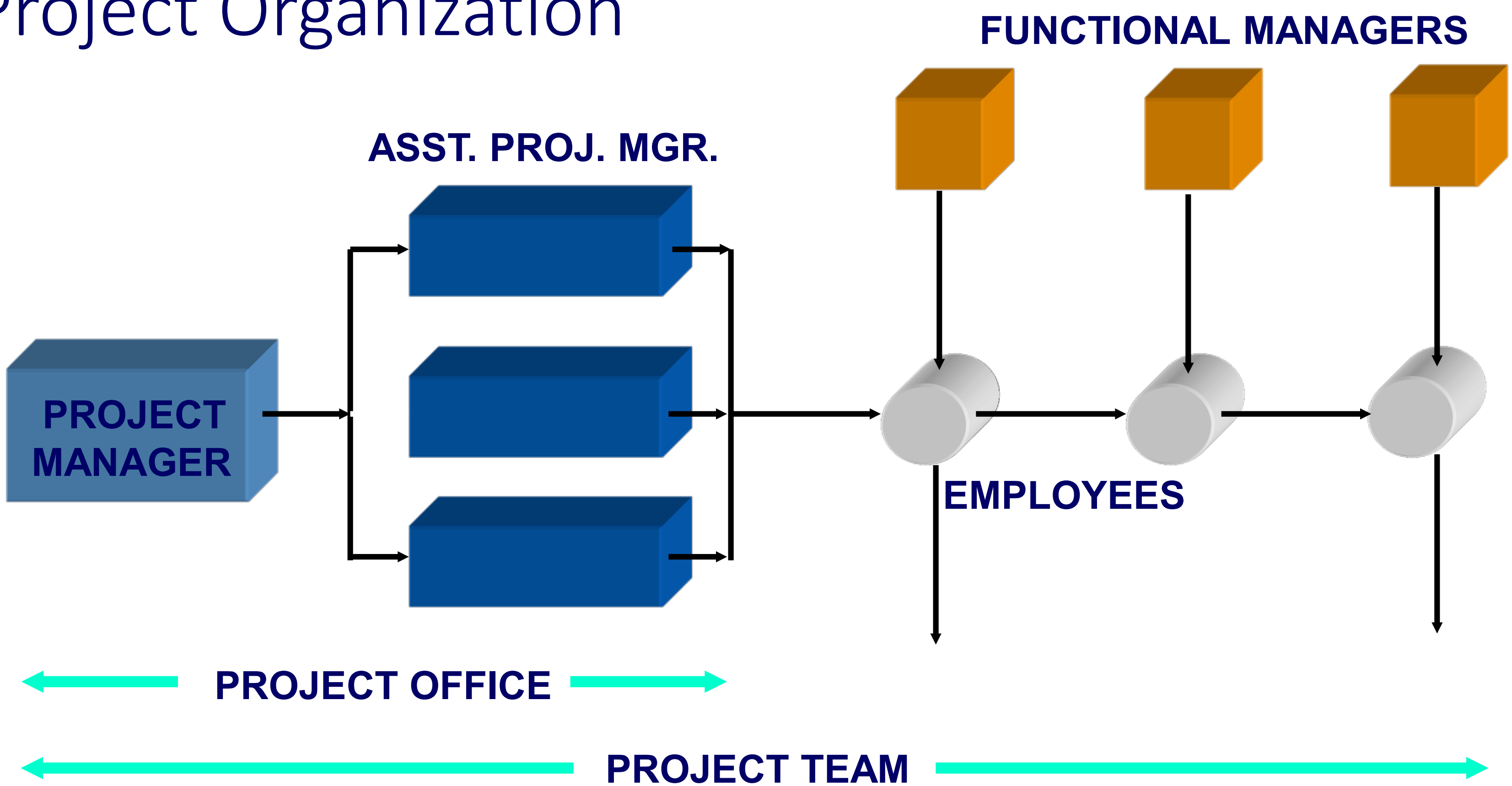
Project Organization



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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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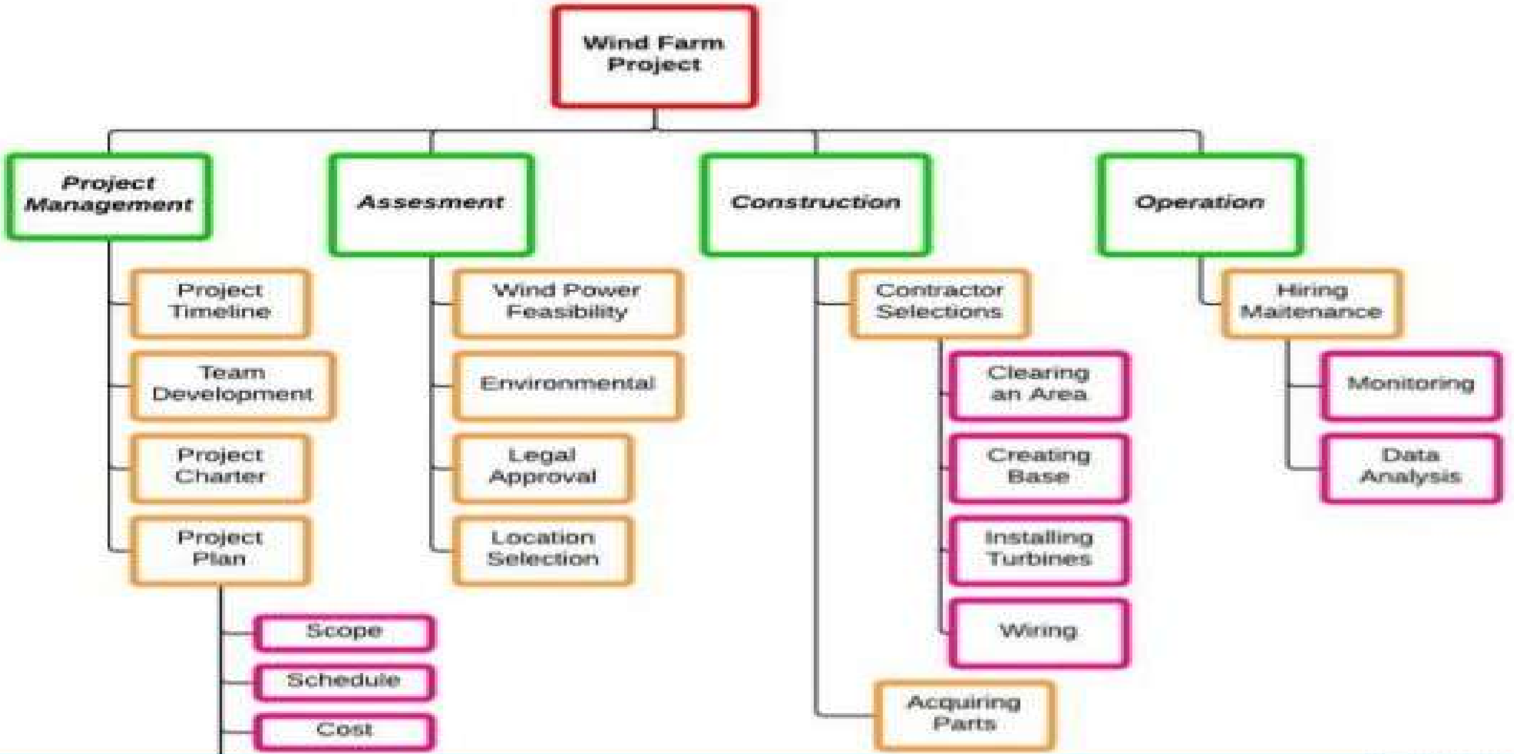
Work Breakdown Structure



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Module 2.4 Implementation of Wind Energy Systems

- **PILOT WTG M100**
  - **Design**
    - Design OPTS D100
    - Design Pod Substructures (2 No.) D200
    - Design Piles D300
    - Design Onshore Substation Modifications D400
    - Specify Tower, Nacelle & Rotors D500
    - Design Offshore Cables D600
  - **Procurement**
    - Procure & Fabricate OPTS P100
    - Deliver OPTS to Barge P150
    - Procure & Fabricate Pod Substructures (2 No.) P200
    - Procure & Fabricate Piles P300
    - Deliver Foundation Piles to Barge P350
    - Procure & Deliver Substation Equipment & Materials P400
    - Procure Tower, Nacelle & Rotors P500
    - Deliver Tower, Nacelle & Rotors to Yard P550
    - Procure all Cables P600
    - Deliver Offshore Cables to Lay Barge P650
  - **Construction**
    - Install & Mate OPTS C100
    - Load Out WTG Pod Substructure C200
    - Sea Fasten WTG Pod Substructure & Piles C210
    - Float & Install WTG Pod Substructure C220
    - Pile And Secure WTG Pod C230
    - Load Out OPTS Pod Substructure C240
    - Sea Fasten OPTS, Pod Substructure & Piles C250
    - Float Out & Install OPTS Pod Substructure C260
    - Pile & Secure OPTS Pod Substructure C270
    - Assemble Tower, Nacelle & Rotors (WTG) C500
  - **Test & Commission**
    - WTG Commissioning TC500
    - OPTS Commissioning TC100
    - Substation Commissioning TC400
    - Complete Test & Connect to NG TC700

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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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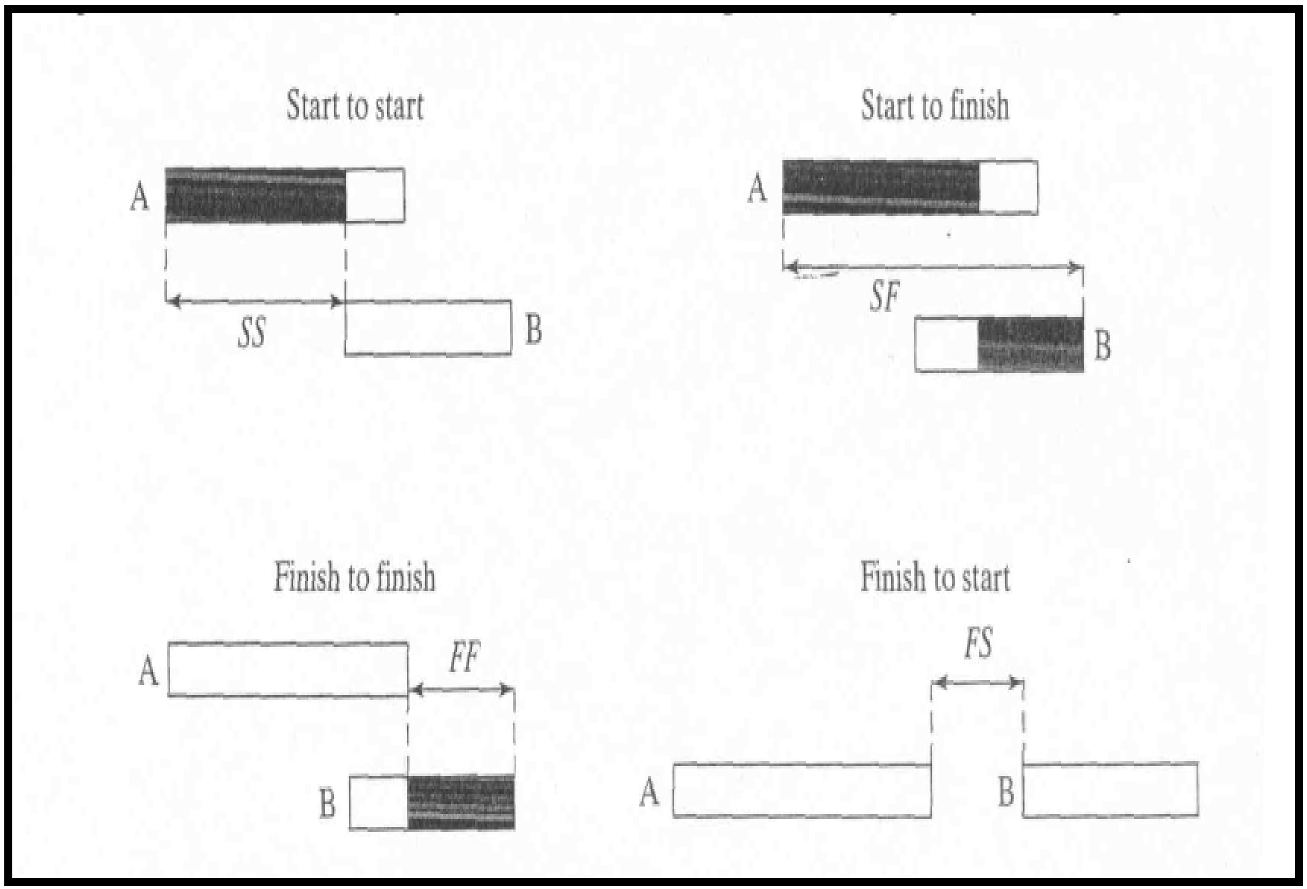

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Precedence Relations Among Activities

- 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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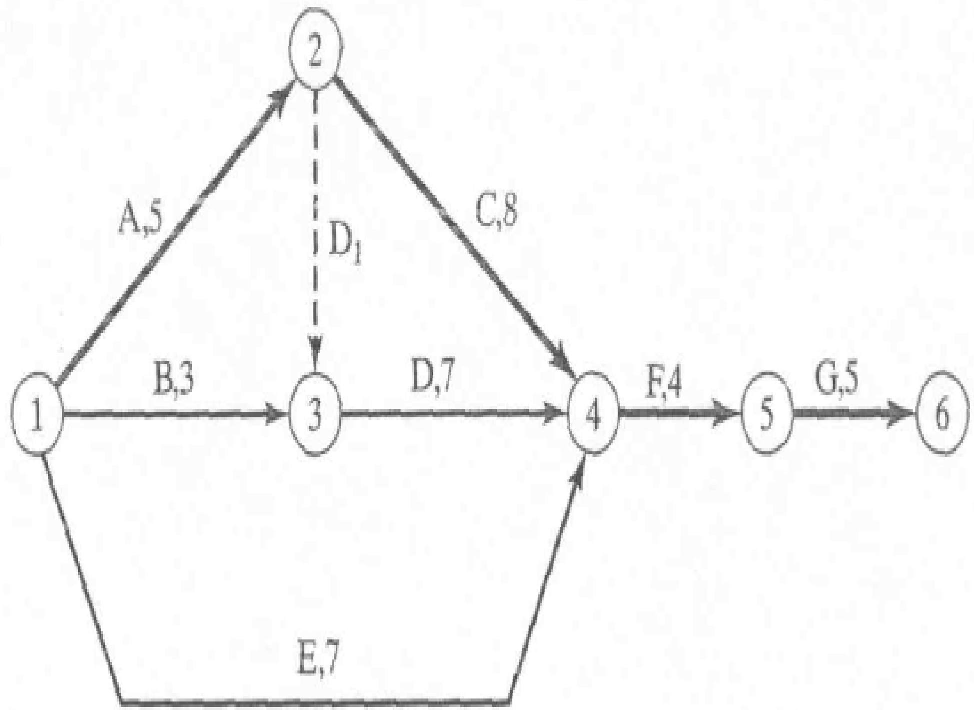

Figure VI.d Complete AOA project network.

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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

	Activity								
Week	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

Week	Activity 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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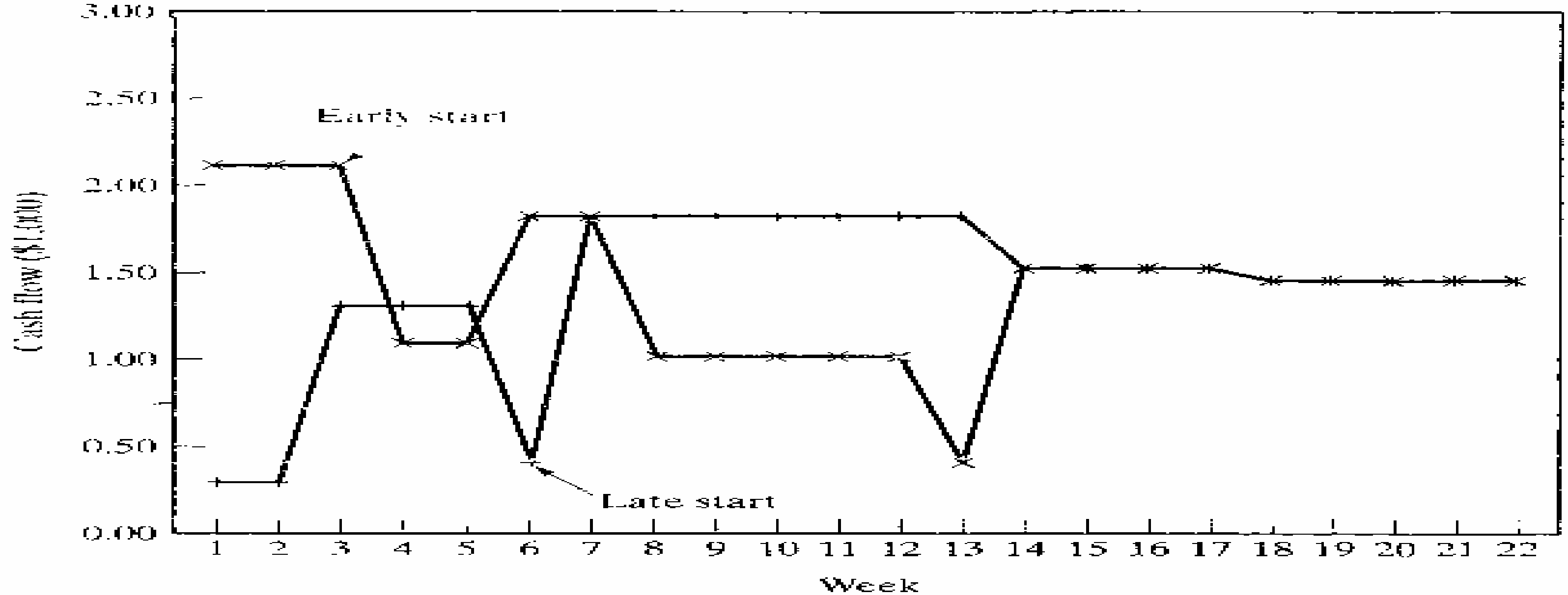
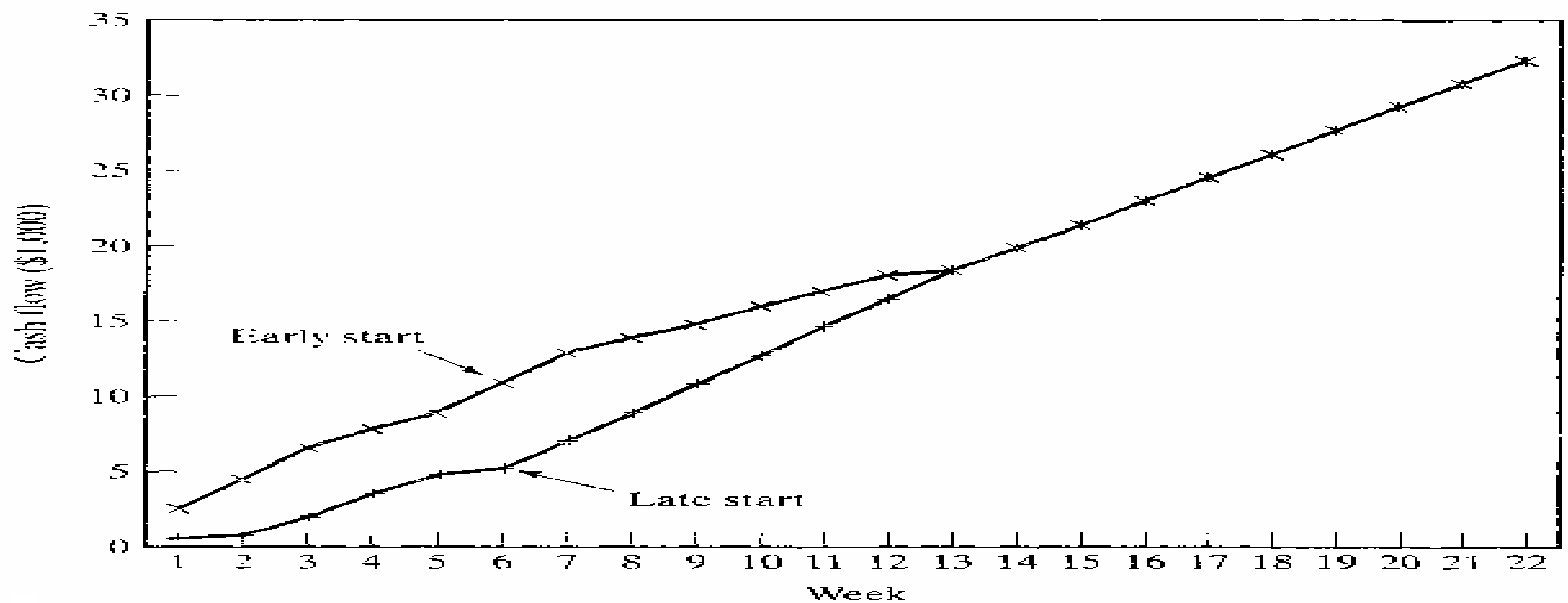


Cash flow for early-start and late-start schedules.



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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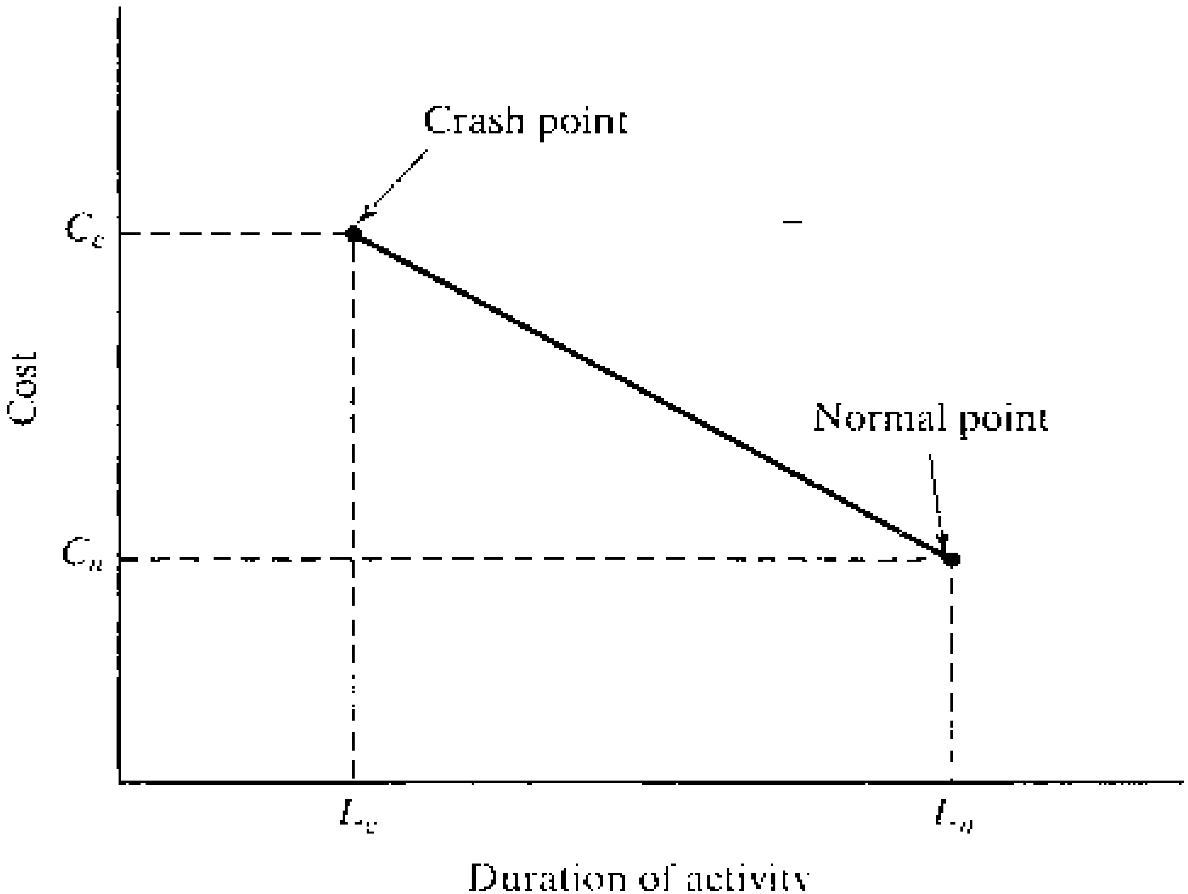

Typical Time-Cost Tradeoff Curve

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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

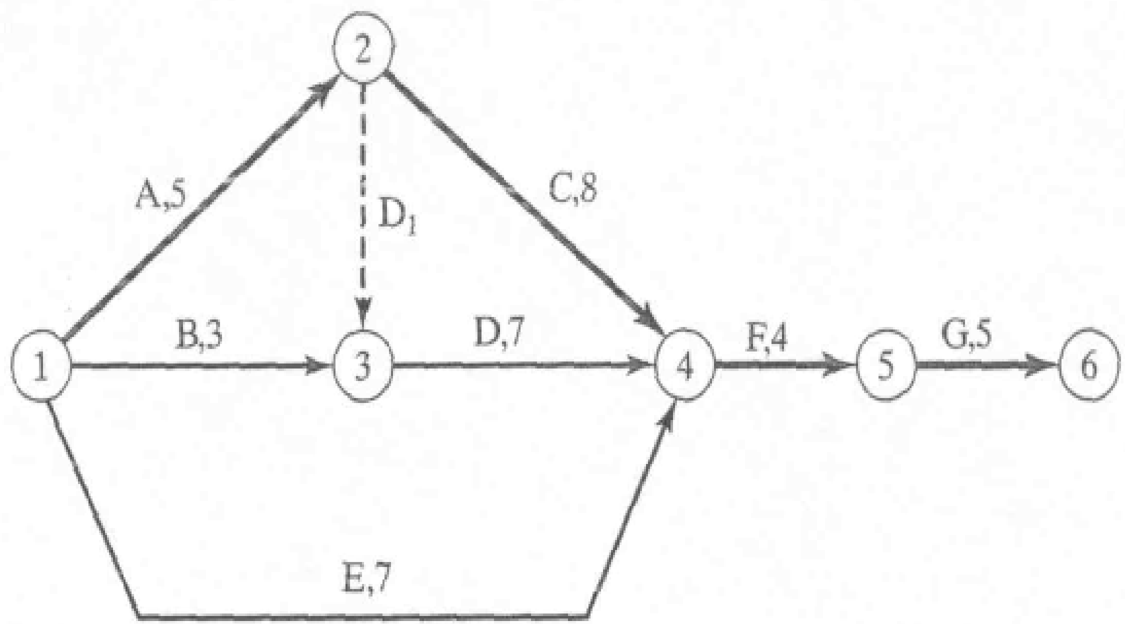

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TABLE 11.6 Duration and Cost for Normal and Crashed Activities

	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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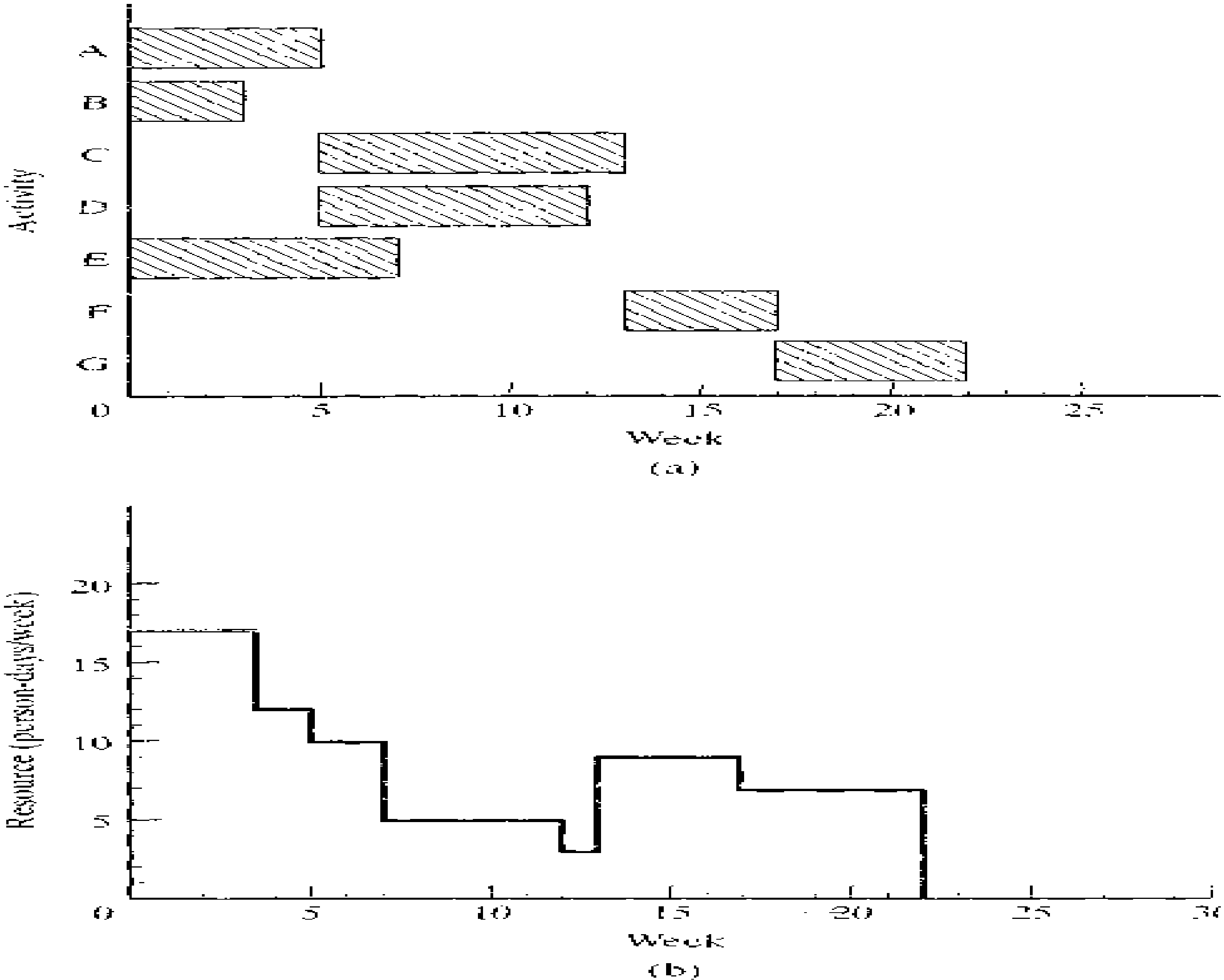

Figure 10.2 (a) Gantt chart and (b) resource profile for the early-start schedule.

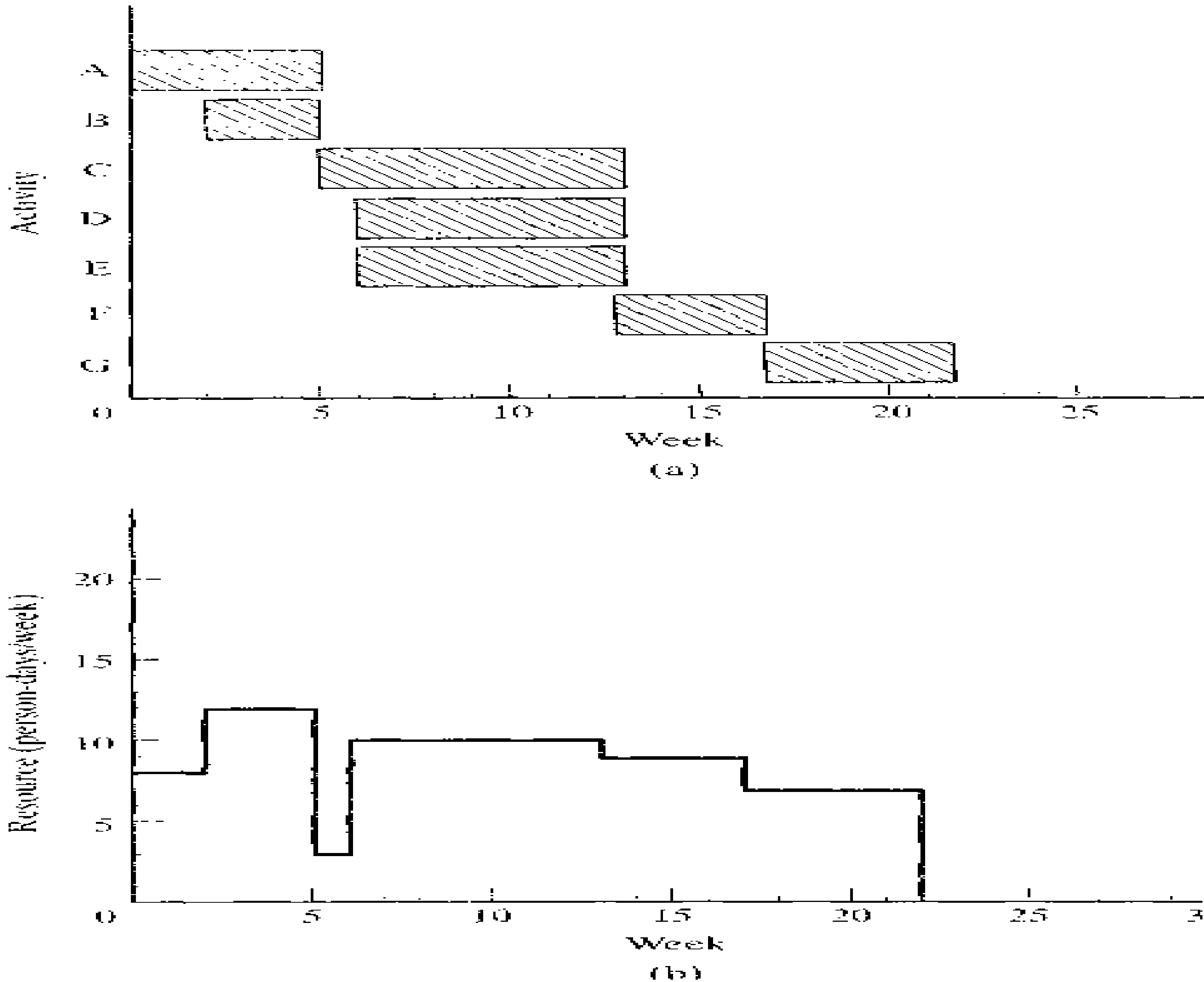

Figure 10.3 (a) Gantt chart and (b) resource profile for the late-start schedule.

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)		Costs ($)		Immediate Precedence Relationship
		Normal	Crash	Normal	Crash	
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

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References and Acknowledgements

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