LAB # 12

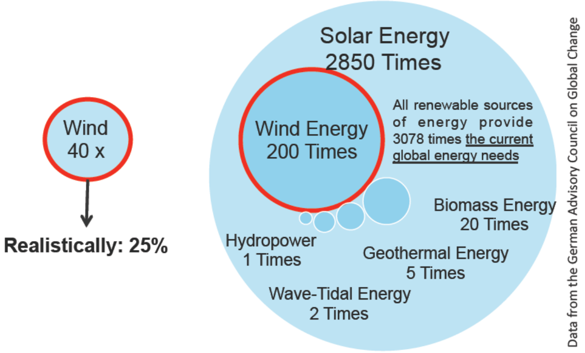
To Study and Identify Various Parameters of Wind Turbine

Objectives:

- To enumerate the main sources of wind and study the differences in wind velocity profile between onshore & offshore wind
- To analyze some theoretical aspects of wind power generation
- To study and understand the different operational regimes of a wind turbine, to quantify the dependency of the power produced with the wind speed, and to define & explain the notion of capacity factor
- To compute the energy yield of a wind turbine based on its power curve and the wind characteristics, and to understand the concept of velocity deficit and its impact on wind farm layout
- To understand how the energy captured from the wind is converted into electrical energy and fed into the electric power system

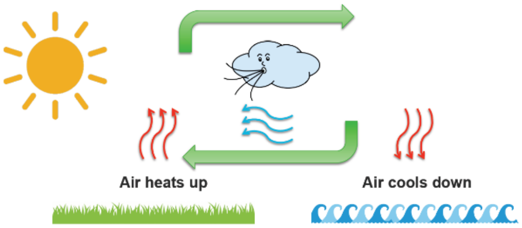
Related Theory:

Studies have shown that the total ***wind energy resource*** available in the lower atmosphere is roughly ***200 times*** the current global energy demand. Compared to other sources of renewable energy, wind energy therefore comes ***second*** after solar power, which is by far the dominant renewable energy resource. Of course, not all the wind energy potential in the lower atmosphere can be harnessed.



Data from the German Advisory Council on Global Change

More realistic studies have shown that if wind turbines are placed only in ***technologically feasible locations***, the wind energy resource is still ***40 times larger*** than the current energy demand. These scenarios will however never be achieved, due for example to policy restrictions. However, scientists in the field do believe that wind power can provide a ***quarter (25%)*** of the total energy demand worldwide.



The sun heats the Earth differently at different locations. This creates ***temperature gradients*** across the globe. ***Hot air*** tends to ***rise*** in the atmosphere, while ***cold air*** tends to ***fall*** towards the ground. This generates ***global recirculation*** of air between regions at different temperatures. These motions are of course influenced by additional factors, such as the Earth rotation. But ***wind*** power does ***originate*** from the ***sun***. The hotter air above the land will rise while the colder air above the sea will fall. This creates a local recirculation region between land and sea. The localized wind directed towards the shore is called a ***sea breeze***.

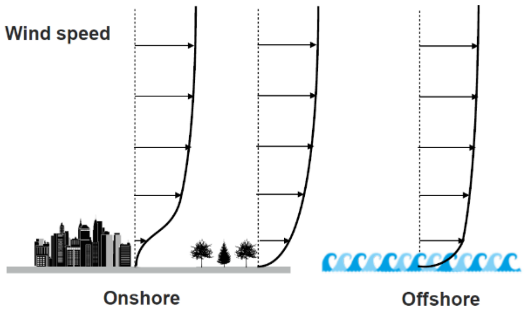
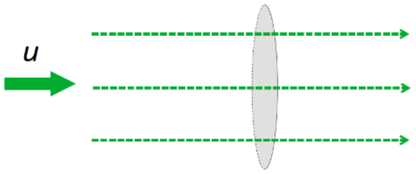
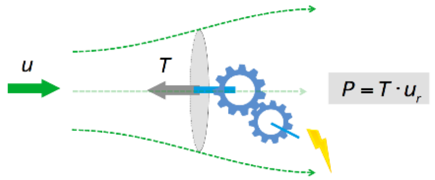


Figure illustrates some typical wind velocity profiles as a ***function of the altitude***. The wind velocity increases from zero at the ground to a certain value in the atmosphere. The exact ***shape*** of the profile depends however on the ***local topography***. Above sea, the increase will be much steeper. This means that offshore the wind speed is more uniform with the altitude. By contrast, in urban areas, the wind is slowed down by the presence of buildings, trees, etc. This means that the ***wind*** speed will reach a fairly ***constant*** value at a much higher altitude than offshore. In short, ***offshore*** wind turbines generally benefit from much stronger and ***uniform*** winds.

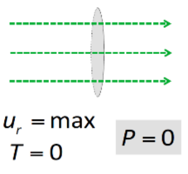
Aerodynamics:

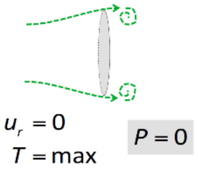


In order to understand the process of ***wind energy conversion***, it is useful to represent the wind turbine ***rotor*** in a simple way, as a ***disk***. So, what happens to the wind flow in the presence of this disk. If the disk is ***free to move*** with the wind, it does ***not exert*** any ***force*** on the flow, and therefore, the wind is completely ***undisturbed***. In this case, ***no energy*** is extracted from the wind. By contrast, if the disk is ***fixed***, it tends to ***oppose*** the wind flow by exerting a ***force T*** on it, and the flow is ***disturbed***.



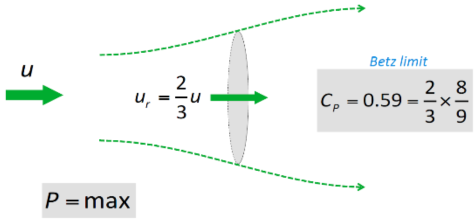
In particular, the flow is ***slowed down*** by the force T and at the same time, it tends to ***go around*** the disk. ***Energy*** can be ***extracted*** from the flow if ***both*** the force ***T*** and the ***wind velocity*** just behind the disk are non-zero. The latter implies that the disk should ***not block completely*** the flow. Instead, it should ***allow*** for ***some wind*** to go through the disk. In other words, the disk should be ***porous***. The ***power*** extracted from the wind at the disk ***equals*** the ***product*** of ***T*** and the ***velocity*** at the disk. This is why both quantities should be non-zero in order to extract power. Considering that the disk represents the ***wind turbine rotor***, the wind velocity at the disk is denoted by **u_r**.





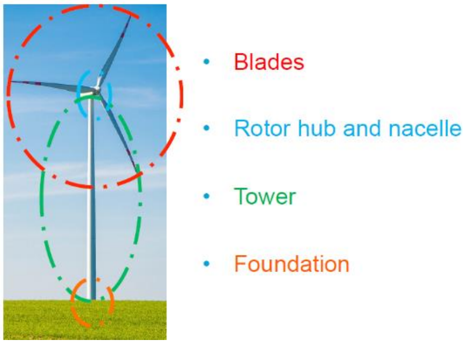
So, to ***summarize***, we can say that if the disk does ***not*** exert any ***force*** on the flow, then the ***velocity*** at the disk (or the rotor) is ***maximum*** but the ***power*** extracted is ***zero***. By contrast, if the ***force*** exerted by the rotor is ***maximum***, the ***velocity*** at the disk is brought to ***zero***. Therefore, the ***power*** is also ***zero***. Thus, even intuitively, there should be an ***optimal combination*** of force ***T*** and ***velocity*** at the rotor that ***maximizes*** the ***power***.

It can be shown that the ***power*** is ***maximum*** when the ***velocity*** at the disk is ***2/3*** of the incoming wind speed. This means that the ***rotor*** acts as a ***porous*** disk, exerting a ***constant force*** on the flow, while still ***letting 2/3*** of the flow through it. In this case, the non-dimensional ***force*** exerted by the rotor is ***8/9***. With these values, the power extracted by the rotor is ***59%*** of the *total power available in the wind* at the location of the rotor. In other words, the non-dimensionalized ***power coefficient*** is ***0.59***. This is called the ***Betz limit***. Without going through the details of the mathematical derivation, this limit is obtained by multiplying 2 third of the velocity with 8 ninth of the force. It gives a ratio of 16/27 which equals 0.59.



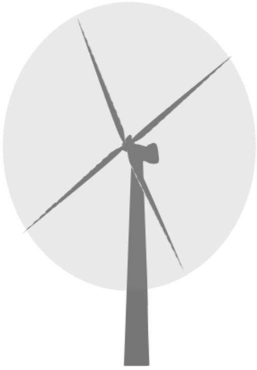
Of course, more advanced models are needed to account for the fact that the ***wind turbines*** have more ***complex geometries*** than a ***disk***.

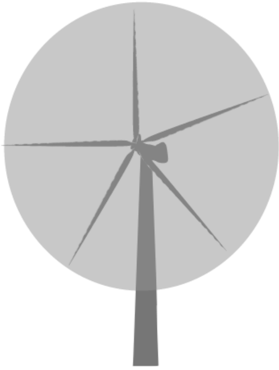
In particular, a wind turbine is composed of: ***Blades***, usually ***2 or 3***. The ***hub*** and ***nacelle***, which connect the blades and also encompass the generator. The ***tower***, which supports the rotor-nacelle assembly. And the ***foundation*** mounted either on land or offshore.

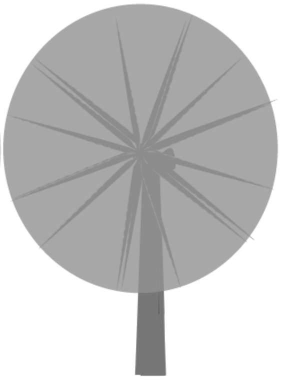


We've just mentioned above that a wind turbine rotor is composed of usually 2 or 3 blades. *Why don't we use more blades? 4, 5, 6 or even more?* Well, as the ***number*** of ***blades increases***, the ***force*** on the rotor also ***increases*** but the ***velocity*** of the wind going through it ***decreases***. So, the ***higher*** the ***number*** of ***blades***, the ***higher*** the ***blockage*** of the flow. In the limit of an ***infinite number*** of blades, the rotor would be a ***solid disk*** with ***no air*** going through.


3 blades


4 blades

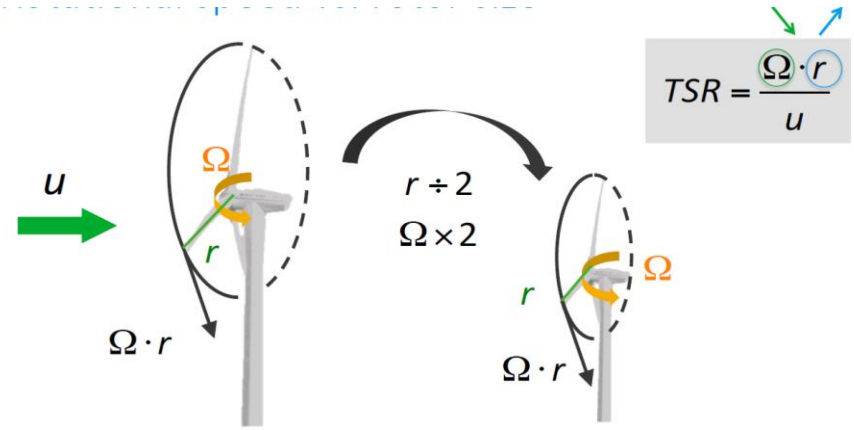

5 blades


6 blades or More

Similarly, there is a ***limit*** to the ***rotational speed*** of the ***rotor***. For a given number of blades, for example 3, *the higher the rotational speed the higher the blockage of the flow*. At very ***low*** rotational speed, the flow ***sees 3 blades*** spinning. But as the rotational speed ***increases***, the flow sees effectively a rotor with ***more than 3 blades***. Therefore, ***less wind*** will go through, resulting in less power. In conclusion, a wind turbine that ***rotates faster*** does ***not*** necessarily ***produce*** more power. This is why, for each wind speed, there is an ***optimal rotational speed*** that maximizes the power.

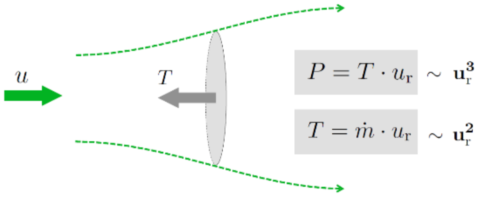
It ***means*** that a wind turbine is designed to operate at a given ***tip speed ratio***, that is, the *ratio between the velocity of the tip of the blade and the incoming wind speed*. This ratio is commonly denoted as ***TSR***.

Note that the ***velocity*** of the tip of the blade is the ***product*** of the ***rotational speed of the rotor*** (here ***omega***) and ***the length of the blade*** (***r***). As you can see from the formula given in below figure, for a given wind speed ***u***, if the length of the blade ***r increases***, ***omega*** has to ***decrease*** in order to keep the ***tip speed ratio constant***. Thus, in theory, *a rotor half as small will rotate twice as fast*.

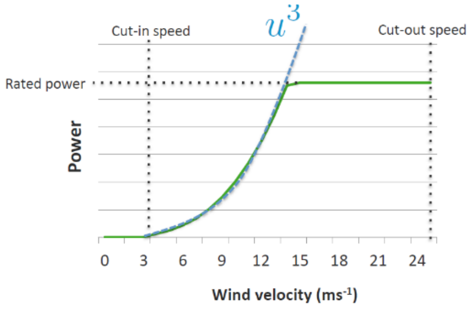


Power Curve:

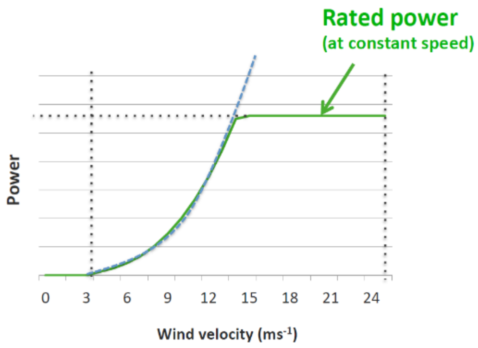
In the previous discussion, we learnt that the ***power*** extracted by the wind turbine ***equals*** the ***force*** exerted by the flow on the rotor ***times*** the ***flow velocity*** at the rotor. An important concept in fluid mechanics is the notion of ***conservation laws***.



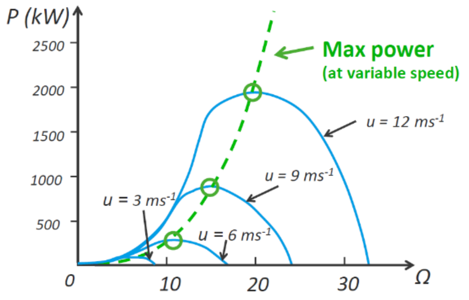
In particular, ***mass*** is conserved, when the fluid moves along the stream tube shown by the green dash line. It can be shown that the ***force*** exerted by the rotor equals the mass flow rate ***m-dot times the velocity*** at the rotor. Since the *mass flow rate is itself a function of the velocity*, ***T*** is a function of the ***velocity squared***. And by inserting this result in the definition of the power, it follows that ***P*** is a function of the ***cube*** of the ***velocity***.



Thus, across a wide range of wind speeds, the ***power*** produced by a wind turbine ***varies*** with the ***cube*** of the ***wind speed***. This is shown on this plot, which illustrates the power as a function of the wind speed. This however ***holds*** only for a ***certain range*** of wind speeds. Indeed, at very small speeds, there is not enough wind for the turbine to actually rotate. The wind speed at which the rotor starts to rotate is called the ***cut-in speed***. Below this value, no power is produced. The cut-in speed is typically about ***3-4 m/s***. On the other hand, if the wind is very strong, the loads on the rotor can become too large. Therefore, the so-called ***cut-out speed*** is the maximum wind speed at which power can be safely produced. This lies typically around ***25 m/s***. Finally, the ***electrical generator*** also imposes a ***limit*** on the ***power*** that can be ***output***. Thus, beyond a certain wind speed, the ***power*** is limited to a ***constant value***. This value is called the ***rated power*** and typically occurs for wind speeds between ***12*** and ***17 m/s***.



In this context, wind turbine ***control*** has ***two*** main purposes: in ***normal conditions***, it makes sure that the power does not exceed the rated power, and in ***off-design conditions***, it brings the system to a safe state for example during extreme wind gusts. Of course, safety systems should always be able to overrule the nominal controller.



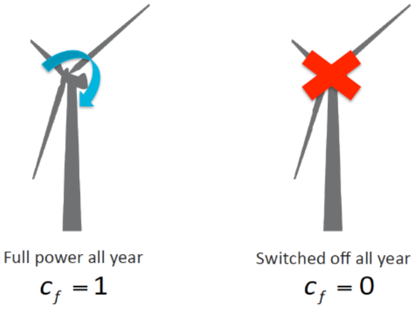
In above discussion, we saw that, for each wind speed, there is an optimal rotational speed for which the power is maximum. Thus, if we plot the ***power extracted by the wind turbine as a function of the rotational speed***, it will look like this. Of course, the exact values on this ***power*** curve ***change*** with the ***wind speed***. The larger the wind speed, the more the extracted power. For each wind speed, control in normal conditions aims at changing the rotational speed of the rotor to achieve the maximum power. Below rated power, this is done through the generator torque, and is therefore called ***torque control***. Eventually, when ***rated power*** is ***attained***, the ***power*** is ***kept constant*** by turning the blades along their axis, that is by ***pitching*** them.

An important concept used in energy production is the ***capacity factor***. The capacity factor indicates the percentage of time a system runs at full power over a reference period of time.

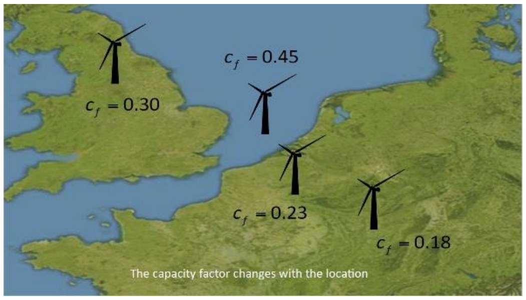
$$C_f = \frac{T_{equivalent}}{T_{actual}}$$

In this formula, T_{actual} is the reference time to achieve the given production, for example 1 year, if we are considering the yearly production. $T_{equivalent}$, on the other hand, is the time needed to achieve the same yearly production, if the wind turbine was running all the time, at full power. By definition, $T_{equivalent}$ is always smaller than T_{actual}, so that the ***capacity factor*** is always ***smaller*** than ***unity***.

As a consequence, in the ***ideal case*** of a wind turbine running all year at full power, without interruption, the capacity factor equals ***1***. By contrast, if the same wind turbine does ***not*** run at all during the year, the capacity factor is ***zero***. Thus, crucially, the capacity factor is not a measure of the ***quality*** of the system! Because no matter how good a wind turbine is, if it's always switched off, its capacity factor is zero.

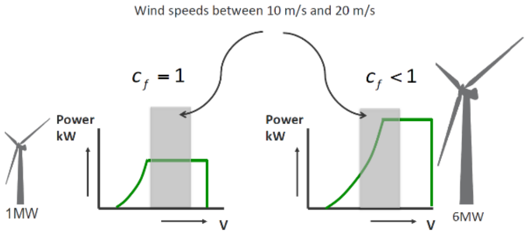


This figure shows how a given wind turbine (of a given quality) can have ***different capacity factors*** depending on where it is installed. In particular, the ***capacity factor*** of a given wind turbine generally ***increases*** with the ***wind speed***. This is also, why the capacity factor is usually ***greater offshore than onshore***. As indicated on this figure, offshore, the capacity factor C_f is around 0.45.



The capacity factor changes with the location

It should be kept in mind that a very ***large capacity factor*** is not necessarily the ***economic optimum***. For example, in a given wind, a ***smaller wind turbine*** might have a larger capacity factor than a ***large wind turbine*** but eventually produce less power. Imagine that the wind speed varies between 10 m/s and 20m/s at a given location. Placing let's say a ***1MW*** turbine at this location might mean that it will run all the time at rated power, thus producing 1MW all year long. By contrast, a ***6MW*** turbine might not be running at rated power all the time (thus its capacity factor will be lower than one). However, when it does run at full power, it will produce 6MW. So, despite its lower capacity factor, the overall power produced by the 6MW turbine over one year might well be ***larger*** than that of the 1MW turbine.



Energy Yield:

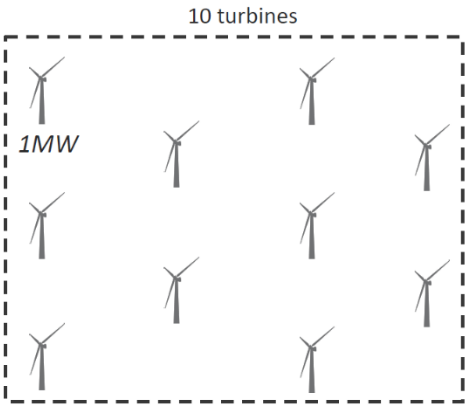
We can compute a rough estimate of the ***energy yield*** using the ***capacity factor***. Remember that the capacity factor is an indicator of the percentage of time a wind turbine runs at full power. So, knowing the rated power of the turbine, we can multiply this value by the capacity factor to get a rough estimate of the energy yield. If we further multiply this quantity by the numbers of hours in a year, the estimate is expressed in terms of Wh/year, which is a measure of energy. As we discuss previously, typical values of the capacity factors are: ***0.25 onshore*** and up to ***0.45 offshore***. Again, remember that the capacity factor depends on the size of the turbine and its location.

$$\textbf{Energy Yield} = \frac{\textbf{hours}}{\textbf{year}} * \textbf{installed power} * \mathbf{C_f}$$

E.g. a large onshore wind turbine of 50MW is installed, calculate its annual energy yield?

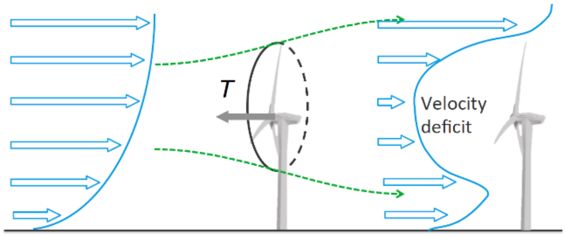
$$\boldsymbol{EY = \frac{8760\ h}{y} * 50\ MW * 0.25}$$

$$\boldsymbol{EY = \frac{110,000\ MWh}{y} = \frac{110\ GWh}{y}}$$



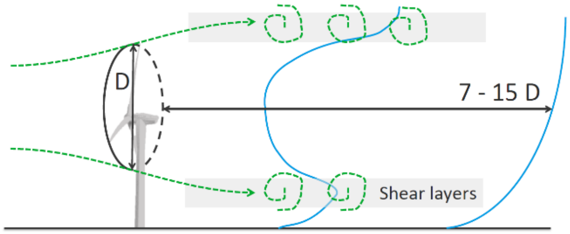
So now we know how to compute (or estimate) the energy produced by a wind turbine. But what about the energy produced by a ***farm*** of, let's say, ***ten wind turbines?*** Is it simply ten times the power produced by one of the wind turbines? Well, the answer is generally no, because of the ***interaction*** between the turbines.

We discussed previously that a wind turbine rotor ***disturbs*** the incoming ***wind flow***. It exerts a force, which is necessary to produce power, and therefore ***slows down*** the flow. We have also seen what a typical (undisturbed) profile of wind velocity looks like. The wind speed equals zero at the ground and gradually increases with altitude.

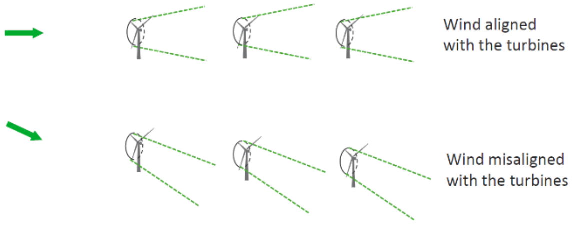


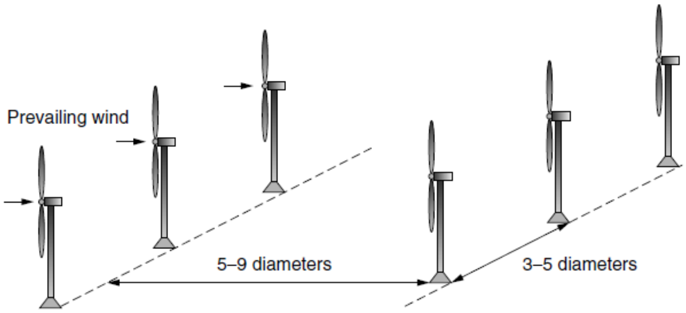
Downstream of the rotor, the wind velocity profile is substantially modified. The force exerted by the rotor creates a ***velocity deficit***, that is a significant reduction in wind speed. If another wind turbine is placed in this ***wake region***, it will experience a ***reduced*** incoming ***wind*** speed, and consequently, it will produce ***less power***.

The presence of a velocity deficit also implies that there are ***strong gradients*** of the velocity profile, especially at the ***bottom*** and the ***top*** of the rotor. These shear ***layers*** are the source of ***vortex*** generation, meaning that turbulent eddies are ***shed*** in the wake region. These vortices tend to ***suppress*** the ***velocity deficit*** by bringing air from outside into the deficit region. This mixing ***helps recover*** the original velocity profile. It can however take a ***distance*** of several ***turbine diameters*** before a full wake recovery is achieved. This has ***consequences*** on the wind turbine placement in a farm.



The given figure shows the ***impact*** of the wake on other turbines depends on the ***wind direction***: as wind changes, the region in which the wake develops moves around, hence increasing or decreasing the velocity seen by any given wind turbine. Finding the optimal wind turbine layout in a farm is no easy task, and indeed an ***active area of research***. In general, a ***good placement*** results from a compromise between ***power generated and area of land used***. Today, we can ***limit*** the ***loss*** in the ***power*** produced by a farm due to wake effects to only ***5- 10%***.





Electrical System:

So now we characterize the wind resource, and we know, how the kinetic energy contained in wind is converted into mechanical energy by the aerodynamics of the rotor. Now, this *mechanical energy has to be converted into electrical energy* and ***fed*** into the power system.

The ***requirements*** of the electric system that makes this connection are as following:

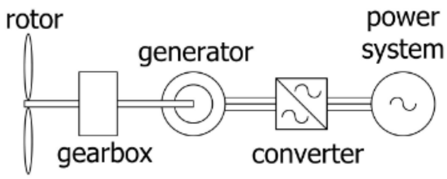
1. The turbine has a power curve and that power must be converted into electrical power.
2. This system has to operate at a varying speed.
3. The power has to be supplied to the power system at the voltage and frequency of that power system.
4. This has to be done in a cost-effective way (minimizing the cost of energy).
5. There are all kinds of control, protection and safety systems around this.

The ***electrical system*** that makes this connection can be divided into ***two*** parts:

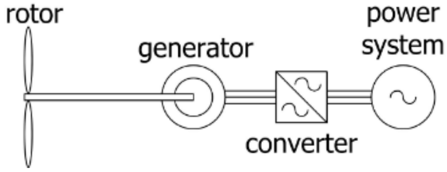
1. A part ***inside*** the wind turbine called the ***generator system*** (This system converts the mechanical power into electrical power)
2. A part ***outside*** the wind turbine called the ***collection and transmission system*** (This system collects the power within a wind farm and transmits it to the power system)

First, we will have a look at the ***generator system***. In wind turbines, different generator systems are applied. The most important difference is between ***geared drive*** systems and ***direct drive*** systems. In a geared drive system, the mechanical speed of the main shaft is increased by a gearbox to a speed of roughly 1500 rotations per minute. Then a high-speed generator converts the mechanical power into electrical power. In a direct drive system, the generator is directly driven by the main shaft of the wind turbine, so it rotates at a very low speed.

Geared drive
- Gearbox
- Small high speed generator



Direct drive
- No gearbox
- Large low speed generator

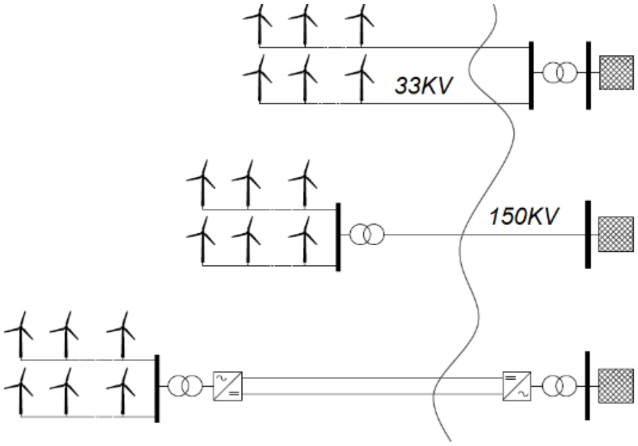


The most important ***reason*** to develop ***direct drive*** systems is to ***get rid of the maintenance*** and the ***failures of gearboxes***. However, the ***consequence*** is that a ***large and expensive direct-drive generator*** is needed. *Both systems need a power electronic converter for the connection to the power system*. The generators operate at a varying speed and therefore generate at a varying voltage and a varying frequency. The power system has a constant voltage and a constant frequency. A *power electronic converter converts the varying voltage and frequency into constant voltage and frequency*. At ***full load***, the typical efficiencies of gearboxes, generators and power electronic converters are in the order of ***97%***. At ***partial load***, these efficiencies may ***decrease***, especially for gearboxes.

We will now have a look at the ***collection and transmission system***. For a ***single onshore wind turbine***, this is normally done by ***connecting*** it to the power system using a ***transformer*** to ***increase*** the ***voltage level*** of the generator system to that of the power system.

For a ***wind farm***, especially ***offshore***, this is more complicated. In a wind farm, a large number of wind turbines are generating electrical power. This power has to be ***collected*** within the wind farm, it has to be converted to the right voltage level and then it has to be ***transmitted*** to shore. The way in which this is done mainly depends on the ***distance*** to the power system onshore.

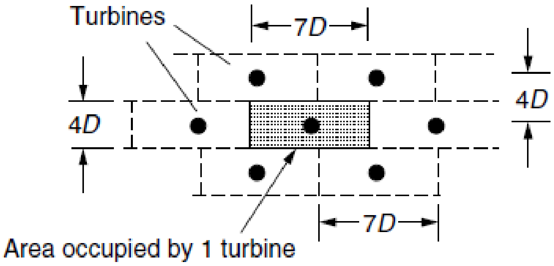
- OWEZ
  - 108 MW
  - 10 km
- Prinses Amalia
  - 120 MW
  - 23 km
- Bard Offshore 1
  - 400 MW
  - 90 km



Lab Task:

1. A NEG Micon 60-m diameter wind turbine having a rated power of 1000 kW is installed at some site, calculate Capacity Factor. The total energy produced is 2.851 x 10^6 kWh/yr.

2. Suppose that a wind farm has 4-rotor-diameter tower spacing along its rows, with 7-diameter spacing between rows (4*D* × 7*D*). Assume 30% wind turbine efficiency and an array efficiency of 80%.
   a) Find the annual energy production per unit of land area in an area with 400-W/m2 winds at hub height
   b) Suppose that the owner of the wind turbines leases the land from a rancher for $100 per acre per year. What does the lease cost per kWh generated?



Note: you can take help from example 6.12 (from Recommended book of RES lab) to solve this lab task. Where A = πr^2, r = D/2, 1 acre = 4047 m^2 and 1$ = 100¢.

Conclusion and Comments: