Power & Energy systems II
Introduction to Wind Energy : Technologies

Florimond Guéniat
florimond.gueniat@bcu.ac.uk

1st of May, 2018

Birmingham City University, Engineering and Built Environment

What will you learn

These lessons will be mostly, obviously, about wind turbines :

- what it is - general knowledge
- why it works - physics
- how it works - engineering
- why it is interesting - economics & challenges

I try to explain in details (maybe too much). *Please* let me know if you do not understand something.

What will you learn

These lessons will be mostly, obviously, about wind turbines :

- what it is - general knowledge
- why it works - physics
- how it works - engineering
- why it is interesting - economics & challenges

I try to explain in details (maybe too much). *Please* let me know if you do not understand something.

What will you learn in this section

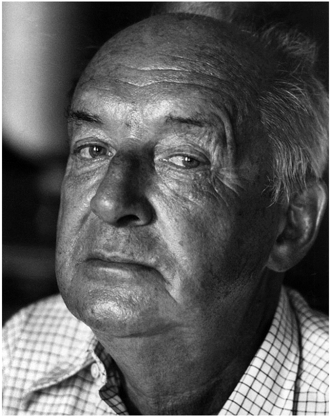
We will cover the basic engineering of wind turbines :

- what pieces compose a wind turbine
- the possible orientations
- the range of operation
- the number of blades

About the components

" Somehow these dull components formed a wonderfully comfortable and harmonious whole. "

Vladimir Nabokov, "Bend Sinister"



Main components of a wind turbine

Rotor blades	Captures the wind and transfers its power to the rotor hub
Hub	Attaches the rotor to the low-speed shaft
Low speed shaft	Connects the rotor hub to the gearbox
Gear box	Connects low-speed shaft and high-speed shaft *ratio* ≈ 50 *for a 600 kW turbine*
High-speed shaft	Drives the electrical generator *Rotates at approximately* 1500 *RPM.* *Mechanical brake is used for service or as backup for the aerodynamic brake*
Electric generator	Induction or asynchronous generator 500 *to* $1,500kW$
Nacelle	Contains the key components of the wind turbine

Main components of a wind turbine

Yaw mechanism	Turns the nacelle to the wind.
Electronic controller	Monitors the condition of the wind turbine. *Controls pitch and yaw mechanisms* *In case of any malfunction (e.g., overheating), it stops the wind turbine*
Hydraulic system	Resets the aerodynamic brakes of the wind turbine
Cooling system	Cools the electrical generator
Tower	Carries the nacelle and the rotor
Anemometer and wind vane	Measures the speed and the direction of the wind

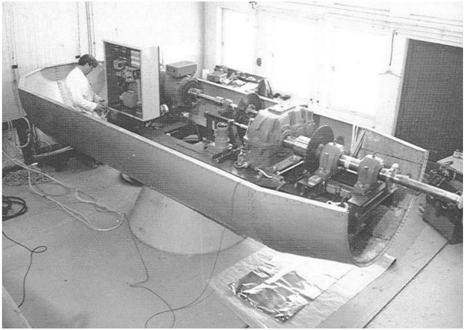
Main components of a wind turbine : Tower

What holds the turbine.

The first piece of the wind turbine !
It holds something...

Main components of a wind turbine : Nacelle

Contains the key components of the wind turbine

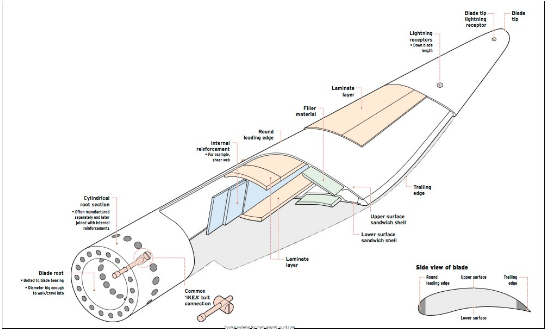


Nacelle and interior of a Saab Sania.

The nacelle contains all the stuff. Something important is attached to it...

Main components of a wind turbine : Blades

Captures the wind and transfers its power to the rotor hub



Scheme of a blade.

[windpowermonthly.com]

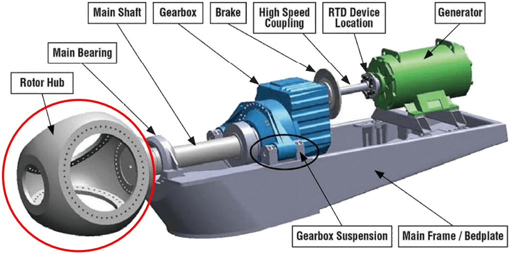
High speed wind machine rotors usually have blades with an airfoil cross section.

The blades are usually made of wood solid or laminated, fiberglass, or metal.

But wait, the blades are turning ! How are they attached to the nacelle ?

Main components of a wind turbine : Hub

Attaches the rotor to the low-speed shaft



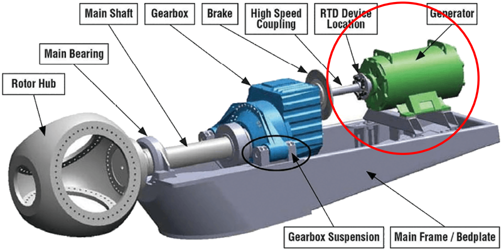
Scheme of the drive train.
[windpowerengineering. com]

The blades are attached by a hub assembly to a main shaft.
If the blades are designed for pitch control, the hub can be fairly intricate.

So now we want to produce the electricity...

Main components of a wind turbine : Generator

Induction or asynchronous generator $500\ to\ 1,500kW$
Transform the rotation movement in electricity



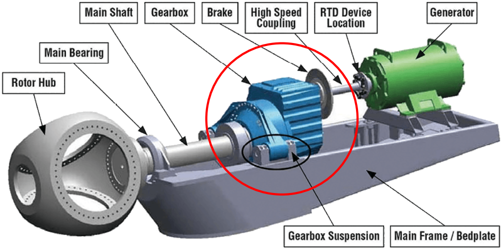
Scheme of the drive train.
[windpowerengineering. com]
Rotating magnetic field induces current.

We need the part that adapt the low speed from the blade to the high speed of the generator !

Main components of a wind turbine : Gear Box

Connects low-speed shaft and high-speed shaft and adapt the speed from the rotor to the generator

ratio ≈ 50 for a 600 kW turbine



Scheme of the drive train.

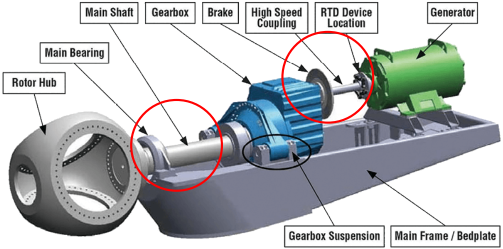
[windpowerengineering.com]

Common ratios range from 30 :1 to 90 :1.

And what is the pieces between the gearbox, the generator and the hub ?

Main components of a wind turbine : Shafts

Connects the rotor hub to the gearbox // Drives the electrical generator



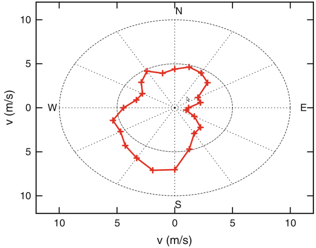
Scheme of the drive train.
[windpowerengineering. com]
Compare the shafts' dimensions !

Okay, it seems to work. But what if the wind turns ?

Main components of a wind turbine : Yaw mechanism

Turns the nacelle to the wind.

Yaw Error : if the rotor is not perpendicular to the wind.
$\rightsquigarrow$ lower share of the energy in the wind will be running through the rotor area.
The share drops to the cosine of the yaw error.



Wind direction near Hamburg
[A. Schaffarczyk, 2014]

Fine. But how the turbine knows that the wind is turning ?

Main components of a wind turbine : Yaw mechanism

Turns the nacelle to the wind.

Passive yaw mechanism from the turbine in the park !

Wind forces direct the rotor.
Common on small turbines.

Fine. But how the turbine knows that the wind is turning ?

Main components of a wind turbine : Yaw mechanism

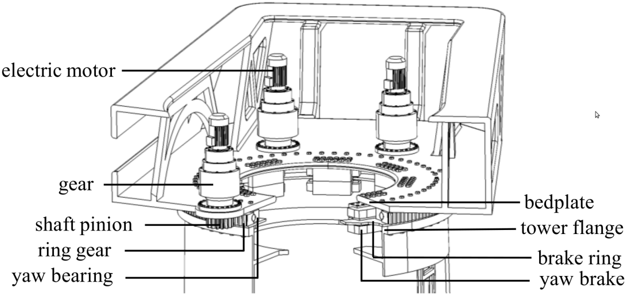
Turns the nacelle to the wind.

Passive yaw mechanism from the HevAir 3k.
[hevenergies.ie/index.php/products/hevair-3k/]
Wind forces direct the rotor.
Common on small turbines.

Fine. But how the turbine knows that the wind is turning ?

Main components of a wind turbine : Yaw mechanism

Turns the nacelle to the wind.



Sketch of a yaw mechanism.
[M.G. Kim & P.H. Dalhoff 2014]
Yaw drive turns the rotor into the wind.

Fine. But how the turbine knows that the wind is turning ?

Main components of a wind turbine : Anemometers

Measures the speed and the direction of the wind

Sensors.

Used for turning on/off the turbine
and for the orientation of the rotor (yaw mechanism)

About axis

" Life isn't some vertical or horizontal line. "

Patti Smith

Axis

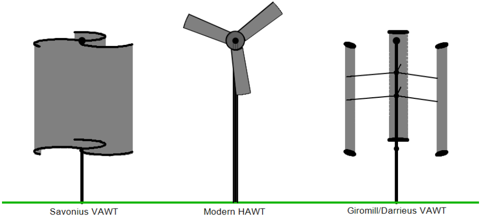
Two orientations of turbine are possible - Horizontal axis (HAWT) and Vertical axis (VAWT).

HAWT In horizontal axis turbine, it is possible to catch more wind and so the power output can be higher than that of vertical axis.
But in horizontal axis design, the tower is higher and more blade design parameters have to be defined.

VAWT In vertical axis turbine, no yaw system is required and there is no cyclic load on the blade, thus it is easier to design.
Maintenance is easier in vertical axis turbine whereas horizontal axis turbine offers better performance.

Axis

Two orientations of turbine are possible - Horizontal axis (HAWT) and Vertical axis (VAWT).



HAWT & VAWT *[wikipedia commons]*

Orientation

Two types of orientations with respect to the wind are also possible :

Downwind

The downwind turbine has its rotor on the *back side* of the turbine. The nacelle typically is designed to seek the wind, thus negating the need for a separate yaw mechanism.

Pros The rotor blades can be *flexible* (no risk of hitting the hub). They can be *less expensive* to make and they can relieve stress on the tower during high or gusty wind conditions : some energy can be dissipated by flexing of the blade instead of the hub.

Cons The flexing may fatigue the blades. Since the rotor blades are actually passed behind the tower, there is a *tower shadowing* phenomenon (turbulence, loss of power). It results in increased fatigue and *lower energy* that can be harvested from the wind.

Orientation

Two types of orientations with respect to the wind are also possible :

Upwind

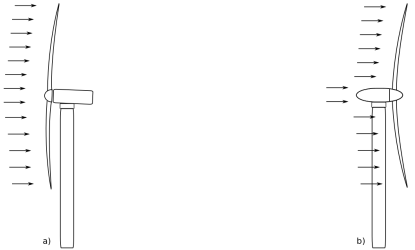
The rotor on an upwind turbine is in the *front* of the unit (like oldie airplanes). This is the most common type of small turbines operating. To keep it oriented into the wind, a *yaw mechanism* is needed.

Pros It reduces tower shading. If the air will start to bend around the tower before it passes it (due to viscosity), there is *less loss of power* from the interference.

Cons The extended nacelle that is required to position the rotor away from the tower (blade strike). The blades are (somewhat) *stiff* to avoid bending back into the tower. This will mean the point where the blade attaches to the rotor hub will be stressed during high, gusty wind conditions.

Orientation

Two types of orientations with respect to the wind are also possible :



upwind downwind

[wikipedia commons]

About turbine's wake

" There is a need for a model that handles both single and multiple wake and the wind farms interaction with the atmospheric boundary layer. "

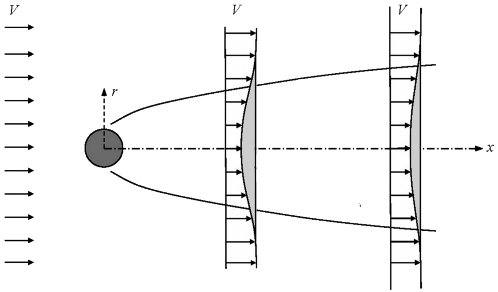
Sten Frandsen, 2006

Tower shadow and Wake effect

The wind turbine (resp. tower) produces a *wind deficit* in the downwind direction, named *wake* (resp. *tower shadow*).

Tower shadow and Wake effect

The wind turbine (resp. tower) produces a *wind deficit* in the downwind direction, named *wake* (resp. *tower shadow*).



[A. Prasad, 2014]

Tower shadow and Wake effect

The wind turbine (resp. tower) produces a *wind deficit* in the downwind direction, named *wake* (resp. *tower shadow*).

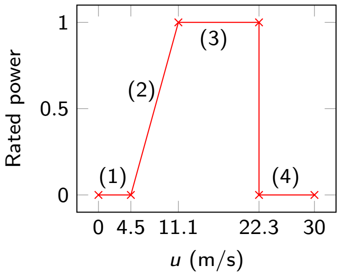
It is related to two main issues :
The *blades pass through* that wake every revolution.
$\rightsquigarrow$ *periodic loads* (fatigue damage and variations in power output), noise.
The other wind turbines, if in the wake, are facing a wind with more turbulence and a *lower velocity*.
$\rightsquigarrow$ lower and less clean power output.

This effect can be reduced. Space between turbines $L_{\parallel}, L_{\perp}$ should be :

- main wind direction : *four times the rotor diameter* - $L_{\parallel} = 4D$.
- perpendicular to main wind direction : *two time the rotor diameter* - $L_{\perp} = 2D$.

Range of operation

There is four regimes :



1. The wind is not strong enough to generate power. The torque produced by the wind is below the level needed to overcome the resistance of the load.
2. The wind is fast enough (*cut-in speed*) and the wind turbine is operational. The generated power increases with the wind speed. Typical wind turbines reach the *rated power* (or maximum operating power) around $u_c = 11.1$m/s.
3. Wind faster than u_c will not really lead to an increase in the delivered power.
4. The wind is too strong (*cut-out speed*, generally around 22.3m/s). The rotor is locked for preventing structure failures.

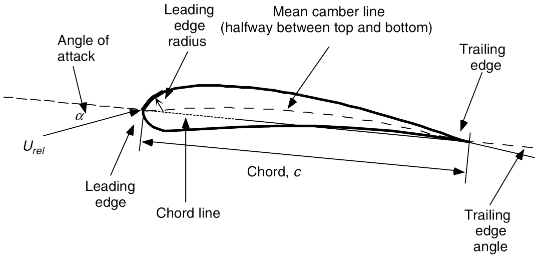
About airfoils

" Airfoils are structures with specific geometric shapes that are used to generate mechanical forces "

J. Manwell et al., 2009

Nomenclature of an airfoil

There are many types of airfoils, that can be depicted by a few parameters :

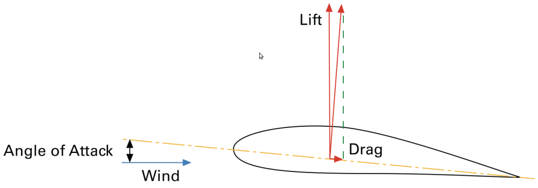


- The *chord* c is the line between the Leading and Trailing edges.
- The *thickness* is the distance between the upper and lower surfaces, measured perpendicular to the chord line.
- The *angle of attack* α is the angle between the relative wind and the chord line.

The draft and lift are mostly driven by the leading edge radius, the mean camber line, the maximum thickness and its distribution of the profile, and the trailing edge angle.

Lift and Drag

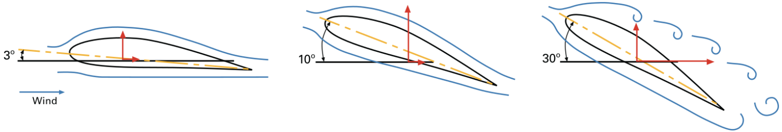
The lift force *increases* with the angle of attack.
At large angles of attack the blade stalls and the lift decreases.
$\rightsquigarrow$ there is an *optimum angle of attack*.



If the angle is too large, the drag increases dramatically.

Lift and Drag

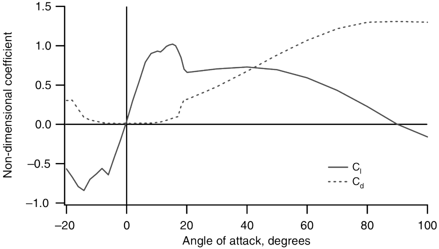
The lift force *increases* with the angle of attack.
At large angles of attack the blade stalls and the lift decreases.
⇝ there is an *optimum angle of attack*.



If the angle is too large, the drag increases dramatically.

Lift and drag coefficients

C_D and C_L are *somewhat comparable*, even if *usually* $C_L > C_D$.



Lift and drag coefficients, for the S809 airfoil.
[J. Manwell et al., 2009]

Shape of the blade

The blade can be optimize by changing the shape over its length .

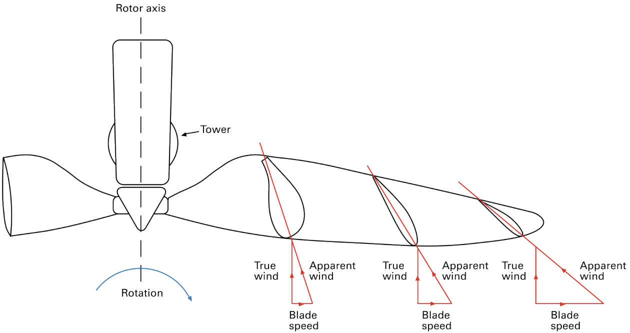


Illustration of the relative speed among the blade.
[http ://kimerius.com/]

Shape of the blade

The blade can be optimize by changing the shape over its length .

The relative wind $u_{rel} = u - \omega r$ is the wind seen by the part of the blade at distance r from the center.
Consequently, the relative wind has hence *steeper angle* at the end of the blade. With no change in the angle of attack, the blade will *stall* and induce some drag.

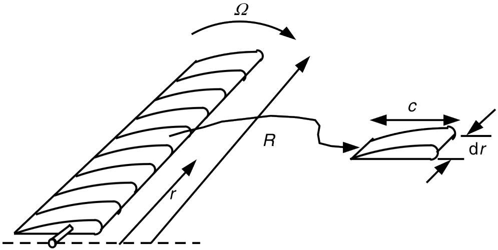
To optimize the lift, the angle of attack has to remain around a given value for a given airfoil shape. It is important to harvest the maximum power.

The blade is hence *twisted* along its span, so the angle between the relative wind and the blade stays close to the optimal angle of attack.

In a similar manner, the shape of the airfoil can be optimize along the blade's span.

Shape of the blade

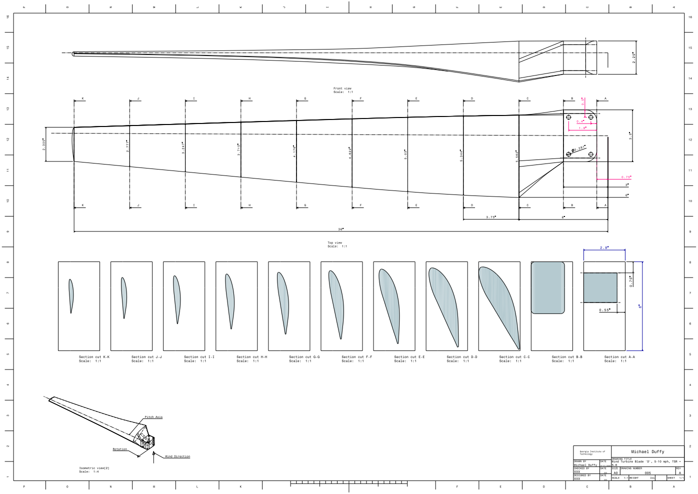
The blade can be optimize by changing the shape over its length .



A method is to decompose the blade in elements and to locally optimize the angle and shape of the blade. *See [J. Manwell et al., 2009] for details.*

Shape of the blade

The blade can be optimize by changing the shape over its length .



[http ://www.aerodyndesign.com]

About the number of blades

" The first Blade was very stylish. "

Guillermo Del Toro, 2002

Constrains imposed by the generator

The generator needs to operate at *high and constant speed* to be more efficient.

- A *control mechanism* is needed to keep the shaft speed as constant as possible, *the pitch control*.
- A *high shaft rotational speed*, or a high *TSR* λ is desirable

Pitch control

The purpose of pitch control is to maintain the optimum blade angle to :

- maintain a certain rotor speeds - in case of high wind.
  It prevents damages.
- power output - in nominal condition.
  It controls the low-speed shaft speed for a more clean power curve

Pitch adjustment will either stall or furl.

Stalling : The angle of attack increases - the flat side of the blade face further into the wind.

Furling : The angle of attack decreases -the edge of the blade to face the oncoming wind.

Intuition about the number of blades

More blades implies a *slower rotational speed* (the drag increases and the optimal TSR is lower).
Note that it also generates more torque, but the generator does not need much (it would be different for other applications, such as pumping water).

So, the *fewer the number of blades, the better* suited the system is for producing power.

Reminder : Tip speed ratio

The *Tip Speed Ratio* (TSR) is a dimensionless number quantifying the tip speed with respect to the speed of the wind :

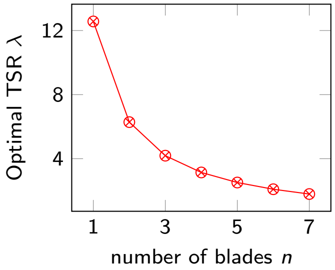
$$TSR = \lambda = \frac{\text{speed of tip}}{\text{speed of wind}} = \frac{\omega D}{2u}$$

The optimal TSR for maximum power extraction is inferred by relating the time taken for the *disturbed wind to reestablish itself* to the time required for the *next blade to move into* the location of the preceding blade.
The optimal TSR is hence :

$$\lambda_{opt} = \frac{\omega_{opt} D}{2u} \approx \frac{4\pi}{n}$$

Reminder : Tip speed ratio

The *Tip Speed Ratio* (... ing the tip speed with respect to the speed of



The optimal TSR depends on the number of blades n !

The optimal TSR for ... relating the time taken for the *disturbed wind* ... for the *next blade to move into* the location of the preceding blade.

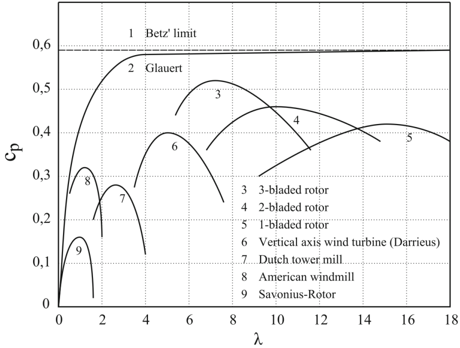
The optimal TSR is hence :

$$\lambda_{opt} = \frac{\omega_{opt} D}{2u} \approx \frac{4\pi}{n}$$

Optimal, really ?

With proper *airfoil design*, the optimal TSR values may be approximately 25 to 30% higher.
These highly-efficient rotor blade airfoils allow to increase the rotational speed of the blade (hence of the shaft), and thus can generate *more power*.

The optimal TSR for a three-bladed rotor would be in the range of 5.2 to 5.5, instead of 4.2.



[A. P. Schaffarczyk, 2014]

Issues related to tip speed

If a high TSR is desirable, disadvantages are numerous :

- *Erosion* on the edges from dust/sand,
  Erosion happens for speed larger than 80m/s (for $D = 80m$, it correspond to a frequency $f \approx 0.3s^-1$) $\rightsquigarrow$ special treatments like helicopter blades.
- *Noise and vibrations* are generated, especially in 2 or 1 blade rotors, *details will come in a few slides*.
- Reduced rotor efficiency due to drag and *tip losses*. *Details will come in a few slides*.

Usually, how many blades can you see on wind turbines ?

Number of blades

A *one-bladed* wind turbine has the *highest potential TSR*.
But many problems structurally and dynamically (large moments on the tower), so it is not very feasible on a large scale.

Number of blades

A *one-bladed* wind turbine has the *highest potential TSR*.
But many problems structurally and dynamically (large moments on the tower), so it is not very feasible on a large scale.

A *two-bladed* turbine has the second highest TSR.
But it induces *vibrations* (noise and stress on the tower/blades) when yawing.

1. There is *less rotational inertia when the blades are vertical* rather than when horizontal. *This is why ice-skater bring their arms to them when spinning !!*
2. When the blades are vertical, the bottom blade is shaded by the tower.

Number of blades

A *one-bladed* wind turbine has the *highest potential TSR*.
But many problems structurally and dynamically (large moments on the tower), so it is not very feasible on a large scale.

A *two-bladed* turbine has the second highest TSR.
But it induces *vibrations* (noise and stress on the tower/blades) when yawing.

1. There is *less rotational inertia when the blades are vertical* rather than when horizontal. *This is why ice-skater bring their arms to them when spinning !!*
2. When the blades are vertical, the bottom blade is shaded by the tower.

A *three-bladed* wind turbine *does not have these issues* and can still have a high highest TSR.

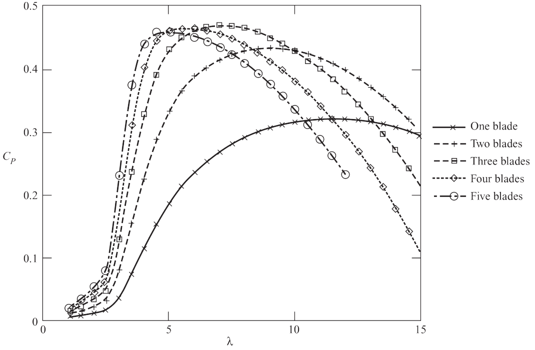
Number of blades

A *one-blac*
But many ... ver), so it is not very

A *two-blac*
But it indu ... g.

1. The ... when horiz ... *ning !!*
2. Whe ... r.

A *three-bl* ... high highest TS



[T. Burton et al., 2001]

Tip loss

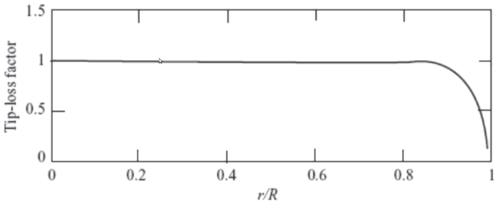
Air tends to *flow around the tip* instead of from the lower to upper surface, as it is easier.
⇝ There is a *reducing power production* (because of less lift) near the tip.

[NASA]

Tip loss

Air tends to *flow around the tip* instead of from the lower to upper surface, as it is easier.
⇝ There is a *reducing power production* (because of less lift) near the tip.

It is possible to take this effect in account in design, by using empirical formulas.
This effect is most noticeable with fewer and/or wider blades.



[Emrah Kulunk, 2011]
This is why you should always have high res/vector pictures !

How much can we harvest, again ?

The Betz' law states that, at max, we can harvest 59.3% of the power available in the wind.
Is it realistic ?

How much can we harvest, again ?

The Betz' law states that, at max, we can harvest 59.3% of the power available in the wind.
Is it realistic ?

Of course not.
Considering the frictional losses, blade surface roughness, and mechanical imperfections, inertia and unsteadiness in the wind, between *35 to 40 percent of the power is extractable under practical conditions*.

Final law

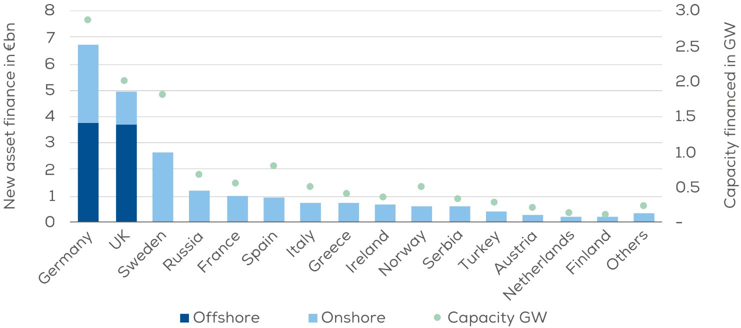
When considering all the factors, engineers use this power law :

$$P = \frac{1}{2}\rho A u^3 C_p N_g N_b$$

with

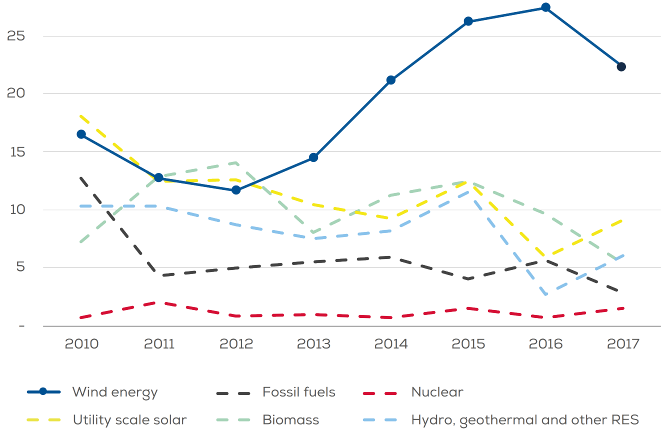
- N_g is the generator efficiency (around 80%)
- N_b is the gearbox efficiency (can be higher than 95%)
- C_p is here the coefficient of performance (inferior to the Betz' limit, around 35%)

Size of the market



[WindEurope 2017]

Evolution of market



[WindEurope 2017]

Capacity Factor

The fraction of the year the turbine generator is operating at rated (i.e., peak) power :

$$CF = \frac{\text{average power}}{\text{rated power}}$$

It is affected by :

- the turbine
- the site

It is around 30% for a well-chosen site.

Estimation of the production

The power is $P_{out} = C_p P_{in}$. Of course, $P_{in}(t) = \frac{1}{2}\rho A u(t)^3$.
It means that the average power is :

$$\begin{aligned} < P_{out} >_T &= < C_p(t)\frac{1}{2}\rho A u(t)^3 >_T \\ &= \frac{1}{T}\int_0^T C_p(t)\frac{1}{2}\rho A u(t)^3 \mathrm{d}t \\ &= \frac{1}{T}\int_0^T C_p(\lambda(t))\frac{1}{2}\rho A u(t)^3 \mathrm{d}t \end{aligned}$$

So this expression depends on

- the distribution of the wind $u(t)$.
- the choice of a rule for $\lambda(t) = \lambda(u(t))$.

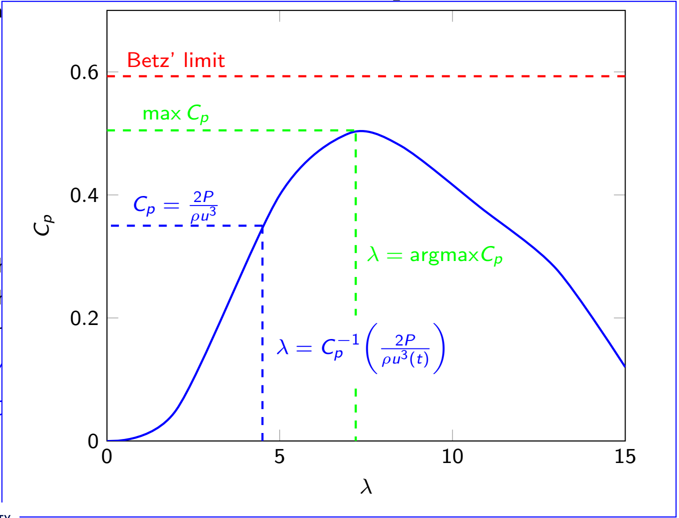
Then there is two solutions :

- *Maximum power* $\rightsquigarrow \lambda(t) = \mathrm{argmax} C_p(\lambda)$
- *Clean power curve* $(P_{out}(t) = cste = P) \rightsquigarrow \lambda(t) = C_p^{-1}\left(\frac{2P}{\rho u^3(t)}\right)$

Estimation of the production

The power is $P_{out} = C_p P_{in}$. Of course, $P_{in}(t) = \frac{1}{2}\rho A u(t)^3$.

It mean



So this

- th
- th

Then th

- *M*
- *C*

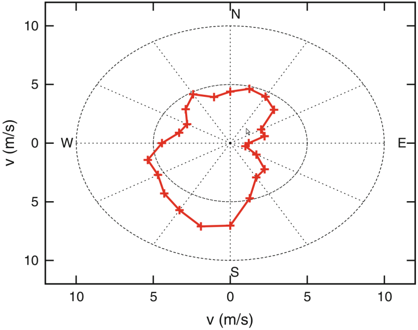
About the wind statistics

" Statistics is the grammar of science. "

Karl Pearson

Why statistics about wind ?

The direction and intensity of the wind vary over time.
It is hence important to describe it statistically to have prediction on the energy production.



wind direction near Hamburg
[A. Schaffarczyk, 2014]

Weibull distribution

Distribution of wind speeds is *skewed* : i.e. not symmetrical. Low speed winds are more frequent that strong winds.

Wind speeds around $5.5m/s$ per second are the most frequent in the UK : it is the *modal value* of the distribution. The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface.

Weibull distribution

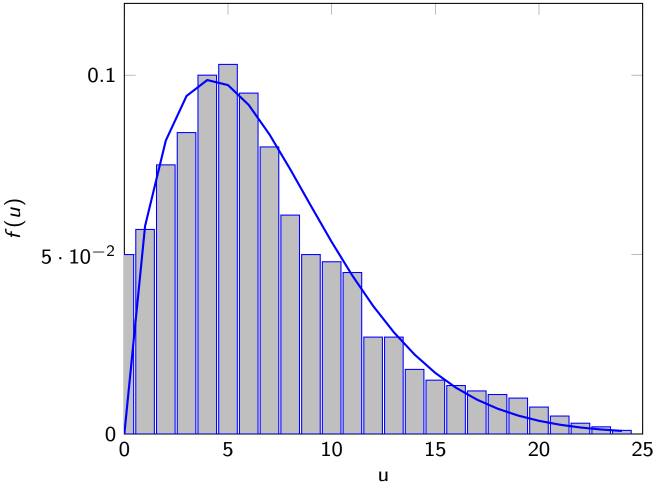
Distribution of wind speeds is *skewed* : i.e. not symmetrical. Low speed winds are more frequent that strong winds.

Wind speeds around $5.5m/s$ per second are the most frequent in the UK : it is the *modal value* of the distribution. The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface.
The Weibull distribution is a useful approximation of the wind distribution, that can be used for *modeling the average harvested energy*.

$$f(u) = \frac{k}{A_w}\left(\frac{u}{A_w}\right)^{k-1} \exp\left(\left(\frac{u}{A_w}\right)^{k}\right)$$

A_w is the Weibull scale parameter in m/s ; a measure for the characteristic wind speed of the distribution. A is proportional to the mean wind speed.
k is the Weibull form parameter. It is related to the shape of a Weibull distribution. A small value for k signifies very variable winds, while constant winds are characterized by a larger k.

Weibull distribution

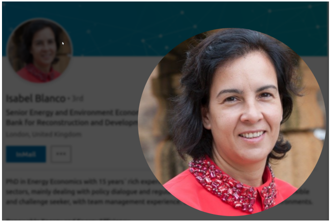


Average wind distribution in 72 stations distributed all over the UK.
[W.G. Früh, AIMS Energy 2015]

In the last two to three years, wind energy companies have repeatedly reported an acute shortage of workers within certain fields.

" Isabel Blanco "

EWEA-Wind at Work,2009



Price of a typical offshore project

It is pretty pricey.

The average price is around $1.3b£$.
It is for financing around 31 *turbines, and for producing* $252MW$.

Generally, 25% is financed by *investors*, and the rest through *loans*.

[WindEurope 2017]

Cost of construction

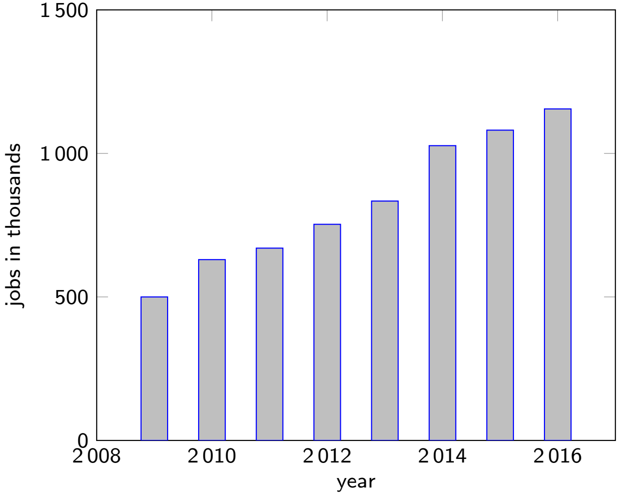
Component	*Share in price*
Tower	26.3%
Rotor blades	22.2%
Rotor hub	1.37%
Rotor bearing	1.22%
Main shaft	1.91%
Main frame	2.80%
Gearbox	12.91%
Generator	3.44%

Component	*Share in price*
Yaw system	1.25%
Pitch system	2.66%
Power converter	5.01%
Transformer	3.59%
Brake system	1.32%
Nacelle	1.35%
Cables	0.96%
Screws	1.04%

total = 89.13%

[EWEA 2009]

Jobs in wind energy, worldwide



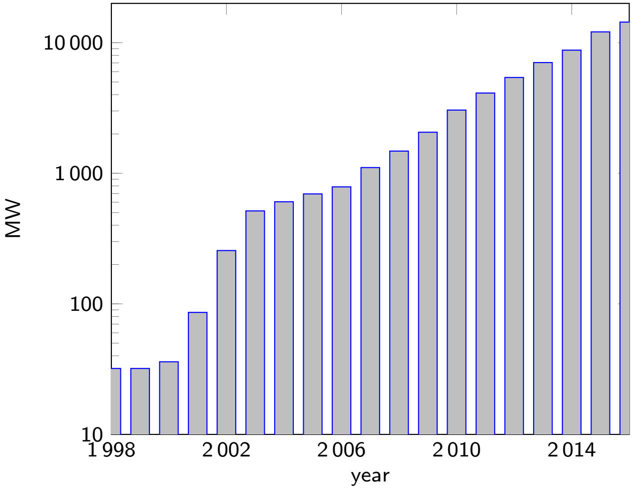
[Renewables 2017 Global Status Report]

Jobs in wind energy, UK

Employment has double from 2010 to 2015, and is expect to *double again from 2015 to 2020*, to reach 80000 direct and indirect jobs.

Offshore wind is the favoured technology by the UK Government to improve the energy infrastructure.
[Renewable Energy Association, 2017]

Offshore wind energy



Global cumulative offshore capacity
[GWEC & EWEA]

It is an *exponentially growing* market !

Offshore wind energy

It cancels *many issues* associated with on-shore with wind-turbines :

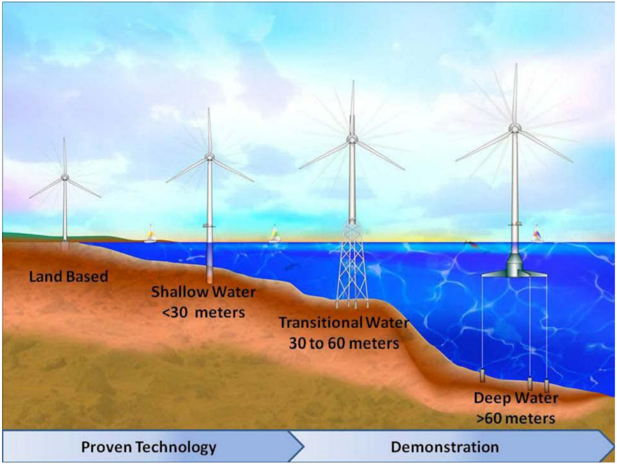
- Does not affect the landscape
- Roughness length (wind shear) is minimal
- Noise is not an issue
- Less impact on birds
- Space is less an issue

Nevertheless

- it is more expensive
- the technology is less mature

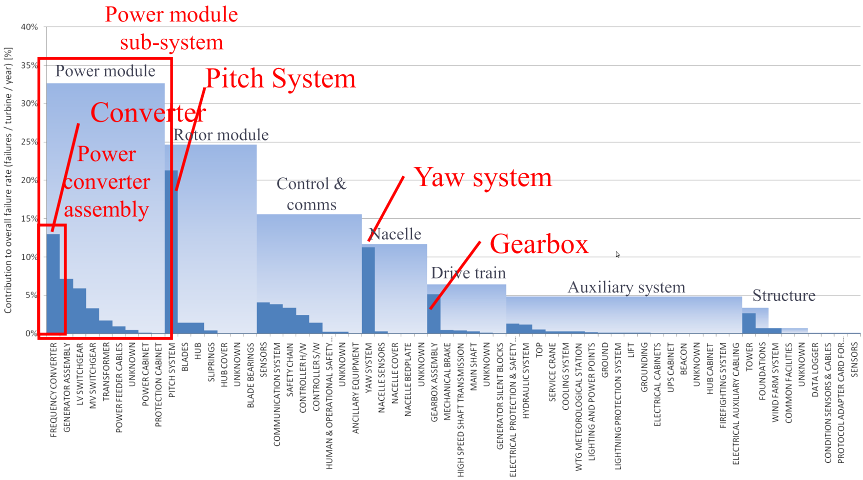
Current and future technologies

Technologies borrow much from *oceans-bases oil/gas wells* ! *More next week in the offshore/tidal energy courses.*



[wiki commons]

What can go wrong ?



[P.J. Tavner et al., Wind Energy, 2007]

What can go wrong ?

[Sam Lennon]

Material

Support structures that are able to carry a mass placed at $153 m height$ are still not possible.

Blade that would exceed $120m$ (would be the worlds largest ever manufactured composite element) cannot be produced as a *single piece* with today's technologies.

A lot of research on *composite materials* are ongoing to produce *lighter larger and more stress resistant* materials,

Fatigue and aerodynamics

The application of *distributed aerodynamic* blade control is still investigated by the industry, as the used theories are mostly valid for 2D flows. Fatigue loads could hence be reduced 20-40%.
Control features for nonlinear systems is still an (my !) undergoing research topic.

Gearbox

Loads and environmental conditions make the design of gearbox challenging.
Indeed, the rotor applies *large moments and forces* on the drivetrain :

- The drivetrain has to be isolated
- The gearbox has to support loads
- The rotations are unsteady

Controlling Farm

Advanced control strategies are particularly relevant for *large offshore* arrays, where *20% of the power* output can be lost due to wake effects between turbines.

Optimised wind *farm layouts* still has to be identified.

There is room for innovative control strategies.

For instance, lowering the power output of the first row facing the undisturbed wind, allows for higher overall wind farm efficiency.

Local Weather predictions

Developing preventative load alleviation strategies by *detecting and evaluating the upcoming gust or vortex* before it arrives at the turbine is still a research topic.

Two talks this week

Please feel free to attend to :

- Wednesday, 12 :30 to 13 :30, MP 438
  Rob Dare, Evolution measurement, will talk about
  "The technology of pressure measurement"
  It is self-explanatory.
  Rob Dare is an Fluid flow Engineer specialized in metrology.
- Thursday, 10 :00 to 11 :00, MP 492
  Matthew Maskell, Glen Dimplex, will talk about
  "The Zeroth Energy System. "
  It is about efficient, green way to balance needs for cooling (AC) and heating in habitation complex.
  Matt is an Heating and Ventilation Engineer, specialized renewable energy.

Questions !

1. What is the cut-in wind speed and the stop wind speed for a turbine ?
2. At what wind speed do you have maximum efficiency ?
3. Why is it impossible to reach the Betz limit of about 60% ? Discuss.
4. What would be the ideal wind speed for the turbine ? Discuss.
5. How many jobs can we expect worldwide in wind energy in 2022 ?
6. Why even number of blades are usually discouraged ?
7. Downwind or Upwind ?
8. How many turbines (diameter 80m) can you install in a field of $2km \times 1km$ in the worst/best cases ?
9. What happens if the tip speed is larger than 80m/s ?

Problem !

1. Sketch the ideal power curve of a turbine, knowing that :
   - rated speed is 14 m/s
   - cut-in speed is 5 m/s
   - rated power is 1.25 MW
   - cut-out speed is 20 m/s
2. Calculate the energy produced in one day if the wind blows continuously between 15 and 20 m/s all day
3. Can the energy produced in one year be determined if you are told that the average wind speed is 14 m/s ? Explain why.

Why bigger is better ?

We shall recall that the energy is $E = P \times \Delta t = \frac{1}{2}\rho A u^3 \Delta t$.
The construction cost is roughly proportional to the size of length of blades :

$$C \approx \gamma R$$

with C the cost (in £), R the length of the blades (in m) and the price factor $\gamma = 60\text{k£/m}$.

Say you can sell the kWh for 0.02£. What is the discount rate ($\frac{\text{income per year}}{\textit{investment}}$) when building a wind turbines with $R = 25\text{m}$ blades ? And for $R = 50\text{m}$ blades ?
bigger wind turbines are hence more cost effective : it explains the growth in size over the years !
Assume that $u = 10\text{m/s}$ and $C_p = 0.45$.