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The Wind Turbine

The Wind Turbine Generator (WTG) is the machine capable of turning an air flow or wind, into electricity, currently there are thousands of WTG's of different sizes deployed around the globe, and most of them share a particular set of characteristics.

The purpose of this paper is to illustrate the main components of a WTG, and how they function to convert an air flow into usable electricity, in addition to this, the reader is briefly introduced to the main principles that make this technology possible, considering the main constrains of the current technology.

Ideally, the reader will then have a comprehensive knowledge over the main functions of the technology in our current economy, as well as what is needed for its widespread deployment, and what can be achieved by implementing it. The readers that desire to obtain more knowledge about the technology should be inspired to investigate and learn further into the technology.

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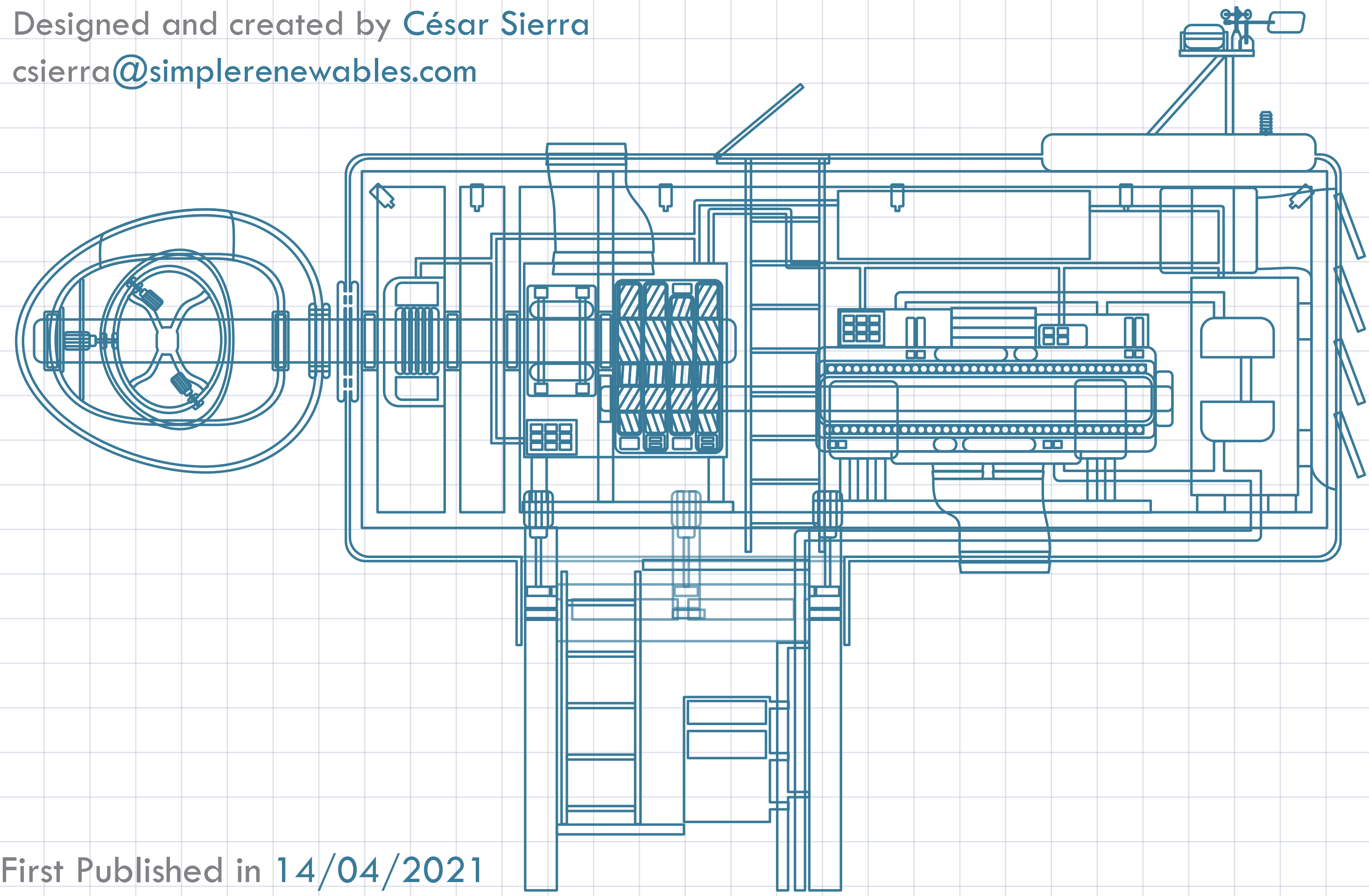

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Wind

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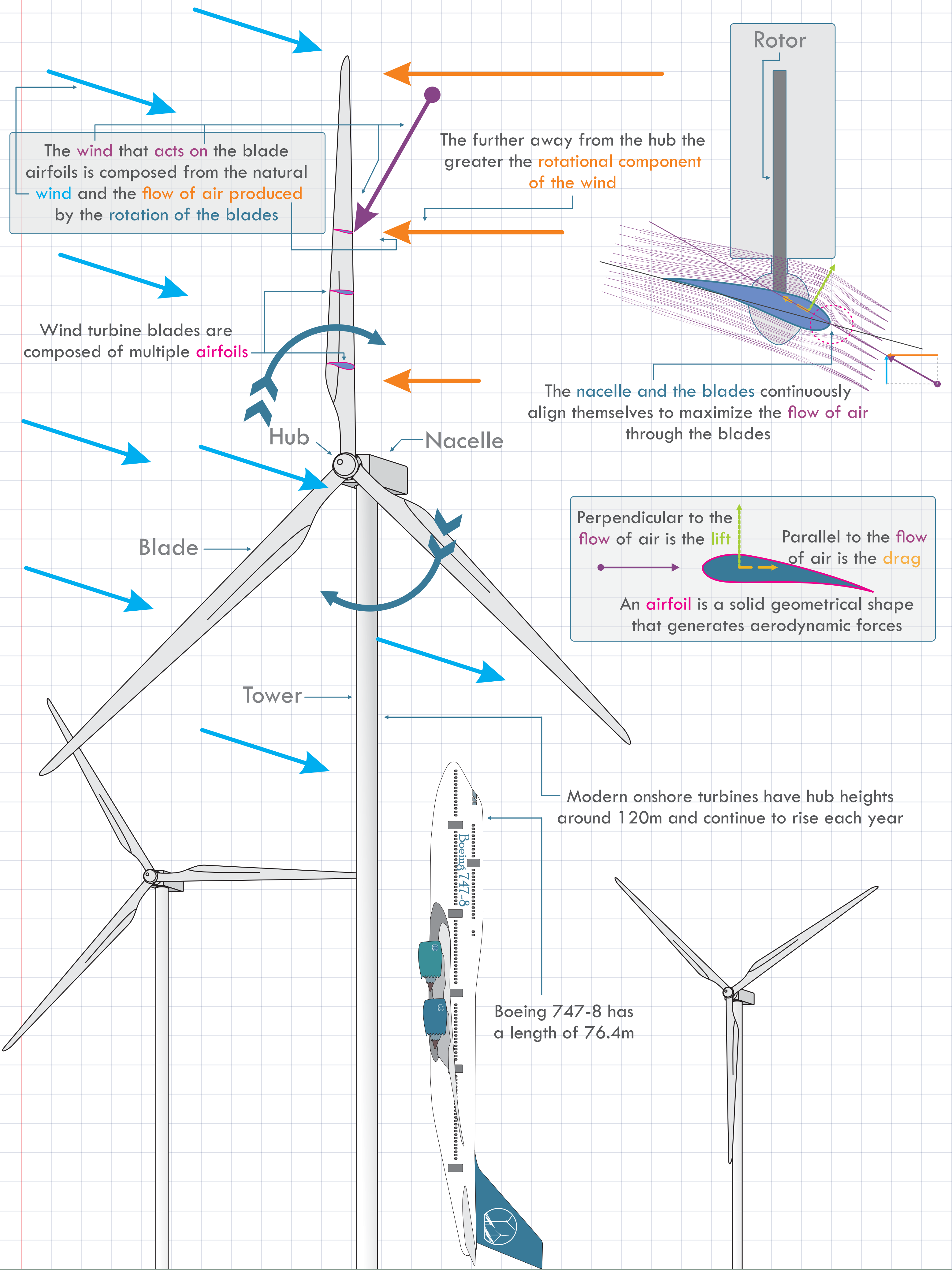

Power output and efficiency

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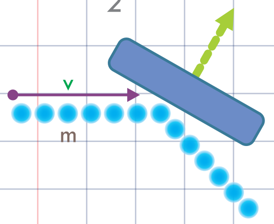
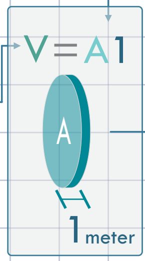
An oversimplification of how WTG's generate energy, is partially given by the power equation which is derived from the kinetic energy equation. However, the turbine components efficiency must be considered to obtain the final power output. The power equation is dependent of 3 main things, rotor diameter, air density and wind speed.

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



Wind turbine blades extract energy form wind particles crossing the swept area, the particles that hit the blades transmit energy by reducing their speed, since their mass is constant.

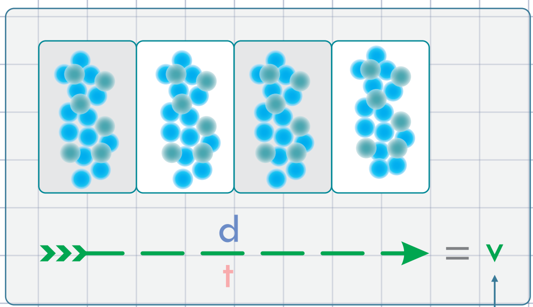


The swept area is given by the length of the blades, and it is the main mechanical improvement that increase the power of a turbine.

$m = V\rho$

$m = A 1 \rho$

$\frac{m}{t} = \text{Mass flow} = V \rho v$

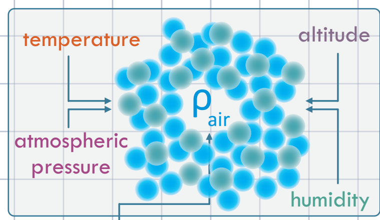


$P = \frac{E}{t}$, $E = \frac{1}{2} m v^2$

$P = \frac{\frac{1}{2} m v^2}{t}$, $\frac{m}{t} = A 1 \rho v$

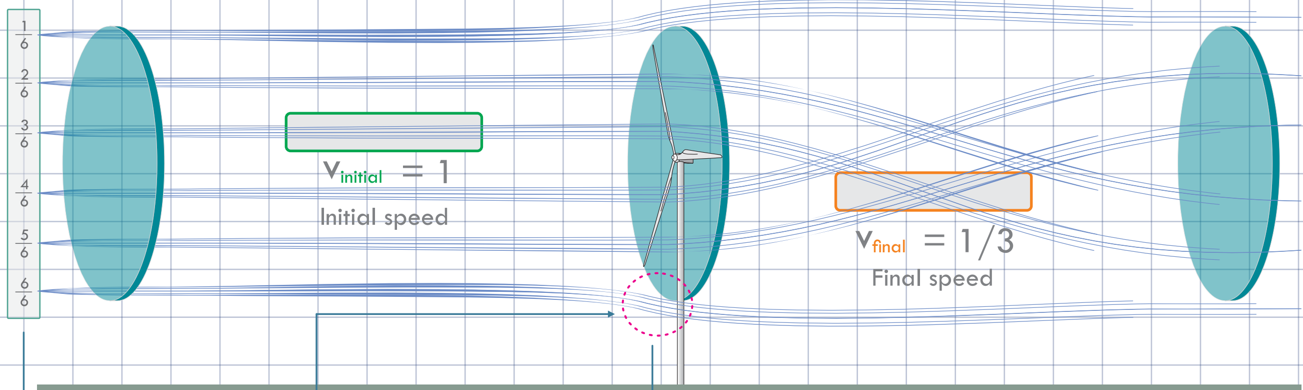
$P = \frac{1}{2} A 1 \rho v v^2$

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



Wind speed affects the power output more than any other factor, the derivation of the mas flow and kinetic energy, results in a cubic wind speed.

The air density is dependent of multiple factors, the altitude and temperature are the most influential.



$\frac{3}{3} V$

Not all wind is affected by the WTG and not all energy can be extracted from the wind

$\frac{2}{3} V \times 88\% =$ 59.26% Betz limit

The most optimal WTG would reduce 2/3 of the wind speed, from 2/3 of the air volume passing through the swept area, this is the theoretical limit of energy that a turbine can extract form the wind.

Theoretical energy extracted

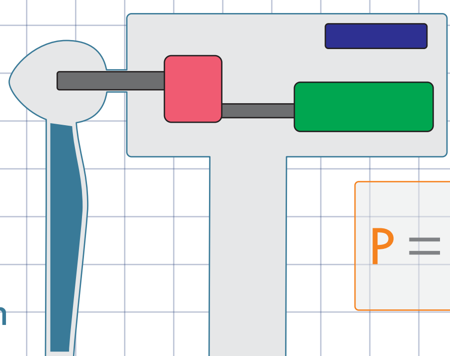
$= (1)^2 - (1/3)^2 = 88.88\%$

$= v_{initial}^2 - v_{final}^2$

Other components → WTG efficiency ← Generator

Gearbox

Blade design



Modern turbines efficiency

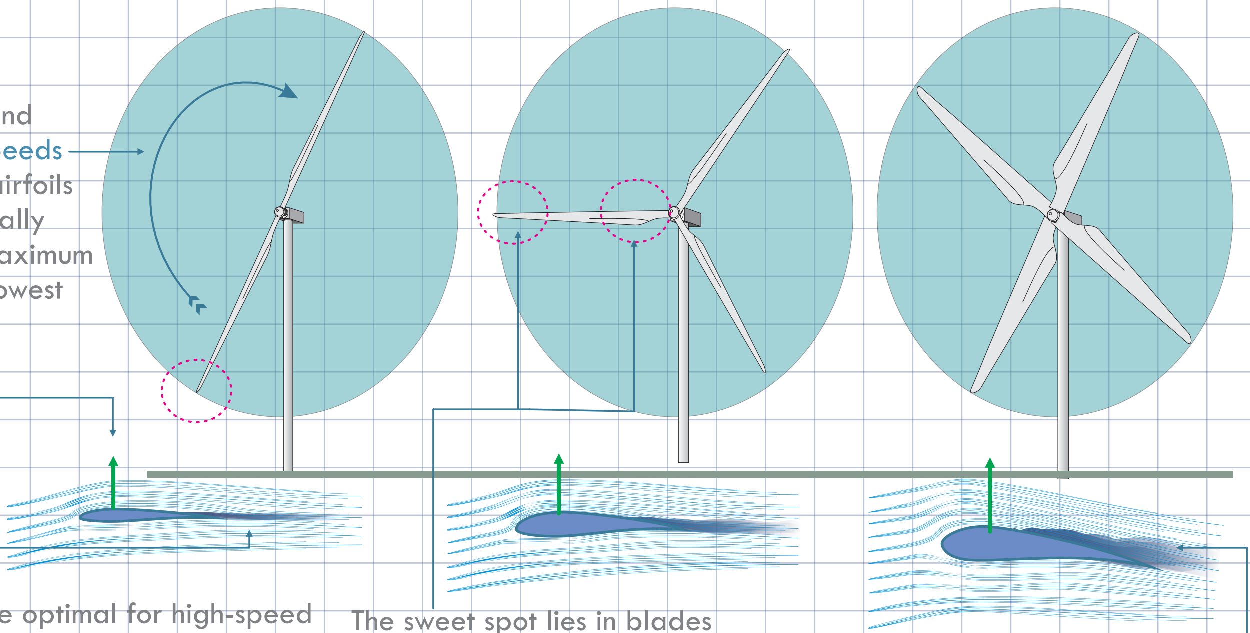
30% - 50%

$P = \frac{1}{2} A \rho v^3 \, WTG_{efficiency}$

Blade design

Faster, longer or thicker? Ideal rotors should be allowed to spin faster and with long blades that cut through air with minimum drag, nevertheless these traits come with their constrains. Modern turbines are optimized to generate as much torque possible within the possibilities of their mechanical and environmental constrains.

Depending on the wind speeds, rotational speeds or angle of attack, airfoils work differently, ideally they generate the maximum lift possible for the lowest drag possible

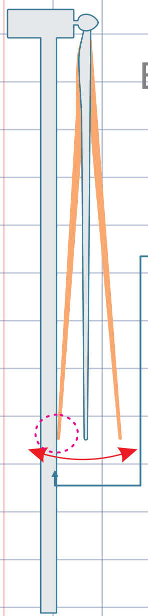


Lift vs Drag

Slim airfoils are optimal for high-speed rotations generating low drags

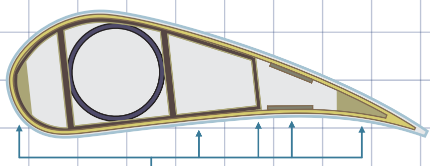
The sweet spot lies in blades that combine multiple airfoils according to their wind speeds

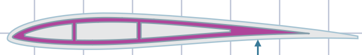
Thicker airfoils generate higher lifts even in low speeds although they tend to have large drags



Blade Length

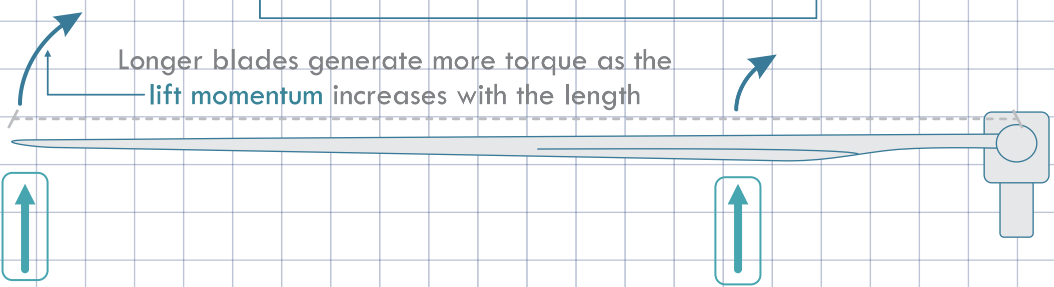
The main constrain of longer blades come with the material stiffness vs cost, long elastic blades could hit the WTG tower in high winds



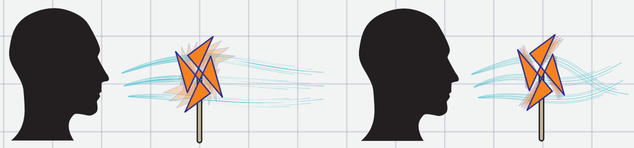


Thicker airfoils require additional structure to maintain their form while slimer airfoils may not have enough space for structure, and require expensive materials to compensate

Longer blades generate more torque as the lift momentum increases with the length

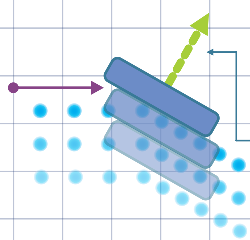


Rotational speed

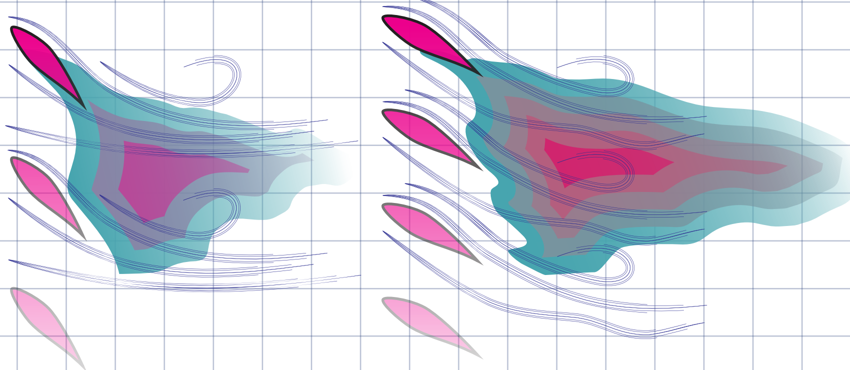


Naturally turbines want to rotate faster, similar to a pinwheel, the faster you blow the faster they rotate

High rotational speeds are ideal as blades are able to extract more energy from the wind and even generate less turbulence, however this comes with an increase on mechanical stress and heavy noise



Fast rotating blades disrupt air flow less and can extract more energy from it

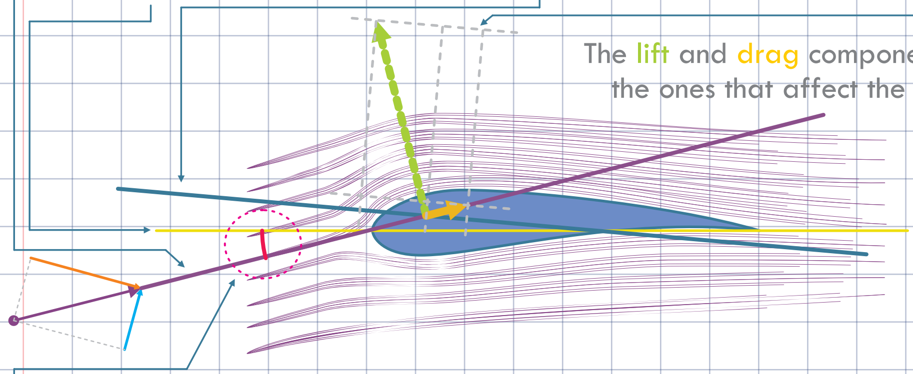


The acting forces

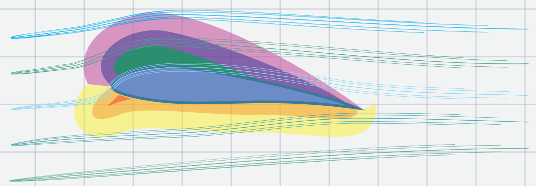
Due to their geometry and orientation the lift and drag forces decompose into different components regarding the WTG's orientation, in the end two forces result, torque and thrust, the first one rotates the generator, the second one is "absorbed" by the structural components of the turbine.

3 different planes act over the airfoil, the direction of the wind, the direction of the airfoil and the direction of the rotation

The lift and drag components on the rotation plane are the ones that affect the energy output of the WTG



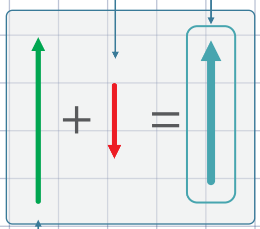
The difference between wind direction and airfoil direction is called angle of attack, this is controlled by the pitch of the blades

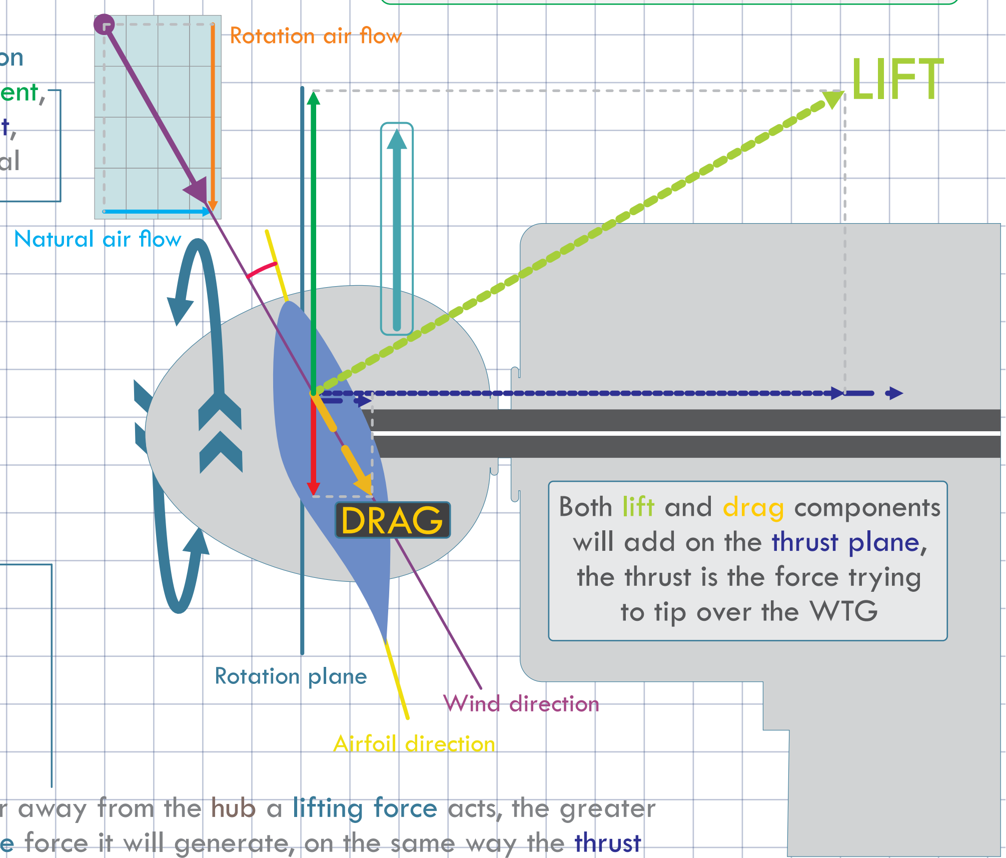


Lift Theory

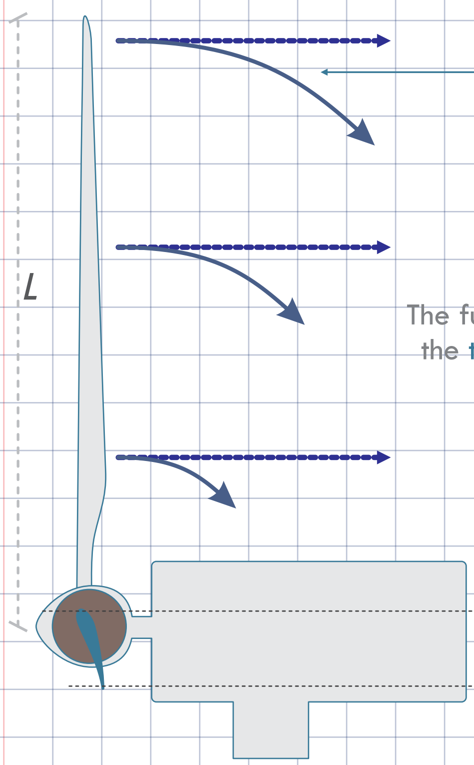
The same way as an airplane, air molecules passing through a blade create different pressure zones that generate the lift

The lift and drag component on the rotation plane will result on 3 forces, a lift component, a drag component and a thrust component, the first two will subtract resulting on a final acting lift that contributes to the torque

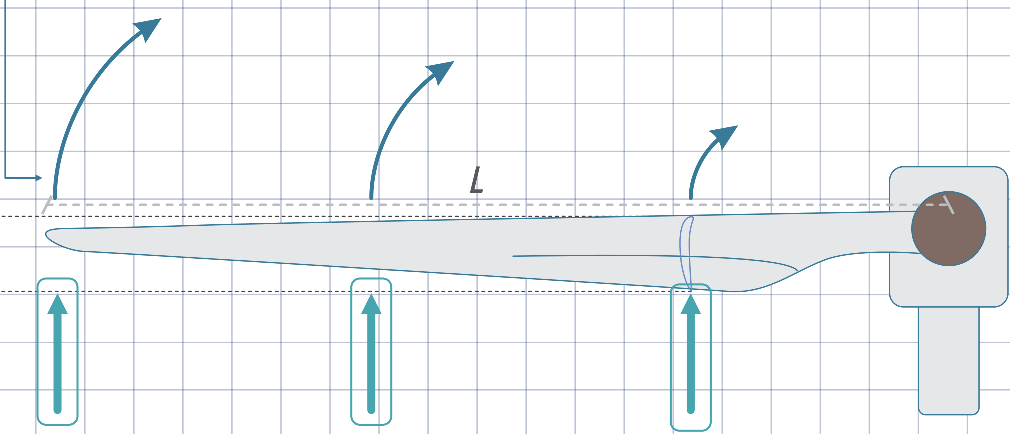




Both lift and drag components will add on the thrust plane, the thrust is the force trying to tip over the WTG

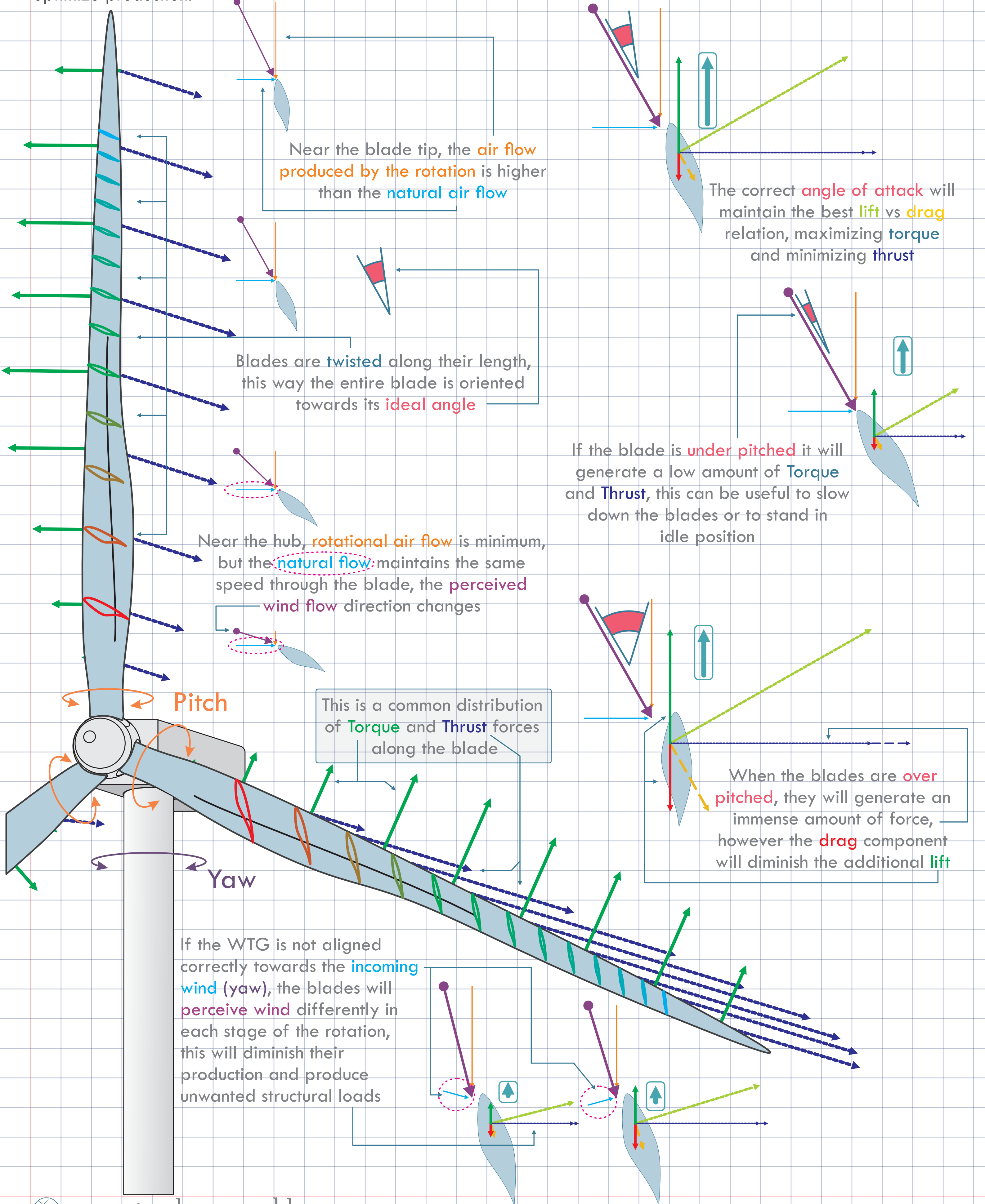


The further away from the hub a lifting force acts, the greater the torque force it will generate, on the same way the thrust forces will act on the turbine structure



Yaw and Pitch control

Yaw and pitch control are essential for an optimal energy production, any misalignment in the blades angle of attack (pitch), or in the turbines direction towards the wind flow (yaw), will result in a diminish of torque, in addition to unwanted stress in the structural components. WTG's have systems that continuously change yaw and pitch to optimize production.



Main Components

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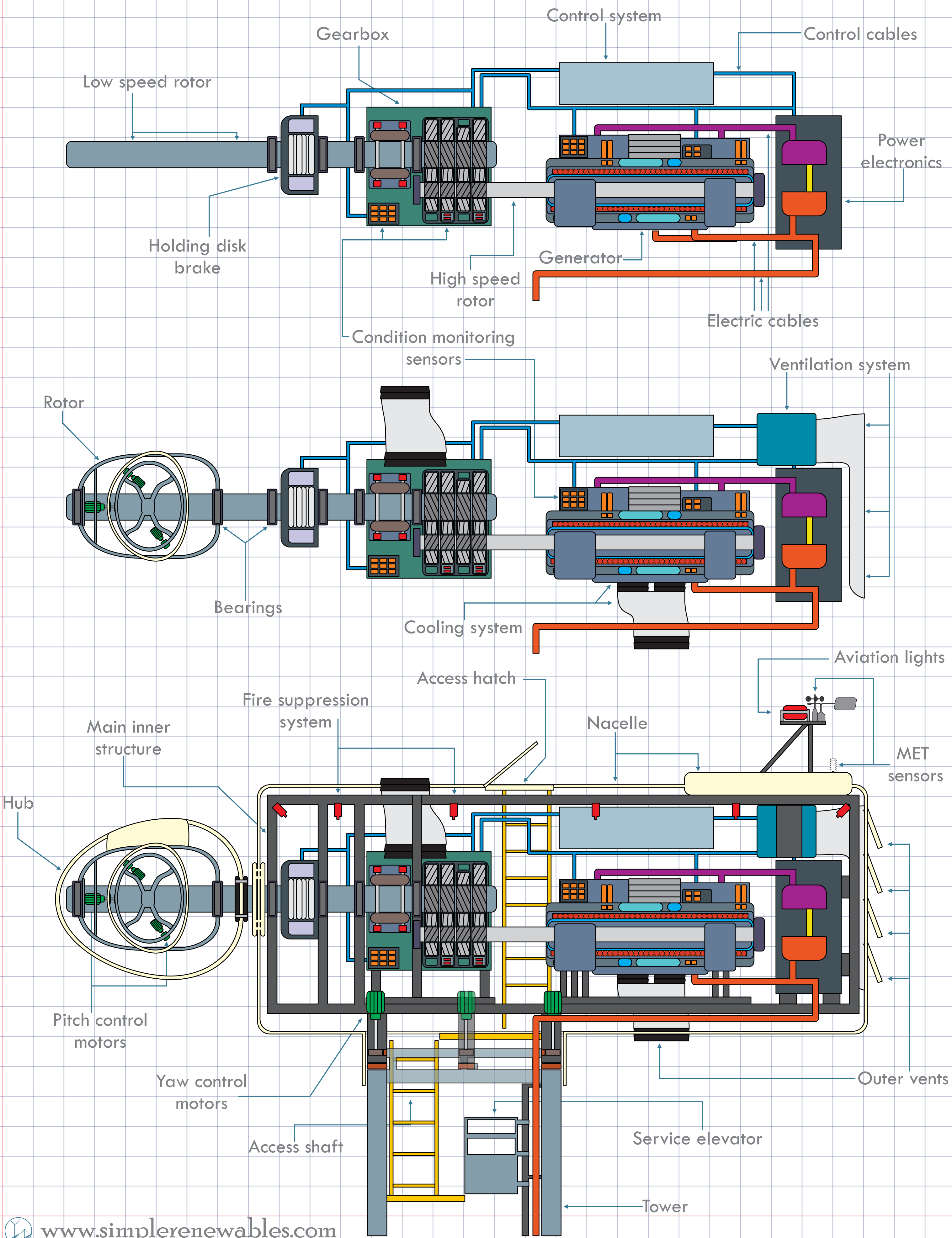
What's inside the box? Most modern WTG's share similar characteristics, the size, the location and layout may vary among manufacturers but most modern turbines look alike, most components are located inside the nacelle but some can also be found at the bottom of the tower or even outside the turbine.



Power Curve

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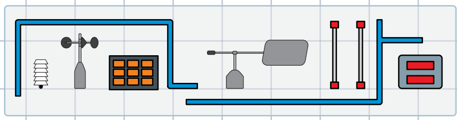
The mind and soul of the WTG lies in its generating system, the controller unit which acts as the brain, uses a network of sensors to monitor and orchestrate the functionality of the main components, this allows WTG to convert variable wind speed into reliable and usable high voltage alternating electric current. The final power output of the WTG is plotted in a graph called the power curve, this graph demonstrates de capabilities of the system for a different range of conditions, the power curve is essential for the development and commissioning of wind farms.

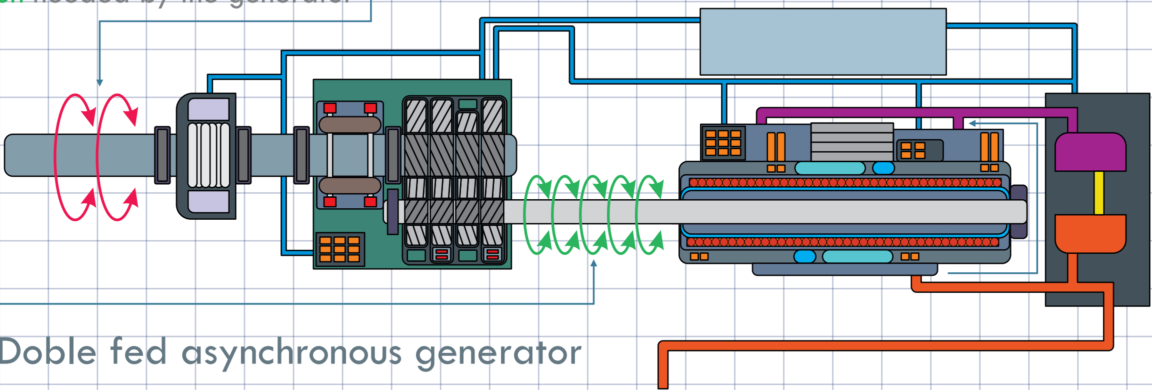
Gearbox

Most WTG use a single stage planetary gearbox, that transform the low speed rotation of the blades into the high speed rotation needed by the generator



Controller & sensors

A continuous monitoring system is in the core of the controller, measuring rotation speeds, wind speeds, vibrations, temperatures, power outputs, etc, processing al the data inputs and adjusting the WTG as needed



Variable alternating current

Direct current

Synchronized alternating current

Doble fed asynchronous generator

Wind turbine generators differ from conventional generators as they are asynchronous, since the rotational speed that feeds them is not constant, power electronics are used to compensate by feeding one of the windings (Stator / rotor) with alternative current, that constantly variates in phase and frequency, these variations are calculated to compensate with the rotational variations, therefore the other set of windings produces synchronous alternating current (50/60Hz)

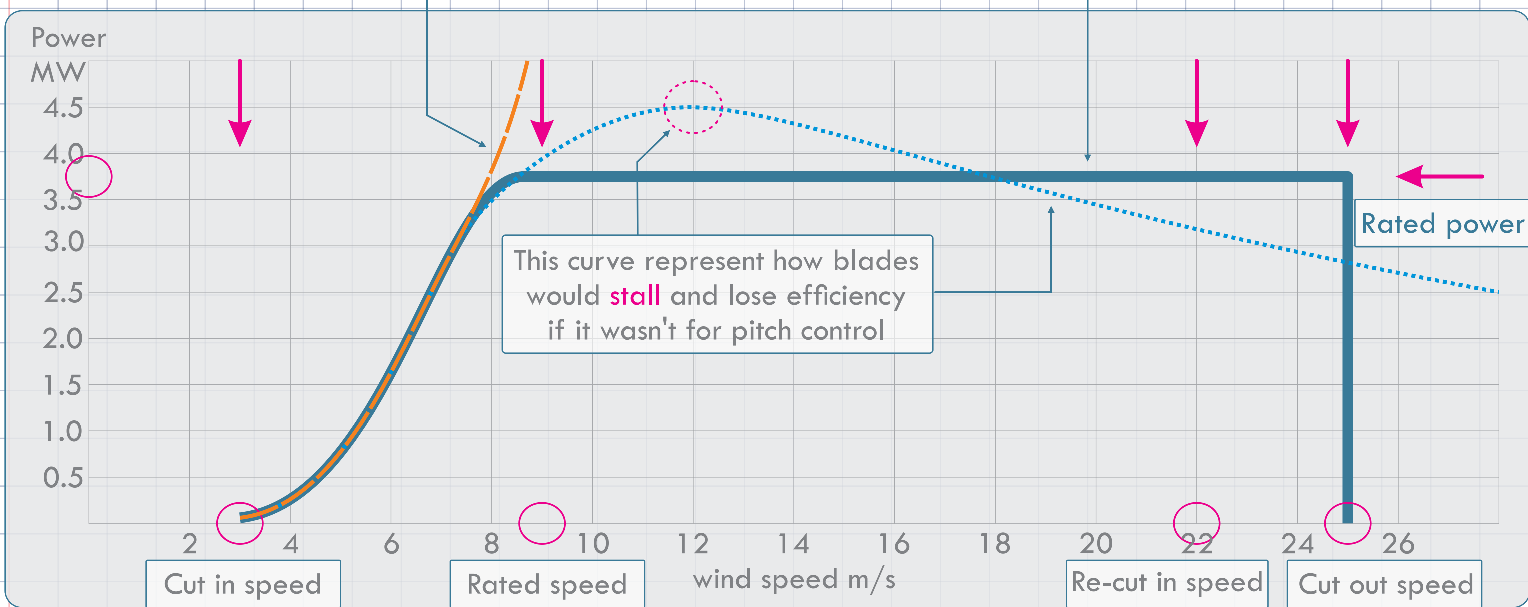
Power Electronics

The system is feed from the output AC, which is then converted to DC, and then converted back to AC in the frequency and phase needed by the generator

The initial part of the curve is given by the power formula

$$P = \frac{1}{2} A \rho v^3 \, WTG_{efficiency}$$

The WTG constrains and capabilities limit and stabilize the power output into its rated power



Cut in speed: The minimum wind speed for operation

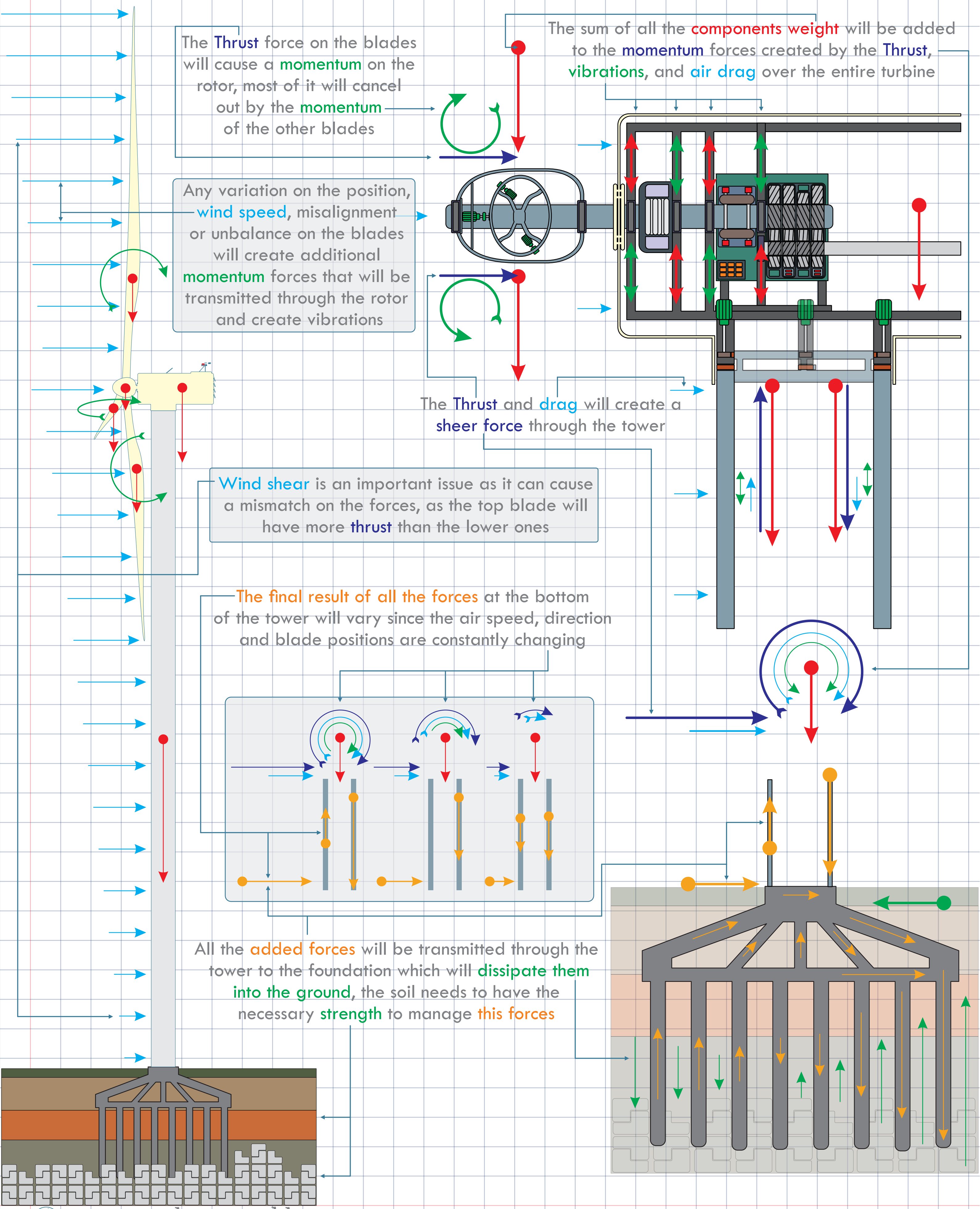
Rated speed: The minimum speed needed to achieve rated power

Re-cut in speed: The average speed needed to restart operation

Cut out speed: The maximum speed for safety operation

Structure

New materials have made possible for turbines to keep growing, but the structural design of WTG is quite a complex subject, modern turbines are massive moving objects subjected to variable forces, and must be able to withstand the constant changes without losing efficiency or having major wear on its components.



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Wind Farm development & construction

Most of this section is a working progress, keep checking www.simplerenewables.com for any updates.

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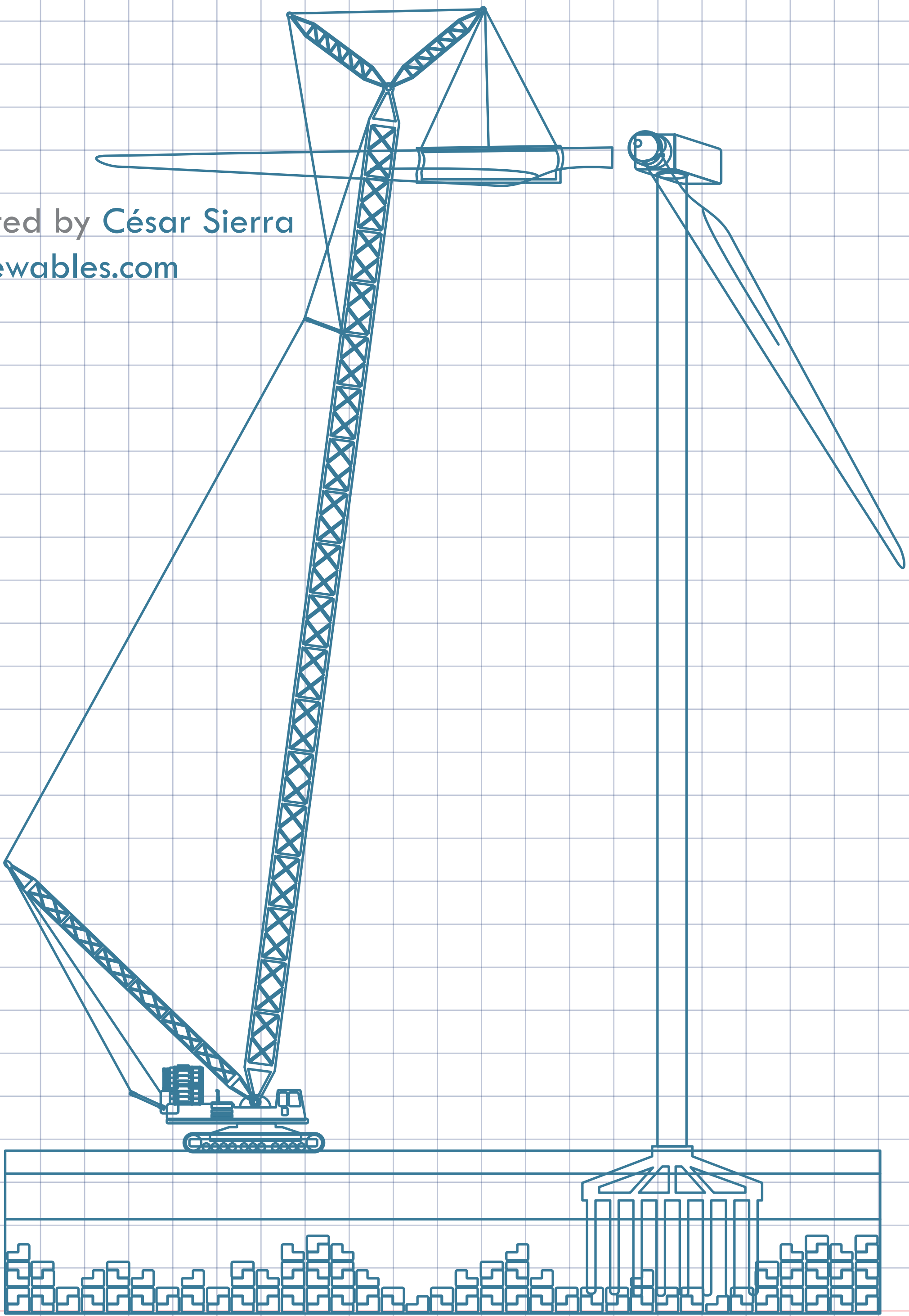

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The Wind Measurement campaign

The measurement of the wind is an essential although lengthy process, that any large scale wind energy project must undertake, a successful campaign will result with the selection of an ideal site and the optimal turbine for that specific site, additionally a successful campaign will result in a precise production forecast that in the end will provide a financially healthy project.

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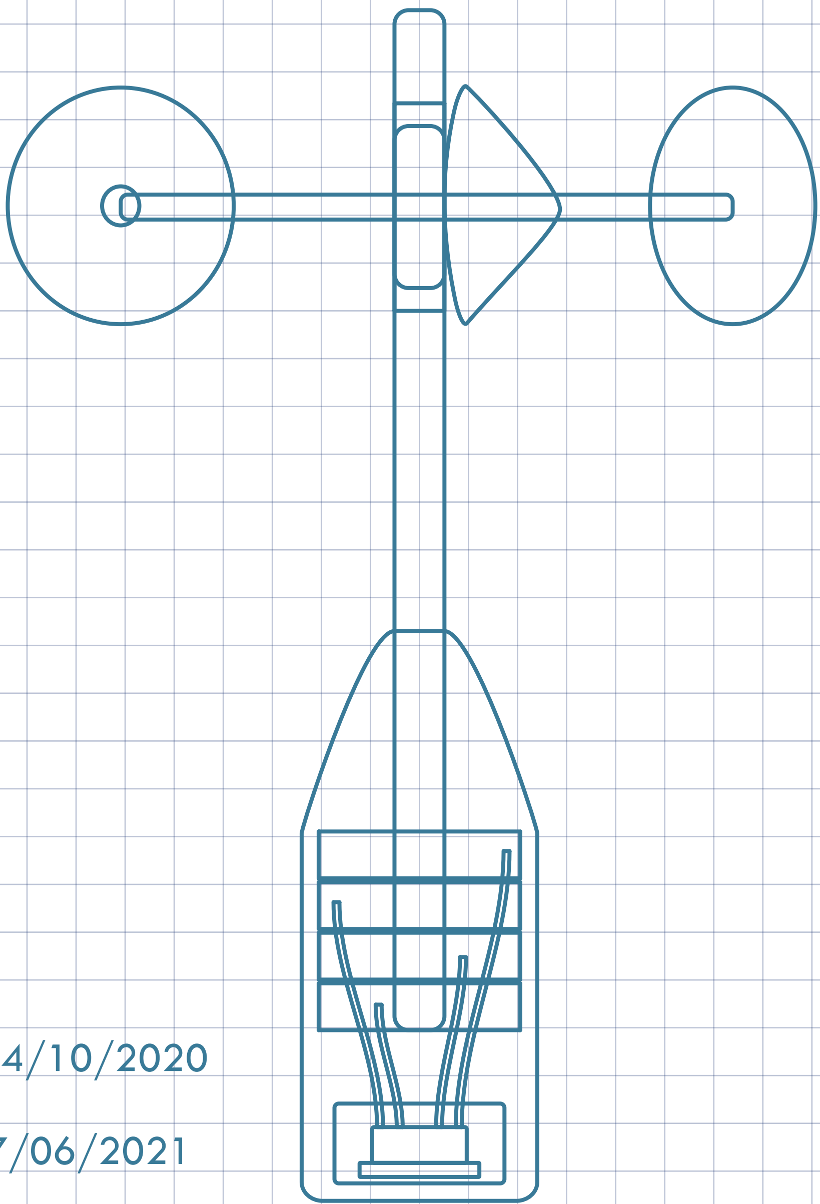

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Site Selection for wind projects

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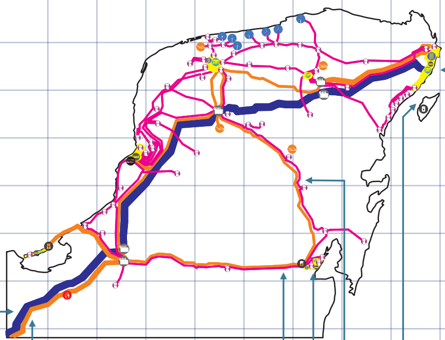
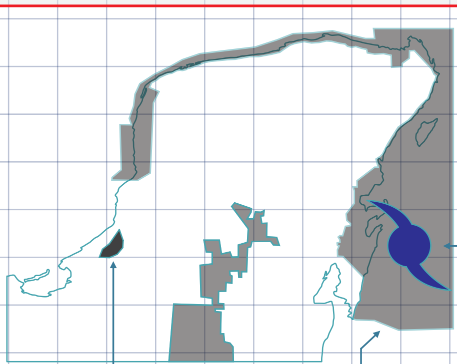
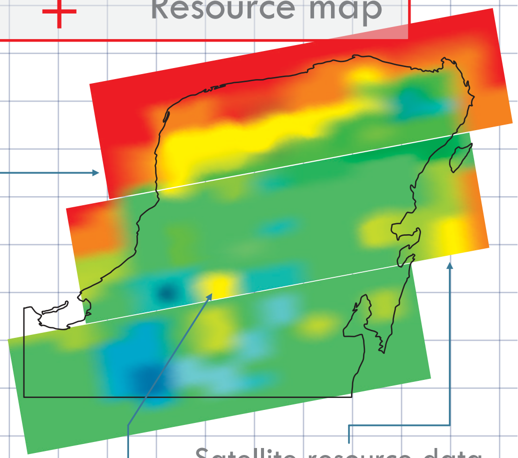
What is the first step in developing a wind project?

In most cases it will be the collection of multiple information sources related with the needs of the project, a demand for energy, a way to transmit power, available land and most important windy areas (resource). A Geographical Information System is the perfect way to combine and visualize multiple layers of information, highlighting essential information. High resolution wind maps are a combination of metadata obtained of multiple sources and processed to show the fundamental information.

Transmission map + Constrains map + Resource map





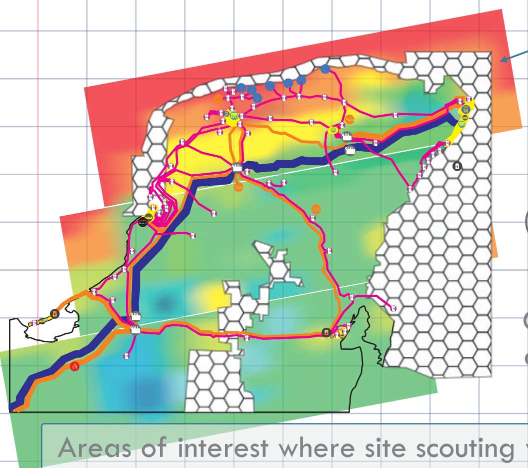


Transmission voltage
Projected grid works
Consumption areas
Line saturation

Roads, urban areas & infrastructure projects
Geographical limitations
Archaeological sites

Protected areas
Possible natural disasters

Satellite resource data
Nearby site measurements
Usual error is between 2.0 and 0.5 m/s



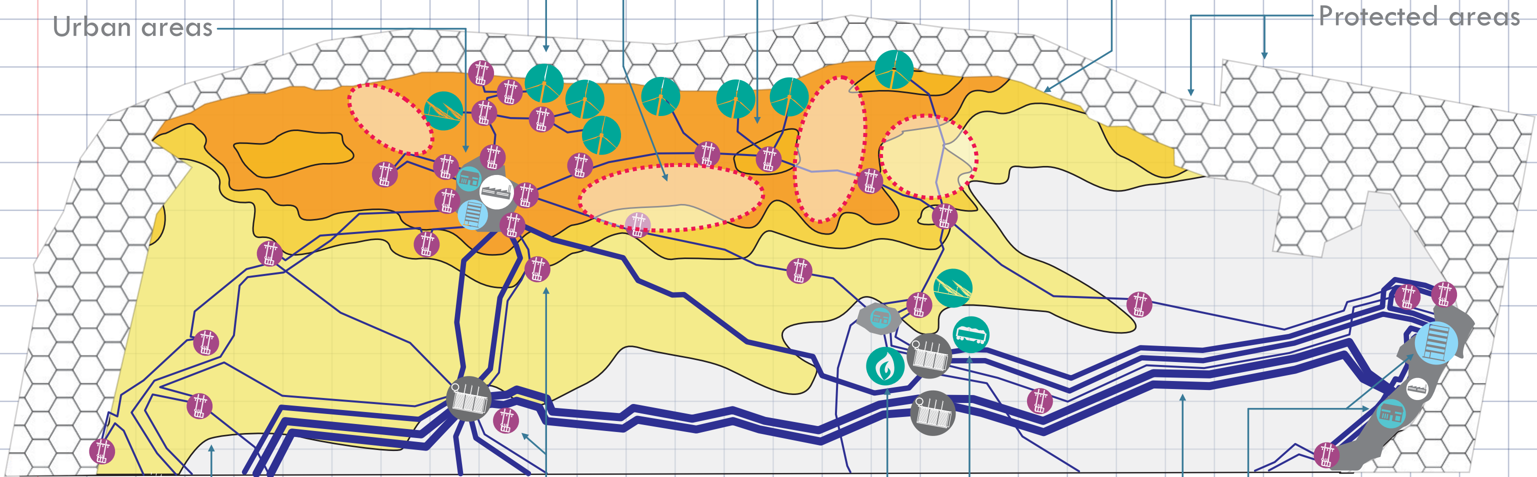
GIS can integrate multiple and complex spatial data with the goal of highlighting areas of interest.

(Geographic information system) GIS Map

Once all the layers are added a regional, detailed, high resolution map is extracted, showing the main areas of interest

- Land availability
- Environmental impact
- Social Impact
- Site access
- Potential consumers
- Local constrains
- Existing wind farms
- Available infrastructure
- Existing MET stations

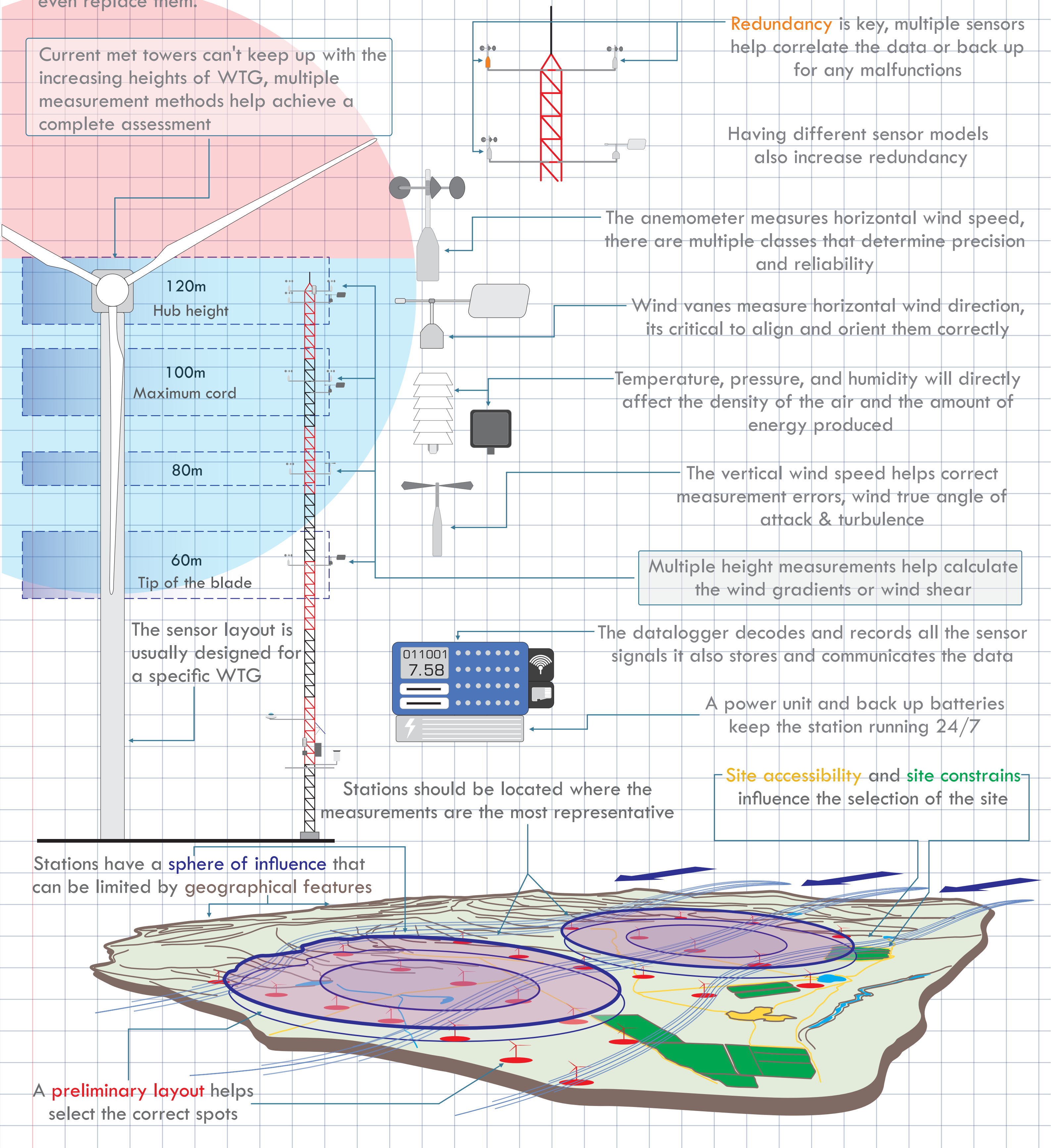
Areas of interest where site scouting will be done, are marked on the GIS map



The MET station

The Meteorological station is the backbone of a wind development project and essential for lowering the risk taken to develop and finance a wind project.

It's important to know where to install the station and what to install on them, there is a series of methods to determine the ideal spot, regional wind maps & topographical data can be simulated to find ideal spots, and satellite images help identify local constrains, however a site visit is always useful as there are always accessibility and geographical issues that affect. Secondly adding a few more sensors will increase the station precision and reliability while only increasing a fraction of the overall cost of the station. Met stations are still key elements in the development and operation of wind farms but new technologies are looking to improve their performance or maybe even replace them.



SODAR' & LIDAR'

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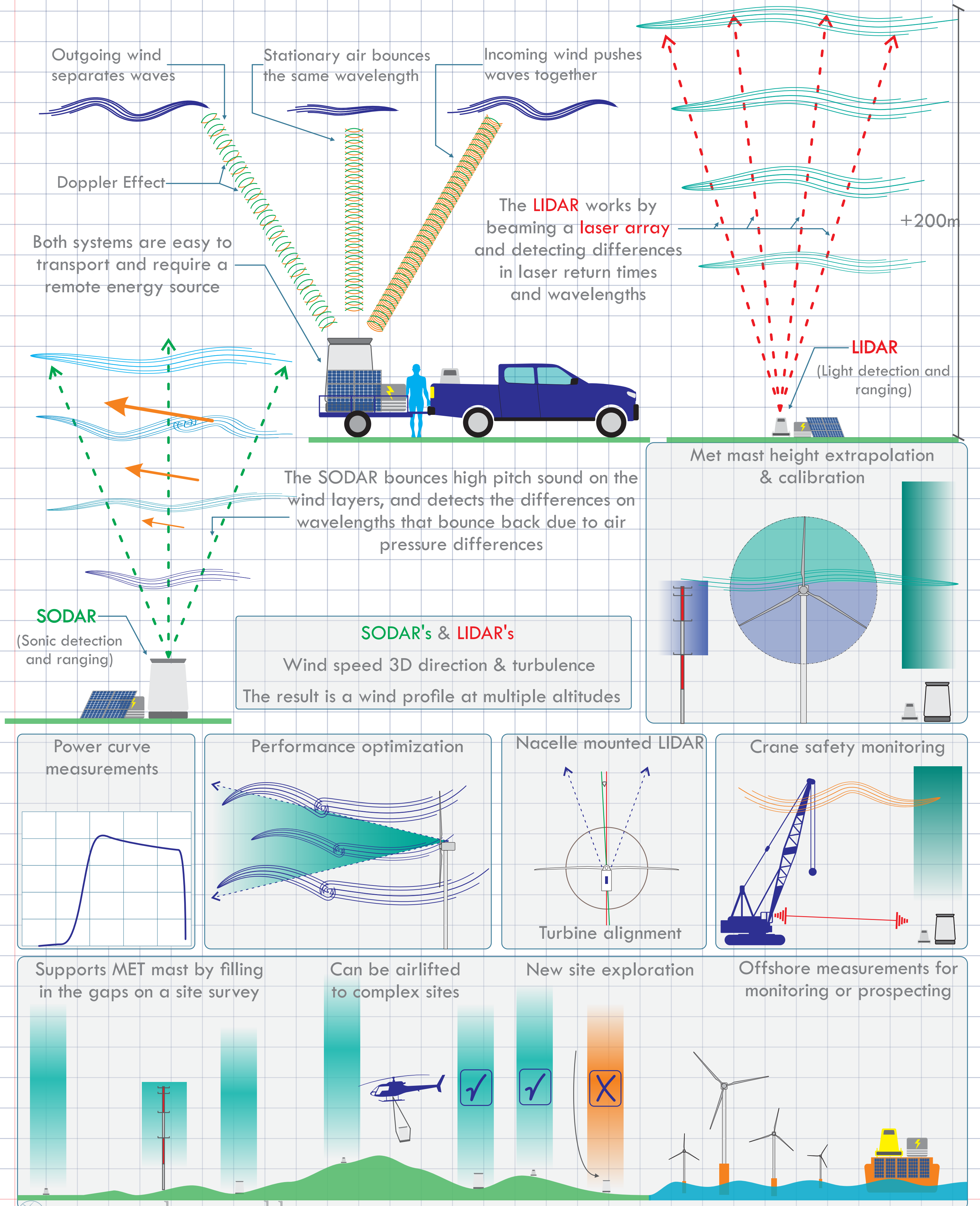
The solution may lie on new technologies such as SODAR's and LIDAR's that are now allowing us to complement the measurement campaigns, study the behavior of existing WTG's and even reach out into new sites that previously where to difficult or expensive to access. SODAR and LIDAR technologies are becoming increasingly widespread mainly due to the multiple applications and life span of a single unit, adding to this, is the cost reduction that the systems have had over the last years, makes them an even more attractive solution.



MET Data analysis

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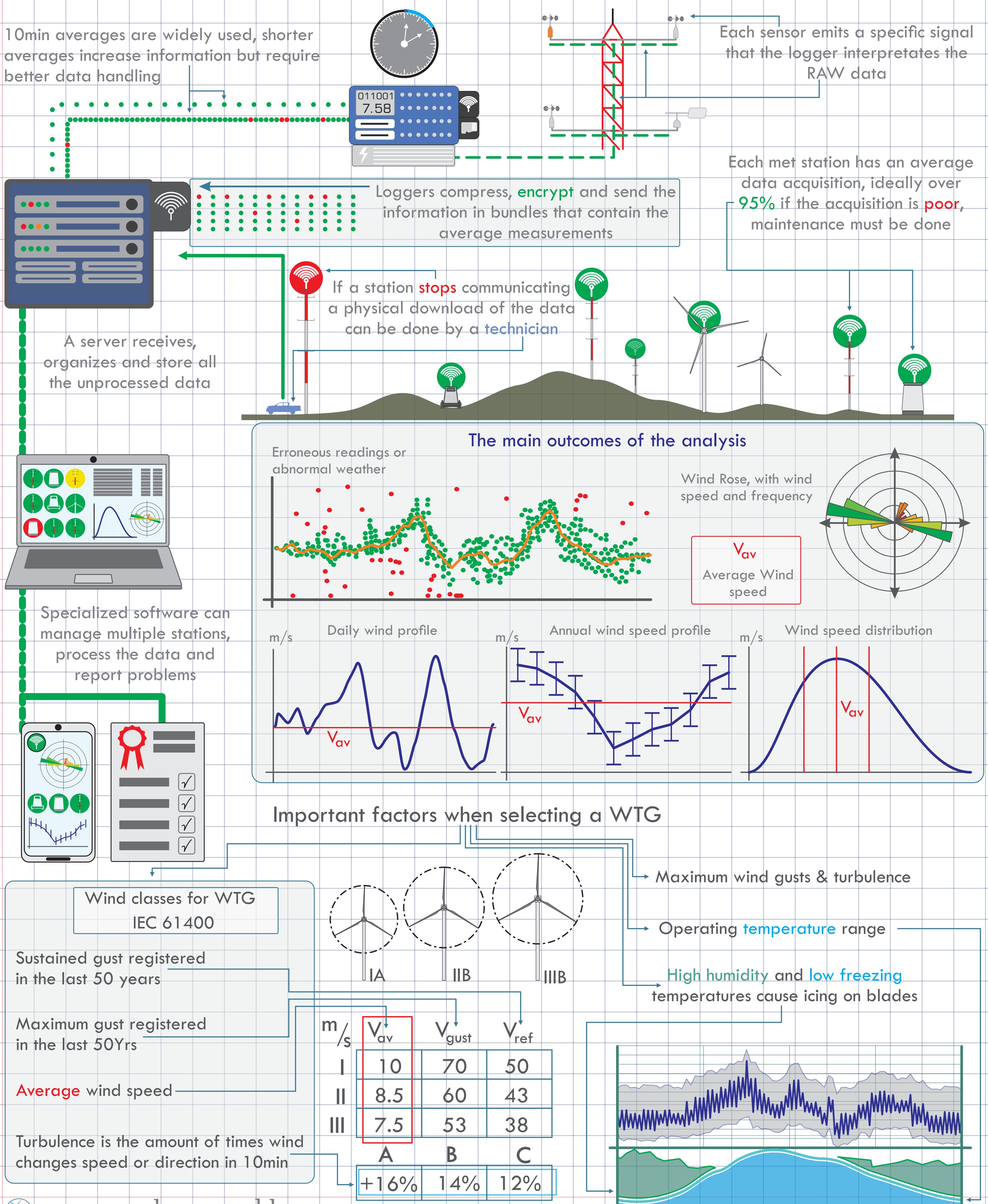
On average a MET station generates 6 packages of information every hour, each package contains the 10min average reading of about 10 to 15 sensors, when we start to add up the amount of information that a group of stations generate on a year it can become too much to handle. Fortunately, automatization and new data management technologies enable us to be manage "big data", and new algorithms also show us analyzed data and reports sometimes in real time, now a days most resource analysis charts come from automatized reports, however it is always convenient to know how to process all this raw data.



m/s	V_{av}	V_{gust}	V_{ref}
I	10	70	50
II	8.5	60	43
III	7.5	53	38
	A	B	C
	+16%	14%	12%

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Layout design

This section is a working progress, keep checking www.simplerenewables.com for any updates.

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