Vertical Axis Wind Turbines: History, Technology and Applications

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Abstract

In these Master Thesis a review of different type of vertical axis wind turbines (VAWT) and an preliminary investigation of a new kind of VAWT are presented.

After an introduction about the historical background of wind power, the report deals with a more accurate analysis of the main type of VAWT, showing their characteristics and their operations. The aerodynamics of the wind turbines and a review of different type on generators that can be used to connect the wind mill to the electricity grid are reported as well.

Several statistics are also presented, in order to explain how the importance of the wind energy has grown up during the last decades and also to show that this development of the market of wind power creates new opportunity also for VAWT, that are less used than the horizontal axis wind turbine (HAWT).

In the end of 2009 a new kind of vertical axis wind turbine, a giromill 3 blades type, has been built in Falkenberg, by the Swedish company VerticalWind. The tower of this wind turbine is made by wood, in order to get a cheaper and more environment friendly structure, and a direct driven synchronous multipole with permanent magnents generator is located at its bottom. This 200 kW VAWT represents the intermediate step between the 12 kW prototype, built in collaboration with the Uppsala University, and the common Swedish commercial size of 2 MW, which is the goal of the company.

A preliminary investigation of the characteristics of this VAWT has been done, focusing in particular on the value of the frequency of resonance of the tower, an important value that must be never reached during the operative phase in order to avoid serious damage to all the structure, and on the power curve, used to evaluate the coefficient of power (Cp) of the turbine. The results of this investigation and the steps followed to get them are reported. Moreover a energy production analysis of the turbine has been done using *WindPro*, as well as a comparison with and older type on commercial VAWT.

Sommario

In questa Tesi vengono presentate sia una panoramica della tecnologia delle turbine eoliche ad asse verticale (VAWT) sia una indagine preliminare di alcune caratteristiche di un nuovo tipo di turbina di questo genere.

Dopo un’introduzione sulla storia dell’energia eolica, l’analisi si focalizza sull’illustrare le caratteristiche principali e il principio di funzionamento dei diversi tipi di VAWT. Successivamente viene descritta la teoria aerodinamica che sta alla base dei rotori eolici e viene fornita una panoramiche dei principali tipi di generatori elettrici che possono essere adoperati per mettere in connessione la turbina con la rete elttrica.

Sono riportate anche diverse statistiche, al fine di mostrare come negli ultimi decenni l’energia eolica stia diventanto sempre più utilizzata e come uno svilupo di tale mercato possa porre le basi per uno sviluppo di nuove tipologie di turbine eoliche, come le VAWT, le quali, attualmente sono molto meno usate rispetto a quelle aventi l’asse di rotazione orizzontale (HAWT).

Verso la fine del 2009, nella città svedese di Falkenberg, è stata costruita, da parte della compagnia svedese VerticalWind una turbina di nuova concezione ad asse verticale di tipo giromill con tre pale. La torre è costituita da legno lamellare, al fine di ottenere una struttura più economica e meno impattante sull’ambiente, e il generatore sincrono, multipolo, a magneti permanenti, di tipo direct driven è collocato alla base della torre stessa. Questa turbina di potenza nominale pari a 200 kW è da considerarsi come il passo intermedio tra il prototipo da 12 kW, costruito in collaborazione con l’Università di Uppsala, e l’obiettivo finale dell’azienda, ossia il raggiungimento della taglia cosiddetta commerciale, che per la Svezia corrisponde a 2 MW.

E’ stata svolta un’analisi preliminare delle caratteristiche di questa turbina, focalizzando l’attenzione principalmente sul valore della frequenza di risonanza, il quale non deve mai essere raggiunto durante la fase operativa pena il serio danneggiamento di tutta la struttura, e sulla curva di potenza, utilizzata per stimare il valore del coefficiente di potenza (Cp) della turbina. Sono riportati i risultati di queste analisi e i passi principali svolti per ottenerli. Infine, è stata eseguita, mediante il software *WindPro*, una stima della produzione energetica della turbina e anche un confronto con una diversa e più datata tecnologia.

Contents

Preface

Wind power was first used long time ago by many civilizations during mankind history to produce mechanical energy or for navigation. Only with the use of coal and oil in the last two centuries its importance decreased, but during the last decades the interest on this topic grew as much as the possible business around it.

Since the beginning, two types of windmills and turbines have been built to use this renewable source: some machines with horizontal axis of rotation (HAWT) and some other with vertical axis (VAWT). The firs type is the most common today, but growing market asks for machines with different proprieties to fit different requests.

VAWT design have been always mistreated by literature and market, but with some new or improved technologies and decreasing prices for valuable materials such as permanent magnet, together with the peculiarity of VAWT turbines to operate were other types have problems, this turbine can have a very important advantage in the actual market.

This Thesis wants to investigate some structural and very important characteristics of a new kind of VAWT, built in Falkenberg, Sweden, that is made by wood, like the frequency of resonance of the tower. Moreover an analysis of energy production has been also made and reported in order to show that in certain conditions of wind, like turbulence, gusts or fluctuations, the technology of the vertical axis can be more performant than the usual horizontal axis one. By a comparison with a older type of VAWT, in the report it’s also possible to observe how the technology of the vertical axis wind turbine has improved a lot during the last decades.

1 Brief history of wind power

The first known use of wind power are placed, according to various sources, in the area between today's Iran and Afghanistan in the period from 7^{th} to 10^{th} century. These windmills were mainly used to pump water or to grind wheat. They had vertical axis and used the *drag* component of wind power: this is one of the reason for their low efficiency. Moreover, to work properly, the part rotating in opposite direction compared to the wind had to be protected by a wall.

Figure 1-1 Persian Windmills

Obviously, devices of this type can be used only in places with a main wind direction, because there is no way to follow the variations.

The first windmills built in Europe and inspired by the Middle East ones had the same problem, but they used an horizontal axis. So they substitute the *drag* with the *lift* force, making their inventors also the unaware discoverer of aerodynamics.

During the following centuries many modifies were applied for the use in areas where the wind direction varies a lot: the best examples are of course the Dutch windmills, used to drain the water in the lands taken from the sea with the dams, could be oriented in wind direction in order to increase the efficiency.

Figure 1-2 Dutch Windmill

The wind turbines used in the USA during the 19th century and until the ’30 of 20th century were mainly used for irrigation. They had an high number of steel-made blades and represented a huge economic potential because of their large quantity: about 8 million were built all over the country.

Figure 1-3 American multi blade Windmill

The first attempt to generate electricity were made at the end of 19th century, and they become more and more frequent in the first half of the following century. Almost all those models had an horizontal axis, but in the same period (1931) Georges Jean Marie Darrieus designed one of the most famous and common type of VAWT, that still bears his name.

Figure 1-4 Éole Darrieus wind Turbine, Quebec

The recent development led to the realization of a great variety of types and models, both with vertical and horizontal axis, with rated power from the few kW of the beginning to the 6 MW and more for the latest constructions. In the electricity generation market the HAWT type has currently a large predominance.

2 Types of Vertical Axis wind Turbines

2.1 Darrieus

2.1.1 Historical background

French aeronautical engineer Georges Jean Marie Darrieus patented in 1931 a “Turbine having its shaft transverse to the flow of the current”, and his previous patent (1927) covered practically any possible arrangement using vertical airfoils.

It’s one of the most common VAWT, and there was also an attempt to implement the Darrieus wind turbine on a large scale effort in California by the FloWind Corporation; however, the company went bankrupt in 1997. Actually this turbine has been the starting point for further studies on VAWT, to improve efficiency.

2.1.2 Use and operation

The swept area on a Darrieus turbine is $A = \frac{2}{3} \cdot D^2$, a narrow range of tip speed ratios around 6 and power coefficient C_p just above 0.3.

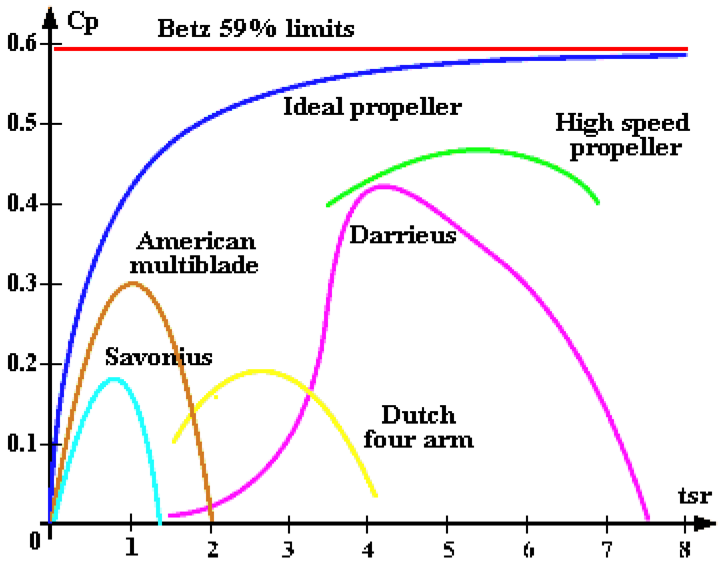


Figure 2-1 Cp-λ diagram for different type of wind turbines [3]

Each blade sees maximum lift (torque) only twice per revolution, making for a huge torque (and power) sinusoidal output that is not present in HAWTs. And the long VAWT blades have many natural frequencies of vibration which must be avoided during operation.

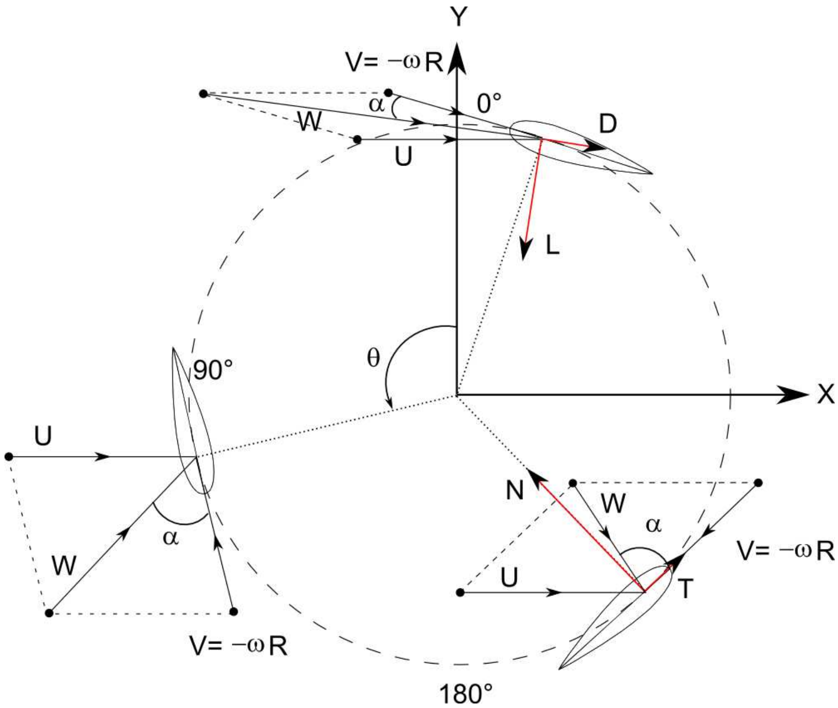


Figure 2-2 Forces that act on the turbines [3]

One problem with the design is that the angle of attack changes as the turbine spins, so each blade generates its maximum torque at two points on its cycle (front and back of the turbine). This leads to a sinusoidal power cycle that complicates design.

Another problem arises because the majority of the mass of the rotating mechanism is at the periphery rather than at the hub, as it is with a propeller. This leads to very high centrifugal stresses on the mechanism, which must be stronger and heavier than otherwise to withstand them. The most common shape is the one similar to an egg-beater, that can avoid in part this problem, having most of the rotating mass not far from the axis. Usually it has 2 or 3 blades, but some studies during the ’80 demonstrate that the 2 bladed configurations has an higher efficiency.

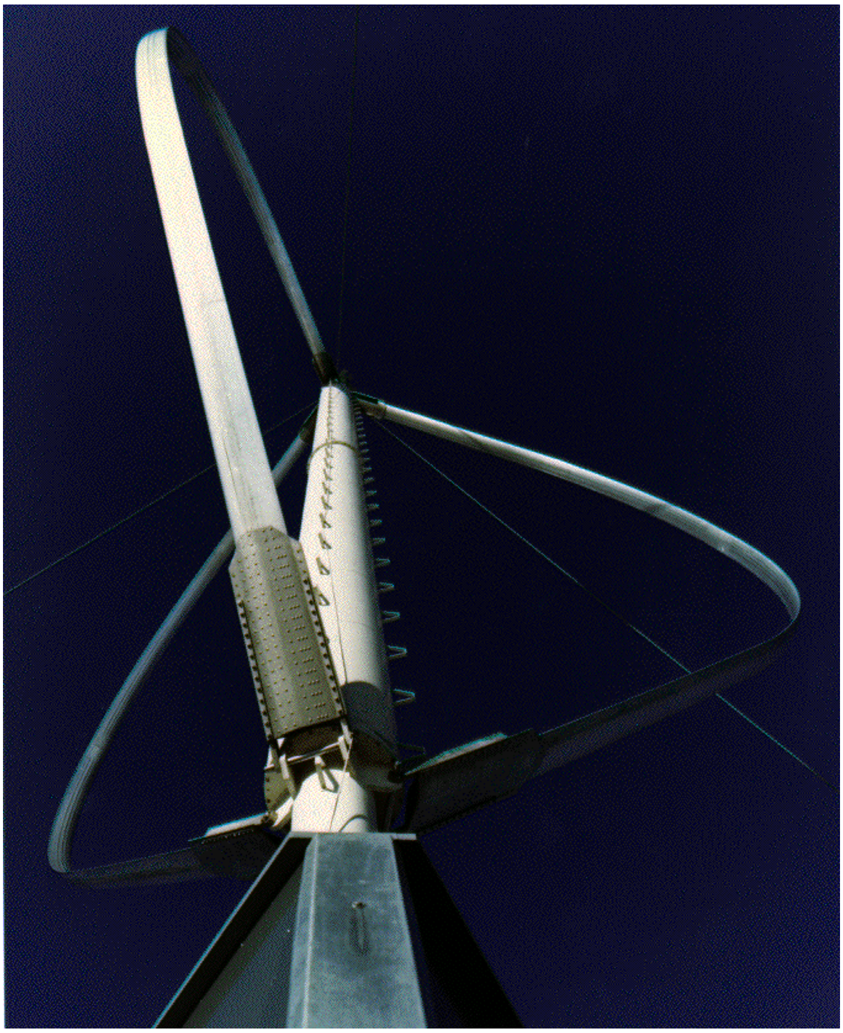


Figure 2-3 Three-bladed Darrieus wind turbine

2.1.3 Examples

The biggest example of this type of turbine was the EOLE, built in Quebec Canada in 1986. Its height is about 100 m, the diameter is 60 m and the rated power was about 4 MW, but due to mechanical problems and to ensure longevity the output was reduced to 2.5 MW. It was shut down in 1993.

2.2 Savonius

2.2.1 Historical background

Savonius wind turbines were invented by the Finnish engineer Sigurd J. Savonius in 1922, but Johann Ernst Elias Bessler (born 1680) was the first to attempt to build a horizontal windmill of the Savonius type in the town of Furstenburg in Germany in 1745.

Nowadays they are not usually connected to electric power grids.

2.2.2 Use and operation

The Savonius is a drag-type VAWT, so it cannot rotate faster than the wind speed. This means that the tip speed ratio is equal to 1 or smaller, making this turbine not very suitable for electricity generation. Moreover, the efficiency is very low compared to other types, so it can be employed for other uses, such as pumping water or grinding grain. Much of the swept area of a Savonius rotor is near the ground, making the overall energy extraction less effective due to lower wind speed at lower heights.

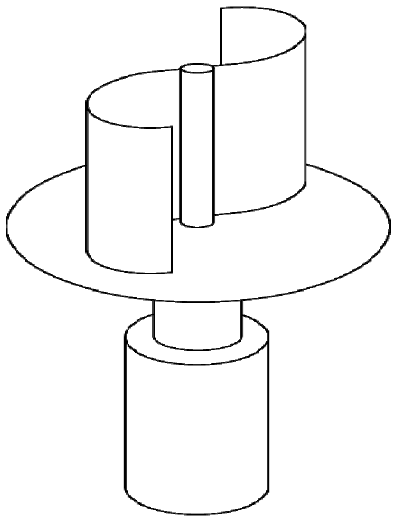


Figure 2-4 Savonius Rotor

Its best qualities are the simplicity, the reliability and the very low noise production. It can operate well also at low wind speed because the torque is very high especially in these conditions. However the torque is not constant, so often some improvements like helical shape are used.

Figure 2-5 Savonius wind turbine

2.2.3 Examples

The Savonius can be used where reliability is more important than efficiency:

- small application such as deep-water buoys
- most of the anemometers are Savonius-type
- used as advertising signs where the rotation helps to draw attention

2.3 Giromill

2.3.1 Historical background

The straight-bladed wind turbine, also named Giromill or H-rotor, is a type of vertical axis wind turbine developed by Georges Darrieus in 1927.

This kind of VAWT has been studied by the Musgrove’s research team in the United Kingdom during the ’80.

Figure 2-6: Giromill wind turbine (2 blades) [10]

In these turbines the “egg beater” blades of the common Darrieus are replaced with straight vertical blade sections attached to the central tower with horizontal supports. These turbines usually have 2 or 3 vartical airfoils. The Giromill blade design is much simpler to build, but results in a more massive structure than the traditional arrangement and requires stronger blades.

In these turbines the generator is located at the bottom of the tower and so it can be heavier and bigger than a common generator of a HAWT and the tower can have a lighter structure.

While it is cheaper and easier to build than a standard Darrieus turbine, the Giromill is less efficient and requires motors to start. However these turbines work well in turbulent wind conditions and represent a good option in those area where a HAWT is unsuitable.

2.3.2 Use and operation

The operation way of a Giromill VAWT is not different from that of a common Darrieus turbine. The wind hits the blades and its velocity is split in lift and drag component. The resultant vector sum of these two component of the velocity makes the turbine rotate.

The swept area of a Giromill wind tubine is given by the length of the blades multiplied for the rotor diameter.

The aerodynamics of the Giromill is like the one of the common Darrieus turbine (Figure 2-2): the wind force is splited in lift and drag force and it make the tubine rotate.

2.3.3 Examples

Figure 2-7 VerticalWind giromill wind turbine (3 blades, 200 kW, Falkenberg, Sweden)

The VAWT-850 was the biggest H-rotor in Europe when it was built in UK in the 1989. It had a height of 45m and a rotor diameter of 38m. This turbine had a gearbox and an induction generator inside the top of the tower. It was installed at the Carmarthen test site during the 1990 and operated until the month of February of 1991, when one of the blades broke, due to an error in the manufacture of the fiberglass blades.

In the 90's the German company Heidelberg Motor GmbH developed and built several 300 kW prototypes, with direct driven generators with large diameter. In some turbines the generator was placed on the top of the tower while in others turbines it was located on the ground.

In 2010 the VerticalWind AB, after a 12 kW prototype developed in Uppsala, Sweden, has developed and built in Falkenberg the biggest VAWT in Sweden: it's a 3 blades Giromill with rated power of 200 kW, with a tower built in with a wood composite material that make the turbine cheaper than other similar structure made by steel.

2.4 Cycloturbine

A variant of the Giromill is the Cycloturbine, which uses a vane to mechanically orient the pitch of the blades for the maximum efficiency. In the Cycloturbines the blades are mounted so they can rotate around their vertical axis. This allows the blades to be pitched so that they always have some angle of attack relative to the wind.

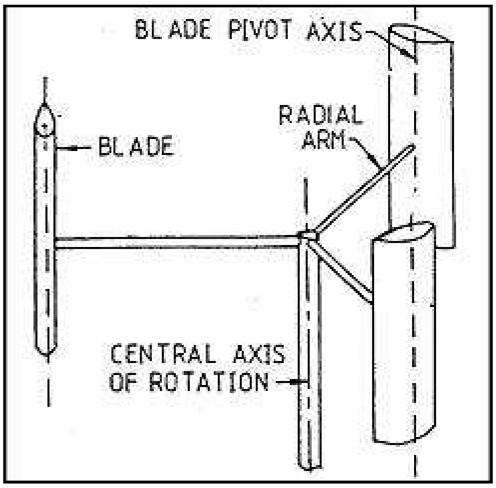


Figure 2-8: Cycloturbine rotor [10]

The main advantage of this design is that the torque generated remains almost constant over a wide angle and so the Cycloturbines with 3 or 4 blades have a fairly constant torque. Over this range of angles the torque is near the maximum possible and so the system can generated more power.
Compared with the other Darrieus wind turbines, these kind of VAWT shows the advantage of a self-starting: in low wind conditions, the blades are pitched flat against the wind direction and they generated the drag forces that let the turbine start turning. As the rotational speed increases, the blades are pitched so that the wind flows across the airfoils generating the lift forces and accelerating the turbine.
The blade pitching mechanism is complex and usually heavy, and the Cycloturbines need some wind direction sensors to pitch the blades properly.

2.5 References

[1] http://www.energybeta.com

[2] http://www.energybeta.com/windpower/windmill/wind-power-from-the-darrieus-wind-turbine/

[3] http://www.windturbine-analysis.netfirms.com/

[4] http://www.awea.org

[5] http://www.awea.org/faq/vawt.html

[6] http://telosnet.com/wind/govprog.html

[7] http://en.wikipedia.org/

[8] http://www.reuk.co.uk/Giromill-Darrieus-Wind-Turbines.htm

[9] http://dspace1.isd.glam.ac.uk

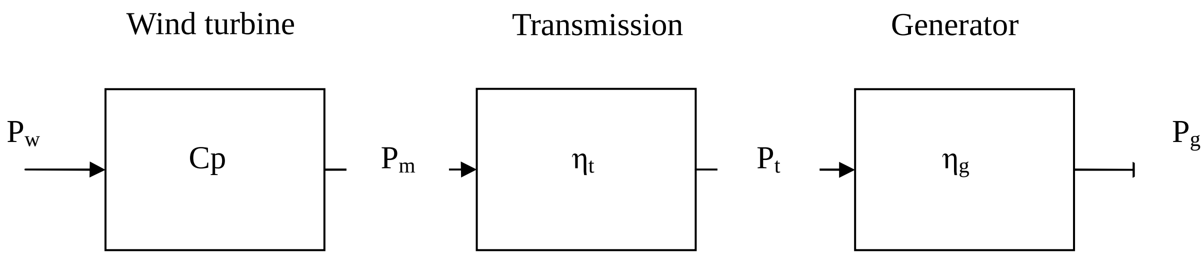
[10] http://www.reuk.co.uk/OtherImages/cycloturbine-vawt.jpg

3 Theory of Aerodynamics

3.1 Introduction

From an aerodynamic point of view, the different VAWT, have a number of aspects in common that distinguish them from the HAWT.
The blades of a VAWT rotate on a rotational surface whose axis is at right angle to the wind direction. The aerodynamic angle of attack of the blades varies constantly during the rotation. Moreover, one blade moves on the downwind side of the other blade in the range of 180° to 360° of rotational angle so that the wind speed in this area is already reduced due to the energy extracted by the upwind blades. Hence, power generation is less in the downwind sector of rotation. Consideration of the flow velocities and aerodynamic forces shows that, nevertheless, a torque is produced in this way which is caused by the lift forces. The breaking torque of the drag forces in much lower, by comparison.

In one revolution, a single rotor blade generates a mean positive torque but there are also short sections with negative torque. The calculated variation of the total torque also shows the reduction in positive torque on the downwind side.
The alternation of the torque with the revolution can be balanced with three rotor blades, to such an extent that the alternating variation becomes an increasing and decreasing torque which is positive throughout. However, torque can only develop in a vertical axis rotor if there is circumferential speed: the vertical axis rotor is usually not self starting.
The qualitative discussion of the flow conditions at the vertical axis rotor shows that the mathematical treatment must be more complex than with propeller type. This means that the range of physical and mathematical models for calculating the generation of power and the loading is also wider.
Various approaches, with a variety of weightings of the parameters involved have been published in the literature. Most authors specify values of 0,40 to 0,42 for the maximum Cp for the Darrieus type wind turbine.
In order to analyze the aerodynamics of a rotor and to get information about its power generation, it's necessary to start by considering that a wind turbine works converting the kinetic energy of a wind flow in electricity, following several steps:



From the wind flow the turbine gets the energy to rotate the blades. The energy produced by this rotations is given to the main shaft (or to a gearbox, if it is present) and from here to the electrical generator, that provide the electricity to the grid.

3.2 Power in the wind

The power of the wind is described by:

$$P_{kin} = \frac{1}{2} * \dot{m} * V^2$$

Where:

P_{kin} = kinetics power [W];

$\dot{m}$ = mass flow = ρ*A*v [kg/s];

ρ = density [kg/m^3];

A = area [m^2];

v = speed [m/s];

The frequency distribution if the wind speed differs at different sites, but it fits quite well with the Weibull distribution. An example of how measured data fit the Weibull distribution is shown in the picture below (source: www. re.emsd.gov.hk).

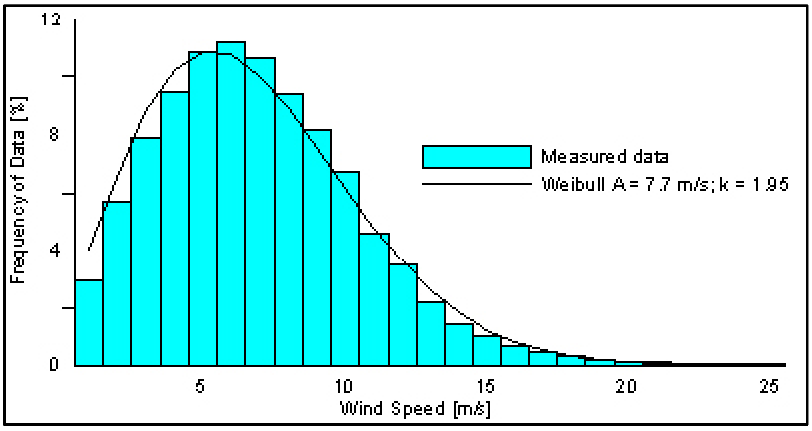


Figure 3-1 Example of Weibull distribution [2]

The wind turbine swept area is calculated in different way, according to the geometry of the rotor. For a HAWT, the swept area is described by:

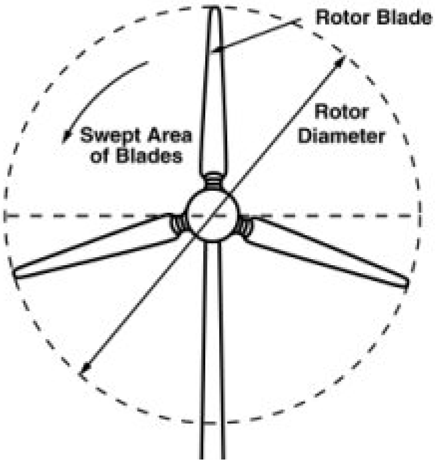


Figure 3-2 HAWT swept area

$$A = \pi * r^2$$

Where the parameter r is the radius in [m] of the rotor.

For a giromill VAWT, also named H-rotor, the swept area is:

$$A = d * h$$

Where:

d = diameter of the rotor [m];

h = length of the blades [m];

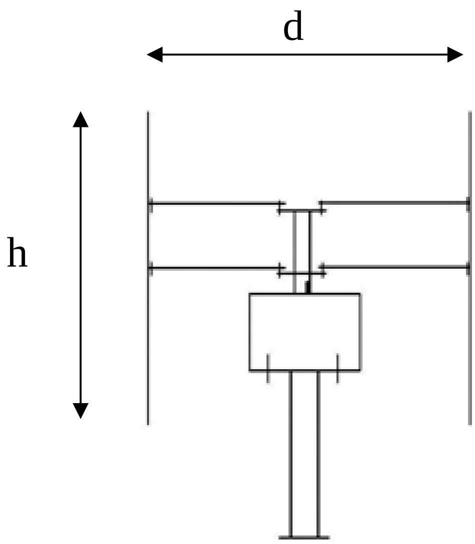


Figure 3-3 VAWT swept area [3]

The formula of the power in the wind can be written also as:

$$P_{kin} = \frac{1}{2} * \rho * A * v^3$$

The density of the air varies with the height above sea level and temperature. The standard value for Sweden used usually are density at sea level (1 bar) and a temperature of 9°C. Using these values, the density of the air is 1,25 kg/m^3.

The maximum mechanical power that can be got from a wind turbine depends on both the rotational speed and on the undisturbed wind speed, as shown in the picture below.

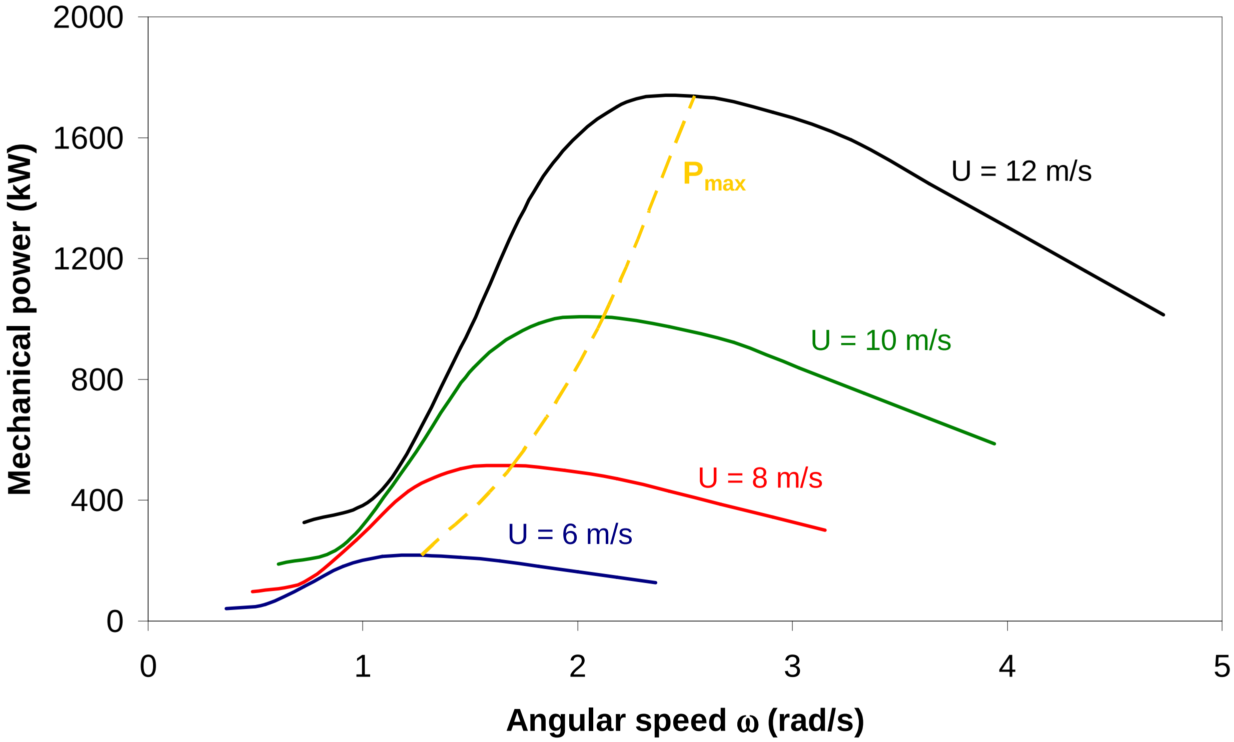


Figure 3-4 Mechanical power and rotational speed for different wind speed

3.3 Power Coefficient

When a wind turbine is crossed by a flow of air, it can get the energy of the mass flow and convert it in rotating energy. This conversion presents some limits, due to the Betz' law.

This law mathematically shows that there is a limit, during this kind of energy conversion, that cannot be passed.

In order to explain this limit, a power coefficient Cp and it is given by:

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

The coefficient Cp represents the amount of energy that a specific turbine can absorb from the wind. Numerically the Betz' limit, for a HAWT, is 16/27 equal to 59,3%. It means that, when a wind turbine operates in the best condition, the wind speed after the rotor is 1/3 of the wind speed before, as shown in the picture below.

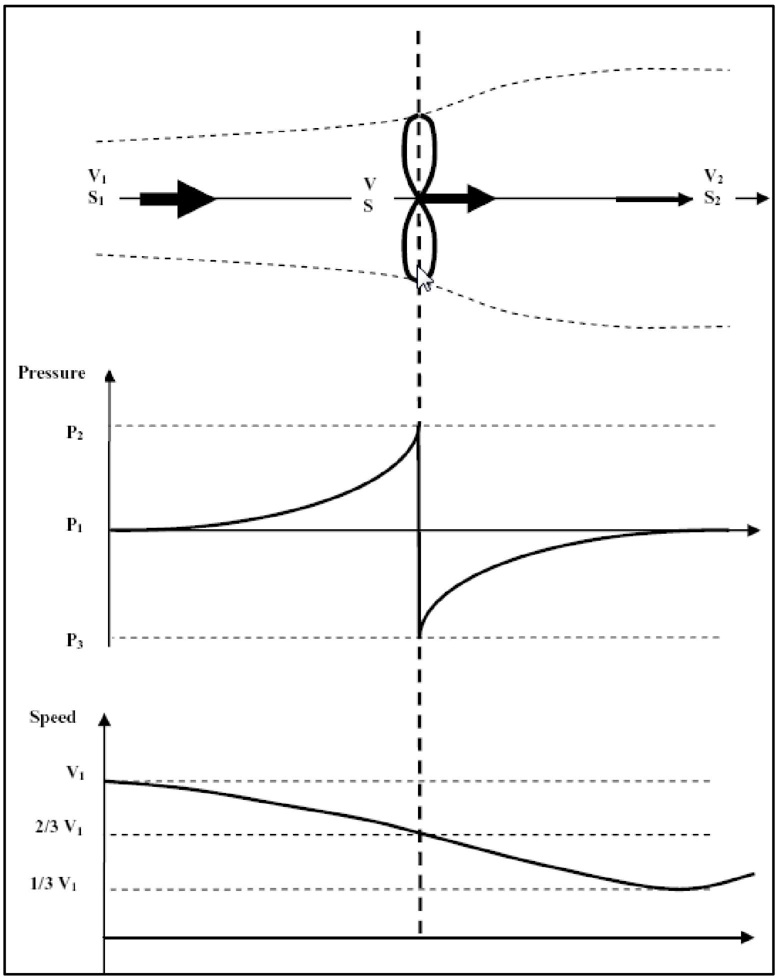


Figure 3-5 Air Flow, pressure and speed before and after the turbine

The value of the coefficient Cp is affected by the type of wind turbine and the value of the parameter λ, which is named tip speed ratio and is described by:

$$\lambda = \frac{\omega * r}{v}$$

Where:

ω = rotational speed of the turbine [rpm];

r = radius of the rotor [m];

v = undisturbed wind speed [m/s];

The relation between Cp and tip speed ratio is shown in the picture below (source: Developing wind power projects", T. Wizelius)

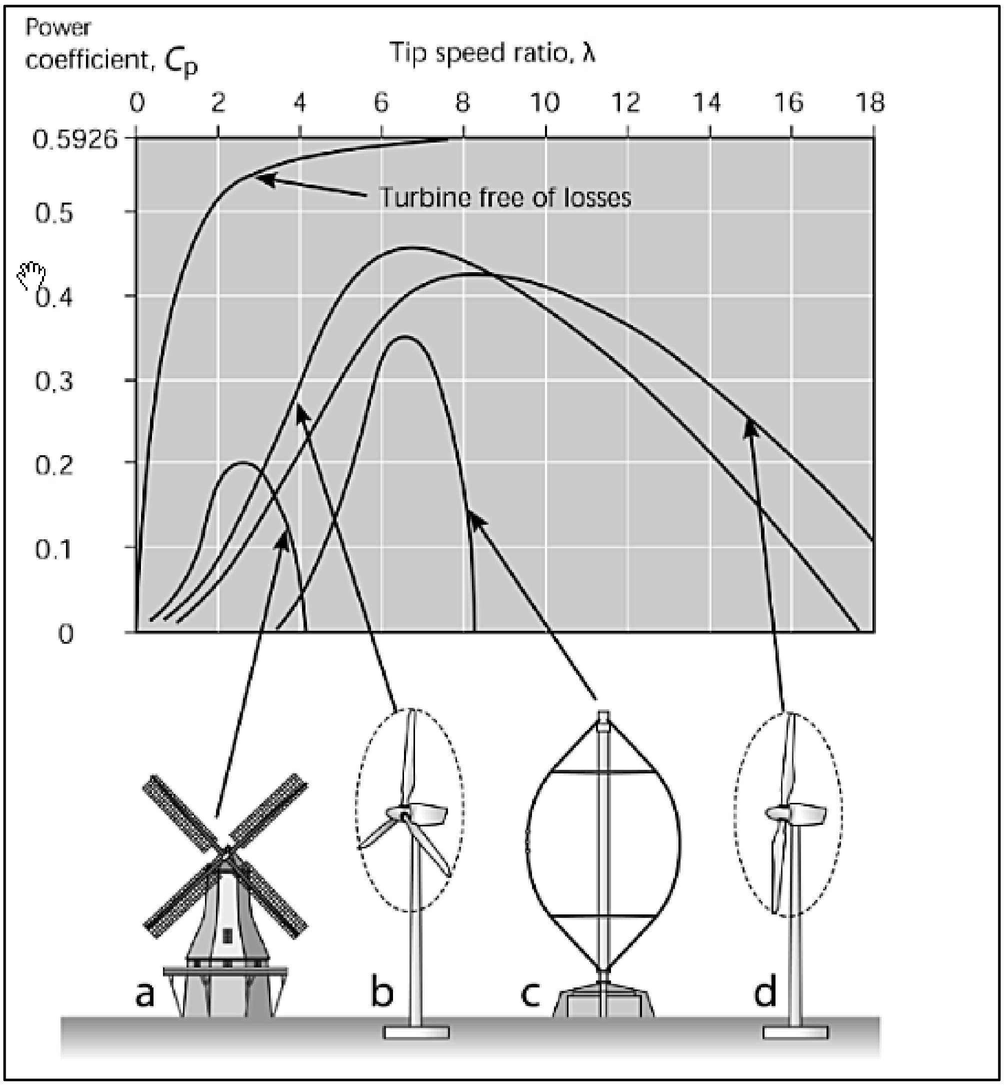


Figure 3-6 Cp curves for different types of turbines [6]

The different types of wind turbine have various value of optimal wind speed ratio and optimal coefficient of power.

Savonius rotor, not shown in the picture above, usually presents an optimal λ value around 1, as shown in the picture (source: Claesson, 1989)

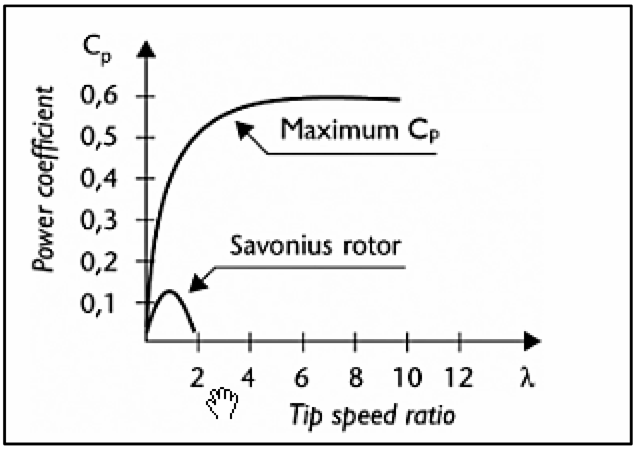


Figure 3-7 Cp curve, Savonius rotor [6]

3.4 Wind gradient

To calculate the wind speed at the height of the hub, it is necessary to take care that the wind speed varies with height due to the friction against the structure of the ground, which slows the wind. This phenomenon is named wind gradient or wind profile and it is shown in Figure 3-8.

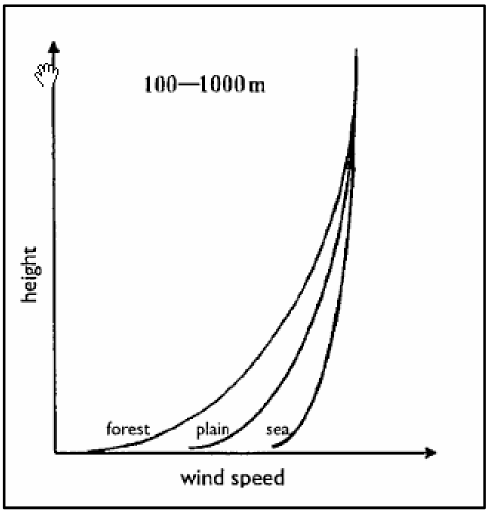


Figure 3-8 Wind speed profile for various locations [6]

If a “z” height is considered, the average of the wind speed at this height is described by:

$$v_z = v_{z0} * \left(\frac{z}{z_0}\right)^{\alpha}$$

Where:

v_{z0} = wind speed at the reference height z_0 [m/s];

z_0 = reference height [m];

α = value depending on the roughness class of the terrain, as shown in the following table;

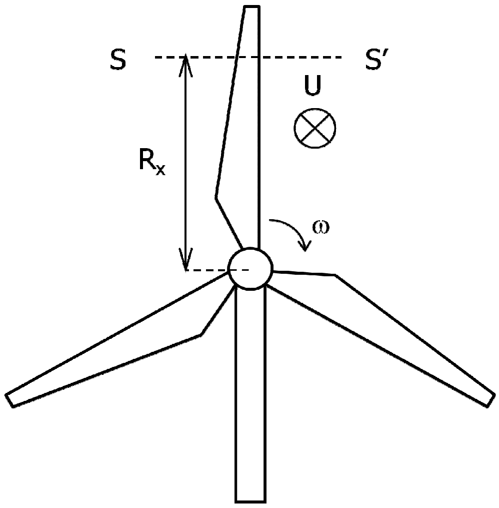
Table 3-1 Roughness classes [6]

Roughness class	Type of terrain	α
0	Open water	0.1
1	Open plain	0.15
2	Countryside with farms	0.2
3	Villages and low forest	0.3

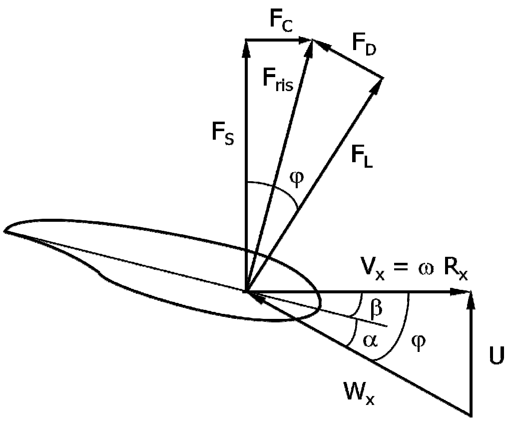
3.5 Lift and drag force:

When the air flow acts on the blade, it generates two kind of forces, named lift and drag, which are responsible for the rotating of the blades.

An analysis of these forces, acting on a 3 blades HAWT, shown in the following picture, can be done:



3-9 Torque generation on a wind turbine [7]



3-10Aerodynamics forces on the blade [7]

Where:

U = undisturbed wind speed;

W_x = component of wind speed that interacts with the blade;

V_x = rotational speed of the rotor;

α = angle of attack;

The undisturbed wind speed hits the blades with a certain angle α, named angle of attack, respect to chord line of the blade.

The relationship between the rotational speed of the turbine and the undisturbed wind speed is related to the angle φ:

$$\lambda = arctg(\varphi) = \frac{V_x}{U} = \frac{\omega * R}{U}$$

In a HAWT with variable speed this angle is used to control the rotational speed, with the stall control or pitch control: a variation of this angle is used to increase the turbine rotational speed when the wind speed is under the rated one and to stop the increasing of the rotational speed when the wind speed gets a value higher than the rated one.

Looking at the previous figure, the lift and the drag force can be described by:

$$F_L \sim C_L(\alpha) * W_x^2$$
$$F_D \sim C_D(\alpha) * W_x^2$$

C_L and C_D are the lift coefficient and the drag coefficient and they depend on the value of angle α. The lift coefficient is higher than the drag one and it increases with the increasing of α until the value of 15°, where it shows a value of about 1,2. After this value it decreased strongly due to the stall effect. Instead the value of C_D increases with the increasing of the angle of attack, passing the value of 0,3 just for α > 20°.

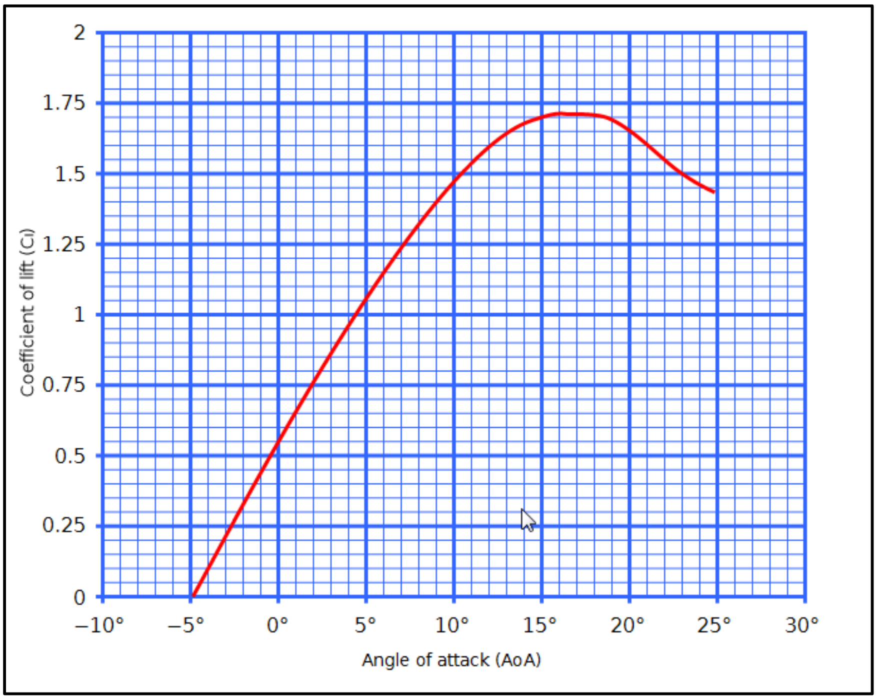


Figure 3-11 Lift coefficient [4]

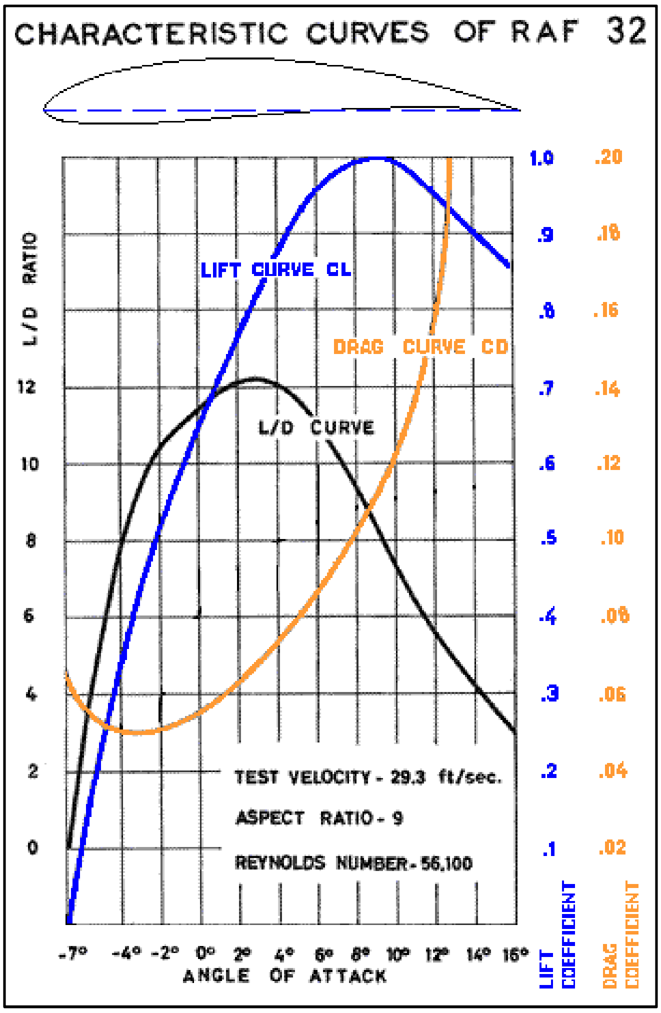


Figure 3-12 Example of Cd and Cl for an airfoil [5]

In a VAWT the angle of attack changes during the rotation and the direction from which the wind invests the rotor is not so important like in the HAWT, where a yam system is necessary to rotate the wind turbine in front of the direction of the wind speed.

The resultant force F_{ris} of the vector sum of F_L and F_D can be divided in two component:

F_c: on the direction of the rotation of the wind turbine; it’s the force that make the turbine rotate;

F_s: releases its energy on the structure of the tower, flexing it.

3.6 Control of the blade

Usually a wind turbine operates in a range of wind speed form 4 m/s to 25 m/s. In this range the generated power increase to the rated power, usually located between 11 m/s and 15 m/s.

After the value of rated power, a control system is necessary to avoid that too much high wind speed causes a too high rotational speed that can create strong stress on the tower and damage it.

By changing the angle attack and the pitch angle, the power of the turbine can be controlled and there are passive control and active control.

The passive control, for a wind turbine with fixed rotational speed, takes advantage from the fact that, when the wind speed increases, α increases and the blade goes toward the stall situation, decreasing the value of the lift force and of the coefficient of power Cp: this is a cheap technique that doesn't need any special equipment, but creates strong stress on the tower structure.

The active control, for wind turbine with variable rotational speed, uses some electronically equipment to rotate the blade around their own axis in order to reach the stall or to reach the feather of the blades, as shown in the following pictures:

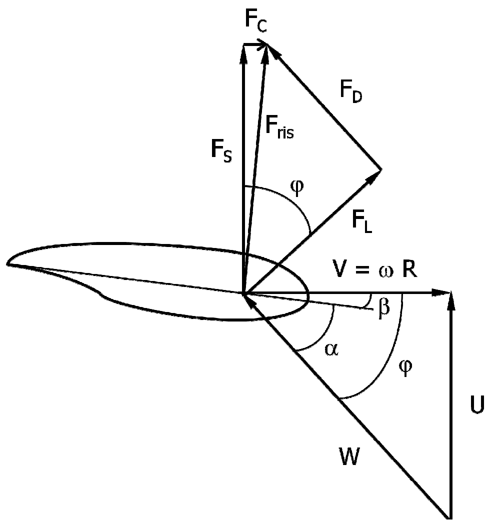


Figure 3-13 Stall control [7]

Pitch control toward the stall:

By rotating the blade, the angle of attack is increased and the β pitch angle is reduced. This situation bring to the stall of the blade, with a strong reduction of the component Fc, the one that make the turbine rotate.

This is a quick way to control the rotational speed, but creates stress on the tower (F_s is still high).

Pitch control toward the feather:

By increasing the angle β, a reduction of the rotational speed can be got, due to the reduction of the component Fc.

This is a slower way of control the blades, compared with the pitch control toward the stall, but it reduces much more the stress on the tower, by decreasing also the value of F_s.

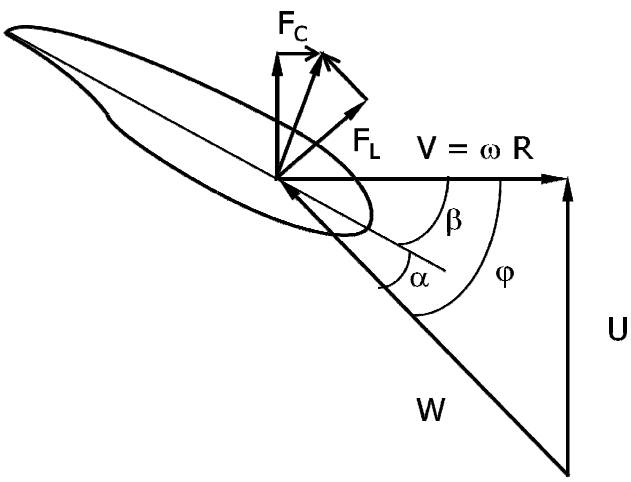


Figure 3-14 Feather[7]

3.7 References

[1] Theory of wind machines, Betz equation; M. Ragheb, 2010

[2] http://re.emsd.gov.hk/wind2006/Wind_Resource_Information.html

[3] http://discoverthewind.com/images/vertical-wind-turbines-o-04.jpg

[4] http://en.wikipedia.org/wiki/Lift_coefficient

[5] http://adamone.rchomepage.com/profile_raf32.gif

[6] Developing wind power projects (Tore Wizelius)

[7] Generatori eolici per la connessione alla rete (F. Spertino)

4 Generators

4.1 Asynchronous

This type of generator generates power if the rotational is speed just above (usually +1%) the frequency of the grid, to which it must be connected to get the current used to magnetize the rotor. This leads to an high reactive power consumption, that is an unnecessary demand and can cause disturbance to the grid, especially in case of large turbines or wind farms.

Fixed speed turbines mount asynchronous generators and, despite the name, they have only a little range of rotational speed for operation, called *slip*. When the rotational speed is close to the nominal value the efficiency of the generator in this little range is high, while it decreases for lower and higher values.

If the rotational speed is lower than the synchronous one (3000 rpm for European 50Hz grid frequency), an asynchronous machine works like a motor. In some cases this propriety can be useful to avoid frequent stop and start operations when the wind speed is close to the cut-in speed.

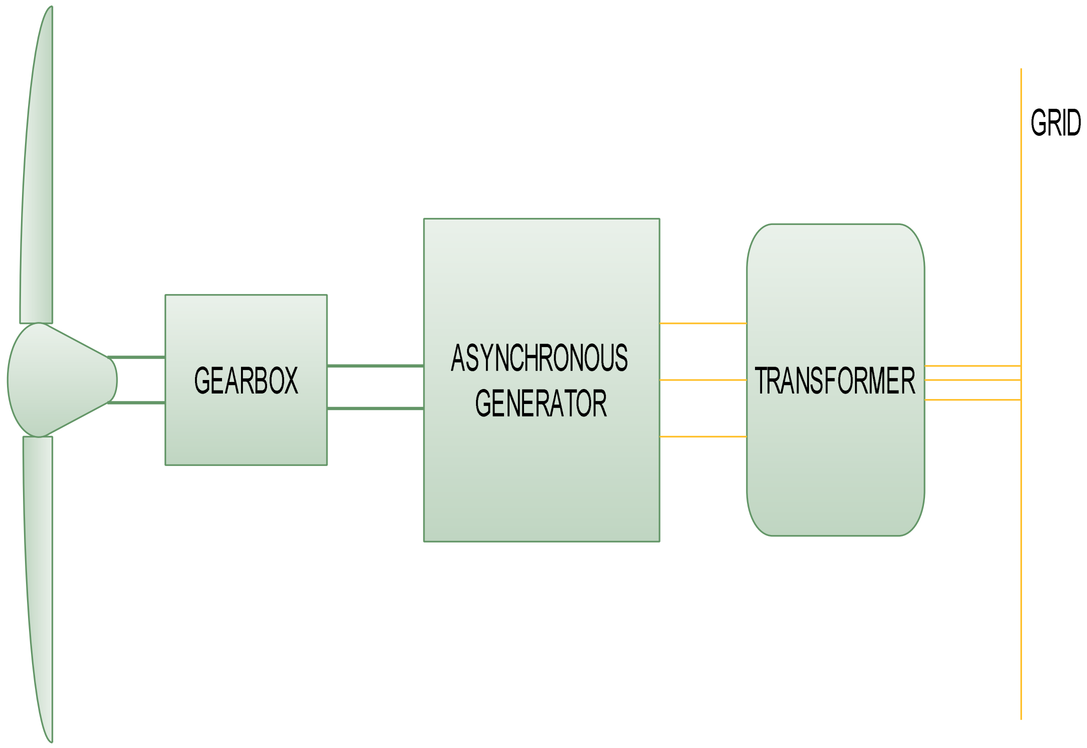


Figure 4-1 Asynchronous generator with gearbox

- Soft start: this equipment is made of capacitors to reduce the reactive power consumption.
- Generator with slip: they use variable resistance in the rotor windings or electronic devices to control the current to make possible wider range of rotational speed to the rotor, usually up to 10%. The turbine will rotate faster without affecting frequency and power output.
- BEC: the use of bidirectional electronic converter (BEC) allows to boost the efficiency with variable speed concept in a wound rotor IG: it is possible to adjust the electric torque apart from the aerodynamic one.

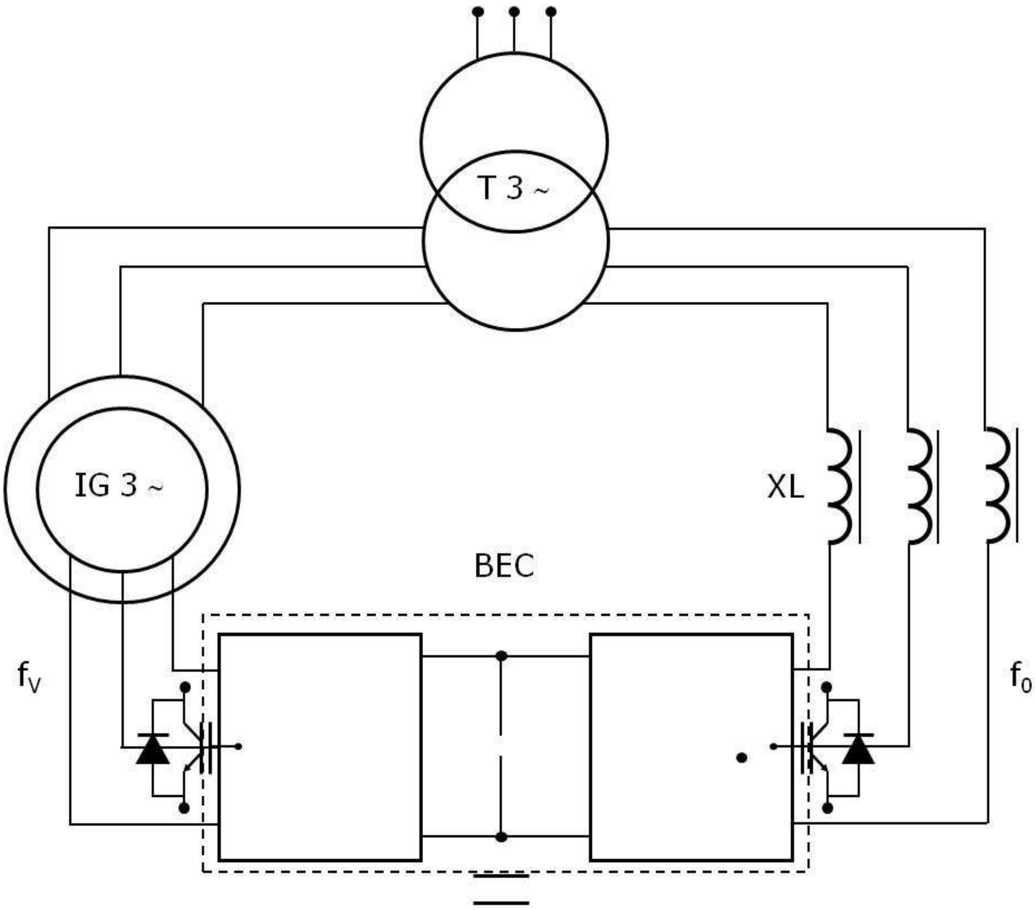


Figure 4-2 Bidirectional electronic converter [7]

The rotor speed can be increased, recovering power into the grid (super-synchronous speed) with extended range up to 30%: the efficiency is high due to the low losses in BEC
On the other hand, the rotor speed can be also decreased, extracting power from the grid (sub-synchronous speed) with extended range down to 30%: that gives high efficiency with low wind speed .

4.2 Synchronous

In its most common form is made of a magnetic field on the rotor with the rotor and a stationary armature with multiple windings. The field in the rotor is made with DC current, normally produced by a small DC generator on the rotor shaft. This means that a synchronous generator doesn't need grid connection to produce power.

- Gearbox: it's between the primary shaft of the turbine and the generator, in order to increase the rotational speed, too low in the blades for AC generation at grid frequency. For a grid connected, variable speed turbine with synchronous generator this means that also a frequency converter is needed. A simplified scheme is shown in the figure below.

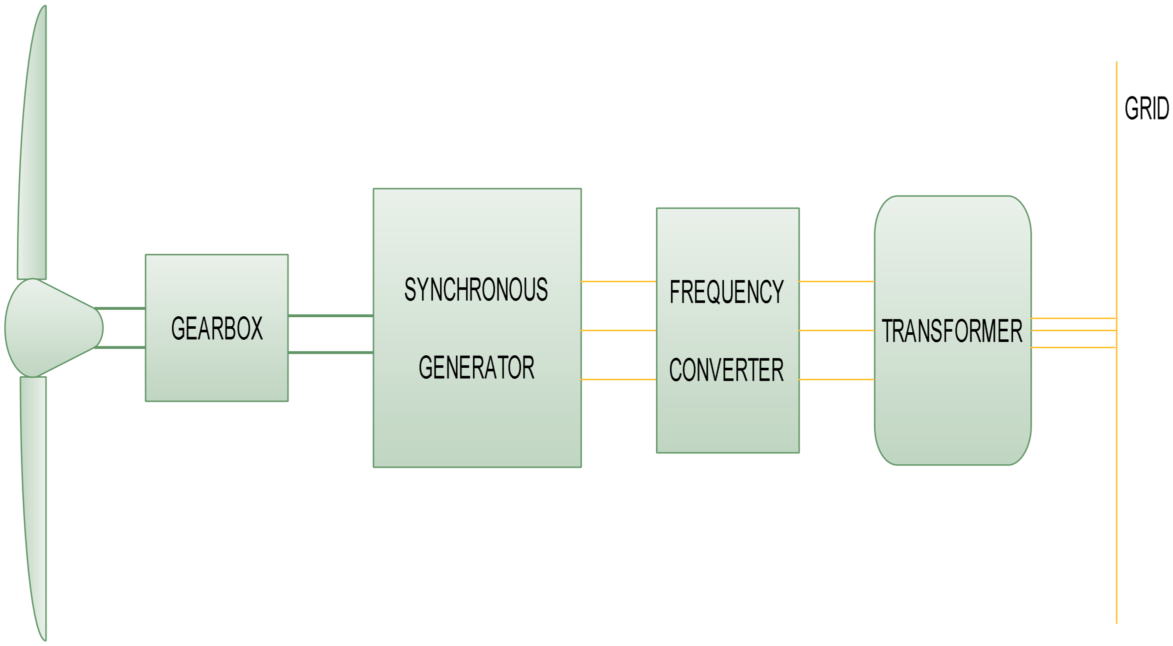


Figure 4-3 Synchronous generator with gearbox and frequency converter

- Direct drive (ring generator): it's a generator with a large number of poles, so that the rotational speed of the blades should not be very high in order to produce power. Anyway, a frequency converter is needed for the connection to the grid. There's no need of gearbox, so the required maintenance is lower, but dimensions and weight are very high: this is not a problem for example in VAWT turbines, where the generator is placed at ground level. This type of generator is used in HAWT mainly by Enercon.

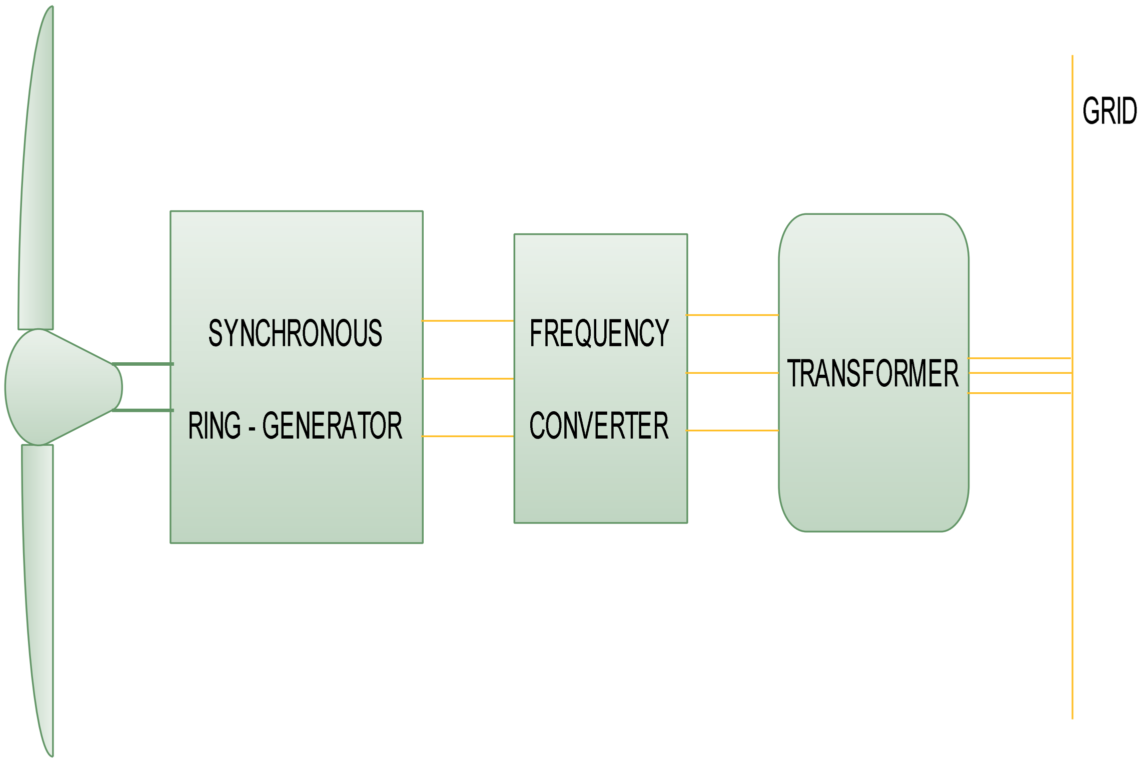


Figure 4-4 Synchronous generator with frequency converter

4.3 Permanent magnet generators

This type of generator uses permanent magnet for self-excitation, that is made without energy supply, thus the efficiency is higher than the induction machine. Power can be generated at any speed, and if provided with a large number of poles it can have a slow rotational speed if compared to conventional generators. Since they don't need gearboxes, the losses are further reduced, as well as the maintenance time and costs, while torque and output power per volume unit are usually higher than electromagnetic excited-machines. The main disadvantages of this type of generators are the expensive materials and the low resistance to high currents and temperature. However in the last years the use of permanent magnet machines has become attractive for wind turbines, due to lower prices and higher resistance materials.

The most common types are listed below:

- radial flux machines
- axial flux machine
- transversal flux machine

4.4 References

[1] Developing Wind Power Projects (Tore Wizelius)

[2] Wind energy explained (Manwell, McGowan, Rogers)

[3] Wind power in power systems (Thomas Ackermann)

[4] Direct Driven Generators for Vertical Axis Wind Turbines (Sandra Eriksson)

[5] Different 600kW designs of an axial flux permanent magnet machine for wind turbines (E. PEETERS, J. VAN BAEL, P. VAN TICHELEN)

[6] Permanent magnet motor technology: design and applications (Jacek F. Gieras, Mitchell Wing)

[7] Generatori eolici per la connessione alla rete (F. Spertino)

5 Wind Energy Statistics

5.1 Europe

5.1.1 Wind installations in 2009

During 2009, 10526 MW of wind power was installed across Europe, 10163 MW of that being in the European Union countries. This represents a market growth in the EU of 23% compared to 2008 installations.

Of the 10163 MW installed in the European Union, 9581 MW was installed onshore and 582 MW offshore. In 2009 the onshore wind power market grew 21% compared to the previous year and the offshore wind power market grew 56% compared to the previous year.

Analyzing the total value, it's possible to note what is reported in Table 5-1:

Table 5-1 Ttotal values of installed capacity (source: EEWA)

European Union	74767	MW
Candidate Countries	829	MW
EFTA	449	MW
Total Europe	76152	MW

The situation of the different countries is reported in Table 5-1Table 5-2 and in Table 5-3:

Table 5-2 Installed capacity for non EU members (sources: EWEA)

	Installed 2008	End 2008	Installed 2009	End 2009
Candidate Countries [MW]				
Croatia	1	18	10	28
FYROM*	0	0	0	0
Turkey	311	458	343	801
Total	312	476	353	829

EFTA [MW]				
Iceland	0	0	0	0
Liechtenstein	0	0	0	0
Norway	103	429	2	431
Switzerland	2	14	4	18
Total	105	443	6	449
Others [MW]				
Faroe Islands	0	4	0	4
Ukraine	1	90	4	94
Russia	0	9	0	9
Total	1	103	4	107
Total Europe	8686	65741	10526	76267

Table 5-3 Installed capacity for EU member (source: EWEA)

EU Capacity [MW]				
	Installed 2008	End 2008	Installed 2009	End 2009
Austria	14	995	0	995
Belgium	135	415	149	564
Bulgaria	63	120	57	177
Cyprus	0	0	0	0
Czech Republic	34	150	44	194
Denmark	60	3163	334	3497
Estonia	19	78	64	142
Finland	33	143	4	147
France	950	3404	1088	4492
Germany	1665	23903	1917	25820
Greece	114	985	102	1087
Hungary	62	127	74	201
Ireland	232	1027	233	1260

	Installed 2008	End 2008	Installed 2009	End 2009
Italy	1010	3736	1114	4850
Latvia	0	27	2	29
Lithuania	3	54	37	91
Luxembourg	0	35	0	35
Malta	0	0	0	0
Netherlands	500	2225	39	2264
Poland	268	544	181	725
Portugal	712	2862	673	3535
Romania	3	11	3	14
Slovakia	0	3	0	3
Slovenia	0	0	0	0
Spain	1558	16689	2459	19148
Sweden	262	1048	512	1560
United Kingdom	569	2974	1077	4051
Total EU-27	8268	64719	10163	74882
Total EU-27	7815	63604	9702	73306
Total EU-12	453	1115	461	1576
Of which offshore and near shore	374	1479	582	2061

Investment in EU wind farms in 2009 was 13 billion of Euros. The onshore wind power sector attracted 11,5 billion of Euros during 2009 while the offshore wind power sector attracted 1,5 billion of Euros.

In terms of annual installations Spain was the largest market in 2009, with 2459 MW installed, while Germany installed 1917 MW. Italy, France and the United Kingdom installed respectively 1114 MW, 1088 MW and 1077 MW. These data show strong development in mature markets, like Spain, Germany, Italy, France and United Kingdom. Portugal (673 MW), Sweden (512 MW), Denmark (334 MW), and Ireland (233 MW) also performed strongly.

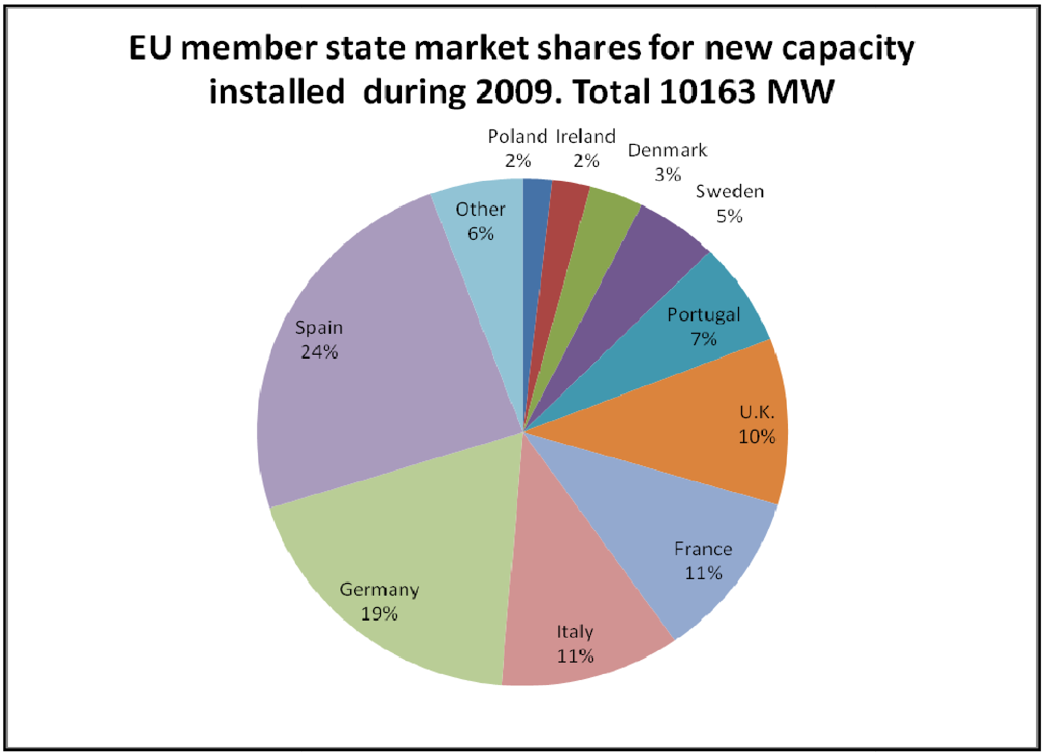


Figure 5-1: source EWEA

5.1.2 Power Capacity installed in 2009

In 2009, for the second year running, in the EU more wind power was installed than any other electricity generating technology. A new capacity of 25963 MW was installed, of which 10163 MW (39%) was wind, 6630 MW was natural gas (26%) and 4200 MW was solar PV (16%). In addition 2406 MW (9%) of new coal was installed, 581 MW (2,2%) of biomass, 573 MW (2,2%) of fuel oil, 442 MW (1,7%) of waste, 439 MW (1,7%) of nuclear, 338 MW (1,3%) of large hydro, 120 MW (0,46%) of concentrated solar power, 55 MW (0,2%) of small hydro, 12 MW (0,04%) of other gas, 3,9 MW (0.01%) of geothermal, and 405 kW of ocean power.

During 2009 some sectors decommissioned more MW than they installed: nuclear power sector decommissioned 1393 MW and the coal power sector decommissioned 3200 MW.

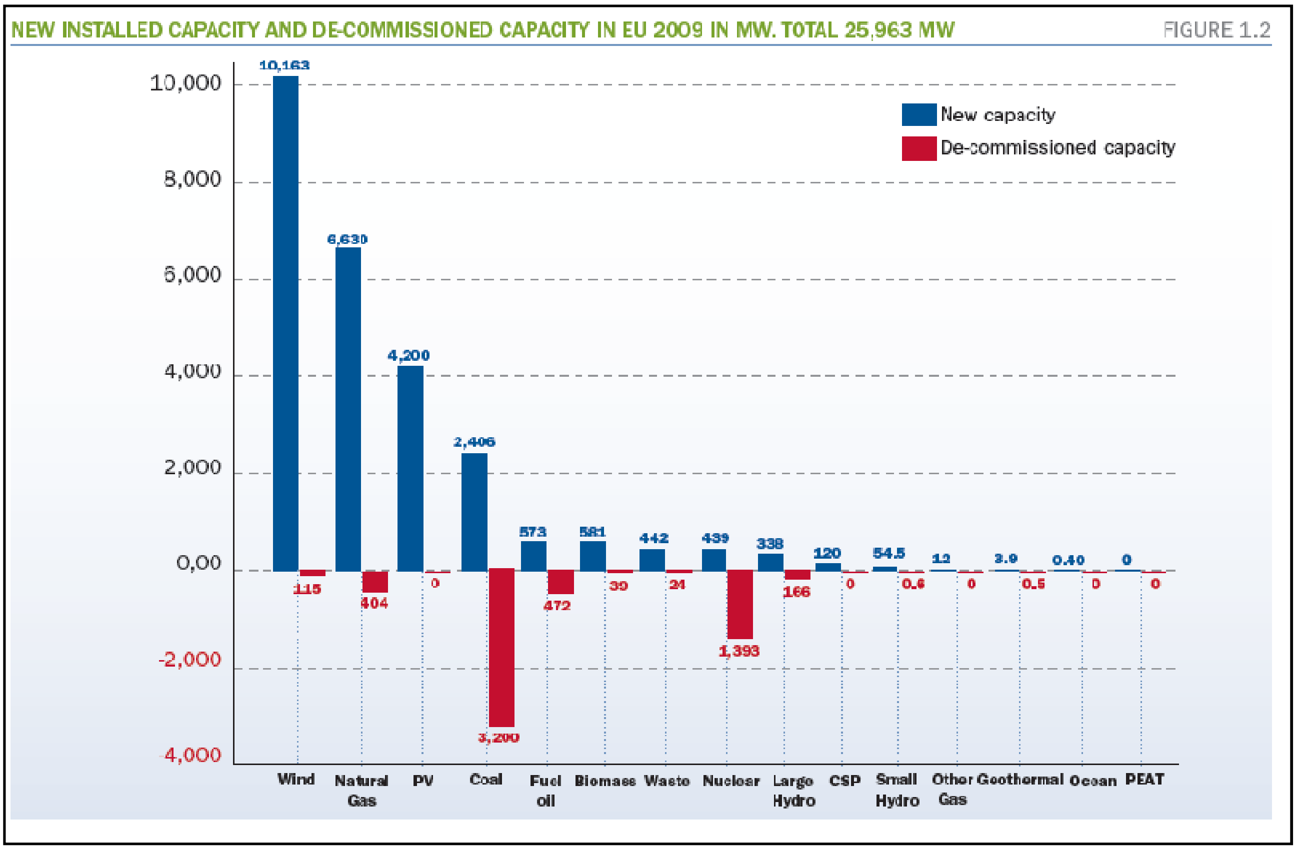


Figure 5-2: source EWEA, "Wind in power: 2009 European statistics"

5.1.3 2009: renewables continue to dominate new power installations

In 2009, for the second year running, more wind power was installed than any other generating technology and also renewables accounted for more than 50% of new installations, cementing a rising trend initiated over a decade ago.

In total, renewable energy accounted for 61% (15904 MW) of all new generating capacity installed in the EU during 2009.

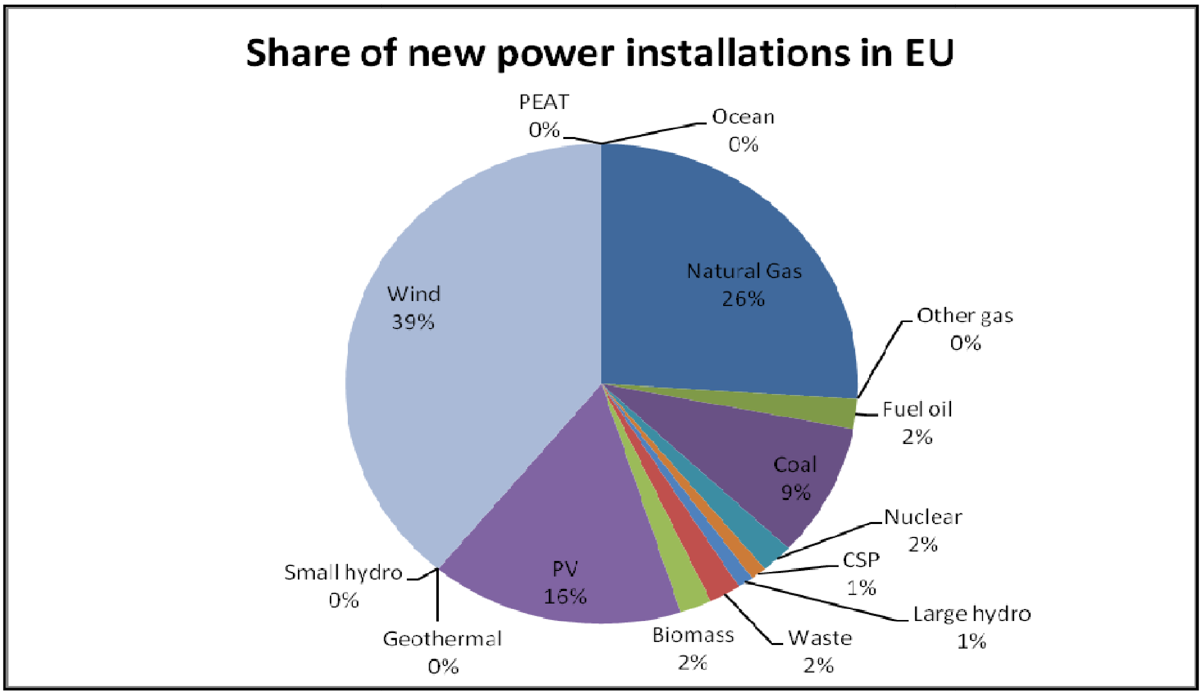


Figure 5-3: source EWEA

5.1.4 Trends & cumulative installations

Since 2008, each year renewable electricity generating technologies, mostly wind power, but also solar PV, hydro power and biomass have accounted for more than 50% of new power installations. This trend has increased from just 14% of new installations in 1995 to 61% in 2009.

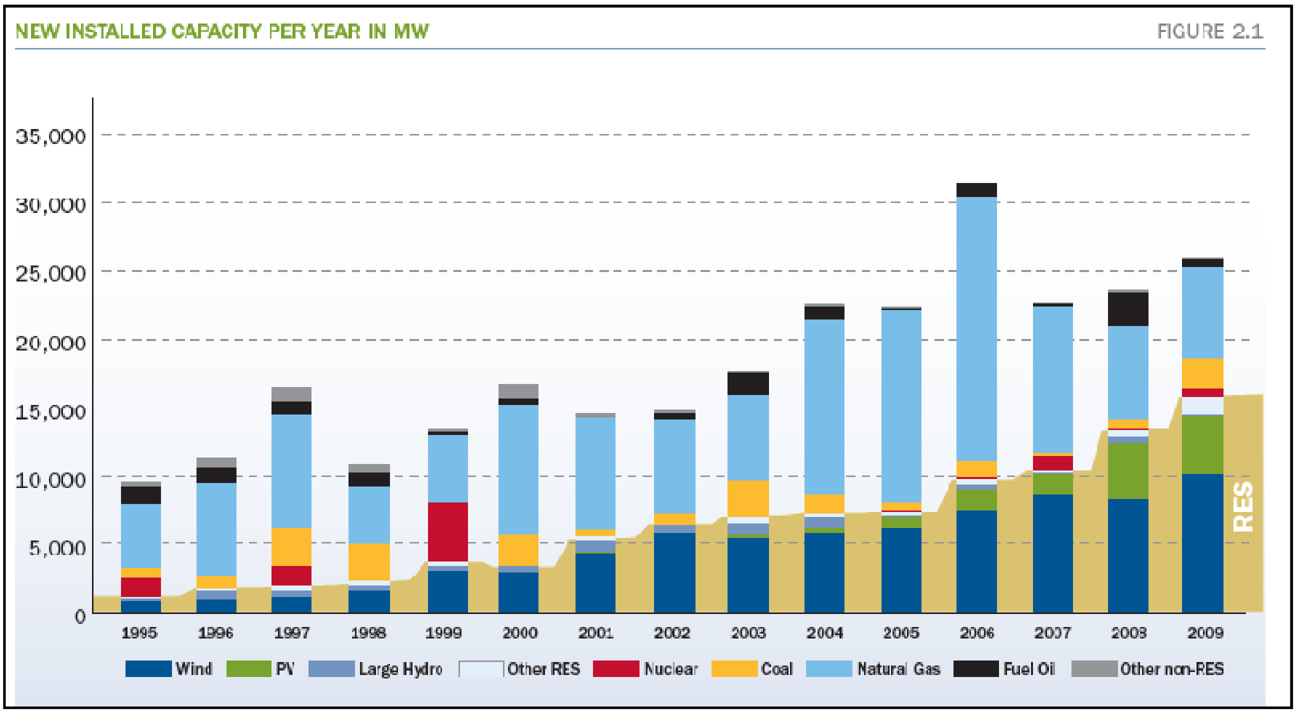


Figure 5-4: source EWEA, "Wind in power, 2009 European statistics"

5.1.5 Net changes in EU installed capacity

The installations of the 2009 continue the trend in changes in EU net installed capacity for the various electricity generating technologies from 2000 to 2009. The net growth of natural gas (81 GW) and wind power (65,1 GW) came about at the expense of fuel oil (down 12,9 GW), coal (down 12 GW) and nuclear power (down 7,2 GW).

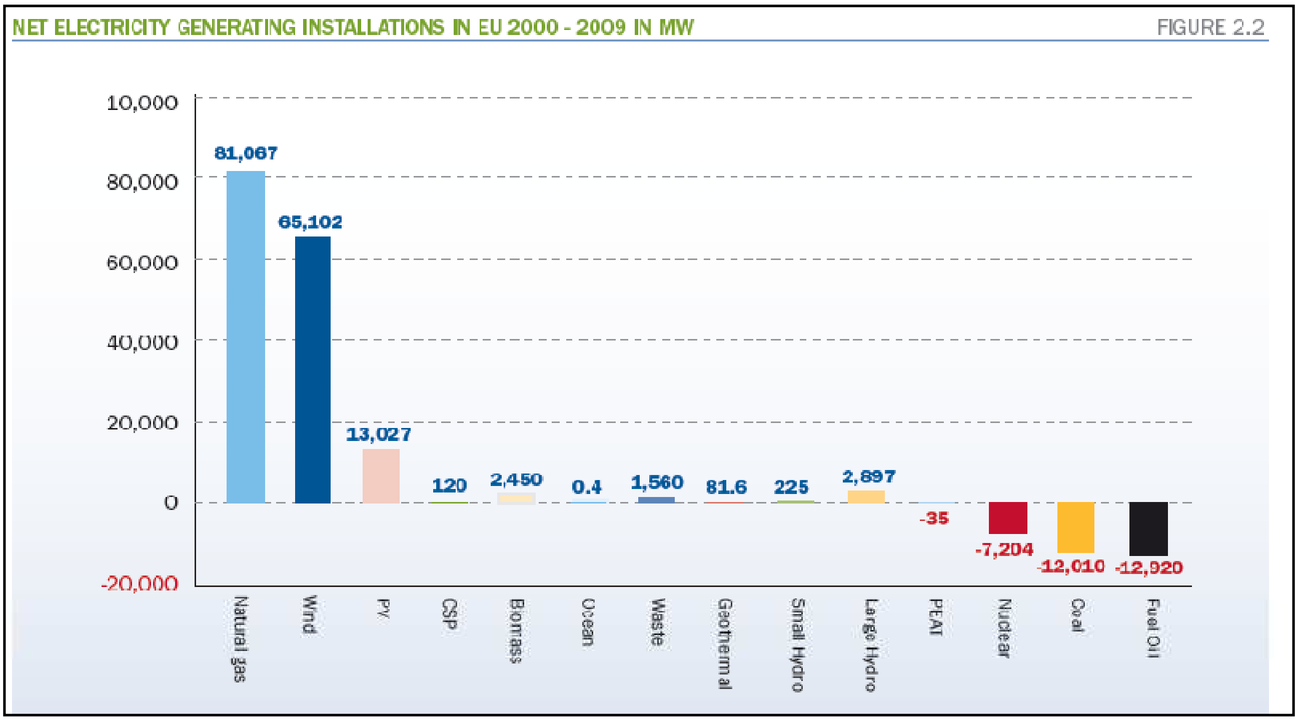


Figure 5-5: source EWEA, "Wind in power, 2009 European statistics"

5.1.6 Total installed power capacity

Wind power's share of total installed capacity in the EU has increased from 2% in 2000 to 9% in 2009, as reported in the following figures.

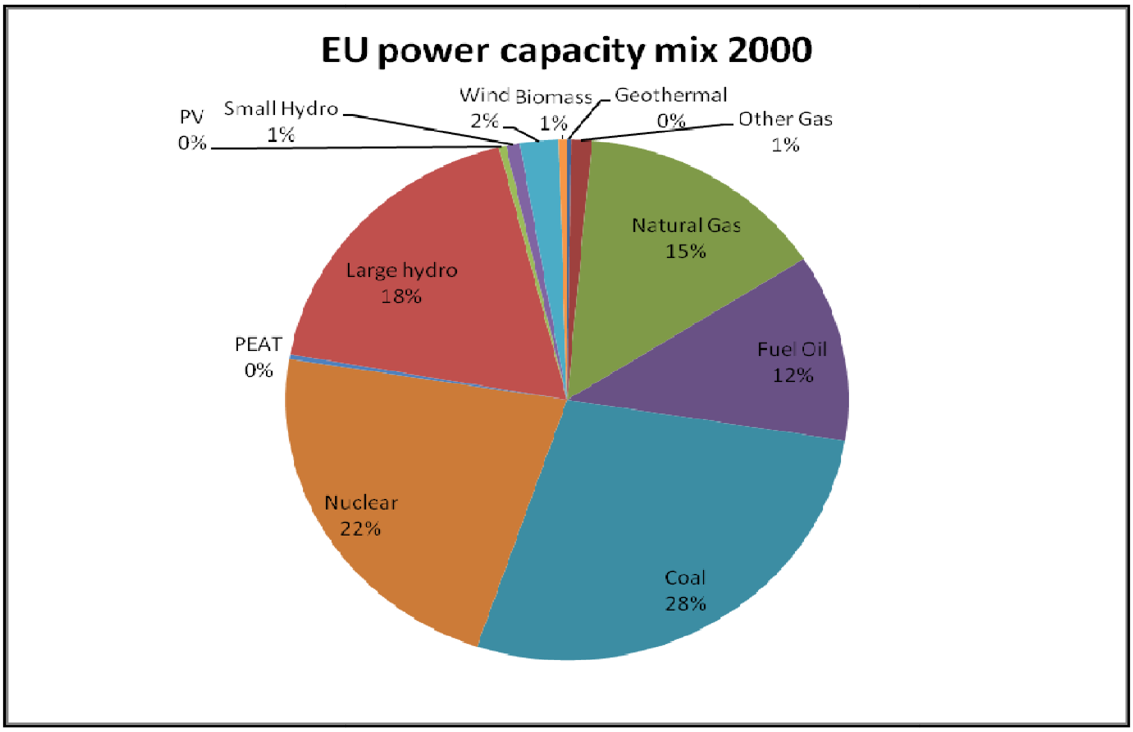


Figure 5-6: source EWEA

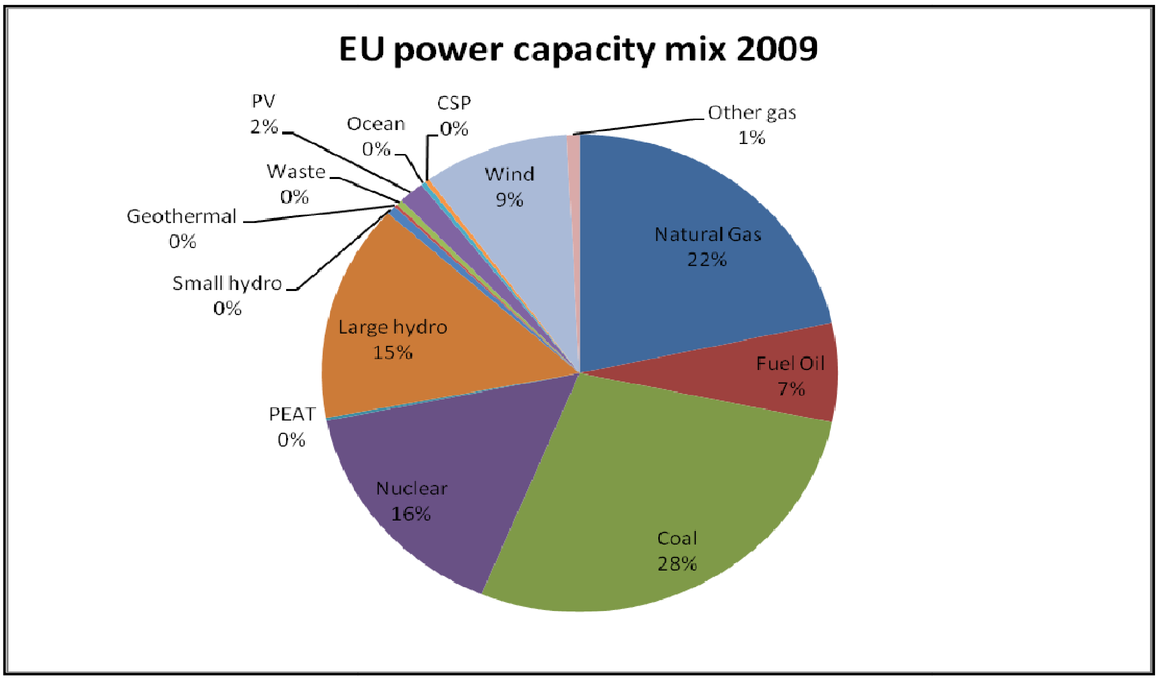


Figure 5-7: source EWEA

5.1.7 Data for wind power installations

Annual installations of wind power in the EU have increased steadily over the last 15 years from 472 MW in 1994 to 10163 MW in 2009, with an annual average market growth of 23%.

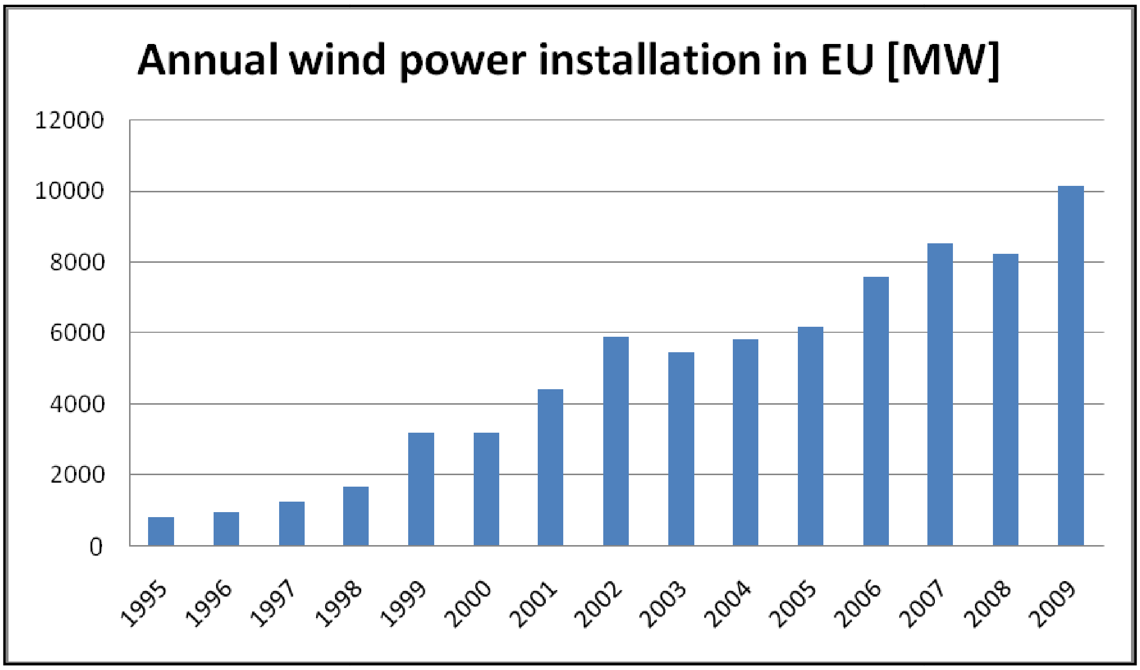


Figure 5-8: source EWEA

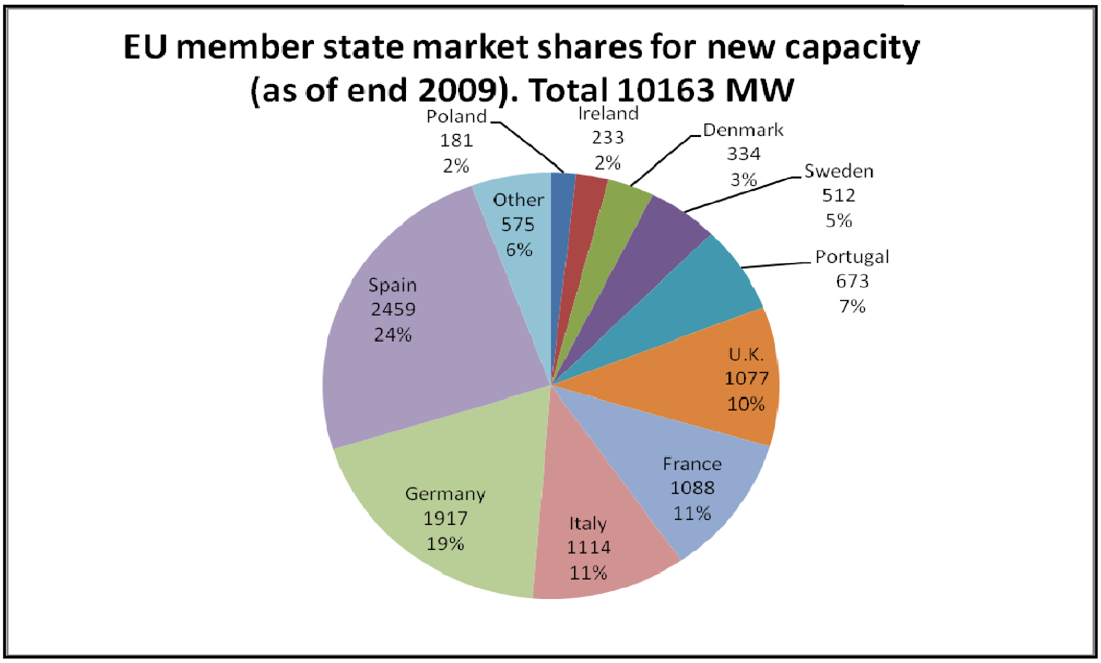


Figure 5-9: source EWEA

5.1.8 Cumulative wind power installations

A total of 74767 MW is now installed in the European Union. Germany remains the EU country with the largest installed capacity, followed by Spain, Italy, France and United Kingdom.

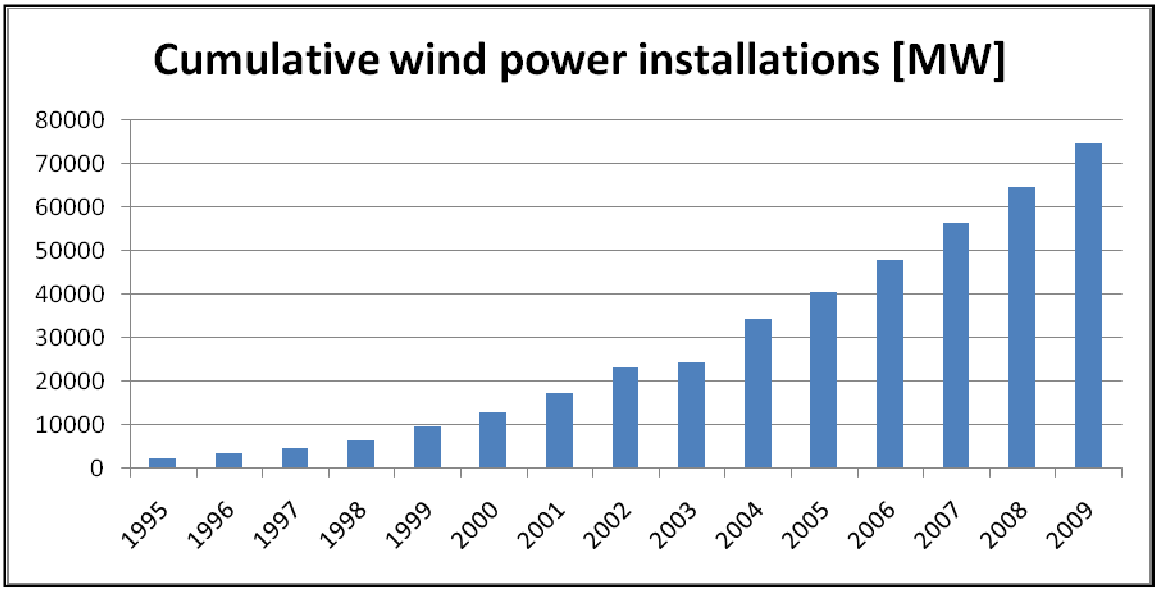


Figure 5-10: source EWEA

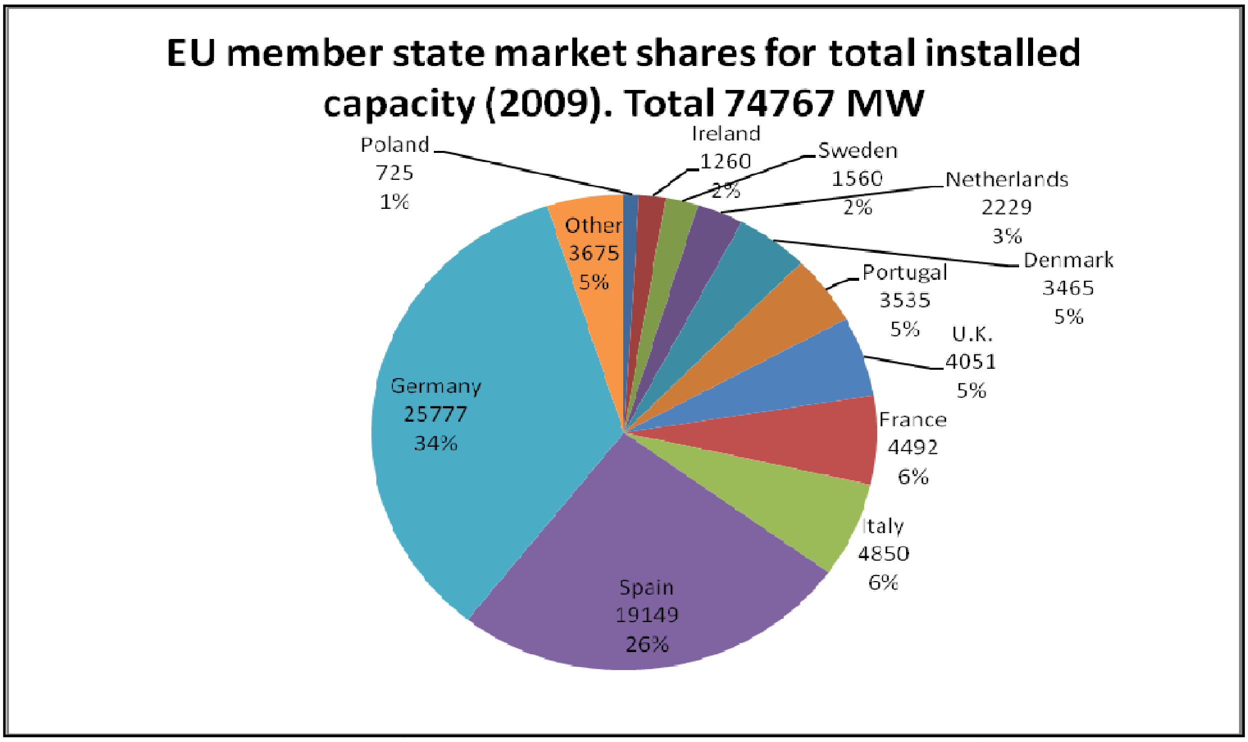


Figure 5-11: source EWEA

5.2 Rest of the World

Wind energy continued its growth in 2008 at an increased rate of 29%:

- all wind turbines installed by the end of 2008 worldwide are generating 260 TWh per annum, equaling more than 1,5 % of the global electricity consumption;
- the wind sector became a global job generator and has created 440000 jobs worldwide;
- the wind sector represented in 2008 a turnover of 40 billion of Euros;
- for the first time in more than a decade, the USA took over the number one position from Germany in terms of total installations;
- China continues its role as the most dynamic wind market in the year 2008, more than doubling the installations for the third time in a row, with today more than 12 GW of wind turbines installed;
- North America and Asia catch up in terms of new installations with Europe which shows stagnation;
- based on accelerated development and further improved policies, a global capacity of more than 1500000 MW is possible by the year 2020;

5.2.1 General situation

Wind energy has continued the worldwide success story as the most dynamically growing energy source again in the year 2008. Since 2005, global wind installations more than doubled.They reached 121188 MW, after 59024 MW in 2005, 74151 MW in 2006 and 93927 MW in 2007. The market for new wind turbines showed a 42% increase and reached an overall size of 27261 MW, after 19776 MW in 2007 and 15127 MW in the year 2006. Ten years ago, the market for new wind turbines had a size of 2187 MW, less than one tenth of the size in 2008. In comparison, no new nuclear reactor started operation in 2008, according to the International Atomic Energy Agency.

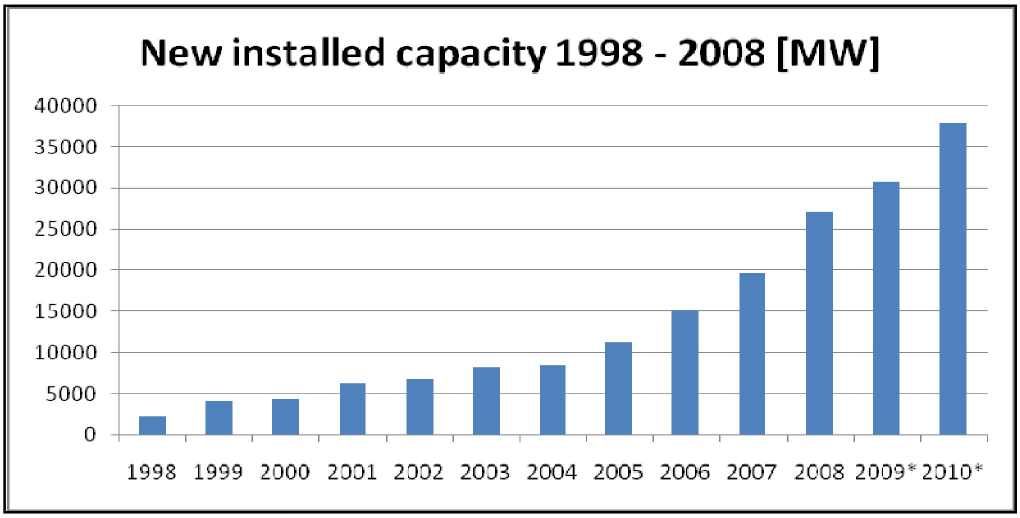


Figure 5-12: source WWEA, "World Wind Energy Report 2008"

5.2.2 Leading wind markets 2008

The USA and China took the lead. USA taking over the global number one position from Germany and China, getting ahead of India for the first time, taking the lead in Asia. The USA and China accounted for 50,8% of the wind turbine sales in 2008. The pioneer country Denmark fell back to rank 9 in terms of total capacity, whilst until four years ago it held the number 4 position during several years. However, with a wind power share of around 20% of the electricity supply, Denmark is still a leading wind energy country worldwide.

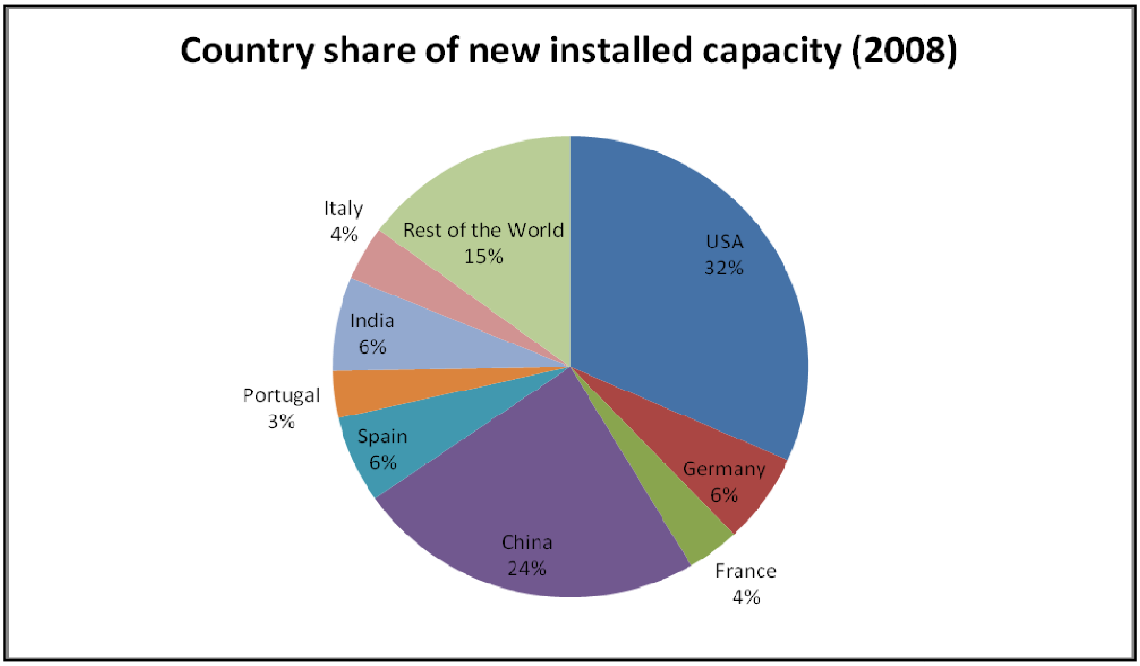


Figure 5-13: source WWEA

5.2.3 Diversification continues

Nowadays 16 markets having installations of more than 1000 MW, compared with 13 countries one year ago. Compared with 24 countries three years ago, 32 countries have more than 100 MW installed. Altogether 76 countries are today using wind energy on a commercial basis. Newcomers on the list are two Asian countries, Pakistan and Mongolia, which both for the first time installed larger grid-connected wind turbines.

5.2.4 Increasing growth rates

An important indicator for the vitality of the wind market is the growth rate in relation to the installed capacity of the previous year. The growth rate went up steadily since the year 2004, reaching 29% in 2008, after 26,6% in 2007, 25,6% in 2006 and 23,8% in 2005 (Figure 5-14). This increase in the average growth rate is mainly due to the fact that the two biggest markets showed growth rates far above the average: USA 50% and China 107%.

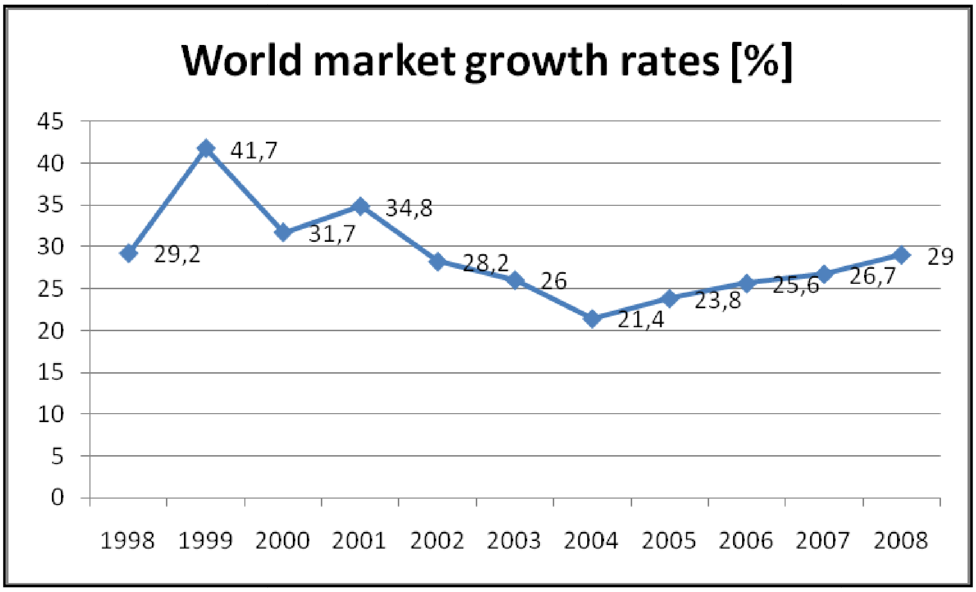


Figure 5-14: source WWEA

5.2.5 Employment: wind energy as job generator

One fundamental advantage of wind energy is that it replaces expenditure on mostly imported fossil or nuclear energy resources by human capacities and labour. Wind energy utilization creates many more jobs than centralized and non-renewable energy sources. The wind sector worldwide has become a major job generator: within only three years, the wind sector worldwide almost doubled the number of jobs from 235000 in 2005 to 440000 in the year 2008. These 440000 employees in the wind sector worldwide, most of them highly skilled jobs, are contributing to the generation of 260 TWh of electricity.

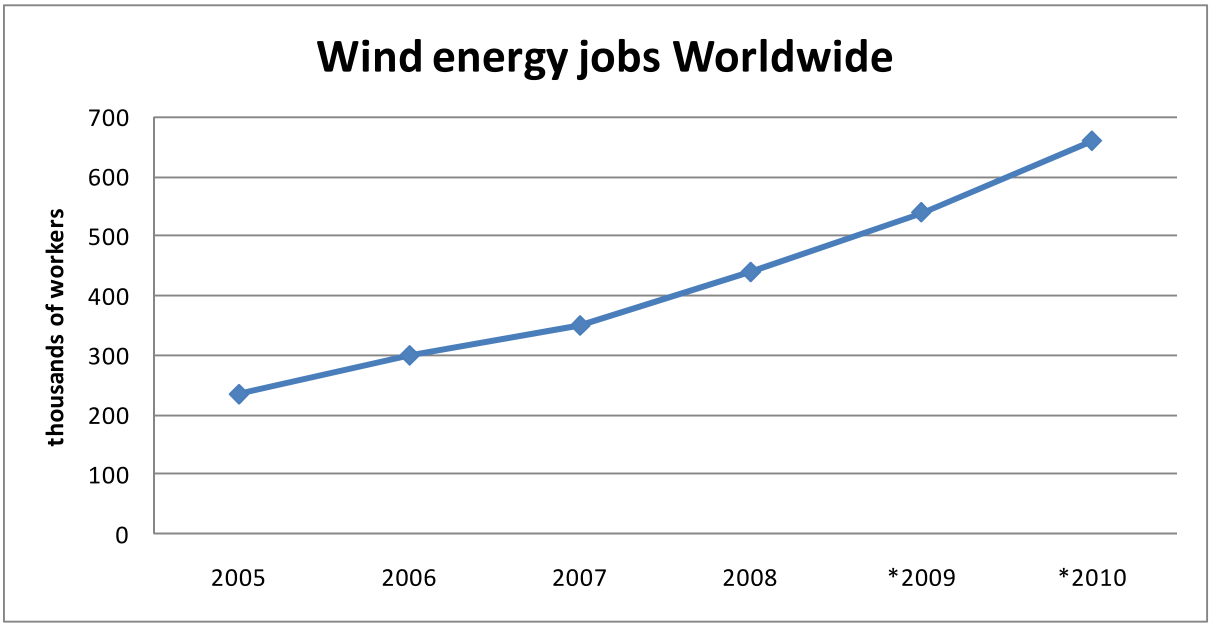


Figure 5-15: source WWEA

5.2.6 Future prospects worldwide

Based on the experience and growth rates of the past years, WWEA expects that wind energy will continue its dynamic development also in the coming years. Although the short term impacts of the current finance crisis makes short-term predictions rather difficult, it can be expected that in the mid-term wind energy will rather attract more investors due to its low risk character and the need for clean and reliable energy sources. More and more governments understand the manifold benefits of wind energy and are setting up favorable policies, including those that are stimulation decentralized investment by independent power producers, small and medium sized enterprises and community based projects, all of which will be main drivers for a more sustainable energy system also in the future.

Carefully calculating and taking into account some insecurity factors, wind energy will be able to contribute in the year 2020 at least 12% of global electricity consumption. By the year 2020, at least 1500000 MW can be expected to be installed globally. A recently published study by the Energy Watch Group reveals, as one out of four described scenarios, that by the year 2025 it is even likely to have 7500000 MW installed worldwide producing 16400 TWh. All renewable energies together would exceed 50% of the global electricity supply. As a result, wind energy, along with solar, would conquer a 50% market share of new power plant installations worldwide by 2019. Global not renewable power generation would peak in 2018 and could be phased out completely by 2037.

The creation of the International Renewable Energy Agency, which was founded in January 2009, will act as a catalyst and further speed up the deployment rates of renewable energies: directly through providing know-how to its currently 76 member countries and through acting as a balancing lobby at international decision making processes such as the UN climate change negotiations.

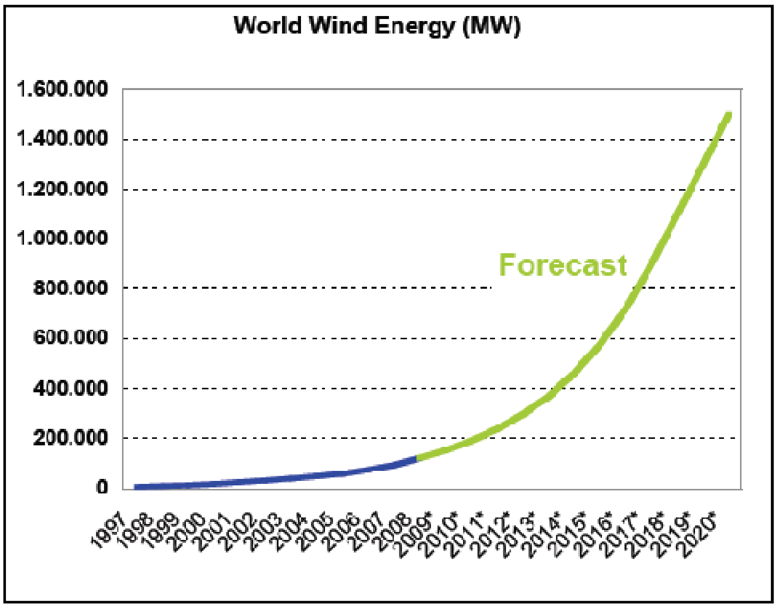


Figure 5-16: source WWEA

5.2.7 Offshore wind energy

By the end of the year 2008, 1473 MW of wind turbines were in operation offshore, more than 99% of it in Europe, representing slightly more than 1% of the total installed wind turbine capacity. Equaling a growth rate of 30%, 350 MW were added offshore in 2008.

5.2.8 Continental distribution

In terms of continental distribution, a continuous diversification process can be watched as well. In general, the focus of the wind sector moves away from Europe to Asia and North America.

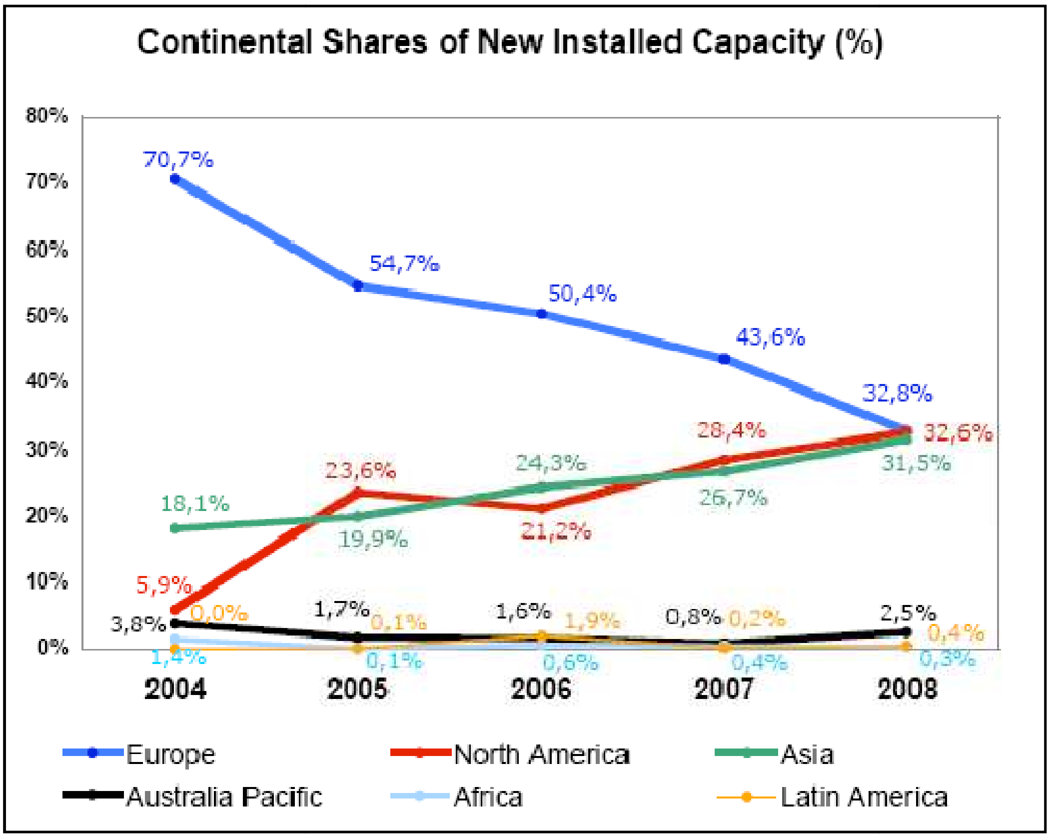


Figure 5-17: source WWEA, "World Wind Energy Report 2008"

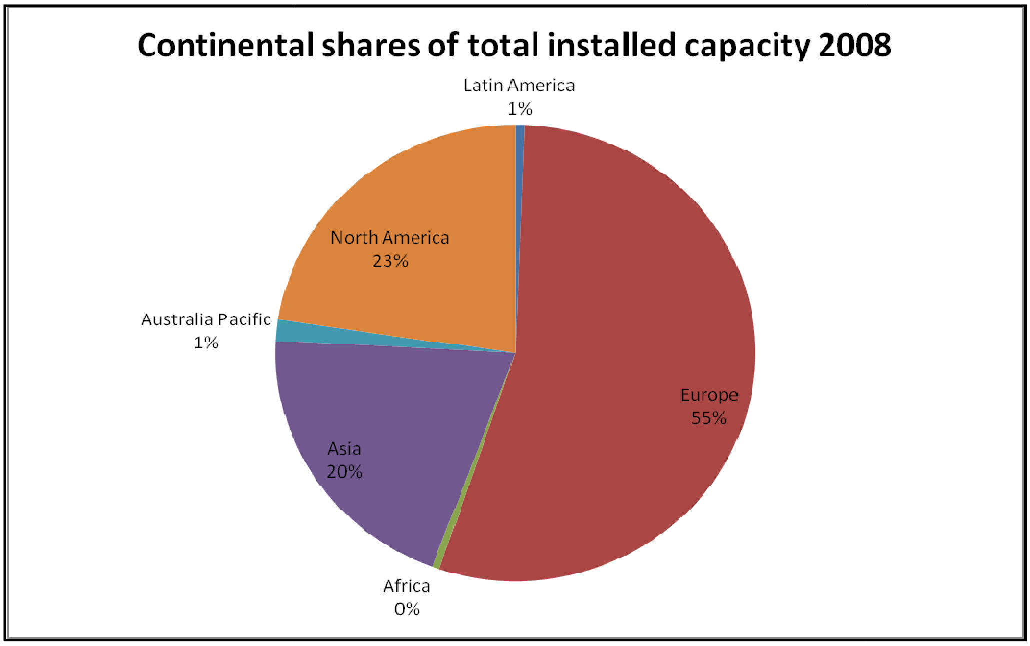


Figure 5-18: source WWEA

Europe decreased its share in total installed capacity from 65,5% in 2006 to 61% in the year 2007 further down to 54,6% in 2008. Only four years ago Europe dominated the world market with 70,7% of the new capacity. In 2008, for the first time, Europe (32,8%), North America (32,6%) and Asia (31,5%) account for almost similar shares in new capacity. However, Europe is still the strongest continent while North America and Asia are increasing rapidly their shares. The countries in Latin America and Africa counted for respectively only 0,6% and 0,5% of the total capacity and fell back in terms of new installations down to respectively only 0,4% and 0,3% of the additional capacity installed worldwide in the year 2008.

A summary of the capacity installed of the rest of the world is reported in the **Errore. L'origine riferimento non è stata trovata.**:

Table 5-4 Continental distribution (source WWEA)

	2006	2007	2008
Africa	337	478	563
Asia	10625	15863	24439
Australia Pacific	988	1139	1819
Latin America	516	550	667
North America	13063	18665	27539

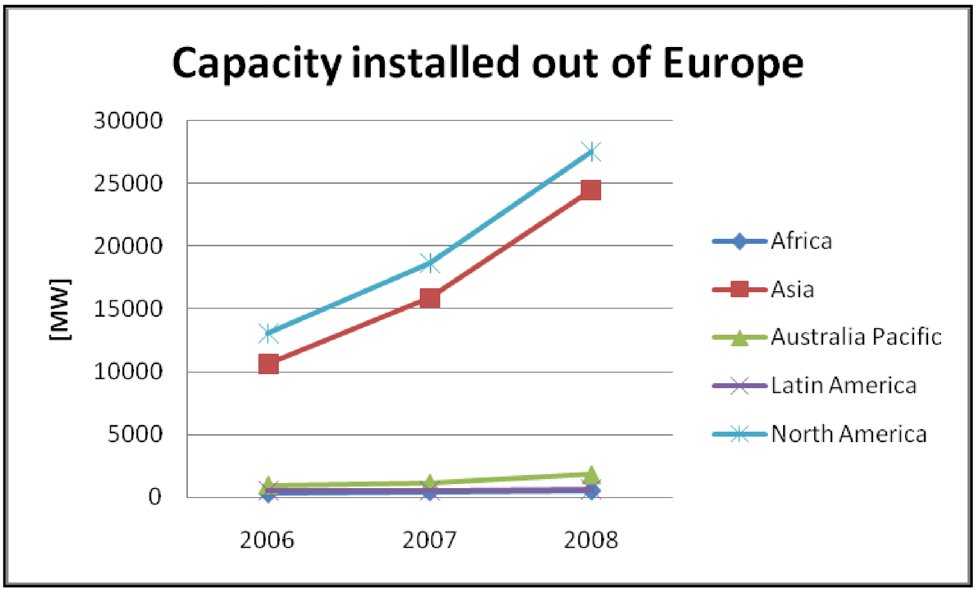


Figure 5-19: source WWEA, "World Wind Energy Report 2008"

5.2.8.1 Africa

In spite of the huge potentials all over the continent, with world's best sites in the North and South of the continent, wind energy plays still a marginal role on the continent with 563 MW of total capacity. Several major wind farms can be found in some of the North African countries like Morocco, Egypt or Tunisia. In the year 2009 and 2010, substantial increases can be expected from projects which are already in the development stage. Companies from the region are showing an increasing interest and have started investing in the wind sector: in Sub-Saharan Africa, the installation of the first wind farm in South Africa operated by an Independent Power Producer can be seen as a major breakthrough. The South African government prepares the introduction of a feed-in tariff which would create a real market, enable independent operators to invest and thus play a key role in tackling the country's power crisis. In the mid-term, small, decentralized and stand-alone wind energy systems, in combination with other renewable energies, will be key technologies in rural electrification of huge parts of so far not served areas of Africa. This process has only started at very few places and the main limiting factor is lack of access to know-how as well as financial resources.

5.2.8.2 Asia

Asia, with the two leading wind countries China and India and 24439 MW of installed capacity, is in a position of becoming the worldwide locomotive for the wind industry. China has again doubled its installations and Chinese domestic wind turbine manufacturers have started for the first time to export their products. It can be expected that in the foreseeable future Chinese and Indian wind turbine manufacturers will be among the international top suppliers. The Indian market has shown robust and stable growth in the year 2008. It has already a well established wind industry which already plays a significant and increasing role on the world markets. Further countries like South Korea (already with 45% growth rate in 2008) start investing on a larger scale in wind energy and it can be observed that more and more companies are developing wind turbines and installing first prototypes. In parallel with the market growth in the country, it can be expected that also new manufacturers will be able to establish themselves. Pakistan installed its first wind farm in the year 2008 and the Government of the country aims at further wind farms in the near future.

5.2.8.3 Australia and Oceania

The region showed encouraging growth rates, reaching 1819 MW by the end of 2008, most of it thanks to Australia. Commitments made by the Australian government to increase their efforts in climate change mitigation and expansion of renewable energies create the expectation that the Australian wind energy market will show further robust growth also in the coming years. New Zealand, after a change in government, may, however, face major delay in its switch to renewable energy.

5.2.8.4 Latin America

Many Latin American markets still showed stagnation in the year 2008 and the overall installed capacity (667 MW) in the region accounts for only 0,5% of the global capacity. Only Brazil and Uruguay installed major wind farms in the year 2008. However, in some countries like Argentina, Chile, Costa Rica and Mexico many projects are under construction.

5.2.8.5 North America

North America showed very strong growth in the year 2008, more than doubling its capacity since 2006 to 27539 MW. The USA became the new number one worldwide in terms of added as well as in terms of total capacity. More and more US states are establishing favorable legal frameworks for wind energy and try to attract investors in manufacturing facilities. It can be expected that the new Obama administration will improve substantially the political frameworks for wind power in the country, especially for those type of investors that have practically been excluded from the production tax credit scheme, like farmers, smaller companies or community based projects. The credit crunch, however, may lead to delays in project development in the short term. The Canadian government has rather been hesitating. However, among the Canadian provinces Quebec and Ontario are showing increasing commitment towards an accelerated deployment of wind energy. During and after the World Wind Energy Conference Community Power held in Kingston (Ontario) in June 2008, the Government of Ontario showed strong commitment to rapid expansion of renewable energy and is expected to present soon a proposal for a Green Energy Act, including feed-in tariffs for the different renewable energies including wind. In Quebec, contracts for new projects were signed for a total of 2000 MW, the first to be operational by 2011.

5.2.9 Summary

Table 5-5 source WWEA

Position 2008	Country	Total Capacity installed end 2008	Added Capacity 2008	Growth Rate 2008	Position 2007	Total Capacity installed end 2007	Total Capacity installed end 2006	Total Capacity installed end 2005
		[MW]	[MW]	[%]		[MW]	[MW]	[MW]
1	USA	**25170,0**	8351,2	49,7	2	16818,8	11603,0	9149,0
2	Germany	**23902,8**	1655,4	7,4	1	22247,4	20622,0	18427,5
3	Spain	**16740,3**	1595,2	10,5	3	15145,1	11630,0	10027,9
4	China	**12210,0**	6298,0	106,5	5	5912,0	2599,0	1266,0
5	India	**9587,0**	1737,0	22,1	4	7850,0	6270,0	4430,0
6	Italy	**3736,0**	1009,9	37,0	7	2726,1	2123,4	1718,3
7	France	**3404,0**	949,0	38,7	8	2455,0	1567,0	757,2
8	United Kingdom	**3287,9**	898,9	37,6	9	2389,0	1962,9	1353,0
9	Denmark	**3160,0**	35,0	1,1	6	3125,0	3136,0	3128,0
10	Portugal	**2862,0**	732,0	34,4	10	2130,0	1716,0	1022,0
11	Canada	**2369,0**	523,0	28,3	11	1846,0	1460,0	683,0
12	The Netherlands	**2225,0**	478,0	27,4	12	1747,0	1559,0	1224,0
13	Japan	**1880,0**	352,0	23,0	13	1528,0	1309,0	1040,0
14	Australia	**1494,0**	676,7	82,8	16	817,3	817,3	579,0
15	Ireland	**1244,7**	439,7	54,6	17	805,0	746,0	495,2
16	Sweden	**1066,9**	235,9	28,4	18	831,0	571,2	509,1
17	Austria	**994,9**	13,4	1,4	14	981,5	964,5	819,0
18	Greece	**989,7**	116,5	13,3	15	873,3	757,6	573,3
19	Poland	**472,0**	196,0	71,0	24	276,0	153,0	73,0
20	Norway	**428,0**	95,1	28,5	19	333,0	325,0	268,0
21	Egypt	**390,0**	80,0	25,8	21	310,0	230,0	145,0
22	Belgium	**383,6**	96,7	33,7	22	286,9	194,3	167,4
23	Chinese Taipeh	**358,2**	78,3	28,0	23	279,9	187,7	103,7
24	Brazil	**338,5**	91,5	37,0	25	247,1	236,9	28,6
25	Turkey	**333,4**	126,6	61,2	26	206,8	64,6	20,1
26	New Zealand	**325,3**	3,5	1,1	20	321,8	171,0	168,2
27	Korea (South)	**278,0**	85,9	44,7	27	192,1	176,3	119,1
28	Bulgaria	**157,5**	100,6	176,7	33	56,9	36,0	14,0
29	Czech Republic	**150,0**	34,0	29,3	28	116,0	56,5	29,5
30	Finland	**140,0**	30,0	27,3	29	110,0	86,0	82,0
31	Hungary	**127,0**	62,0	95,4	35	65,0	60,9	17,5
32	Morocco	**125,2**	0,0	0,0	36	125,2	64,0	64,0
33	Ukraine	**90,0**	1,0	1,1	30	89,0	85,6	77,3
34	Mexico	**85,0**	0,0	0,0	31	85,0	84,0	2,2
35	Iran	**82,0**	15,5	23,3	34	66,5	47,4	31,6
36	Estonia	**78,3**	19,7	33,6	37	58,6	33,0	33,0
37	Costa Rica	**74,0**	0,0	0,0	32	74,0	74,0	71,0
38	Lithuania	**54,4**	2,1	4,0	38	52,3	55,0	7,0
39	Luxembourg	**35,3**	0,0	0,0	39	35,3	35,3	35,3
40	Latvia	**30,0**	2,6	9,5	41	27,4	27,4	27,4
41	Argentina	**29,8**	0,0	0,0	40	29,8	27,8	26,8
42	Philippines	**25,2**	0,0	0,0	42	25,2	25,2	25,2
43	South Africa	**21,8**	5,2	31,4	49	16,6	16,6	16,6
44	Jamaica	**20,7**	0,0	0,0	43	20,7	20,7	20,7
45	Guadeloupe	**20,5**	0,0	0,0	44	20,5	20,5	20,5
46	Uruguay	**20,5**	19,9	3308,3	68	0,6	0,2	0,2

Position 2008	Country	Total Capacity installed end 2008	Added Capacity 2008	Growth Rate 2008	Position 2007	Total Capacity installed end 2007	Total Capacity installed end 2006	Total Capacity installed end 2005
		[MW]	[MW]	[%]		[MW]	[MW]	[MW]
47	Chile	**20,1**	0,0	0,0	46	20,1	2,0	2,0
48	Tunisia	**20,0**	0,0	0,0	45	20,0	20,0	20,0
49	Colombia	**19,5**	0,0	0,0	47	19,5	19,5	19,5
50	Croatia	**18,2**	1,0	5,8	48	17,2	17,2	6,0
51	Russia	**16,5**	0,0	0,0	50	16,5	15,5	14,0
52	Switzerland	**13,8**	2,2	19,2	53	11,6	11,6	11,6
53	Guyana	**13,5**	0,0	0,0	51	13,5	13,5	13,5
54	Curaçao	**12,0**	0,0	0,0	52	12,0	12,0	12,0
55	Romania	**7,8**	0,0	0,0	54	7,8	2,8	0,9
56	Israel	**6,0**	0,0	0,0	55	6,0	7,0	7,0
57	Pakistan	**6,0**	6,0	new	new	0,0	0,0	0,0
58	Slovakia	**5,1**	0,1	2,8	56	5,0	5,0	5,0
59	Faroe Islands	**4,1**	0,0	0,0	57	4,1	4,1	4,1
60	Ecuador	**4,0**	0,9	30,7	58	3,1	0,0	0,0
61	Cuba	**7,2**	5,1	242,9	61	2,1	0,5	0,5
62	Cape Verde	**2,8**	0,0	0,0	59	2,8	2,8	2,8
63	Mongolia	**2,4**	2,4	new	new	0,0	0,0	0,0
64	Nigeria	**2,2**	0,0	0,0	60	2,2	2,2	2,2
65	Jordan	**2,0**	0,0	0,0	62	2,0	1,5	1,5
66	Indonesia	**1,2**	0,2	20,0	65	1,0	0,8	0,8
67	Martinique	**1,1**	0,0	0,0	63	1,1	1,1	1,1
68	Belarus	**1,1**	0,0	0,0	64	1,1	1,1	1,1
69	Eritrea	**0,8**	0,0	0,0	66	0,8	0,8	0,8
70	Peru	**0,7**	0,0	0,0	67	0,7	0,7	0,7
71	Kazakhstan	**0,5**	0,0	0,0	69	0,5	0,5	0,5
72	Namibia	**0,5**	0,0	6,4	70	0,5	0,3	0,3
73	Netherlands Antilles	**0,3**	0,0	0,0	71	0,3	0,0	0,0
74	Syria	**0,3**	0,0	0,0	72	0,3	0,3	0,3
75	North Korea	**0,2**	0,2	2010,0	73	0,01	0,01	0,01
76	Bolivia	**0,01**	0,0	0,0	74	0,01	0,01	0,0
	Total	**121187,9**	**27261,1**	**29,0**		**93926,8**	**74150,8**	**59024,1**

To summarize, in the tables above is possible to observe the role that different countries play in the world of wind power. For every country is showed the position in 2007 and 2008, the total capacity installed at the end of 2005, 2006, 2007 and 2008, the added capacity in 2008 and the growth rate.

5.3 References

EWEA (European Wind Energy Association) (www.ewea.org)

WWEA (World Wind Energy Association) (www.wwea.org)

Energy Watch Group (www.energywatchgroup.org)

6 VerticalWind VAWT 200 kW, Falkenberg

6.1 Introduction

In year 2002 the swedish company VerticalWind was founded and its focus was on the technology of the low speed generator.

After some years, VerticalWind started to co-operate with Uppsala University, Sweden, in order to develop a new type of vertical axis wind turbine.

From this co-operation was born, in 2006, the first prototype of this kind of VAWT, a 12 kW giromill, shown in the Figure 6-1.

Figure 6-1: Uppsala VerticalWind 12 kW prototype [1]

After the building of the first prototype and a period of evaluation of its performance, the next step has been the building of a bigger giromill, with the size of 200 kW.

This turbine must be considered the intermediate size between the prototype of Uppsala and the nowadays swedish commercial size of 2 MW, which is the goal of VerticalWind.

This VAWT has been built in Falkenberg, Sweden, in co-operation with E.On, Falkenberg Energi and the Municipality of Falkenberg.

In Falkenberg is also located the factory where this turbine has been built: for the moment it is a small place, but there are same plans for future development which deal with the engagement of more workers and with an enlargement of the factory.

In the following pictures the location of the city of Falkenberg and of the site of the wind turbine are shown.

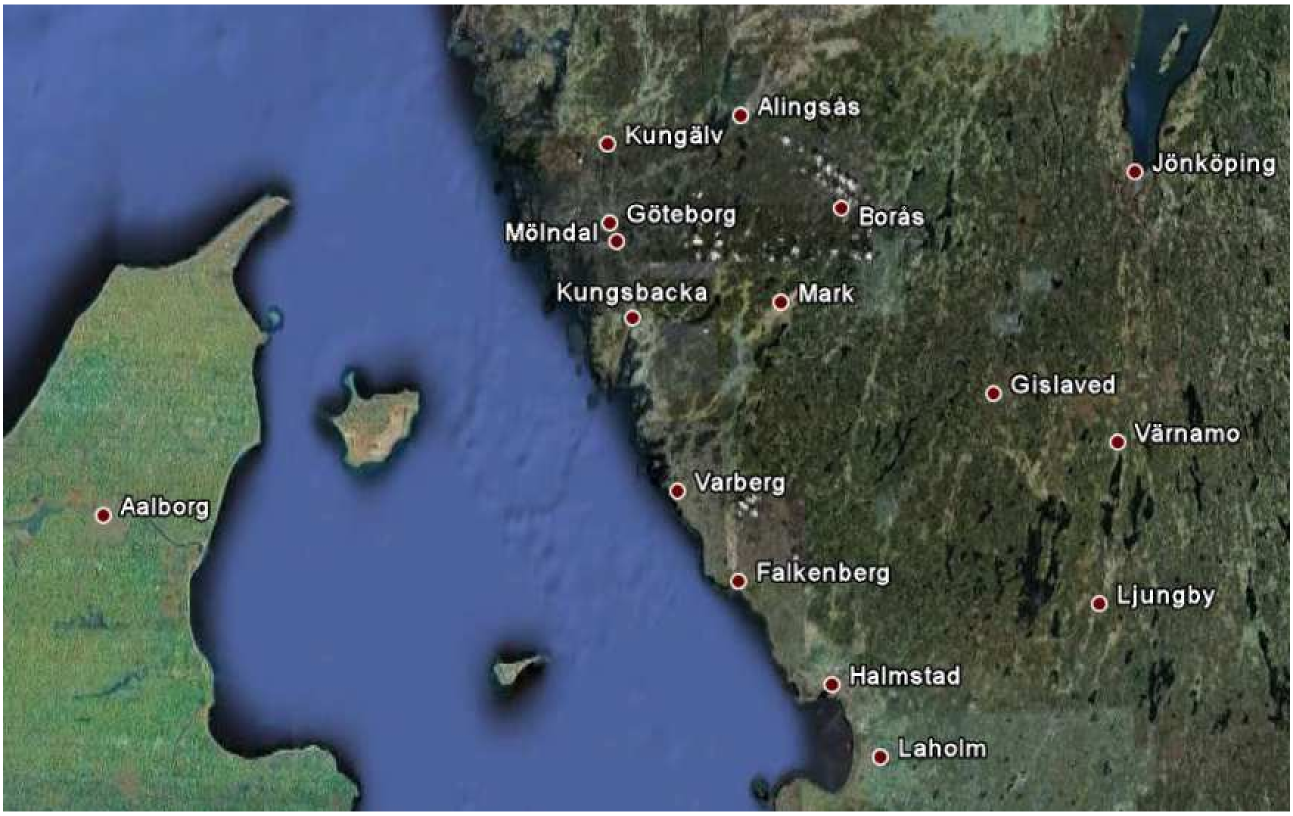


Figure 6-2: Falkenberg geographical position

Falkenberg il located in the Swedish region of Halland, in front of Denmark, one of the most windy place in Sweden. In its municipality there are several wind farms.

Figure 6-3: 200 kW VAWT site

Figure 6-4: 200 kW VAWT site (2)

This wind turbine has been built in an area which doesn't present big obstacles in the proximity and not so far from a 10 turbines wind farm, that Falkenberg Energy erected along the highway E6.

The geometry of the wind turbine is reported in the Table 6-1:

Table 6-1 Wind turbine charateristics

type of Wind Turbine	VAWT
type of VAWT	Giromill
number of blades	3
height of the tower [m]	40
rotor diameter [m]	26
lenght of blades [m]	24
weight of the blade [kg]	300
material of the tower	wood + classified material
material of the blades	glass fiber

For not high value of nominal power, like 200 kW, has been demonstrated that a tower must be high at least 30 m, because under this height the wind cannot be used in an efficient way.

The tower is located on the top of a little terrace due to the fact that the ground water in the areas is close to the surface.

Figure 6-5: the VerticalWind 200 kW VAWT of Falkenberg

The nominal power of the tower is 200 kW and it is the first of a group of 4 towers that will be built in the same area, at a distance of 140 – 150 m one from the other.

The highest wind turbine that VerticalWind will build in the area of Falkenberg will have a height of 51 m.

Figure 6-6: one of the blade of the 200 kW VAWT of Falkenberg

One of the advantage of this type of tower is that the generator, which is synchronous, multi-pole, with permanent magnets, with a diameter of 2,5 m and very heavy, is located at the bottom of the tower. This situation leads to a tower less heavy and also less expensive.

In the picture below is shown the generator used for the 12 kW prototype of Uppsala: the technology is the same used in the wind turbine of Falkenberg, only the size is different (source: verticalwind.se)

Figure 6-7: the generator of the prototype of Uppsala (source: www.vertical.se)

The main shaft, which connect the rotor with the generator, is divided in six parts and there are two big bearings at the top of the tower and two at the bottom, while there are few bearings along the shaft.

When the wind speed reach the value of 4 m/s, the cut-in wind speed for this giromill, the generator starts to act as a motor and the wind turbine start to rotate.

At 4 m/s the rotational speed is 15 rpm and the rated wind speed to get 200 kW as power output is 11,6 m/s, corresponding to a rotational speed of 32 rpm.

After 32 rpm, the speed of the blade is controlled to avoid damages on the tower and the structure. The cut-off speed is 25 m/s and this wind turbine can resist until a wind speed of 150 km/h, a value lower compared to the typical value of HAWT that is about 250 km/h.

The rotational speed is controlled toward the stall using both some hydraulic brakes, located at the top of the tower, and the generator, located at the bottom, by electronically equipment.

A pitch control on the blades is also present in the patent of this turbine, but it has been demonstrated that its implementation is very expensive and generates only a low value of power more than the situation without pitch control.

According to VerticalWind evaluations, the expectation of energy production for this turbine is 450 MWh per year.

From the point of view of the noise, compared with a same size HAWT, this wind turbine emits about 20 dB less and the noise is more constant, while in a HAWT the noise profile presents more peaks due to the fact that it is produced mainly from the movement of the tip of the blades.

6.2 Power Curve

The prediction of the power curve is an important step in the design process of a wind turbine. This calculation involved considerations about the rotor, the generator and the wind speed.
The formula uses to evaluate the power of a wind turbine is described by:

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

Where:
Cp= coefficient of power;
A = swept area of the turbine;
ρ = density of the air [kg/m^3];
v = undisturbed wind speed;
η = efficiency of the generator;

If there are some mechanical equipment, like a gearbox, its efficiency must also be considerate in the previous formula.

All the previous parameters can be calculated or are know because depending on the type of rotor, like the swept area, or on the site of the turbine, like the air density. The efficiency is also noted, once that the kind of generator has been choose.

The coefficient of power is linked to the tip speed ratio λ and the curve Cp-λ present a maximum of Cp corresponding to the best λ value. The variable speed wind turbines can change the rotational speed, using control on the blades, to reach during the working period the best value of λ and, by this, get the best value of Cp.

To evaluate the power curve of the 200 kW VerticalWind turbine, the following assumption has been done:

Table 6-2 Parameters assuption

A	624	m^2
ρ	1,23	kg/m^3
η	0,959	

The value of A has been estimated from the geometry of the wind turbine.
Usually the first step is to get the value of Cp and then, changing the wind speed, calculate the rotor power, but, in this case, it was already known that the nominal value of 200 kW was got for a nominal wind speed of 12 m/s.

The power curve for different wind speed is reported in Figure 6-8:

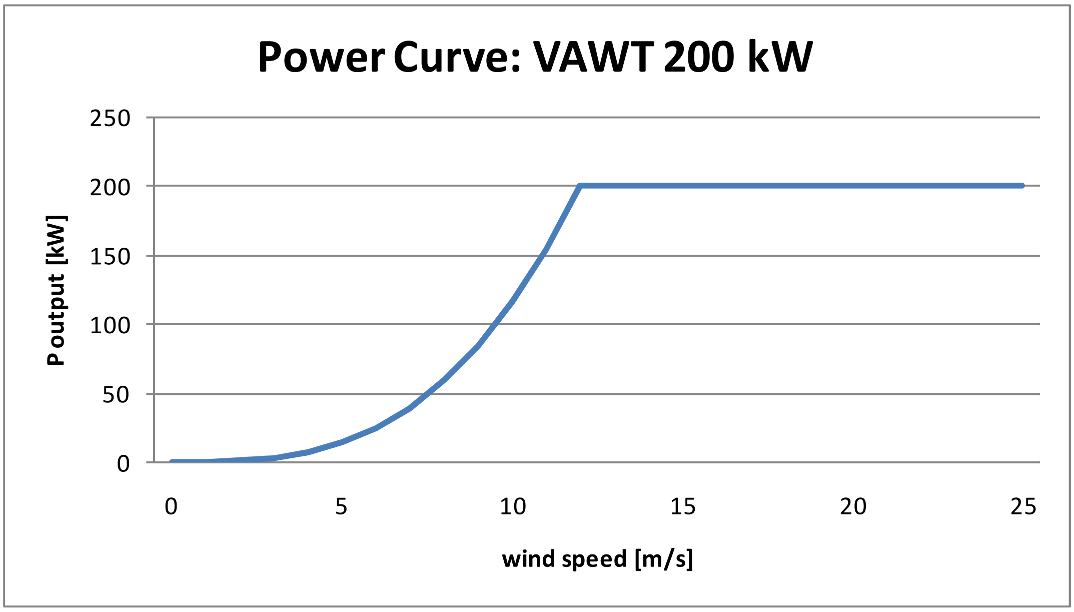


Figure 6-8: power curve of the 200 kW VAWT of Falkenberg

The knowledge of the value of the nominal wind speed to get the nominal power in output has been usefull to estimate the value of the maximum Cp of the wind turbine, which, in the point of the graph (12 m/s, 200 kW) was the only unknown parameter.
After this calculation, a not so low value of 0,314 has been founded for the maximum Cp of the wind turbine.

6.3 Resonance frequency analysis

Resonance is the tendency of a system to oscillate with high amplitude when excited by energy at a certain frequency. This frequency is known as the system's natural frequency of vibration or resonant frequency.

For a wind turbine this means that the rotational speed (ω_r) during normal operations (i.e. not during transients) should never be the same as the natural frequency ($f_n = \omega_n \cdot r$) of its components.

Two methods of determining the natural frequencies of objects are presented in this chapter: mathematical analysis and Fast Fourier Transform analysis (FFT).

6.3.1 Mathematical analysis

For the first method it’s necessary to know both the geometrical data and the material characteristics of the tower.

For the geometry it’s quite easy to get the data (using, in case of missing values, some approximation).

For the characteristics of the material, which is a mix of wood and classified material covered by patent, the typical values of the laminated wood can be used.

The equation used to calculate ω_n is:

$$\omega_n = (n \cdot L)_i^2 \cdot \sqrt{\frac{Y \cdot I}{m \cdot L^4}} \qquad [2]$$

Where:

Y= Young Modulus [Pa];

I = moment of inertia [m^4];

m = mass per unit of length [kg/m];

L = tower total height [m];

The values of $(nL)_i$ are found from numerical solutions of a transcendental equation.

The first four numeric solutions is:

$$(nL)_i = 1.875$$

In the table below are reported the value used for the calculation.

Table 6-3 Parameters assuption

physical quantity	symbol	value	
tower height	L	40	m
tower mean radius	r	1,2	m
tower thickness	t	0,3	m
mass per unit length	m	1558,23	kg/m
laminated wood density	ρ	620	kg/m^3
laminated wood young modulus	Y	6954,2	Mpa
moment of inertia, annulus	I	1,3069	m^4

To calculate the frequency it's possible to use the simple equation:

$$f = \frac{\omega}{2\pi}$$

The result of the calculation gives a value of:

f=0,845 Hz

6.3.2 FFT method

In order to use this method, some experimental measurements on the turbine site are needed. It's possible to get data about resonance even if the turbine is not rotating, since this is a physical characteristic, typical of the structure, not dependent by the operational status of the turbine.

During normal operation some different causes will produce vibrations on the tower: rotation of the blades, brakes, generator electric torque, wind.

During the made measurements only the wind force was applied on the structure. The data about the wind speed in the day of the tests were given by a wind measurements station, which provided values between 3 and 6 m/s.

First of all a 3 axis accelerometer must be placed on the top of the tower. Actually the channel in vertical direction *z* is useless to determine resonance frequency, but its data was stored as well. The cables from the accelerometer are connected at ground level to a data-logger, as shown in Figure 6-9, in turn connected via USB port to a laptop running the software LABVIEW.

Figure 6-9: equipment used for frequency of resonance data collecting

Data are collected with a sampling frequency of 100 Hz, very high for the resonance frequency expected, but good to avoid 50 Hz grid electricity noise. The total time of sampling have been one hour, while also the wind speed data were collected by the anemometer at the same site.

Figure 6-10: anemometer located in front of the wind turbine

Charateristics of the accelerometer:

- Zero level: 2,3 V;
- Sensitivity: 0,5 Volt/g;

Figure 6-11: PMD - 1608FS datalogger [8]

“The PMD-1608FS provides 8 simultaneously sampled, 16-bit analog inputs with continuous multichannel sample rates up to 100 kilosamples per second and burst sample rates up to 200 kS/s. In addition to the powerful analog input capability, the unit provides 8 bits of digital I/O and a 32-bit counter.” [7]

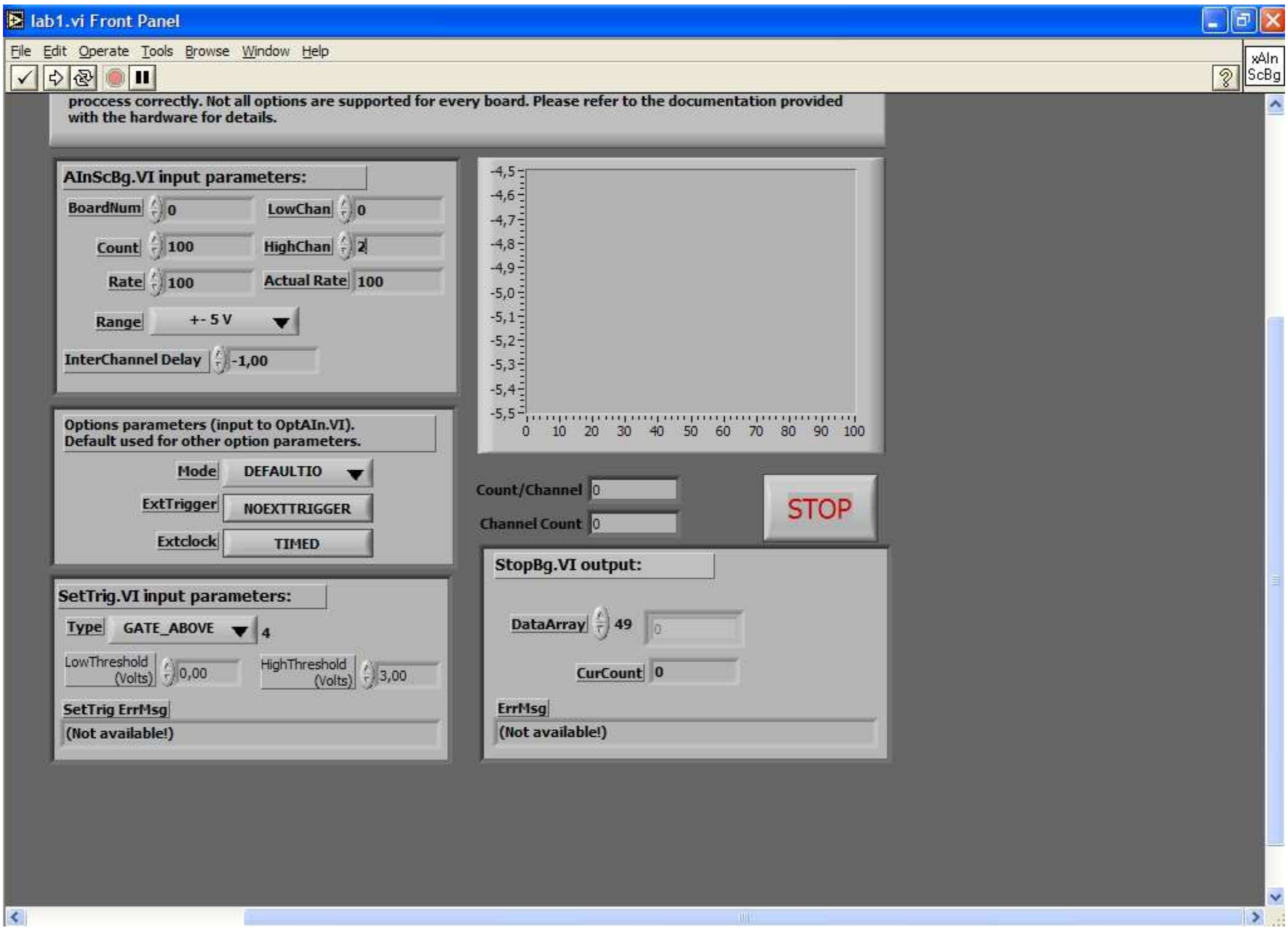


Figure 6-12: LabView layout

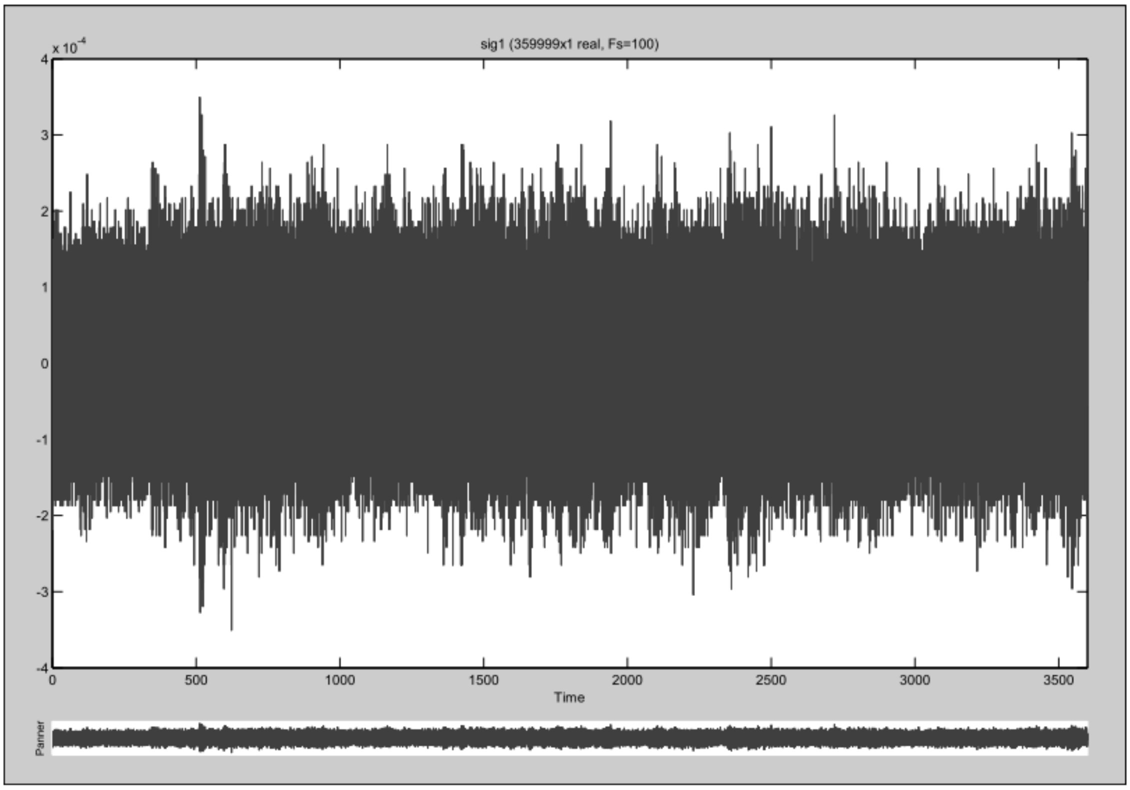


Figure 6-13: signal got from 1 hour of measurement

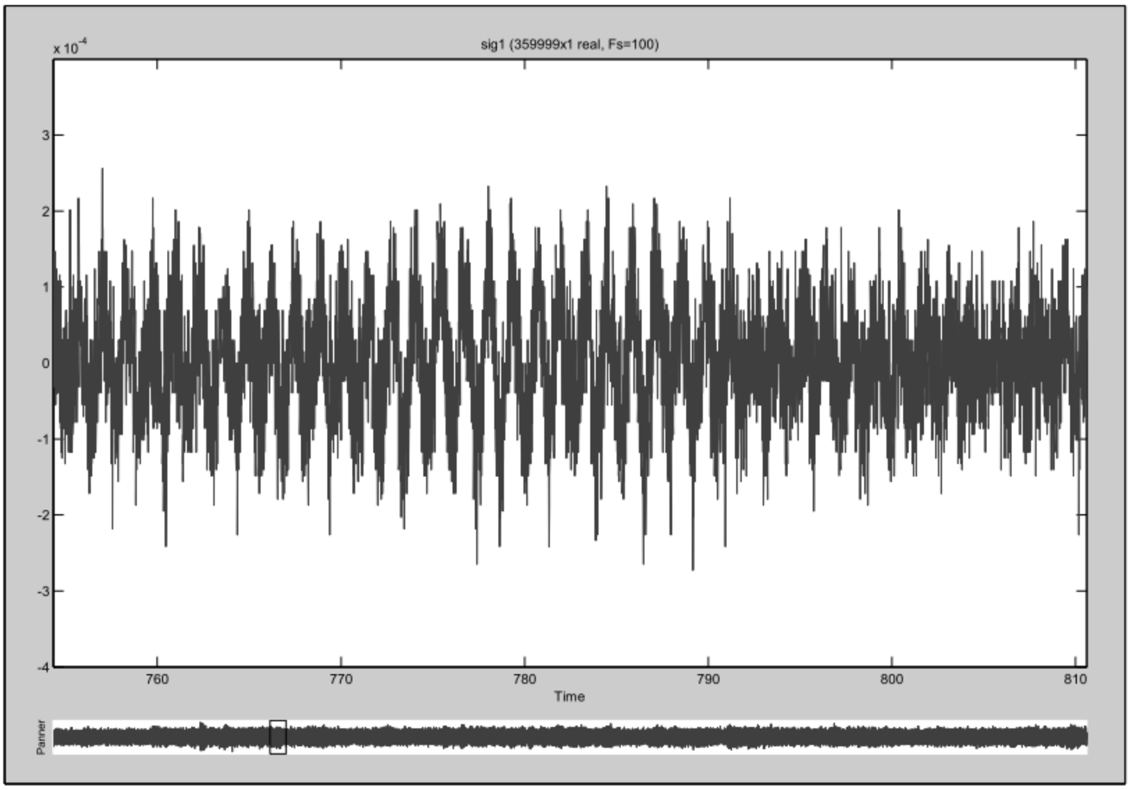


Figure 6-14: few seconds zoom of the 1 hour signal

After the collecting data phase, the MATLAB *"Signal Processing Tool"* have been used to calculate and show the frequency spectrum of accelerometer data.

The result is shown in Figure 6-15:

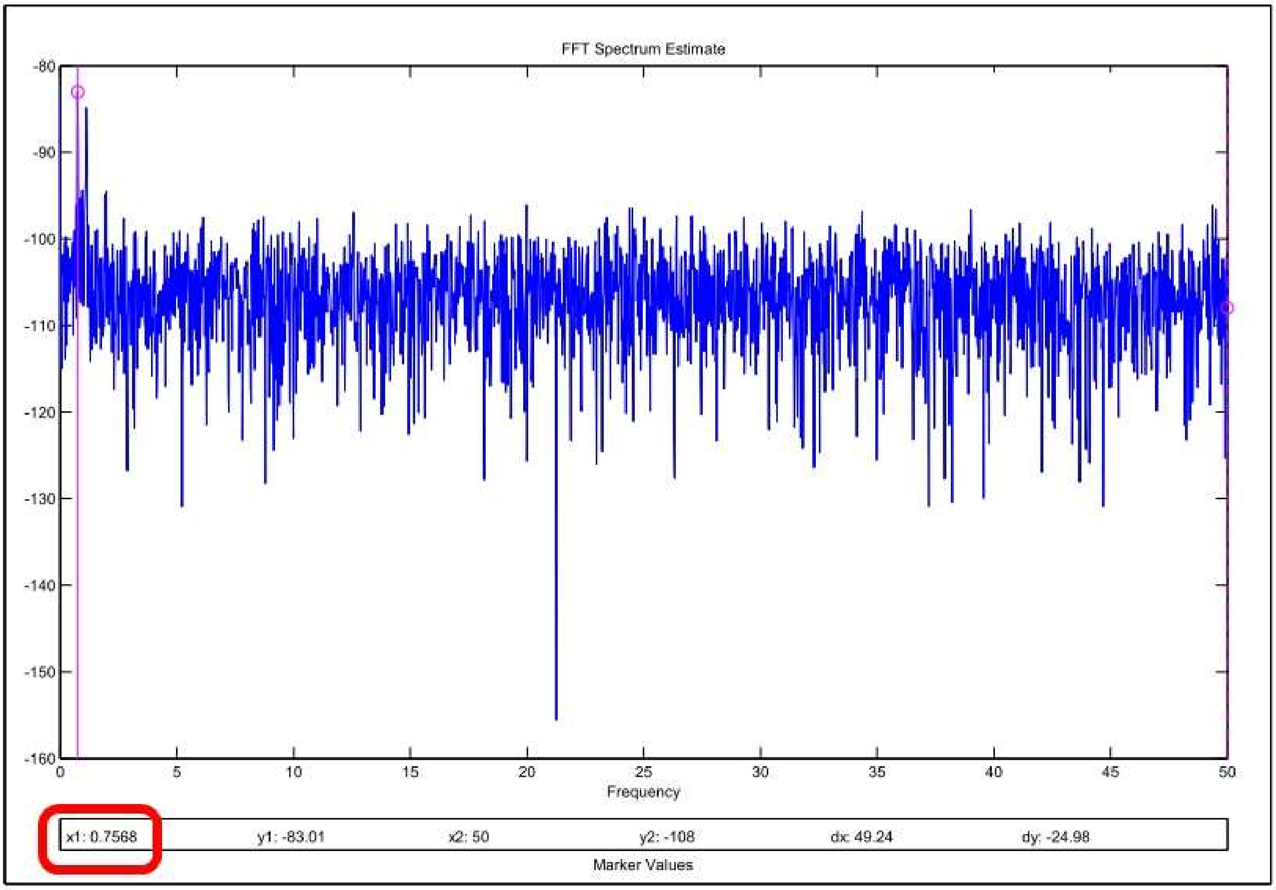


Figure 6-15: graph of the frequency of resonance: peak at 0,7568 Hz

The value x1 marked in red is the position of the peak of amplitude of the frequency spectrum, shown in the figure with a pink line and circle. The value found is f = 0.7568 Hz.

6.3.3 Discussion of the results

The difference between the values calculated with the two methods is not very high, but not negligible. It's important to notice that many approximations have been used and some data were not available from the owner of the turbine because covered by patents so their values have been reasonably assumed from experience, similar structures or materials found in literature.

As an example, in Figure 6-16 is reported a chart that shows the sensitivity of the result to the variation of the two parameters with the highest uncertainty, according to the literature sources about the laminated wood: the density and the Young Modulus.

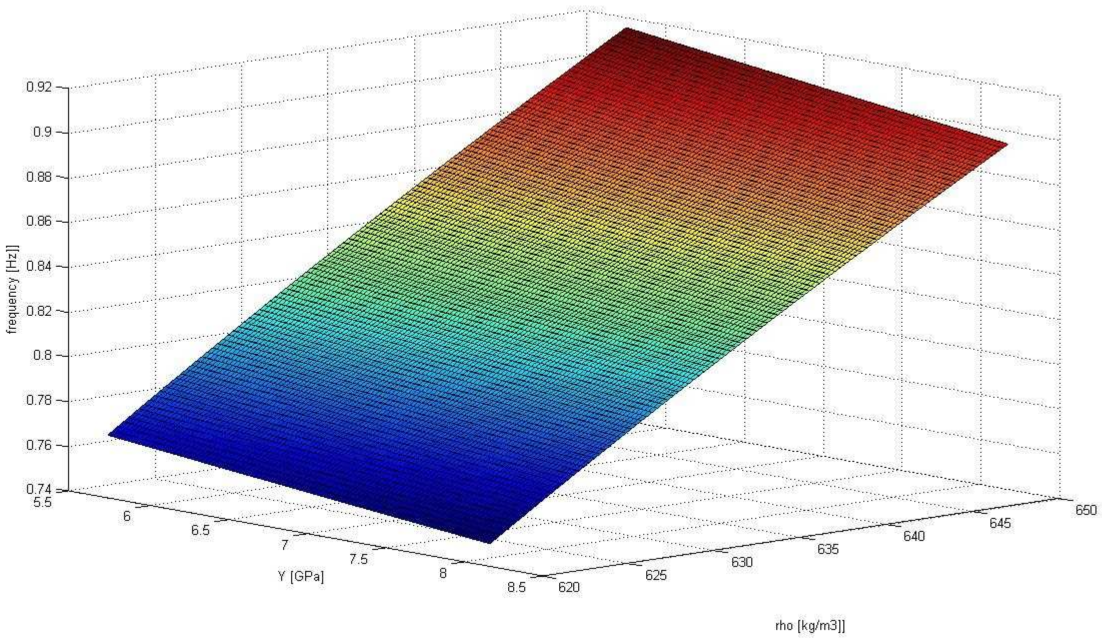


Figure 6-16: variation of f according to the variation of ρ and Y

It’s easy to observe how in these range of values the influence of the density is much higher than the Young Modulus and that in case of extreme values ($Y \approx 8$ GPa, $\rho \approx 620$ kg/m^3) the result is very close to the measured value.

It’s also important to note how the rotational speed of the turbine during normal operations is, according to the owner of the plant, ω=15÷32 rpm.

This means f=0,25÷0.53 Hz, so that the resonance frequency is never reached and potential sources of vibration should be found elsewhere.

6.4 References

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7 WindPro Analysis

7.1 WindPro introduction

There are several softwares that can calculate the energy that a wind turbine produces. The one used in this report is *WindPro*, developed by the Danish company EMD.
This software contains databases with many information useful for an accurate evaluation of the wind turbine performances, like the wind speed in a certain site and a catalogue with the characteristics of a very wide range of wind turbine.
This software also allows the user to add a new wind turbine in the appropriate database by insert its power curve.

There are different steps that must be followed in order to calculate the energy production with this software, more or less quick according to the number of information that are required by the software itself:
Select a country where locate the site of the turbine;

- Insert a map of the site and link it with the software in order to let it understand where the turbine actually is;
- Select a wind turbine from the catalogue or add a new one with its own power curve;
- Insert the right class of roughness around the site;
- Start the calculation;

With *WindPro* it's possible also to simulate wind farms instead of only one wind turbine. Evaluation about noise and shadow are also possible.

7.2 Case A: 200 KW VerticalWind VAWT (1 turbine)

The first simulation made concern a single VerticalWind 200 kW VAWT, located in the area indicated by the company itself. In the Figure 7-1 it is possible to observe the site of the turbine and also the rose of roughness. Starting from the turbine's location, a circle of 20 km of radius has been divided in 12 sectors and for each one an appropriate value of roughness has been inserted. The choice of the roughness classes depends on the characteristics of the terrain and, starting from a value equal to 0 for the open sea, it increases to 4 for large cities or high dense forest.

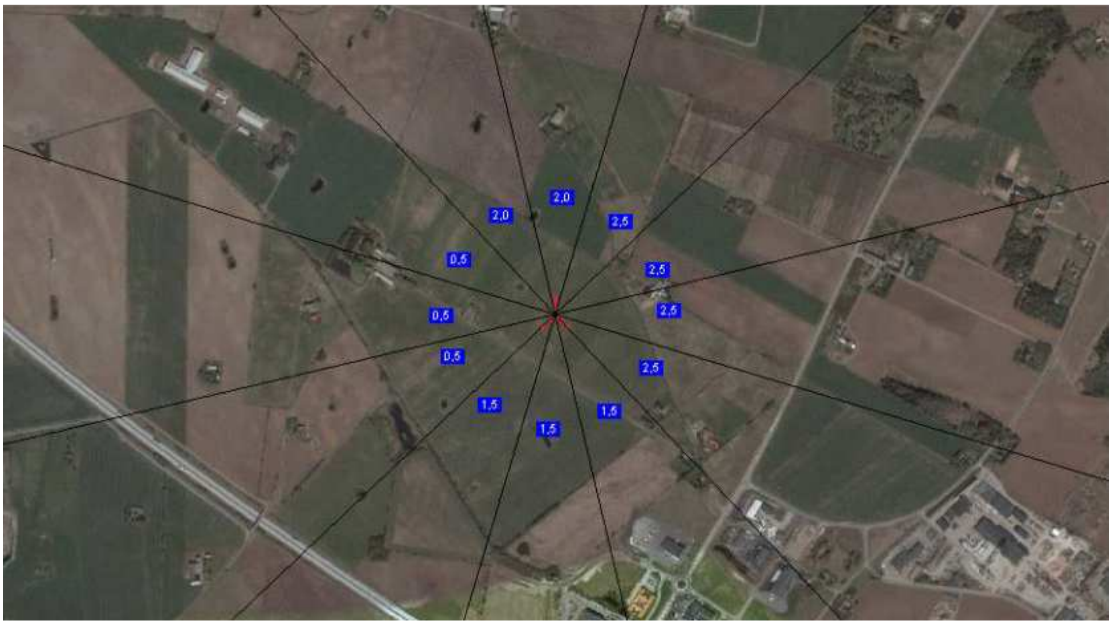

Figure 7-1 Site of the turbine and rose of roughness classes

The mean wind speed at the rotor height is given by the database of Glommen, a locality close to Falkenberg, which is included in the software. Its value is 6,2 m/s and the main direction of the wind is West.

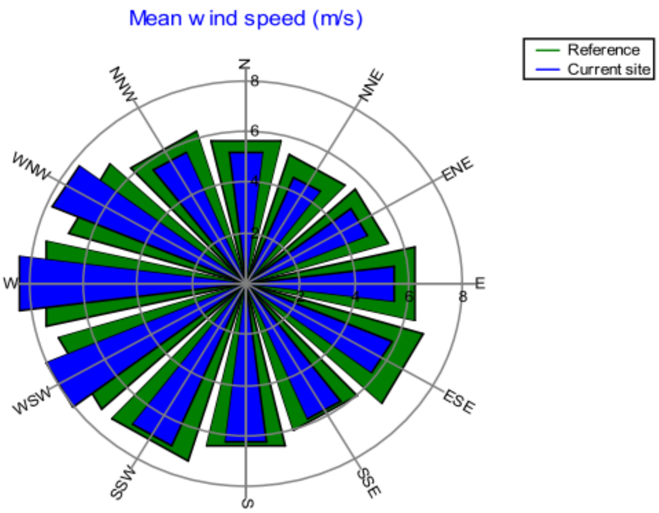

Figure 7-2 Wind rose

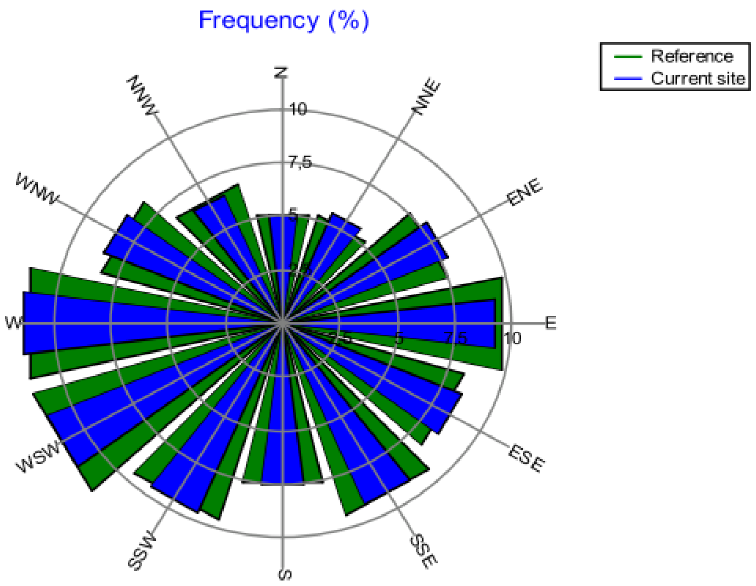

Figure 7-3 Wind direction frequency

The energy rose of the turbine, represented Figure 7-4, shows that, according to the wind rose, the majority of the energy is produced thanks to the wind that blows from the western direction.

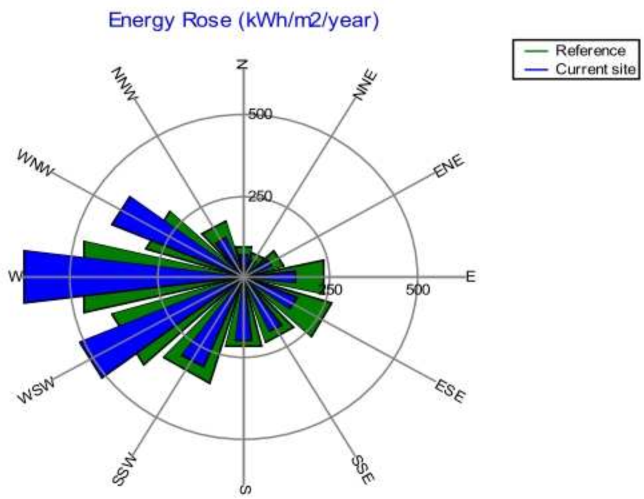

Figure 7-4 Energy rose

The calculation with WindPro gives a value of energy produced per year equal to 423,7 MWh, a bit lower than the 450 MWh expected by VerticalWind, and a capacity factor of 24,2%. This difference can be due mainly to the different choices of roughness classes. In Figure 7-5 and Figure 7-6 the energy produced by different sectors and by different wind speed are reported.

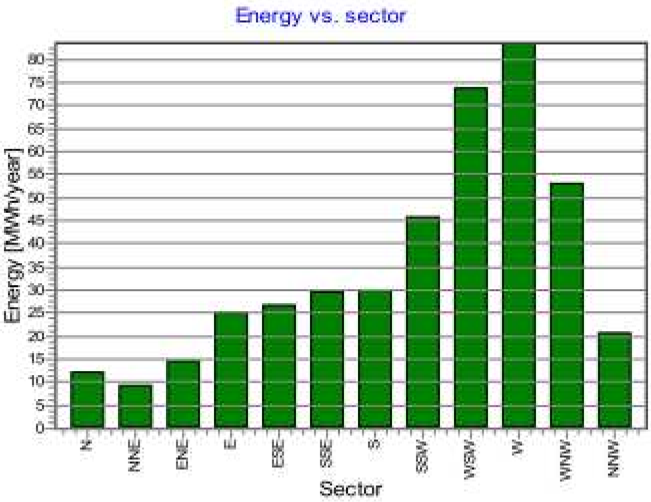

Figure 7-5 Energy production for each sector

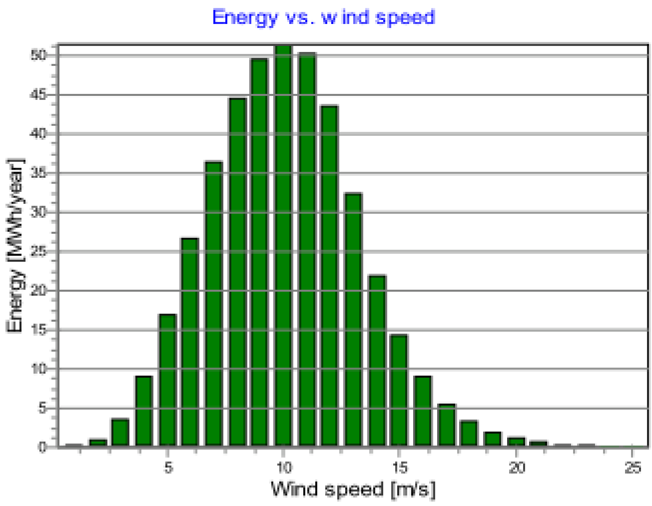

Figure 7-6 Energy production for different wind speed

7.3 Case B: 200 kW VerticalWind VAWT (4 turbines)

The goals of VerticalWind are both to test this new kind of VAWT and build a small wind farms adding in the same area three more wind turbine, in order to create a small wind farm. A simulation about the performance of this wind farm has been done and the turbines have been located in the area according to the information about the wind speed database, in order to avoid that one or more turbines can create obstacle to the wind that hit the others wind mills.

Figure 7-7 Position of the turbines in the wind farm

In Table 7-1 the main distances of the wind farm are reported.

Table 7-1 Distances of the wind farm

Turbine number	Height above the sea	Nearest WTG	Horizontal distance	Distance in rotor diameters
	[m]		[m]	[m]
1	25	3	148	5,7
2	25	3	165	6,3
3	25	1	148	5,7
4	25	1	276	10,6

The energy produced by the wind farm is 1667,3 MWh, with a mean value of 416,8 MWh expected from each turbine, and the capacity factor is 23,8%.

A deeper analysis shows that the most productive wind mill is the number 4, with 421,5 MWh per year, while the one that produces the less value of energy is the number 3, with 413,1 MWh per year expected. The number 1 and the number 2 give, respectively, 415,4 MWh and 417,3 MWh per year.

A summary of the different expected productions is reported in Table 7-2.

Table 7-2 Wind farm expected production

Turbine	[MWh]
1	415,4
2	417,3
3	413,1
4	421,5
Tot	1667,3

Looking at the energy production of the different sectors around the wind farm, it is interesting to observe that the losses due to the position of the turbine in the wind farm are very low and it leads to a global efficiency of the wind park equal to 98,4%.

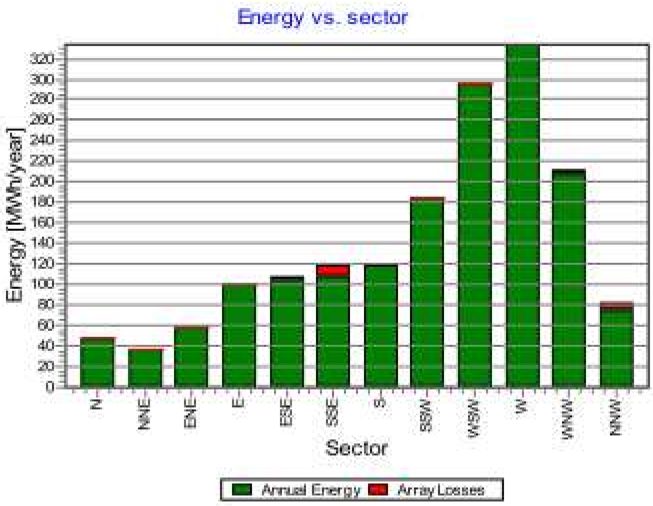

Figure 7-8 Energy production for each sector

7.4 Case C: 2 MW VerticalWind VAWT (1 turbine)

The 200 kW VAWT built in Falkenberg must be considered as an intermediate step between the 12 kW prototype of Uppsala and the main goal of VerticalWind, which is to reach the Swedish commercial size of 2 MW. A simulation of the performance of a VAWT with 2 MW of nominal power has been done. Before start the calculation with *WindPro* it has been necessary to built the power curve of this turbine and also make some hypothesis about the geometry, which are reported in the Table 7-3.

Table 7-3 2 MW VAWT

	value	unit	notes
D	80	m	Values calculated with: $A_{200kW}:A_{2MW}=P_{200kW}:P_{2MW}$ and same D/L rate.
L	74	m	
A	5920	m^2	
$\eta_{generator}$	0,959		Efficiency of Uppsala test generator
c_p	0,33		Reasonable approximation
ρ_{air}	1,23	kg/m3	
h_{tower}	80	m	Reasonable approximation
$v_{optimal}$	12	m/s	Optimal wind speed, same as 200 kW type

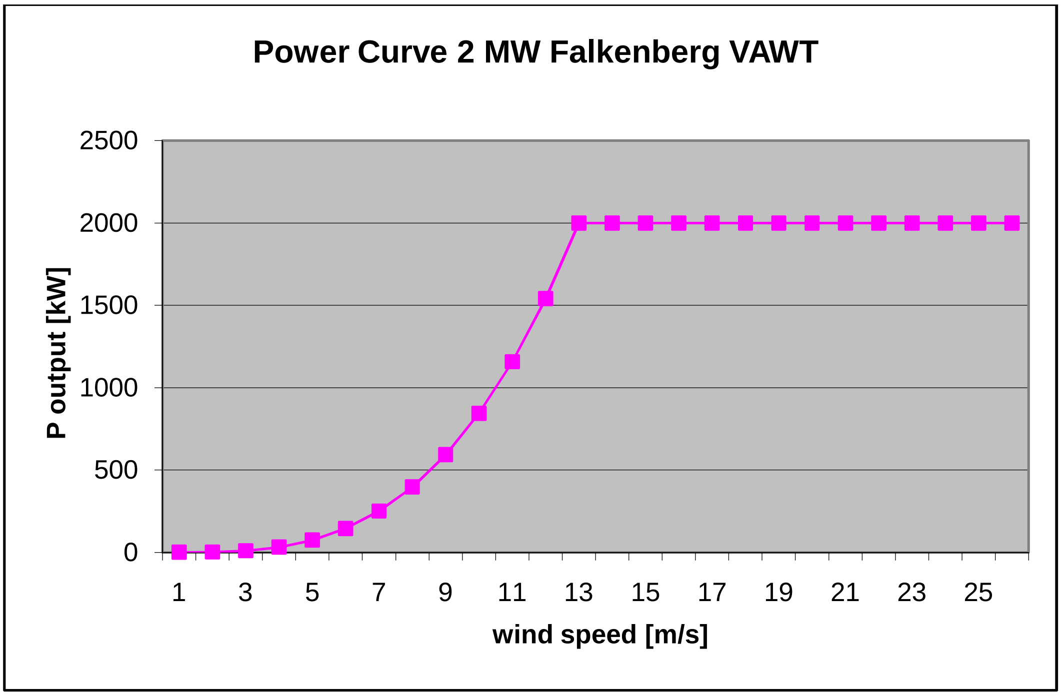

Figure 7-9 Estimated power curve

In order to compare the results of the calculation, the position of the 2 MW turbine is the same as the turbine number 1 in case of the wind farm with 4 turbine of 200 kW. The results are reported in the Table 7-4.

Table 7-4 Energy production of the 2 MW VAWT

Total installed power	kW	2000
Energy produced	MWh/y	5633,9
Energy produced -10%	MWh/y	5071
Mean wind speed	m/s	7,2
Capacity factor	%	32,1
Mean Energy	MWh/y	/
Park Efficiency	%	/

As expected, mean wind speed for an higher turbine is higher as well, and so is the capacity factor. This means that with a 10 times bigger turbine it's possible to produce more than 10 times the energy, because of the better global efficiency.

7.5 Case D: Flowind VAWT vs VerticalWind VAWT

The only example of commercial medium size VAWT is constituted by the Flowind 300 kW VAWT. This turbine was built about 25 years ago in California, USA, and operated for more than 20 years. It's a Darrieus type wind turbine and in Table 7-5 its characteristics are reported.

Table 7-5 Flowind vs VerticalWind

type of Wind Turbine	VerticalWind VAWT	Flowind VAWT
type of VAWT	Giromill	Darrieus
number of blades	3	2
height of the tower [m]	40	30,8
rotor diameter [m]	26	19,2
lenght of blades [m]	24	30,6
weight of the blade [kg]	300	1855
material of the tower	Laminated wood	Unknown
material of the blades	Glass fiber	Aluminum

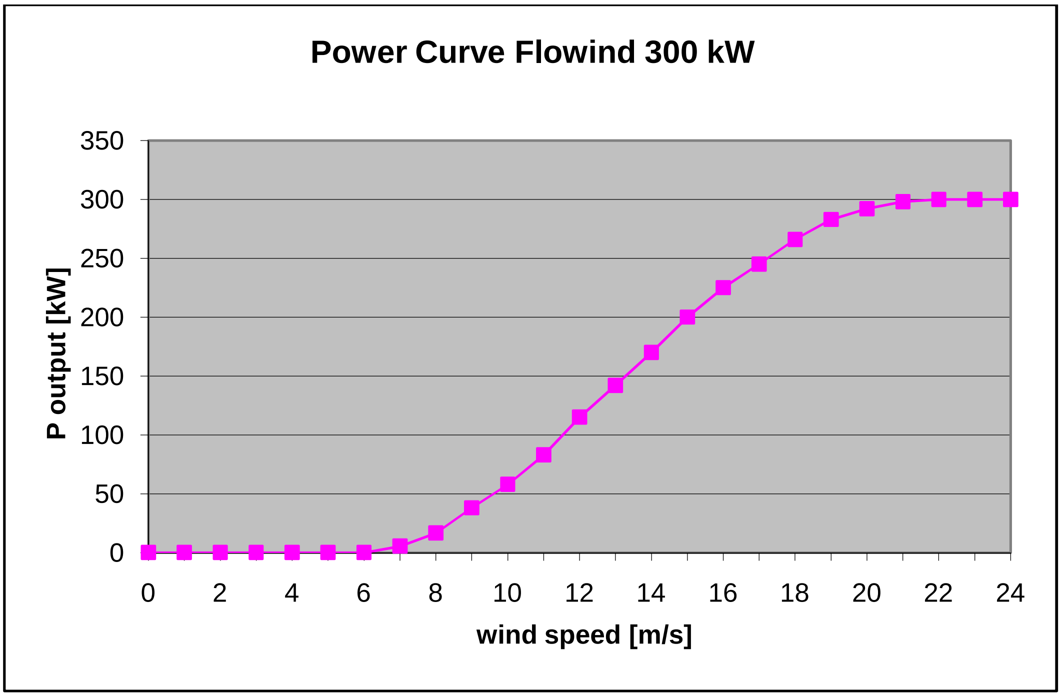

Figure 7-10 Flowind 300 kW power curve

In order to compare the performances of the VerticalWind and the Flowind VAWT, an evaluation, in the same site, of a single Flowind turbine and of a small wind farms has been done. In Figure 7-11 the two power curves are shown.

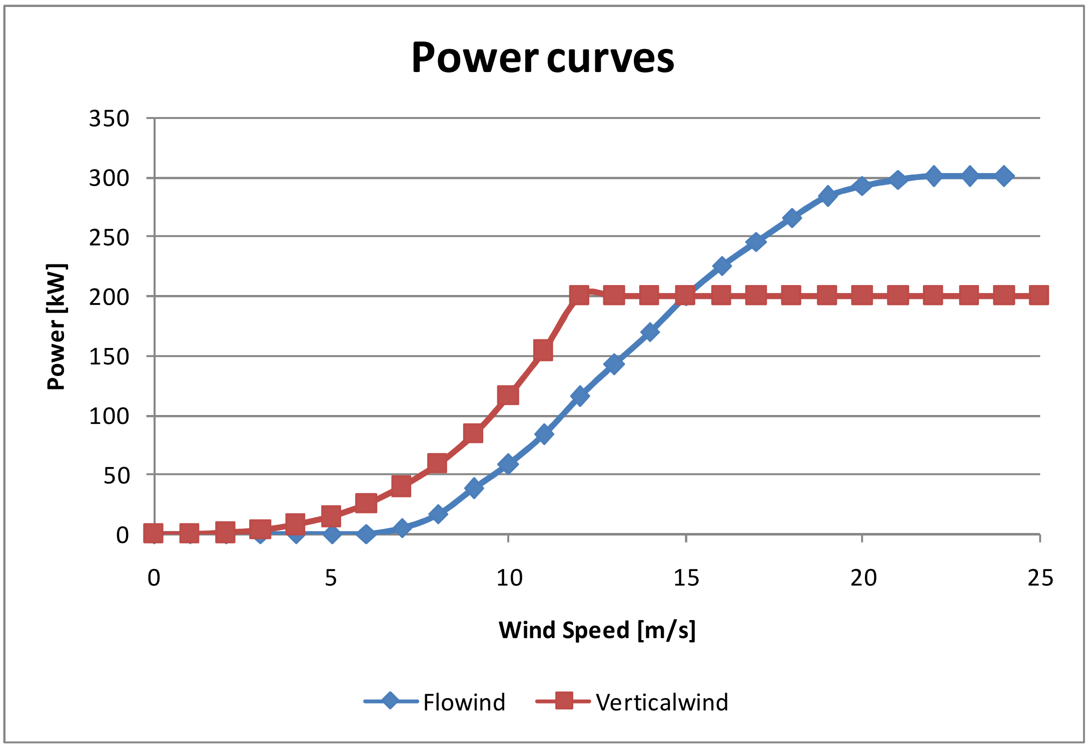

Figure 7-11 Flowind vs VerticalWind power curves

Comparing the two power curves is possible to say that VerticalWind turbine is widely better than its “virtual competitor”, even if the rated power is lower. In a site with mean wind speed around 6-7 m/s the production of FloWind machine is really poor and higher wind speed are needed in order to have good values of power.

The comparisons among the performances of single turbine and wind farms of 4 machines is reported in Table 7-6.

Table 7-6 Flowind vs VerticalWind energy productions

		VerticalWind turbine	FloWind turbine	VerticalWind 4 turbines	FloWind 4 turbines
Total installed power	kW	200	300	800	1200
Energy produced	MWh/y	423,7	132	1667,3	522,2
Energy produced -10%	MWh/y	381	119	1500,5	469,9
Mean wind speed	m/s	6,2	5,3	6,2	5,3
Capacity factor	%	24,2	5	23,8	5
Mean Energy	MWh/y	/	/	416,8	130,5
Park Efficiency	%	/	/	98,4	98,9

It’s possible to note how the FloWind Darrieus type is outclassed in energy production by the new Swedish turbine. This is due to two main reasons:

- Even if the nominal power of the FloWind is higher, the power curve is not so good and not suitable for a site with a mean wind speed around 6 m/s. Moreover, the swept area is about half of the VerticalWind and it’s located too close to the ground level, where the wind speed is lower.
- Technology, materials, aerodynamics and general knowledge of VerticalWind turbine have about 30 years of experience more than the one that FloWind Company had during its operative period. The generator had a gearbox and losses in the rotor for excitation, while the new project has PMS generator with high efficiency and less need of maintenance.

There is no doubt that, although the wind power market changed a lot since the ’80, VerticalWind VAWT will have better results than its precursor.

8 Conclusions

8.1 Economics analysis

A preliminary economic analysis has been done, in order to figure out if VerticalWind project is competitive in the present market of wind power turbines.

The Table 8-1 and Table 8-2 present some calculations to get a Pay Back Time of the wind turbine.

This is the easiest option for economic analysis, but since many of the values are approximations, it would be useless to perform further and deeper analysis.

Starting from a real project of a 2 MW Enercon with a PBT of 9,44 year, the aim of the calculation is to find which price of the VAWT turbine leads to the same value. Two cases are investigated: the small 200 kW type and the 2 MW commercial size, both for a lifetime of 20 years.

It’s important to note that some costs are the same for both HAWT and VAWT, while others are very different. For example, it’s possible to say that foundations are cheaper for a VAWT because on equal installed power the tower is lighter and smaller, being the generator and most of the weight at ground level. The O&M costs are also lower, because of the same reason and also because a PMSG generator requires less maintenance than other types.

Green certificates are taken in account only for the first 15 years. All prices and costs are in Euros, but referred to Swedish market: the conversion rate used is 1 € = 9,3 SEK.

Table 8-1 O&M costs

			VAWT VerticalWind	
		(Wizelius 1 MW)	200 kW	2 MW
Servicing	[k€]	4,3	0,43	4,3
Insurance	[k€]	4,3	0,86	8,6
Measurements	[k€]	0,75	0,75	0,75
Telephone	[k€]	0,215	0,215	0,215
Taxes	[k€]	3,44	0,72	7,2
Fees	[k€]	0,11	0,11	0,11
Administration	[k€]	0,54	0,54	0,54
Tot (1 year)	[k€]	13,655	3,625	21,715
Tot (20 years)	[M€]	0,0273	0,0725	0,4343

Table 8-2 Economics analysis

			VAWT VerticalWind	
		(HAWT 1 MW, hub height 60 m) *source: T. Wizelius*	200 kW	2 MW
PBT (Pay back time)	[years]		9,44	9,44
Foundations	[M€]	0,065	0,01	0,1
Road & Miscellaneous	[M€]	0,011	0,002	0,02
Grid connections	[M€]	0,065	0,016	0,16
Land	[M€]	0,027	0,005	0,01
Project Development	[M€]	0,022	0,04	0,4
O & M [20 years]	[M€]	0,0273	0,0725	0,4343
Green Certificate (per 15 years)	[€/kWh]	0,0023		
	[M€]		-0,01462	-0,19437
Tot (without turbine)	[M€]	1,077	0,130882	0,92993
Energy production	[MWh/year]		423,7	5633,9
Electricity price	[€/kWh]	0,0484		
Income	[M€/year]		0,020502	0,272608
Turbine	**[M€]**	**0,86**	**0,0627**	**1,643**

8.2 Discussion of the results

The investigation accomplished about the VerticalWind 200 kW vertical axis wind turbine has led to interesting results.

The value of the Power Coefficient (C_p), calculated by the power curve of the wind turbine, is 0,31 and it shows that this new kind of VAWT will be able to operate in a range of efficiency not so low and not so distant from other type of existing vertical axis wind turbines.

The frequency of resonance of the tower, evaluated in two different ways in order to have a more complete view of the problem, presents a value that can be considered good compared with the company intentions. The turbine, according to VerticalWind, will operate in a range of angular speed enclosed between 15 and 32 rpm, that leads to a range of frequencies between 0,25 and 0,53

Hz. The frequency of resonance calculated using the Fast Fourier Transform method agrees with the element finite analysis made by VerticalWind and gives a value of 0,75 Hz. It shows that this potential very damaging value of frequency will be never reached during the turbine ordinary operation time.

About the economic analysis it is possible to say that if the cost of a new 2 MW VerticalWind VAWT is about 1,6 million €, the technology is competitive with other types of machines in the present market.

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