OFFSHORE WIND ENERGY

Technical aspects and feasibility study

of offshore on Spanish coasts

Author: Zaira Izaguirre Fernández

Tutor: P. Silva

Department of Energetics

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Abstract

Wind energy is derived from the differential heating of the atmosphere by the sun, and irregularities on the earth's surface. Although only a small fraction of solar energy reaching the earth turns into kinetic wind energy, the total amount is extremely huge.

Therefore, this energy resource should be exploited. What we have tried to proof in this thesis is that if wind farms were built in Spain, it could prevent a large amount of CO_2 from being emitted into the atmosphere and that is an economically viable solution for electricity production.

To reach this conclusion this thesis has been divided into two blocks. The first one, more theoretical, studies in depth wind energy and offshore technology. It describes both the components of a wind turbine as the impacts and potential problems that offshore technology may have.

The second block, analyses three possible wind farms in three areas of Spain with a high wind resource potential. To this purpose, it has been chosen different types of wind turbines with different powers in order to analyse the power generated by each wind farms, the distribution of costs and the economic viability.

CONTENTS

CHAPTER 1: Introduction

1.1. Why offshore wind energy

Offshore wind energy has a promising future, especially in countries with a high population density which reduces the chances of finding suitable sites onshore. At sea, the wind finds variable surface roughness, such as waves, and no obstacles apart from islands. This implies that the wind speed does not experience major changes. Thus, high towers as in onshore are not necessary, reducing materials and therefore costs.

In addition to this, wind is generally less turbulent than on land, extending thereby the period of useful work of a wind turbine. Moreover, the turbulence of the sea floor is lower due to the fact that temperature differences at different altitudes of the atmosphere are lower when they occur over the sea than onshore.

There are also negative aspects, such as the current inability to build wind farms in areas of great depths and certain structural changes are required in the electricity network. Finally, a great funding is needed to build a wind farm.

In spite of the drawbacks of this technology, it is predicted a decreasing of costs and therefore an expansion of this green mode of energy production is expected.

1.1.1. Lack of suitable wind turbine sites on land

As it has been mentioned above, one of the primary reasons for moving wind farm development offshore is the lack of suitable wind turbine sites on land. This is particularly the case in densely populated countries like Denmark or the Netherlands with a relatively flat landscape.

1.1.2. Higher wind speeds

Equally important, however, is the fact that wind speeds are often significantly higher offshore than onshore. An increase of about 20% at some distance from the shore is not uncommon. Given the fact that the energy content of the wind increases with the cube (the third power) of the wind speed, the energy yield may be about 73% higher than on land. Economically optimized turbines, however, will probably yield about 50% more energy at sea than at nearby land locations.

(Bear in mind, that since the fuel is free, economically optimal wind turbines will generally have capacity rates as low as 25 to 30 per cent).

In countries like the UK, however, the difference between good land sites and offshore sites may be smaller or non-existent, since turbines on land are often situated on hilltops where the wind speeds are significantly high, compared to the speed in flat terrain.

1.1.3. More stable winds

It is a frequent misunderstanding that wind power generation requires very stable winds. In fact, in most wind turbine sites around the globe, the wind varies substantially, with high winds occurring rather infrequently, and low winds occurring most of the time.

If we look at the typical statistical wind distribution, most of the energy output is in fact produced at wind speeds close to twice the average wind speed at the site. In addition, in Europe and a number of other locations around the globe wind speeds happen to be positively correlated with peak electricity use (more wind during the day than at night, more wind in winter than in summer) raising the value of the wind to the grid by 40 to 60 per cent, compared to a completely random wind pattern.

Having said this, it should be added, that clearly it is generally an advantage to have a stable power output form for a wind farm. At sea, periods of complete calm are generally extremely rare, and quite short-lived. Thus, the effective use of wind turbine generating capacity will be higher at sea than on land.

1.1.4. Huge offshore wind resources

Offshore wind resources are enormous: Wind energy resources in the European Union seas with water depths up to 50 metres are easily several times larger than the total European electricity consumption.

The offshore wind resource is obviously somewhat unevenly distributed among countries. In the case of Denmark, offshore wind energy may theoretically supply more than ten times national electricity consumption, due to large areas with shallow waters (5 to 15 m depth).

1.1.5. Low surface roughness: cheaper turbines

Another argument in favour of offshore wind power is the generally smooth surface of water. This means that wind speeds do not increase as much with the height above sea level as they do on land. This implies that it may be economic to use lower (and thus cheaper) towers for wind turbines located offshore, as said before.

1.1.6. Lower turbulence: longer lifetime

The temperature difference between the sea surface and the air above it is far smaller than the corresponding difference on land, particularly during the daytime. This means that the wind is less turbulent at sea than over land. This, in turn, will mean lower mechanical fatigue load and thus longer lifetime for turbines located at sea rather than land. No precise calculations are as yet available, but we may guess at something like 25 to 30 year lifetime for a turbine with a design lifetime of 20 years on land.

1.2. Current and future offshore situation

For decades, energy consumption has been increasing severely. This consumption is mainly supplied by fossil fuels, giving off greenhouse gases which damage the earth. Nowadays, both the lack of fossil fuels and the high level of greenhouse gases emissions make people consider other sources of primary energy, such as solar energy, wind power, water energy and so on. In fact, at the moment, wind energy is one of the most promising options to produce electricity. This project is going to focus mainly in offshore wind farms due to its high growth and its good prospects for the future. In 2009, eight new wind farms with a total of 199 turbines offshore were grid connected in Europe with a capacity of 577 MW. This represents a growth rate of 54% compared to the 373 MW installed in 2008. During 2010 the European Wind Energy Association (EWEA) expects to install 1.000 MW more, which means a 75% market growth compared to 2009. There are 17 wind farms under construction in Europe totalling over 3.500 MW, and half of them are being built in United Kingdom waters. Furthermore, more than 52 wind farms have been approved, making a total of 16.000 MW. In 2009, the turnover of the offshore wind industry was approximately 1,5€ billion, and this will double in 2010 to approximately 3€ billion. “The increased participation of the European Investment Bank (EIB) will also contribute positively to the future success of the contribution of offshore wind farms to European recovery, job creation and energetic leadership” said the managing director from the EWEA. Europe has a total of 828 turbines in the offshore market and an accumulative capacity of 2.056 MW in 38 wind farms in nine European countries. The United Kingdom and Denmark are current leaders with a share of 44% and 30%, respectively, as it can be seen in the table below (***table 1.2.1)***. [1]

	United Kingdom	Denmark	Sweden	Germany	Norway
Number of turbines	84	98	10	6	1
MW	284.4	230	30	30	2.3
Number of farms	3	2	1	1	1

Table 1.2.1. 2009 Offshore installation. [EWEA]

In December 2008 the European Union agreed on a binding target of 20% renewable energy by 2020. The European Commission expects 34% of electricity coming from renewable sources by 2020 and believes that "wind could contribute 12% of EU electricity by 2020". EWEA predicts that the total offshore wind capacity installed in 2020 will be 40 GW, up from just less than 1.5 GW today. This means manufacturing, installing and operating approximately 10.000 turbines, which corresponds to an average of three to four offshore turbines being installed per working day over the next 12 years. This scenario can be compared to the growth of the European onshore wind market at a similar time in the industry's development (see f*igure 1.2.2).*[2]

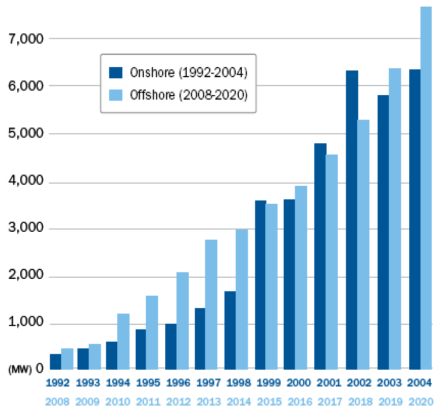


Figure 1.2.2. Historical onshore growth 1992-2004 compared to EWEA's offshore projection 2008-2020 (MW). [EWEA]

The next section is going to be divided into two periods: one comprising the length of time between 2010 and 2020 and another covering that between 2021 and 2030. In each period it will be included a summary of the total capacity installed, annual installations, electricity production, annual investments and the quantity of CO_2 emissions avoided.

The EWEA expects a growth of the number of MW installed during the next 20 years as it can be seen in the following graphics (see f*igure 1.2.3 and 1.2.4)*, beginning from 1.5 GW in 2011, until it reaches 6.9 GW in 2020, 7.7 GW in 2021 and 13.6 GW in 2030 in the second period.

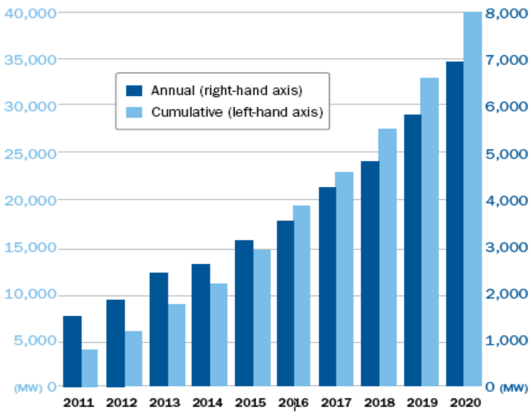


Figure 1.2.3. Offshore wind annual energy and cumulative installations 2011-2020 (MW). [EWEA]

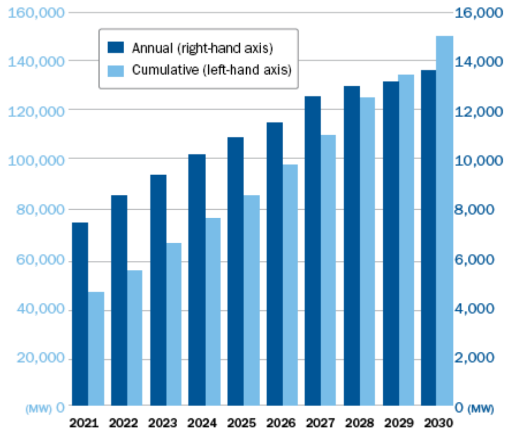


Figure 1.2.4. Offshore wind annual energy and cumulative installations 2021-2030 (MW). [EWEA]

If we talk about wind energy production, in 2020 148 TWh (*see figure 1.2.5)* of electricity would be produced which corresponds to between 3,6% and 4,3% of EU electricity consumption, depending on the development in electricity demand. Approximately a quarter of Europe's wind energy would be produced offshore in 2020. Including onshore, wind energy would produce 582 TWh, about more or less 15% of total EU electricity demand by 2020. If we refer to the second period, 563 TWh (*see figure 1.2.6)* of electricity would be produced in 2030. Half of Europe's wind electricity would be produced offshore in that year. Including onshore production, wind energy will be able to cater to between 26,2% and 34,3% of EU electricity demand.

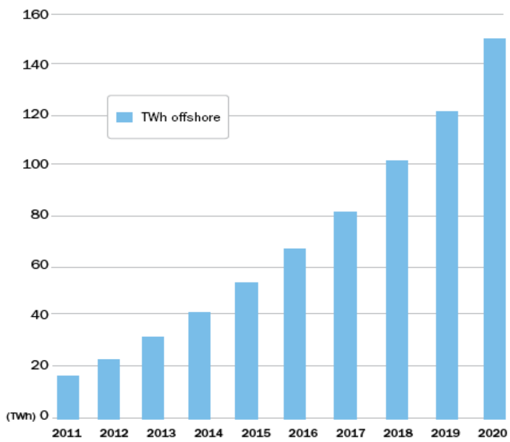


Figure 1.2.5 Electricity production 2011-2020 (TWh). [EWEA]

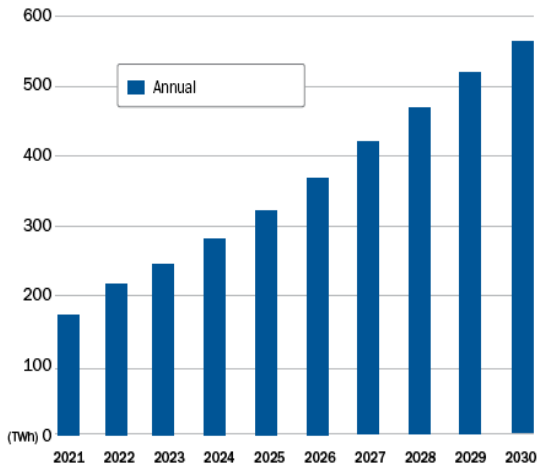


Figure 1.2.6. Electricity production 2021-2030 (TWh). [EWEA]

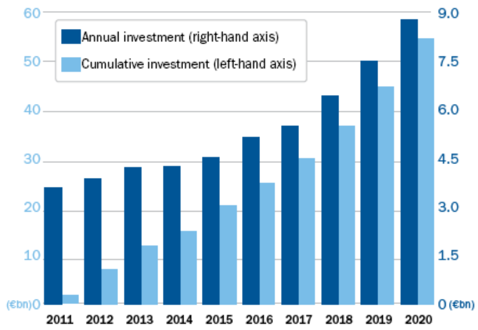


Figure 1.2.7 Annual and cumulative investments in offshore wind power 2011-2020 (€billion). [EWEA]

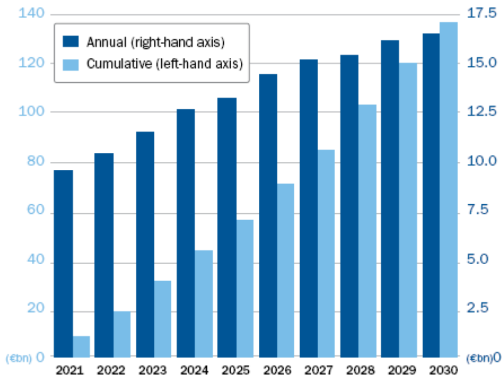


Figure 1.2.8 Annual and cumulative investments in offshore wind power 2021-2030 (€billion). [EWEA]

In the graphics above (*see figures 1.2.7 and 1.2.8)*, it is seen that in the first period a growth of 5,51€ billion in investment is expected. Instead, in the second period the annual investments in offshore wind power are expected to increase from 9,8€ billion in 2021 to 16,5€ billion in 2030.

As regards climate change, it can be said that offshore wind power will avoid the emission of 10Mt of CO_2 in 2011 and this number will rise to 85Mt in 2020. At the end of the second period, in 2040, this will increase until 292 Mt of CO_2.

CHAPTER 2: Introduction to wind energy

2.1. Wind energy conversion

2.1.1. Where does wind energy come from?

All renewable energy, except tidal and geothermal power, and even the energy in fossil fuels, ultimately comes from the sun. The sun radiates $174.423 \cdot 10^9$ kWh of energy to the earth. About a 2% of the energy coming from the sun is converted into wind energy, which represents almost two billion tons oil equivalent (TOE) per year (200 times more than the total consumed by all the world's nations). However, in practice, only a very small part of this amount can be used, given its randomness and dispersion, which is around a 5%. This is due to the fact that technology only allows horizontal winds, close to the ground as long as the speed is neither too high nor too low (usually more than 3 m/s and less than 25 m/s). The amount of energy involved means that wind power is one of the sources of renewable energy with the greatest potential.

Solar energy, absorbed on an irregular basis by the atmosphere, gives rise to air masses with different temperatures and, therefore, different densities and pressures. When the air travels from high to low pressures it does so in the form of wind.

The regions around equator, at 0º latitude are heated more by the sun than the rest of the globe (*see figure 2.1.1)*. Hot air is lighter than cold air and will rise into the sky until it reaches approximately 10 km and it will spread to the North and the South. If the globe did not rotate, the air would simply arrive at the North Pole and the South Pole, sink down, and return to the equator. Since the globe is rotating, any movement on the northern hemisphere is diverted to the right, if we look at it from our own position on the ground, but in the southern hemisphere it is bent to the left (*see figure 2.1.2)*. This apparent bending force is known as the Coriolis force or Coriolis Effect, which was described by the French scientist Gustave-Gaspard Coriolis in 1835. This force not only appears during the rotation of the Earth but, in general, for any object with mass moving at a certain rate on another rotating object. The Coriolis force plays an important role in weather patterns, which predominantly affects the winds and the rotation of storms, as well as to the direction of ocean currents. [3]

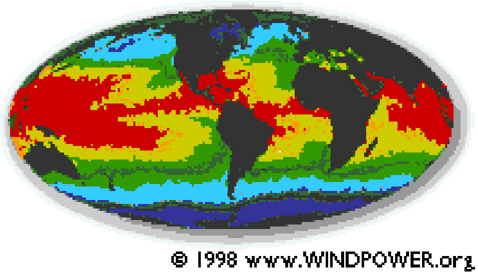


Figure 2.1.1 Hot areas are indicated in the warm colours red, orange and yellow in this infrared picture of sea surface temperatures (taken from a NASA satellite, NOAA-7 in July 1984)

Figure 2.1.2 Globe rotating, northern hemisphere to the right, southern hemisphere to the left.

2.1.2. How the Coriolis force affects wind directions on the globe

The wind rises from the equator and moves north and south in the higher layers of the atmosphere. Around 30º latitude in both hemispheres, the Coriolis force prevents the air from moving much farther. At this latitude there is a high pressure area, as the air begins sinking down again. As the wind rises from equator there will be an area of low pressure near ground level attracting winds from north and south. At the Poles, there will be high pressure due to the cooling of the air. Bearing in mind the strength of curvature of the Coriolis force, the following general results of the prevailing wind direction are obtained (*see table 2.1.3, see also figure 2.1.4 and 2.1.5)*:

Latitude	90-60º N	60-30º N	30-0º N	0-30º S	30-60º S	60-90º S
Direction	NE	SW	NE	SE	NW	SE

Table 2.1.3 Prevailing wind directions

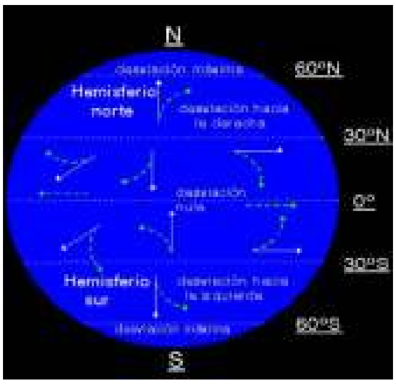


Figure 2.1.4 and Figure 2.1.5 Wind directions on the globe affected by the Coriolis force.

The prevailing wind directions are important when sitting wind turbines, since it is obviously required to put them in the areas with fewer obstacles from the prevailing wind directions. Local geography, however, may influence the general results in the table above.

The winds considered before were global winds, which are actually geostrophic winds. These winds are mainly generated by the difference of temperature and pressure, and are not very much influenced by the surface of the earth. The geostrophic wind is found at altitudes above 1.000 metres from the ground level. Its speed can be measured using weather balloons. But for wind energy it will be interesting to know the surface winds, because the winds are much more influenced by the ground surface at altitudes up to 100 metres. Roughness and obstacles are the cause of the slowdown of the wind and the wind directions near the surface will be slightly different from the direction of the geostrophic wind because of the earth's rotation due to the force of Coriolis.

Although global winds are important in determining the prevailing winds in a given area, local climatic conditions may wield an influence on the most common wind directions. Local winds are always superimposed upon the larger scale wind systems, which means that the wind direction is influenced by the sum of global and local effects and when larger scale winds are light, local winds may dominate the wind patterns.

The first step in order to build a wind farm is to identify an area with adequate wind conditions. Therefore it should be created a map of flatulence, monitor speed and wind direction for high periods of time. The perfect place to install the wind farm would be one which had a speed between 5 and 25 m/s, better if it is constant an close to the maximum, always blowing in the same direction and for long periods of time. This last point should be borne in mind because the wind resource in the same area could change dramatically depending on the season in which we find ourselves. That is why the measures should be carried out in a long period of time.

The measurement of wind speeds is done with an anemometer. There are different kinds of anemometers such as hot-wire anemometers, winged wheel, sealed portable pocket size and cup anemometers. The last one is one of the most used (*see figure 2.1.6).*The cup anemometer has a vertical axis and three cups which capture the wind. The number of revolutions per minute is registered electronically, although it can be read directly by a metre or recorded on a paper strip, in which case it is called anemograph. In order to measure the sudden changes in wind speed, especially in the turbulence, the hot wire anemometer is used, which consists on a thin electrically heated platinum or nickel: the wind action tends to cold it and varies its resistance; hence the electric current through the wire is proportional to wind speed.

The advantage of non-mechanical anemometers may be that they are less sensitive to icing. In practice, however, cup anemometers tend to be used everywhere, and special models with electrically heated shafts and cups may be used in arctic areas.
There is a huge difference in price from one anemometer to another, but cheap anemometers are not usable for wind speed measurement in the wind energy industry, since they may be very inaccurate and calibrated poorly, with measurement errors of maybe 5% and even 10%.

Figure 2.1.6. Cup anemometer.

As it is said before, information of the direction and speed of the wind is needed to build a wind farm, which is why we also use the wind rose. The wind rose shows the information about the distributions of wind speeds, and the frequency of the varying wind directions and it is based on meteorological observations of wind speeds and wind directions. There is a picture of a wind rose in *figure 2.1.7.* Any information that can be extracted from maps of flatulence, wind roses and software must be taken into account, but it cannot be forgotten that wind conditions in a particular area may be different from the reality and therefore this type of analysis cannot replace measurements taken on site.
It can be seen in the next *figure 2.1.8*, that the seas of Northern Europe and the coast of Marseille have very favourable wind conditions, with a capacity of above 1.100 W/m^2 at a height of 100m. This wide availability is also why the pioneers in offshore wind energy are in northern Europe. Other favourable places, if we refer to wind conditions, are also the Gulf of Lions and the Aegean Sea near Turkey, but not all areas with favourable winds are used. There are several factors that should be considered:

- Areas with a close contact with the coast should be discarded for visual impact reasons.
- In areas far away from the coast it will be important to consider the costs of electrical connections.
- In the sea there are also other activities such as sailing, fishing and military and therefore exclusive use of offshore industry cannot be provided.

- Some sites are considered nature reserves and it is inconceivable to make a wind offshore farm.
- As it will be seen afterwards, the type of marine foundations and depth are important factors in site selection.

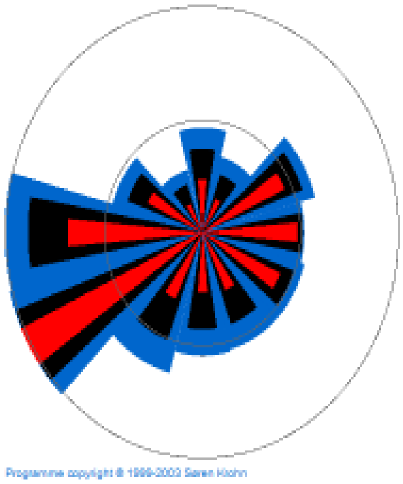


Figure 2.1.7. Wind rose made with the Wind Rose Plotter Programme of Windpower.org

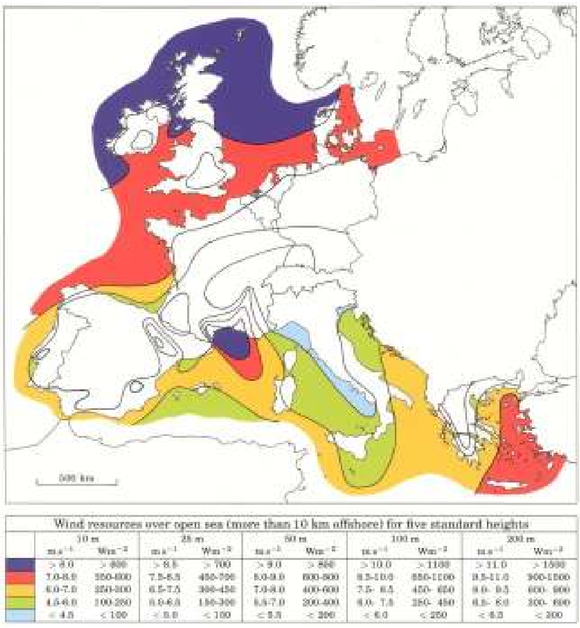


Figure 2.1.8. Wind resources over open sea. Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark.

2.2. Betz limit

The energy available in the wind is basically energy from an air mass which is moving. This air mass acts on the blades of the wind turbine, producing its rotation. Once the rotation is produced, the energy can be transformed to electricity or used as mechanical energy, depending on the final use. In this case the kinetic energy is transformed to electrical energy with a generator. Nevertheless, not all energy from the movement of an air mass can be transferred to the rotor of the turbine. As Albert Betz established in 1919, any turbine cannot capture more than 59.3% of energy available in a wind stream. This number is known as Betz limit and can be proved with the following equations. [4]

The kinetic energy of mass of air *m* at velocity *v* is:

$$E = \frac{1}{2}mv^2 \qquad (1.1)$$

Considering a wind rotor of cross sectional area *A*, through which the air passes at a velocity *v*, the volumetric flow is:

$$\dot{V} = Av \qquad (1.2)$$

And multiplying it by the air density, the mass flow is obtained:

$$\dot{m} = \rho A v \qquad (1.3)$$

Power is energy per time unit, and by combining equations (1.1) and (1.3) the following equation is obtained:

$$P = \frac{1}{2}\rho A v^3 \qquad (1.4)$$

P is the power available in a free-stream airflow. Now, the maximum power that can be transferred to the rotors has to be found. The only way to extract energy from the air stream is transforming some of its kinetic energy to mechanical energy. Thus, the velocity of the air stream will decrease behind the energy converter.

Furthermore, the continuity equation has to be taken into account:

$$\rho A_1 v_1 = \rho A_2 v_2 \qquad (1.5)$$

Since the mass flow is constant, as velocity decreases, the cross-sectional area will increase (see *figure 2.2.1)*:

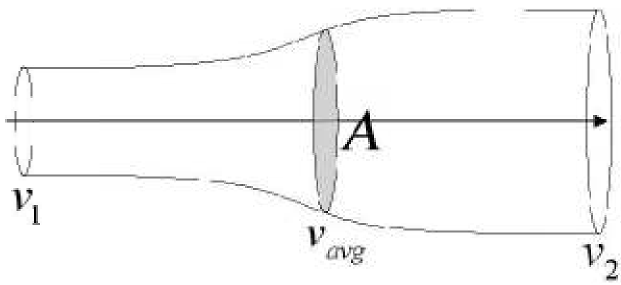


Figure 2.2.1. Flow cross-sectional area as the air runs through the rotor or energy converter. v_1 is the velocity before the air stream reaches the converter and v_2 is the flow velocity behind the converter. [5]

From equation (1.4) the expression of the power extracted from the energy converter is:

$$P = \frac{1}{2}\rho A_1 v_1^3 - \frac{1}{2}\rho A_2 v_2^3 = \frac{1}{2}\rho(A_1 v_1^3 - A_2 v_2^3) \qquad (1.6)$$

And from equations (1.5) and (1.6):

$$P = \frac{1}{2}\rho v_1 A_1 (v_1^2 - v_2^2) \qquad (1.7)$$

This can be expressed also as:

$$P = \frac{1}{2}\dot{m}(v_1^2 - v_2^2) \qquad (1.8)$$

From this equation, v_2 should be zero in order to obtain the maximum theoretical power. However, v_2 equals to zero means that the air is brought to a complete standstill by the converter; and this makes no sense because v_2 equals to zero means that v_1 must equal also to zero to fulfil the continuity equation (1.5). As a result, there would not be air flowing through the converter, and the power transformed would be zero. Then, the ratio v_2/v_1 will be used to find the maximum theoretical power. In addition, another equation is required to find the maximum power. According to the law of conservation of momentum, the force that the converter receives from the air can be expressed as:

$$F = \dot{m}(v_1 - v_2) \tag{1.9}$$

According to Newton's third law "To every action there is an equal and opposite reaction", so if the converter pushes the air mass at air velocity v', the power required is:

$$P = Fv' = \dot{m}(v_1 - v_2)v' \tag{1.10}$$

Making equal equations (1.8) and (1.10):

$$\frac{1}{2}\dot{m}(v_1^2 - v_2^2) = \dot{m}(v_1 - v_2)v' \tag{1.11}$$

And if it is simplified:

$$v' = \frac{1}{2(v_1 + v_2)} \tag{1.12}$$

As equation (1.12) shows, v' is the arithmetic mean of v_1 and v_2. Combining equations (1.3) and (1.12), the mass flow becomes:

$$\dot{m} = \rho A v' = \frac{1}{2}\rho A(v_1 + v_2) \tag{1.13}$$

And now substituting equation (1.13) in equation (1.8) a new expression for the power is obtained:

$$P = \frac{1}{4}\rho A(v_1^2 - v_2^2)(v_1 + v_2) \tag{1.14}$$

Taking equation (1.4) for a flow running through the same cross-sectional area without interaction with any energy converter, the power of the undisturbed air stream is:

$$P_0 = \frac{1}{2}\rho A v^3 \tag{1.15}$$

Dividing P (equation (1.14)) by P_0 (equation (1.15)), the "power coefficient" c_p is obtained:

$$c_p = \frac{P}{P_0} = \frac{\frac{1}{4}\rho A(v_1^2 - v_2^2)(v_1 + v_2)}{\frac{1}{2}\rho A v^3} = \frac{1}{2}\left|1 - \left(\frac{v_2}{v_1}\right)^2\right|\left|1 + \frac{v_2}{v_1}\right| \tag{1.16}$$

Therefore, the "power coefficient" c_p is the ratio of the extractable mechanical power to the power contained in the air stream, and it only depends on the ratio of the air velocities before and after the converter. The last step here is to find the maximum value, which can be calculated both numerically and graphically.

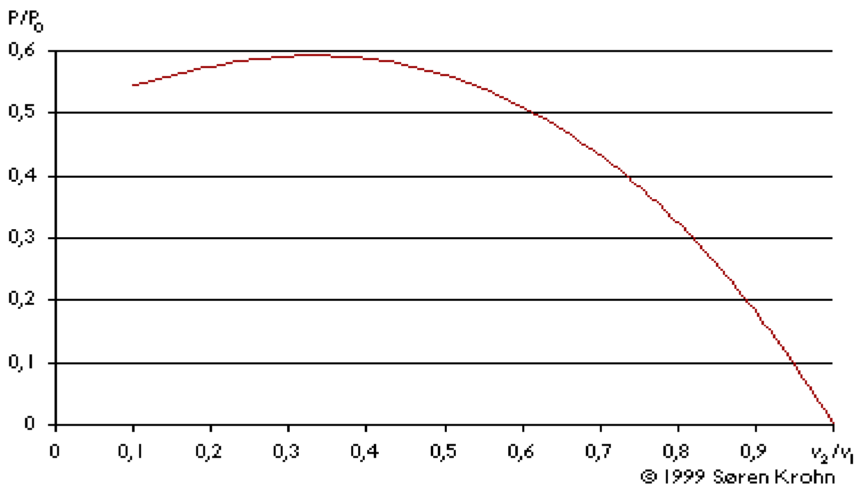
If the Betz limit is calculated numerically, in order to find the maximum value, first of all c_p is derived and equalized to zero, then the equation is solved and finally, the value obtained is replaced into the original equation:

$$\frac{\delta c_p}{\partial\left(\frac{v_2}{v_1}\right)} = \frac{1}{2}\left[\left(1+\frac{v_2}{v_1}\right)\left(-2\left(\frac{v_2}{v_1}\right)\right)+\left(1-\left(\frac{v_2}{v_1}\right)^2\right)\right] = \frac{1}{2}\left[1-2\left(\frac{v_2}{v_1}\right)-3\left(\frac{v_2}{v_1}\right)^2\right]=0$$

Solving the quadratic equation $\frac{v_2}{v_1}=\frac{1}{3}$,

And replacing this value in equation (1.16), $c_p = \frac{32}{54} = 0{,}5926$ which is the Betz limit stated at the beginning of this section.

Based on the equation (1.16) the next *figure 2.2.2* can be drawn, P/P_0 as a function of v_2/v_1:



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Updated 12 May 2003
http://www.windpower.org/en/stat/betzpro.htm

Figure 2.2.2. Betz limit graphically.

It can be seen that the function reaches its maximum for $\frac{v_2}{v_1}=\frac{1}{3}$, and that the maximum value for the power extracted from the wind is 0.59 or 16/27 of the total power in the wind.

2.3. The Weibull distribution

As it has been said before, it is very important for the wind industry to be able to describe the variation of wind speeds to minimize the costs and optimize the designs and to estimate the income from electricity generation. If wind speeds are measured throughout the year, it can be noticed that in most areas strong gale force winds are rare, while moderate and fresh winds are quite common. The wind variation for a typical site is usually described using the so called Weibull distribution, which was discovered by the Swedish Weibull Walodi and was first announced in a letter in 1951.

The performance of the Weibull distribution is controlled by the factor of scale *c* (closely related to the average velocity of air at the site) and the form factor *k* (related to standard deviation of the distribution and therefore the dispersion). The shape parameter *k* indicates how peaked the distribution of wind speeds is. If they tend to be near a certain value, the distribution will have a high value of *k* and will be very sharp. A widely used value is *k=2*, which is called Rayleigh distribution. For wind speeds below 15 km/h, Rayleigh distribution has little accuracy, not being useful in areas with average wind speeds below 13km/h. [6]

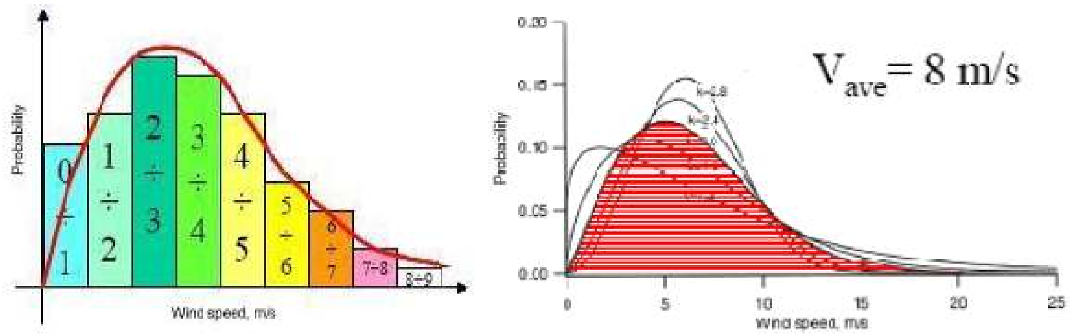
$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \tag{2.1}$$

Where *V* is the wind speed, and the expression of *c* is:

$$c = \frac{\bar{V}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{2.2}$$

Where $\bar{V}$ represents the average annual rate, and Γ indicates the Euler Gamma function. The analytic expression allows to obtain a good approximation of the frequency of the wind in a long period, but do remember that it is always an idealization of the phenomenon and therefore does not always correspond to physical reality.

The next *figures 2.3.1 and 2.3.2* show how Weibull distribution is influenced by the form factor: if it increases, the probability function gets closer to the average speed (practically it is as if the wind blew almost constantly at the same speed). Then the likelihood of weak winds and strong winds will decrease, influencing the available power density of the air stream (power density increases with the cube of wind speed, so not having strong winds will imply having a heavy penalty).



Figures 2.3.1 and 2.3.2. Probability distribution of the frequency of the wind (left) and influence of the shape factor in the Weibull distribution (right). The red area is obtained for k=2.

2.4. Trends in wind speed with altitude

A typical feature of the wind is the dissimilarity of its distribution on the vertical; this means that the velocity near the ground is different from that at a higher altitude. The simple reason is due to the braking effect that the land opens to the wind because of its roughness. Then different distributions of the wind should be taken into account as the area concerned.

There are different models used to describe the evolution of wind speed with height, the most used is the following exponential profile:

$$\frac{V(z)}{V_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (2.3)$$

Where V_{ref} and z_{ref} are respectively the velocity and height reference, and $V(z)$ is the unknown velocity at the z height. The parameter α is calculated as:

$$\alpha = \frac{1}{\ln \frac{Z}{Z_0}} \qquad (2.4)$$

where the parameter z_0 indicates the roughness of the surface through which the air flows. α is closely linked to the roughness of the surface and it can be assumed equal to 0,15 for sea surfaces and 0,4 for rock surfaces. The following *figure 2.4.1* represents the vertical gradient of velocity of various morphologies of the land. It is noted that in the case of the sea the flow rate is almost constant with the height and hence, as it will be seen later, the wind power available is bigger than in the other cases.

Another widely used model is the logarithmic velocity profile:

$$\frac{V(Z)}{V_{ref}} = \frac{\ln\frac{Z}{Z_0}}{\ln\frac{Z_{ref}}{Z_0}} \qquad (2.5)$$

These last two models have some limits, for example, they do not consider the change in velocity profile and are only valid in the laminar substrate. Nevertheless, these representations are largely used.

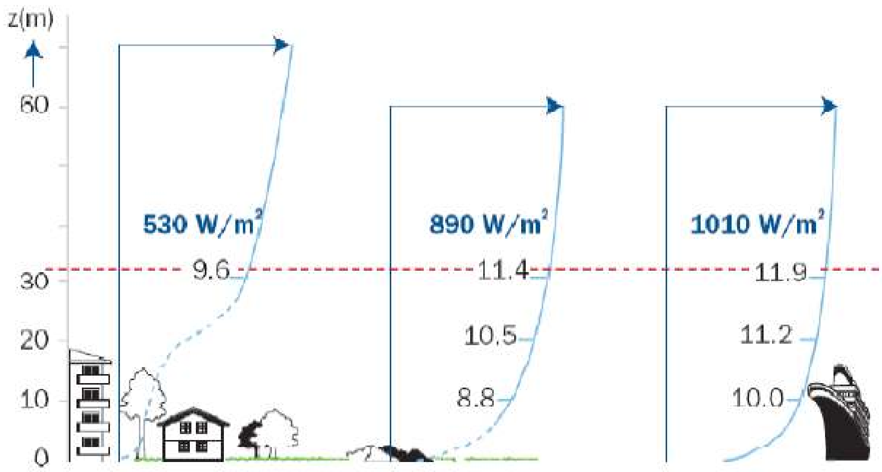


Figure 2.4.1. Vertical velocity gradient according to different roughness of the surface and power contained in wind at a height of 30m. There is a radical change by varying the roughness of the surfaces.

2.5. The energy in the wind

A wind turbine obtains its power input by converting the force of the wind into torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

- Density of the air:

  The kinetic energy of a moving body is proportional to its mass (or weight). Thus, the kinetic energy in the wind depends on the density of the air, i.e. its mass per unit of volume. So the heavier the air, the more energy is received by the turbine. At normal atmospheric pressure and at 15º Celsius air weights some 1225 kilogrammes per cubic metre, but the density decreases slightly with increasing humidity. Also, the air is denser when it is cold than when it is warm.

- Rotor area:

  The rotor area determines how much energy a wind turbine is able to harvest from the wind. Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive four times as much energy. A typical 1000 kW wind turbine has a rotor diameter of 54 metres, i.e. a rotor area of about 2300 square metres. The size of the wind turbines will be explained further on.

- Wind speed:

  The wind speed is extremely important for the amount of energy a wind turbine can convert to electricity: the energy content of the wind varies with the cube (the third power) of the average wind speed, e.g. if the wind speed is twice as high it contains eight times as much energy. As it is seen the formula of the wind's power is:

$$P = \frac{1}{2}\rho A v^3 \qquad (3.1)$$

Where $$A = \pi r^2 \qquad (3.2)$$

So combining these two last equations we obtain:

$$P = \frac{1}{2}\rho \pi r^2 v^3 \qquad (3.3)$$

Where *P* = the power of the wind measured in W (Watt)

ρ = the density of dry air = 1.225 kg/m^3 (at average atmospheric pressure at sea level at 15 ºC)

v = the velocity of the wind measured in m/s

r = the radius (half the diameter) of the rotor measured in m (metres).

π = 3.14159...

2.5.1. The power curve of a wind turbine

The wind turbine is not always able to transform wind energy into mechanical energy, in fact, there is a minimum speed (cut in) in which the machine does not start and a top speed (cut off) in which the machine stops working at too strong winds in order not to damage the turbine.

The power curve of a wind turbine (*see figure 2.5.1)* is a graph that indicates how large the electrical power output will be for the turbine at different wind speeds. Power curves are found by field measurements with an anemometer. If the wind speed is not fluctuating too rapidly, then one may use the wind speed measurements from the anemometer and read the electrical power output from the wind turbine. Power curves are based on measurements in areas with low turbulence intensity, and with the wind coming directly towards the front of the turbine. Finally, it is needed to account for the fact that the turbine may not be running at standard air pressure and temperature, and consequently make corrections for changes in the density of air.

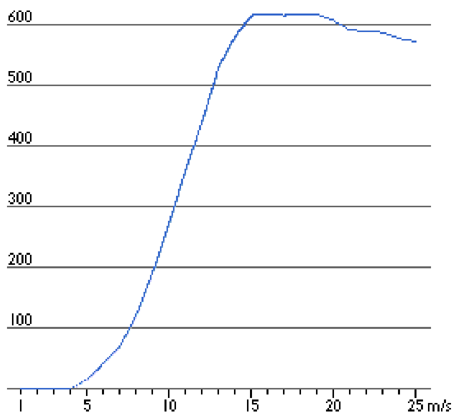


Figure 2.5.1. Power curve for a typical Danish 600 kW wind turbine.
[windpower.org]

2.5.2. The power coefficient

The power coefficient says how efficiently a turbine converts the energy in the wind to electricity.

How is it calculated? The electrical power output has to be divided by the wind energy input to measure how technically efficient a wind turbine is. The power curve is taken and divided by the area of the rotor to get the power output per square metre of rotor area. For each wind speed, the result is divided by the amount of power in the wind per square metre.

In the graphic below (*see figure 2.5.2)* it can be seen a power coefficient curve for a typical Danish wind turbine. Although the average efficiency for these turbines is more or less 20%, the efficiency varies a lot depending on the wind speed. In this case, the mechanical efficiency of the turbine is 44% at a wind speed around some 9 m/s.

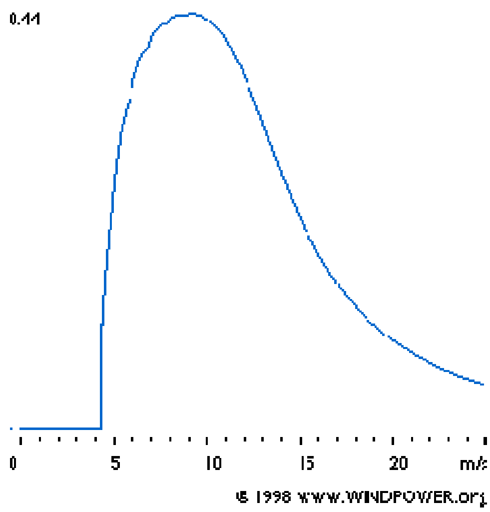


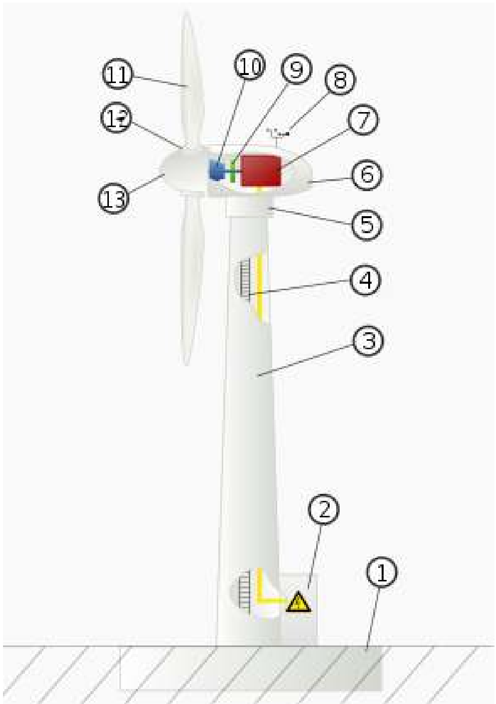
Figure 2.5.2. Power coefficient for a typical Danish wind turbine.
[windpower.org]

CHAPTER 3: Wind turbines technology

3.1. Components of a wind turbine

Wind turbines consist of four large main components: a foundation unit, a tower, a nacelle (turbine housing) and a rotor. The following section provides a brief explanation of the various parts of modern horizontal axis wind systems. They are the most widely used and this chapter will focus on them.

The forthcoming *figure 3.1.1* shows the diagram of a wind turbine where the different parts are indicated.



1. Foundations
2. Electrical grid
3. Tower
4. Stairway
5. Yaw mechanism
6. Nacelle
7. Generator
8. Anemometer and wind vane
9. High speed shaft with its mechanical brake
10. Transmission
11. Blade
12. Blade’s inclination
13. Hub

Figure 3.1.1 Diagram of a wind turbine.

<u>The nacelle:</u>

It contains the key components of the wind turbine, including the gearbox and the electric generator. Its size is such that the maintenance operators can stand in it and walk from side to side for perfect handling and repair of machinery.

Hub:

The hub is at the junction of the blades with the rotation system. The hub and blade assembly is called wind rotor. There are two types of hub: rigid and swivel, depending on whether the blades behave as a cantilever beam or can swing freely with the rotation's system.
The rotor of the turbine is one of the most visible wind energy systems. Most wind turbines manufactured nowadays, are horizontal axis machines, upwind with two or three blades. The main type of rotor has an axis which is parallel to ground, and therefore, horizontal to wind.

Gearbox:

The gearbox is responsible for converting the low speed of the blades' rotation (about 24 revolutions per minute (rpm)) at high speed, around 1.500 rpm to match the speed of the generator. In some turbines, the gear ratio may exceed 1:100. This is achieved in three separate stages. The first stage is generally a planetary gear, while the others are parallel or helical gears. The gearbox is force-lubricated and the oil is continuously filtered and cooled. With preventive maintenance being standard practice, it is common to monitor the temperature of the gearbox, as well as the vibrations.

Electrical generator:

The electrical generator is actually an alternator which is coupled to the gearbox through the small shaft. It has the charge of producing electricity, which is conveyed through the interior of the tower to the transformer. It is basically the unit that transforms the mechanical energy into electric power. Usually it is an asynchronous or induction generator. (This will be explained in more detail in 3.3).

Anemometer:

The anemometer measures wind speed, as explained in the point 2.1.2, and sends this information to the controller, which logs it and acts accordingly on the brake. Anemometer electronic signals are used by the electronic controller to connect the wind turbine when the wind reaches about 5 m/s. The computer will stop automatically if wind speed exceeds 25 m/s, in order to protect the turbine and its surroundings.

Motor orientation and slewing ring:

Motor orientation:

The yaw motor turns the nacelle so that the rotor faces the wind. The controller indicates the yaw motor when to turn the nacelle.

The slewing ring:

The slewing ring, located at the bottom of the nacelle is responsible along with the guidance system to position the nacelle in the direction best suited for optimal use of wind, and hence increase the power generated.

Figure 3.1.2. Slewing ring

The wind vane:

The wind vane, which is associated to the guidance system, is which informs the control system of the wind direction at any time.

Low speed shaft:

Attaches the gearbox with the rotor.

The braking system.

It is used to block the rotor when the maintenance is being carried out or the system must be repaired.

Radiator:

The generator is hot when spinning. But if it becomes too hot it will spoil. This is the reason why it should be refrigerated. In some wind turbines, the generator is cooled by water.

Electronic controller:

The electronic controller is a computer that continuously monitors the conditions of the turbine and controls the yaw mechanism. Orients the nacelle into the wind and allows the rotor to start when the wind vane indicates that there is enough wind. In case of any malfunction (e.g. overheating in the gearbox or generator), it automatically stops the turbine and calls the computer operator in charge of the turbine through a telephone link.

Blades:

The blades are the components which interact with the wind. Their shape is designed in order to obtain good aerodynamic efficiency. In fact, rotor blade designers often use classical aircraft wing profiles as cross sections in the outermost part of the blade. The next *figure 3.1.3* shows a typical wind turbine blade outline, together with several cross-sections at different locations along the length. Near the hub, the blade has a circular section. As the distance from the hub axis (radius) increases, the thickness of the wing decreases, as well as the chord.
The aerodynamic forces vary with the square of the local relative air velocity and increase rapidly with the radius. It is thus important to design the part of the blade near the tip with good lift and low drag coefficients. The blades are flexible and therefore can be deflected by the wind. In order to avoid the blades hitting the tower, the rotor axis is frequently tilted at a small angle. The cross-section of a wind turbine blade is quite thick in order to obtain the high rigidity necessary to resist the different mechanical loads acting during operation. Several examples are explained below:
The *centrifugal force* due to rotation is typically six to seven times larger than the blade weight at the root section. [7]
The *weight of the blade* itself creates a bending moment on the root which is alternated at each revolution.
The *wind* exerts a force which is not constant; fluctuations result from turbulence, but also from the fact that wind velocity increases with altitude, as it has been seen before.
A blade in a high *position* is subjected to a stronger wind than in a low position and the corresponding load fluctuation is also repeated at each revolution.
All these alternating loads are responsible for fatigue, which is the biggest technical challenge in blade design. A thorough analysis is required to eliminate the risk of resonance between the different mechanical oscillators (blades, tower, drive train, etc.). Nowadays, the turbine manufacturers make computer models of their machines before building them, to ensure that

the vibrations of different components do not interact to amplify noise. If you look at the chassis frame of the nacelle on some of the large wind turbines on the market today, you may discover some odd holes which were drilled into the chassis frame for no apparent reason. These holes were precisely made to ensure that the frame will not vibrate in step with the other components in the turbine.

Blade's materials:

The blades are made of lightweight materials, like fibre -reinforced plastics, which exhibit good fatigue properties. The fibres are mainly glass woven fabrics but for the largest blades, carbon fibres are used in the blade parts where loads are most critical. Some blades are entirely made of carbon fibres whereas wood laminates are also used by some manufacturers. The fibres are incorporated in a matrix of polyester, vinyl ester or epoxy resin and the blades are made up of two shells which are bonded together. Internal webbing reinforces the structure. The external blade surface is covered with a smooth coat of coloured gel intended to prevent ultraviolet ageing of the composite material.

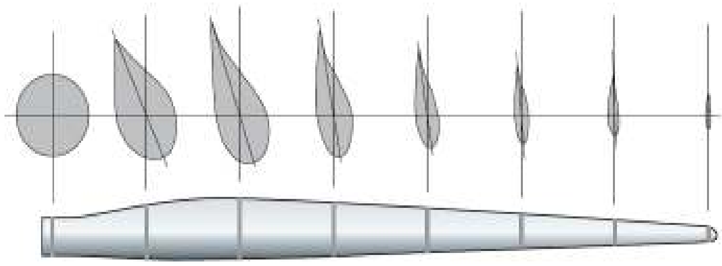


Figure 3.1.3. Blade shape and cross sections (enlarged). [7]

<u>Tower:</u>

The tower of the wind turbine carries the nacelle and the rotor. Towers for large wind turbines may be tubular steel towers, lattice towers, or concrete towers. Guyed tubular towers are only used for small wind turbines.

- Tubular steel towers:
  Most large wind turbines are delivered with tubular steel towers, which are manufactured in sections of 20-30 metres with flanges at either end, and bolted together on the site. The towers are conical (i.e. with their diameter increasing

towards the base) in order to increase their strength and to save materials at the same time *(see figure 3.1.4).*

- Lattice towers:

  Lattice towers are manufactured using welded steel profiles. Its basic advantage is cost, since a lattice tower requires only half as much material as a freely standing tubular tower with a similar stiffness. The basic disadvantage is their visual appearance. Due to aesthetic reasons lattice towers have almost disappeared from use for large modern wind turbines *(see figure 3.1.5).*

- Guyed pole towers:

  Many small wind turbines are built with narrow pole towers supported by guy wires. Its advantage is weight savings, and thus cost. The disadvantages are difficult access around the towers which make them less suitable in farm areas. Finally, this type of tower is more prone to vandalism, hence compromising overall safety *(see figure 3.1.6).*

- Hybrid tower solutions:

  Some towers are made using different combinations of the techniques mentioned above. One example is the three-legged Bonus 95 kW tower *(see figure 3.1.7),* which may be considered a hybrid between a lattice tower and a guyed tower.

Figure 3.1.4 Tubular steel towers.

Figure 3.1.5 Lattice towers.

Figure 3.1.6 Guyed pole towers.

Figure 3.1.7 Hybrid towers.

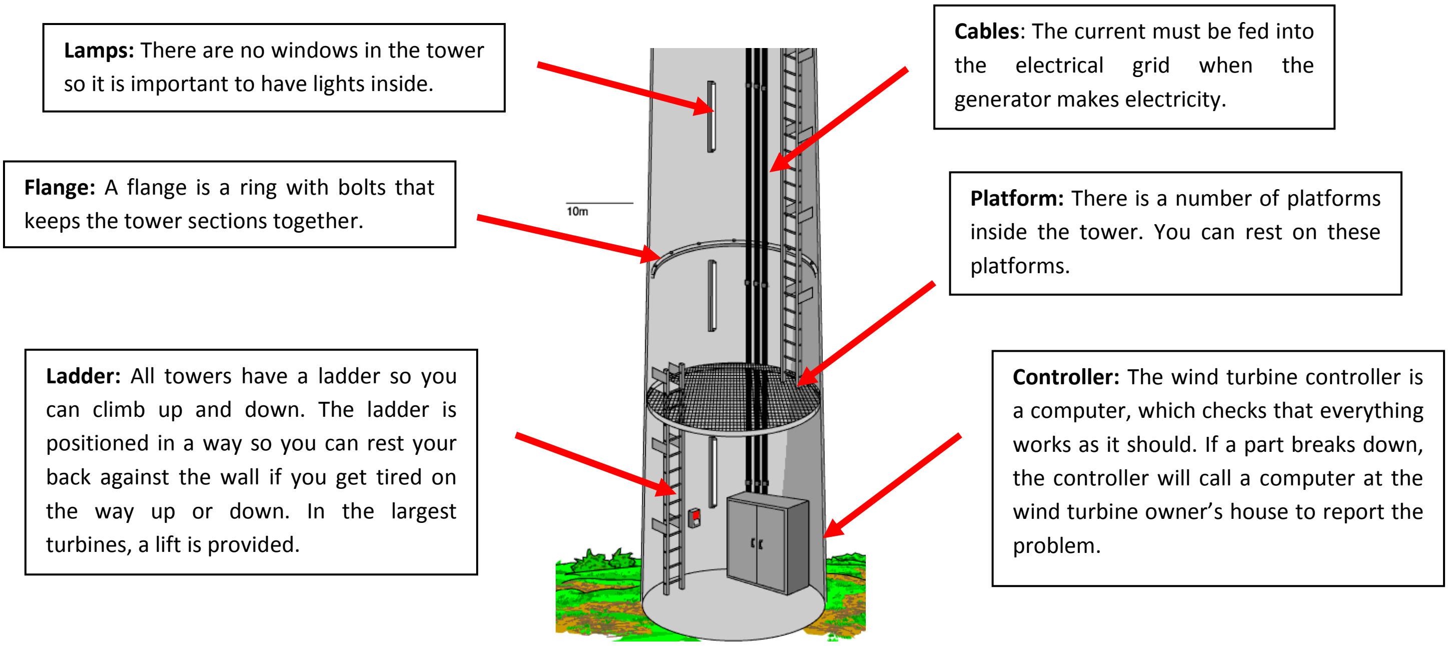


Figure 3.1.8 Inside of the tower of an onshore wind turbine.

In the *figure 3.1.8* above it can be seen the inside of a tower giving each of its parts and its explanation.

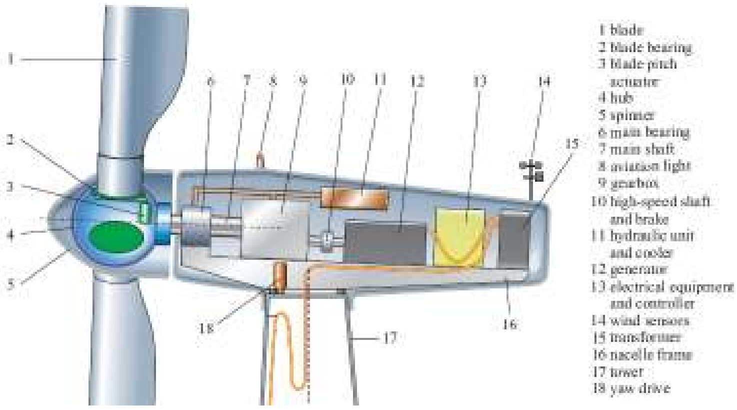


Figure 3.1.9 Different parts of a wind turbine.

3.2. Wind turbines

3.2.1. Aerodynamics of wind turbines

The uptake of wind energy is produced by the action of wind on the blades. The aerodynamic principle whereby the blade assembly rotates is similar to what makes airplanes fly. According to this principle, the air will slide along the upper surface of the wing and will move faster than on the lower surface, generating a pressure difference between both sides, and giving rise to a resultant force acting on the profile.

If this force is separated in two directions the following can be obtained:

- The lift force which is perpendicular to the wind direction.
- The drag force, parallel to the wind direction.

Depending on how the blades are mounted towards the wind and the axis of rotation, the force that will produce the torque will be drag or lift. [8]

3.2.2. Classification of wind turbines

Nowadays, there is a wide variety of wind turbine models, different from each other, both for the power provided as from the number of blades or even how they produce electricity (alone or in direct connection with the conventional distribution network). They can be classified, therefore, by different criteria:

I. By the position of the turbine.

a) Vertical axis:

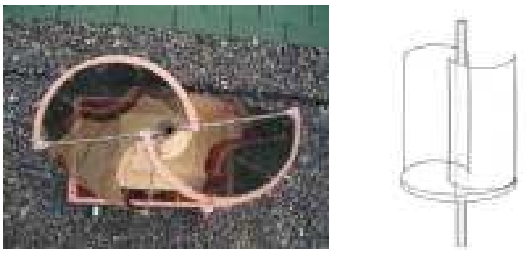
Its main feature is that the rotation axis is perpendicular to the ground. They are also called VAWTs (vertical axis wind turbines). There are three types of these turbines:

Darrieus: They consist of two or three arcs that rotate around the axis (*see figure 3.2.1)*.

Sabonius: Two or more rows of half-cylinders placed in opposite (*see figure 3.2.2 and 3.2.3).*

Panemonas: Four or more semicircles attached to the central axis. The output is low (*see figure 3.2.4).*

Figure 3.2.1 Darrieus



Figures 3.2.2 and 3.2.3 Sabonius
(top and front view)

Figure 3.2.4 Panenomas

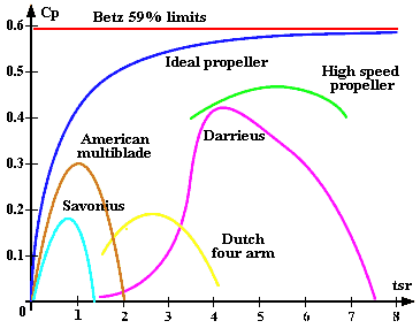


Figure 3.2.5 Efficiencies of different types of turbines

The main advantage of this kind of turbine is the absence of a yaw system. This kind of turbine is less efficient than the horizontal-axis type but its simplification is of interest for small units used in harsh zones like high mountains or the Arctic. The rotor can have high solidity and therefore strong mechanical resistance. In the *figure 3.2.5* above*,* it can be seen the different efficiencies for different types of wind turbines.

b) Horizontal axis:

They are the most common and are also called HAWTs (horizontal axis wind turbines). All grid-connected commercial wind turbines today are built with a propeller-type rotor on a horizontal axis. Therefore, this type of wind turbines will be studied in this thesis.

The purpose of the rotor is to convert the linear motion of the wind into rotational energy that can be used to drive a generator.

II. By the guidance of the equipment to the wind.

a) Upwind machines:

Upwind machines have the rotor facing the wind. The main advantage of upwind designs is that they avoid the wind shade behind the tower. By far most wind turbines have this design.

On the other hand, there is also a wind shade in front of the tower, i.e. the wind starts to deviate from the tower before reaching it, even if the tower is round and smooth. So every time the rotor passes the tower, the wind turbine power drops slightly.

The main disadvantage of upwind designs is that the rotor needs to be fairly inflexible, and be located at a distance from the tower. In addition an upwind machine needs a yaw mechanism to keep the rotor facing the wind.

b) Downwind machines:

Downwind machines have their rotor located on the lee side of the tower. The theoretical advantage is that they can be built without a yaw mechanism, only if the rotor and nacelle have an appropriate design that makes the nacelle passively follow the wind.

However, in large machines this is a somewhat doubtful advantage, since cables are needed to carry the current out of the generator. If the machine has been passively oriented in the same direction for a long period of time and does not have a guidance mechanism, the cables may suffer an excessive torque.

An important aspect is that the rotor can be made more flexible. This is an advantage both in terms of weight and power dynamics of the machine, i.e. the blades will bend at high wind speeds, which will remove part of the load to the tower.

The main drawback is the fluctuation of wind power, due to the passage of the rotor through the shade of the tower. This can create more fatigue loads on the turbine than with an upwind design.

III. By the number of blades.

a) One blade:

Wind turbines with one blade are not very widespread commercially. They have the advantage of saving the cost of two rotor blades and its weight. The problem is that they require a counterweight to be placed on the other side of the hub from the rotor blade in order to balance the rotor. This obviously negates the savings on weight. In addition, they need a higher rotational speed and have the noise and visual intrusion impact.

b) Two blades:

Rotors equipped with two blades must rotate faster than those with three blades and as a consequence, the aerodynamic noise level is higher. A two-bladed rotor is subject to severe imbalance due to wind speed variation with height and to gyroscopic effects when the nacelle is yawed. A way to reduce the corresponding loads is to use teetering hubs with the rotor hinged to the main shaft. Because of these disadvantages, they tend to have a difficulty in penetrating the market. Some of the traditional manufacturers of two-bladed machines have now opted for three-blade designs.

c) Three blades:

Most modern wind turbines are three-bladed designs with the rotor position maintained upwind (as explained before, on the windy side of the tower) using electrical motors in their yaw mechanism. This design is usually called the classical Danish concept, and tends to be a standard against which other concepts are evaluated. The vast majority of the turbines sold in world markets have this design.

d) Multi-bladed turbines:

The rotation speed decreases when the number of blades is increased, but the torque is raised. In low wind areas, these turbines are frequently used in agriculture to drive water pumps.

IV. By the way to adjust the equipment's orientation to the wind direction at all times.

The mechanism of orientation of a wind turbine is used to turn the turbine rotor into the wind. It is said that the turbine has a yaw error if the rotor is not perpendicular to the wind. A yaw error implies that a lower proportion of wind energy will pass through the rotor area (this ratio will decrease with the cosine of the yaw error). Therefore, the efficiency of the orientation mechanism is fundamental to maintain the installation's efficiency. There are several systems that will be briefly explained in this point:

a) By taper:

Those which use the yaw motor to position the nacelle at any moment, depending on which direction the wind blows.

An electric motor and some series of gears allow the rotation of the entire system. The *figure 3.2.6* below shows the yaw mechanism of a typical 750 kW machine. In the outermost part it can be noticed the yaw bearing, and inside the wheels of the orientation engines and the brakes of the guidance system.

Figure 3.2.6 Yaw mechanism of a typical 750 kW machine.

b) By a wind vane:

Using a wind vane is the simplest way possible to guide a wind turbine. They use a kind of flap in the front of the nacelle; the wind hits it, and moves all the equipment. This method is only suitable in small teams of little weight (*see figure 3.2.7).*

c) By auxiliary mills:

Basically several mills are built in different sides of the nacelle, so it gets to turn one or the other depending on the wind direction. An example of this type of guidance mechanism, not too used, is shown in *figure 3.2.8.*

Figure 3.2.7 Wind vane method

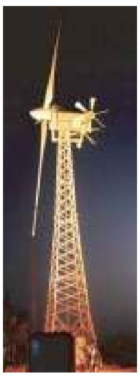


Figure 3.2.8 Auxiliary mills

V. By the power control:

All wind turbines must have a way to control the power generated in order to avoid damage of the different components of such equipment in case of excessive winds. Recall that wind energy increases with the cube of its speed. Therefore, a series of devices that perform exactly this task have been developed. Basically they can be classified into:

a) Pitch control:

A pitch controlled wind turbine consists on the blades varying their angle of incidence to the wind. When the turbine's electronic controller checks that the power output is excessive, the blades begin to rotate about their longitudinal axis (to pitch) into a position called flag.

Then, the resistance opposed to the wind is minimal as so the torque and power generated.

The electronic system monitors both the speed of the wind and the power generated as well as the position of the blades, continuously modifying and adapting it to the intensity of the prevailing winds at that time.

Designing a pitch controlled wind turbine requires some clever engineering to ensure that the rotor blades pitch (turn) exactly the amount required. The pitch mechanism is usually operated using hydraulics.

The advantages of this control system are:

- With its implementation it is achieved a longer life for the turbine due to supporting this under dynamics loads.
- At the same time a higher efficiency can be achieved as the wind always strikes the blades with the optimal angle of incidence.
- It is also possible to take advantage of lower winds regimens.

b) Stall control:

The rotor blades of a (passive) stall controlled wind turbine are bolted onto the hub at a fixed angle. The geometry of the rotor blade profile has been aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind. This stall prevents the lifting force of the rotor blade from acting on the rotor. While the wind speed in the area increases, the angle of attack will increase too, until it begins to lose lift.

If you look closely at a rotor blade for a stall controlled wind turbine you will notice that the blade is twisted slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value.

The basic advantage of this regulation is that it avoids moving parts in the rotor itself, and a complex control system. On the other hand, stall control represents a very complex aerodynamic problem, and related design challenges in the structural dynamics of the whole turbine to prevent the vibrations caused by the stall.

Around two thirds of the wind turbines currently being installed in the world are stall controlled machines. [3]

c) Active stall control:

An increasing number of larger wind turbines (1MW and up) are being developed with an active stall power control mechanism. Technically active stall machines are similar to pitch controlled machines, since they have pitch able blades (they often use only a few fixed steps depending upon the wind speed).

However, when the machine reaches its rated power, it can be noticed an important difference from the pitch controlled machines. If the generator is about to be overloaded, the machine will pitch its blades in the opposite direction from what a pitch controlled machine does. In other words, it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind.

One of the advantages of an active stall is that one can control the power output more accurately than with a passive one. Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds. The pitch mechanism is usually operated using hydraulics or electric stepper motors.

d) Other power control methods:

Some older wind turbine use ailerons (flaps) to control the power of the rotor, just like aircraft. Another theoretical possibility is to yaw the rotor partly out of the wind to decrease power. In practice, this technique is used for very tiny wind turbines.

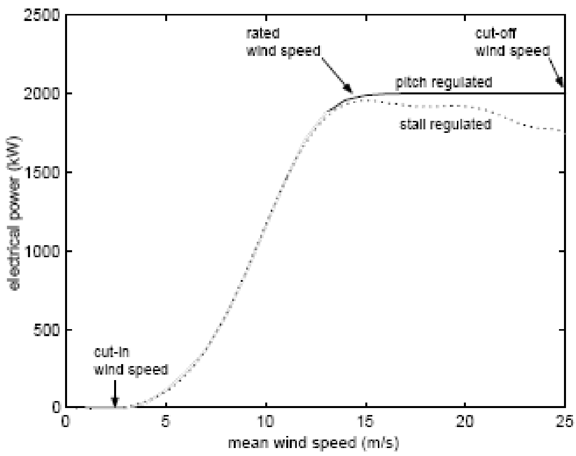


Figure 3.2.9 Power curves of a pitch regulated and stall regulated wind turbine.

3.3. Wind turbine generators

The wind turbine generator converts mechanical energy into electrical energy. It is different compared to other generating units attached to the electrical grid because it has to work with a power source (the wind turbine rotor) which supplies very fluctuating mechanical power (torque). The wind turbine generator efficiency amounts between 90% and 98%.

On large wind turbines (above 100-150 kW) the voltage generated by the turbine is usually 690 V 3-phase alternating current (AC). The current is sent through a transformer next to the wind turbine (or inside the tower) to raise the voltage to 10.000-30.000 volts, depending on the standard in the local electrical grid. Manufacturers supply both 50 Hz wind turbine models for the electrical grids in most of the world and 60 Hz models for the electrical grid in America.

There are two types of generators (asynchronous and synchronous) which are used for wind turbines and will be explained below.

<u>Cooling system:</u>

Generators need cooling while they work. On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for air cooling. There are also manufacturers which use water cooled generators. Water cooled generators may be built more compactly, which also gives some electrical efficiency advantages, on the contrary they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

Grid connection:

Direct grid connection: This means that the generator is connected directly to the (usually 3-phase) alternating current grid (AC). Most wind turbines run at almost constant speed with direct grid connection. The speed of the generator and the rotor is given by the grid. Therefore the rotor cannot always work with the optimal aerodynamic efficiency unless the rotor blade can be mechanically controlled. Another possibility is a generator with a pole switching system. This allows operation under reduced speed and a better adaptation of the current on the rotor during low wind speeds.

Indirect grid connection: This means that the current from the turbine passes through a series of electric devices which adjust the current to match that of the grid. With an asynchronous generator this occurs automatically. With this connection, the wind turbine generator runs on its own, separate mini alternating current (AC) grid. This grid is controlled electronically (using an inverter), so that the frequency of the alternating current in the stator of the generator may be varied. In this way it is possible to run the turbine at a variable rotational speed. The turbine will generate alternating current at exactly the variable frequency applied to the stator.

The AC current is converted into direct current (DC) by using thyristors or large power transistors. The fluctuating DC is converted to AC with exactly the same frequency as the public electrical grid. This AC is not smooth and the waves can be smoothed out by using inductances and capacitors in a so-called AC filter mechanism. This process can be seen in *figure 3.3.1.*

Some disadvantages of the indirect grid connection are that it is costly, it seems that availability rates tend to be somewhat lower than conventional machines and that the power electronics may induce harmonic distortion.

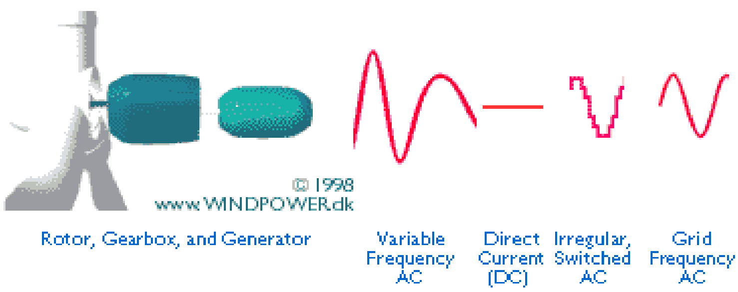


Figure 3.3.1 Indirect grid connection.

Asynchronous (induction) generators:

These machines are basically three-phase induction motors. They are characterized by a synchronous speed, determined by the number of poles of the rotor and the grid frequency. With a 50 Hz grid and a generator manufactured with two pairs of poles on the rotor, the synchronous speed is 1.500 rpm. If the mechanical torque on the shaft forces the machine to rotate faster, electrical energy is delivered to the grid by the generator. The difference between the actual rotating speed and the synchronous speed is called the slip. In conventional asynchronous generators equipped with a squirrel cage induction rotor, the slip is about 1%, so these generators are considered constant speed machines. The magnetizing current for the stator is provided by the grid itself. During start up, the stator is connected to the grid by a soft starter which limits the initial current. The generator consumes some reactive power which must be compensated for by on-board capacitor banks. When a wind gust hits the turbine, the energy output fluctuates and if the short-circuit power of the local grid is low this may result in rapid changes of the power of electrical appliances connected in the vicinity, for instance electric light bulbs. This light fluctuation, or flicker, is particularly unpleasant and has pushed research towards variable speed systems. One solution is to use a coiled rotor supplied with a separate alternating current elaborated by an electronic frequency converter. The synchronous speed is therefore a function of the difference between the grid frequency and the rotor current frequency. [9]

Synchronous generators:

The rotor is made up of a discrete number of electromagnets, or permanent magnets. The frequency of the current produced by this kind of generator is directly proportional to the rotation speed. Directly connected to the grid, such a generator rotates at a fixed speed, with no slip at all. In order to allow variable speed mode of operation, the solution is to convert the generator's variable frequency current into direct current via an electronic rectifier, and to transform the direct current back into alternating current suitable for the grid. All direct-drive generators operate according to this principle. This type of generator is more expensive than the asynchronous one, but the absence of gearbox eliminates a source of maintenance problems and reduces the overall amount of turbine noise. In order to develop the electrical power required, these generators are built with a large diameter. Some turbine manufacturers propose a hybrid solution, with a generator rotating at an intermediate velocity and a gearbox with a limited speed multiplication ratio. Some of the disadvantages of using synchronous generator are that the magnet which is necessary for synchronization is expensive and tends to become demagnetized by working in the powerful magnetic fields inside a generator.

Pole number	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

Table 3.3.2 Synchronous generator speeds (rpm).

In the *table 3.3.2* above it can be seen the different speeds depending on the number of poles and the grid frequency. Although it is written synchronous generator, it refers to the speed of the generator when it is running synchronously with the grid frequency. It is applied to all sorts of generators, but in the case of asynchronous generators it is equivalent to the idle speed of the generator.

3.4. Economics

Offshore projects require initially higher investments than onshore due to turbine support structures and grid connection. The cost of grid connection to the shore is typically around 25% a much higher fraction than for connection of onshore projects. Other sources of additional cost include foundations (up to 30%), operation and maintenance (with expected lower availability) and marinisation of turbines. The next *figure 3.4.1* shows a possible distribution of the capital investment costs. However, water depth and distance to shore can have a significant impact on redistributing the costs. Note that the O&M costs are excluded and these will probably amount to around a quarter of the Levelized Production Cost (LPC). The similar magnitudes of cost for several different components (wind-turbine, support structure, power collection and transmission and O&M) emphasize the importance of an integrated approach to the design of the whole wind farm development.

Investments costs have been reduced from about 2200€/kW for the first Danish offshore wind farms to an estimated cost of 1650€/kW for Horns Rev (equivalent to 4.9€c/kWh). This compares with typical figures for onshore sites of investment 700-1000€/kW and estimated energy cost of 3-8€c/kWh for a mean wind speed of 5-10m/s.

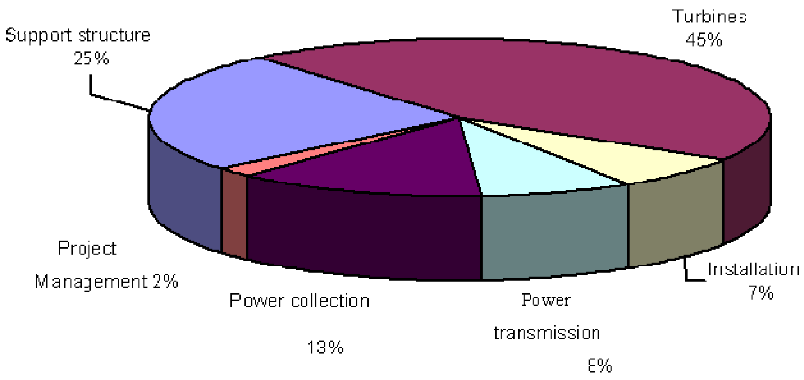


Figure 3.4.1 Typical distribution of costs for offshore wind farm.

Financing: From the current developments of proof offshore projects of various sizes, it would appear that sufficient equity capital is available for financing offshore wind farm projects. Some major oil & gas companies and utilities have announced projects, which could be financed by company equity. However it is still to be determined under which conditions (due to diligence, certification, insurance etc) bank loans will be granted for offshore wind farm projects. Only tests and demonstration projects will provide information to allow an answer to this question. At least they will reduce the present uncertainties related to cost of energy generated. Important support comes from a variety of national incentive mechanisms, such as investment subsidies, tax exemptions, fixed tariffs and green certificate schemes. The distribution of the investment costs for an onshore wind farm show a much heavier focus on the wind turbine as illustrated by a typical example in *figure 3.4.2.*

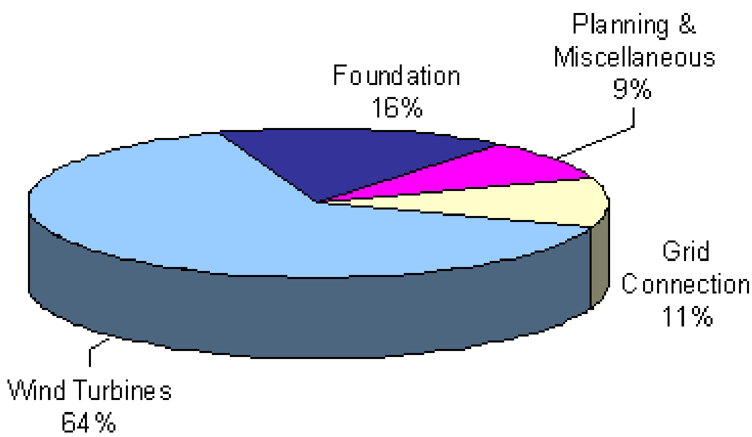


Figure 3.4.2 Typical distribution of costs for onshore wind farm.

CHAPTER 4: Technology offshore

4.1. Change of sitting: from onshore to offshore

The use of wind power in the open sea offers numerous opportunities, in order to achieve ambitious climatic and energy political objectives. Offshore projects are therefore considered to be the important future market for wind power. The wind speeds at sea are higher and more constant than those on land. This is due to the fact that the sea has a limited surface roughness and obstacles to the wind are few. Another advantage of offshore is that the period of useful work of a wind turbine increases as the wind is usually less turbulent. The low turbulence at sea is primarily due to the fact that temperature variations between different altitudes in the atmosphere above the sea are smaller than above land. Sunlight will penetrate several metres below the sea surface, whereas on land the radiation from the sun only heats the uppermost layer of the soil, which thus becomes much warmer. Consequently the temperature difference between the surface and the air will be smaller above sea than above land.

On the other hand, the planning of wind farms offshore is a great technical challenge: the wind turbines must be designed for use in the open sea and the foundations must be adapted to cope with great depths and waves. Last but not least, the long cable connection must also be laid at the bottom of the ocean.

Some of these issues are going to be described in this chapter.

4.1.1. Icing

There are two important issues related to wind turbines performances in offshore sites located in cold climates: sea ice (flows, driving ice, and land-fast ice) and the presence of atmospheric icing (due to water in the air as in-cloud operation, rainfall and sea sprays) which may potentially lead to ice formation on turbines' structures. Icing of rotor blades and some other wind turbine components have effect on the design of turbines, the safety of O&M (Operations & Maintenance) personnel and the overall economics of a wind energy project. In offshore conditions ice pack or floating blocks on the sea surface cause additional static and dynamic forces on the turbine structure. The effects of sea ice occur as a mechanical shock and increased vibrations that may result in additional operational loads. The presence of sea spray, associated with atmospheric icing, determines complex icing phenomena that are highly dependent on the elevation of the turbine rotor over the sea level and on the size and type of wind turbine. Therefore a risk analysis needs to be performed to assess the life reduction and the hazard of ice shedding. Ice mitigation systems should comprise cold weather packages, anti-icing/de-icing devices and systems reducing the actions of sea ice. The design of such systems should be integrated in the design of the turbine to assess the economic benefit of their operation in cold and to set limits for continuous operation during icing periods.

At sites having ambient temperature below zero Celsius degrees and humid environment for large periods of the year, icing will represent an important threat to the durability of wind turbines for two main reasons: the effect of icing on structures (atmospheric and sea sprays) and the mechanical actions of sea ice (sea ice and glacial ice).

Icing of wind turbine affects three different aspects: the design (aerodynamics, load, control system, material), the safety (ice throw, unbalance, over power, fatigue), and the cost-effectiveness (annual energy output expectations, wind measurements, design life duration, wind turbine equipment). Icing also affects wind sensors, both in resource estimation and controlling the turbine. The experience on inshore sites teaches that heavy icing can result in a total stop of the turbine and that the ice can last considerably longer on the blades than the time at which icing conditions occur. As a consequence at harsh sites annual power loss may grow up to 20-50%. [10,11,12,13]

In detail, ice can cause:

- Inefficient or inoperative wind measuring equipments (both during wind assessment and turbine operating phase).
- Rapid performance degradation.
- Increased noise level.
- Increased fatigue on wind turbine and foundations.
- Down time due to excessive vibrations.
- Risk of ice throw (maintenance personnel and near structures safety).
- Additional troubles (site accessibility, site data communication).
- Limited length of “weather window” during project installation.
- Possibly more complicated building permission granting process.

Moreover, at sites with high probability of icing (e.g. several weeks per year) systems that ensure the operation of turbines are needed in order to avoid long stoppages during icing weather events. Many sites in northern Europe offer wind speeds during the icing season which are relatively high, so that long down times due to iced rotor blades may cause severe production losses. An active or passive de-icing or anti-icing systems for the rotor blades is then recommended. [14,15]

De-icing and anti-icing systems are still under development and have been tested on prototypes or small serial production lines. Blades heating systems are used in Finland, Sweden and Switzerland. [10,12] Despite these advancements, only little experience with anti-icing and de-icing systems is available, compared to the large number of turbines that are erected worldwide.

Passive systems such as black coloured coated blades have not offered a solution to the ice problem up to now and in addition may induce large blade thermal stress during hot summer periods. [14]

Active methods that have been developed at least to a prototype stage are based on thermal systems that remove the ice by applying heat to the blade. Thermal anti-icing systems are at the moment the most used systems to face moderate icing. The selection of these systems shall be based on the consistent evaluation of the heat fluxes that the blades exchange with the environment during icing events. There is also the electrical ice protection system, which is based on electrical heating elements, and a heating system that is based on hot air circulation inside the blade structure.

Ice throw risk in a form of ice shedding may pose a major safety hazard in certain environments. This may affect the safe operations of the turbines in wind parks because of the possibility of being hit and damaged by ice pieces. Operator personnel during turbine maintenance could be also seriously injured by ice throw. [16,17]

The ice sheet interacting with the turbine structure produces a wide range of deformation states, each generating different reactions on the structure. [18] Static loads are induced by a stationary contact of the ice with the turbine tower, and the surface forces arise from loads applied by a combination of winds, currents drags and thermal expansion, which slowly push the ice cover against the structure.

Dynamic loadings arise from pieces of floating ice or even ice fields which can cover several square kilometres, hitting against the structure with appreciable velocity (even higher than 1 m/s). The duration and the forces exchanged with the tower depend on the kinetic energy of the ice and on its features. The ice contact area is an important parameter to determine the foundation sliding resistance, foundation shear bearing capacity and overturning moment at the seabed of a wind structure. Such loads need to be estimated in order to evaluate the total load to be sustained and in the design of the internal structure members.

Static and dynamic loads cause different response of the structure. Therefore the prevailing sea ice conditions and icing mechanism should be known in advance to properly design the type of foundation.

Floating and pack ice on the water surface and atmospheric icing induce the wind turbine to excessive vibrations. Ice drift and hitting against the foundation might trigger structural vibrations or even damage it by exciting the tower, while structures' icing will excite flap wise on the blades but the main effect is felt on the tower. [19]

Sea ice accumulation on the tower could possibly modify the tower weight and aerodynamic, thus modifying loads on foundations. Moreover, the ice accumulation could accelerate the corrosion speed process of the tower and support structure if current offshore corrosion protection systems are not adopted. [20]

Not last, a general problem for operation and maintenance has to be considered. Where the sea freezes over completely, the access for maintenance purposes may be often completely impossible for periods of up to several months. [21] This is likely to influence the estimates of the offshore energy output.

It is clear from these considerations that cold climates sites in open seas require to consider ice formation a basic factor for site analysis. Ice prevention systems on blades, accurate sealing, loads mitigation systems for sea ice, cold weather packages, and diagnostic tools integrated to account for ice loads effects will be a sensible part of investment and operating costs. Accurate tools for ice risk assessing are thus necessary and the impact on current design ascertained. It is felt that safety matters will also become a crucial theme for those sites, and certification plans such as regulatory compliance demonstrations for systems against ice will be a mandatory issue in a near future.

Figure 4.1.1 Wind Turbine at Aapua-fjell Sweden.
Photo by Kent Larsson, ABvee.

4.1.2. Environmental load of the waves and currents

Waves induce vortices of water particles, which generate drag forces on obstacles. In addition, a fluid moving horizontally also generates pressures over obstacles. This is why engineers and researchers have developed a new radar system, called *Doppler*, which allows studying further the behavior of waves and their impact on marine structures. This will get a more accurate estimate on the environmental and technical risks of wind farms deployed in the sea.

The analysis of changes in the ocean waves is also of great interest to other scientific and technical purposes, as the observations of bird migration, the measurement of the frequencies of light at sea and the safety of offshore oil platforms, among other applications.

Frequencies caused by large waves are of particular interest to engineers turned to developing wind power plants or oil platforms at sea. For example, each rotor used in wind plants creates air currents and movements in the sea, which may have different effects on the structures and the natural environment. This can lead to vibrations unwanted or even dangerous for the infrastructure provided in the maritime environment. If there is an interaction between the waves and wind farm power plant, can cause different kinds of vibrations.

For example, these interferences can produce huge waves in the vicinity of the plant, which could have a devastating effect on the infrastructure created. With the radar developed, it will be possible to better assess the behaviour of the sea and the force of the waves.

Figure 4.1.2. FINO3 platform, where the new radar is.
[Image Bastian Barton / FH kiel]

4.1.3. Accessibility

Icing and snow drifts can make vehicle access difficult or impossible without snowmobiles or other over snow transport. Access roads are likely to face seasonal restrictions because of ice; snow drifts, and even avalanches during the winter and possibly swampy conditions or flooding during the spring and summer. Storm frequency and avalanche dangers should be assessed, to plan for possible use of snow ploughs or specialized equipment such as snow machines, tracked snow vehicles, and possibly even helicopters. Roads need to be marked with poles that will protrude above snowdrifts for snow ploughs and other vehicles. Flood frequencies and high stream levels caused by snow melt and soil type must also be studied to design adequate road surfaces, culverts, fords, and bridges that will keep the site accessible during the spring and summer. A power supply will be required to fuel the generators. Turbines should be selected according to site accessibility, taking into account road and bridge limitations for heavy cranes and trucks. The logistics of turbine installation must be planned according to seasonal and climatic limitations, and special care may be required to avoid damage to equipment during transportation.

The fact of working at sea presents another problem: where to assemble the whole group. In some cases, it has been preferred to assemble the wind turbine on the coast and later on transport it to the site where it will be installed. In others, it has been preferred to transport the items separately and mounting them directly on the site. The first solution may have better advantages in the reduction of operations at sea (especially complex with large wind turbines), but this selection should be made case by case taking into account the resources (cranes and ships) that are available. *Figure 4.1.3* shows the phases of the transport of wind turbines for the Horns Rev site (in this case it has been chosen to transport the whole wind turbine assembled) and Beatrice (where the turbine is carried in separate parts and the assemblage will be made in the same site).

Figure 4.1.3 Transport of the turbine Horns Rev (left) and Beatrice (right).

4.1.4. Public safety

Ice on turbine blades and tower can pose a safety risk for the general public depending on the site being considered. The fact that no serious accidents caused by ice throw have reported is no reason to think otherwise. Special technical solutions may have to be implemented to prevent accidents associated with the use of turbines in cold climates. Additionally, an assessment should be made of legal protection to limit the risks associated with wind applications at specific sites.

Turbine operation with iced blades may not be permitted in certain countries or permitted only in the case of rime ice, as glaze ice is considered more dangerous. However, rime ice can be almost as dense as glaze ice, so there is no obvious reason to make such an exception. As visibility can be very poor under active icing conditions, warning signs should be closely spaced.

4.1.5. Corrosion

The problems of offshore corrosion are far greater than with similar onshore projects, due to the aggressive marine surroundings. These problems have been reflected in the high cost of offshore maintenance. Regular offshore maintenance is always planned, but unplanned maintenance brought about by premature failure of the coating system can be both costly and potentially hazardous.

Metal corrosion in a marine environment is of electronic type (sea water tends to strike the electrons in the material surface rusting them) and is a process which is strongly influenced by several factors including: the type and quantity of salt, oxygen concentration, temperature and type of environment. Typical values of corrosion of uncoated steel are 0.05 to 0.07 mm/year in atmospheric air and 0.03 to 0.09 mm/year in water. [22] It is not possible to reach the level of "zero corrosion" to a surface, but it is possible to obtain a very low value taking appropriate constructive solutions.

All parts in contact with the outside environment must have sufficient surface protection. This means that painting with for example epoxy coating is not enough. It can be used only on very large and flat surfaces where the coat thickness is well controlled. The alternatives to painting as surface protection are electro-zinc coating or protection with some petroleum based agent. Another way to avoid harmful corrosion is to choose a non-corrosive material. Stainless steel, bronze and plastic materials are examples of this. The welded bed plate will be electro-zinc plated. This is a cost effective procedure compared to painting and gives a lesser inspection requirements of the result. All outside non-load carrying equipment like rail, ladders, screws, masts etc. should be of non-corrosive quality. The quality level should be set with the objective to protect all parts of the turbine from corrosion during at least 10 years. Structural parts like the hub and bed plate should have a life time resistance to corrosion.

A minimum temperature and a dry environment inside the nacelle will be achieved with a combined heating and dehumidifying system. To have a minimum temperature of 15ºC will give protection to the electronics used and will reduce the requirements on the separate oil warming system for oil tanks. External air is taken into the nacelle through filters and is then dehumidified and heated with two parallel working units. Two smaller units instead of one increases the mean time between failures for the total heating system and will also give a step function to control the capacity of the system at different ambient temperatures. If a de-icing equipment for the blades is incorporated an extra tempering unit could be used to pump heated air into the blades which will then have an exhaust valve at the blade tips.

Generally it is easier to heat up than to cool down the interior of a wind turbine. As there is no separate cooling system installed, the ambient temperature is the minimum achievable temperature level. For an offshore station this may be also a problem as the outside air may contain vapor and salt. The gearbox oil is cooled through an oil-to-air-cooler placed outside the nacelle. The generator and the transformer have their separate cooling systems through air intakes in the rear of the nacelle. Both these ventilation systems are separated from the nacelle environment. The wind vane and the anemometer will be warmed up with electric wire heating at low temperatures. The wind logging equipment is also doubled for higher availability. [23]

To decrease the risk of corrosion and salt contamination a closed nacelle compartment will be designed. This is achieved through a pressurized interior. The fans will press outside air into the nacelle and the leakage to the outside is minimized, to achieve an over-pressure.

4.1.6. Protection of the slag

Ocean currents and waves, with their movement, determine the erosion of the upper strata of the seabed which is in contact with the foundation. The current, finding the support, varies its trajectory and generates vortices that tend to raise the upper strata of the seabed and take them with it. In practice, it is verified the weakening of the land, i.e. it removes the ground near the base. It comes as amended the interaction between support and fund critical for correct sizing on the foundation and then support the turbine. In order to safeguard the structure of this situation it is required a deeper immersion of the foundation in the seabed. Alternatively, it can be used a wide range of natural stones (with dimensions of 0,3 to 0,6 m) around the support in mode to create a protective layer. This type of protection is much appreciated; this is why it has become the preferred solution for manufacturers, despite the high costs involved in its implementation, especially in relation to its placing.

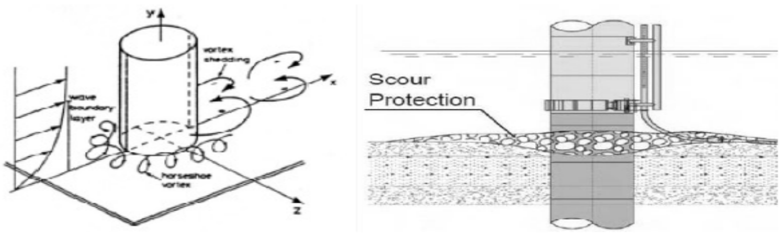


Figure 4.1.4 Generation of vortices and scour protection.

4.1.7. Grid connection and farm layout options

Previous studies have shown that an economic offshore wind farm should be large, particularly due to consideration of the grid connection. The exact size is hard to specify, but somewhere in the region of 60-300 MW total power appears reasonable. There is a number of ways to physically arrange the large number of individual machines required for such installations. The layout chosen will influence both the aerodynamic efficiency of the whole farm, and the cost of wiring the individual turbines together.

In order to provide useful electricity, an offshore wind energy converter system (OWECS) must be connected to a land based power grid. This connection comprises two parts: firstly the individual turbines must be wired together to ‘collect’ the power and secondly one or more cables must run between the offshore site and a public electricity grid onshore (the power transmission). The choice of power collection scheme, however, is closely linked with to the array layout, which is why the two superficially disparate features are considered together in this section.[23]

- **Grid connection**

The grid connection is considered to be the electrical system that collects the power provided at the turbine connection points, collects the power at the central cluster point(s) and transmits it to the onshore connection point with the public grid.
The power collection consists of:

- Transformers to collection voltage (usually at every turbine).
- Switch gear and circuit breakers.
- Cables or transmission lines inside cluster.

The following components can be distinguished as comprising the power transmission system:

- Transformer to transmission voltage.
- Inverters (if any).
- Switch gears and circuit breakers.
- Transformer to voltage of the public grid (if any).
- Cables or transmission lines.

With regard to connection to the public grid, a distinction should be made between a wind farm, of say 60-300 MW, and one or several wind turbines. Due to the large amount of power involved the wind farm will be connected at a higher voltage level. This is advantageous because in general there are less restrictions in case of a connection at a higher level and more options are available for possible required adaptations (e.g. for reactive power).

Basic options for grid connection

In *figure 4.1.5* the basic options for the grid connection are given; in principle these apply for both offshore as onshore wind farms. All kind of variations of these basic options are possible. No real technical restrictions are foreseen because nowadays electronic components are available for a wide variety of applications and they are modular. The main choice which has to be made is between an AC or DC connection to shore. Also for the power collection there is a choice between AC and DC. The first 2 options, A1 and A2, are the ones commonly used for onshore farms. Also an onshore farm exists with the layout according to option B. Option C, AC coupling of all wind turbines together with a DC connection to shore ('AC island'), may cause technical problems with respect to achieving stable operation.

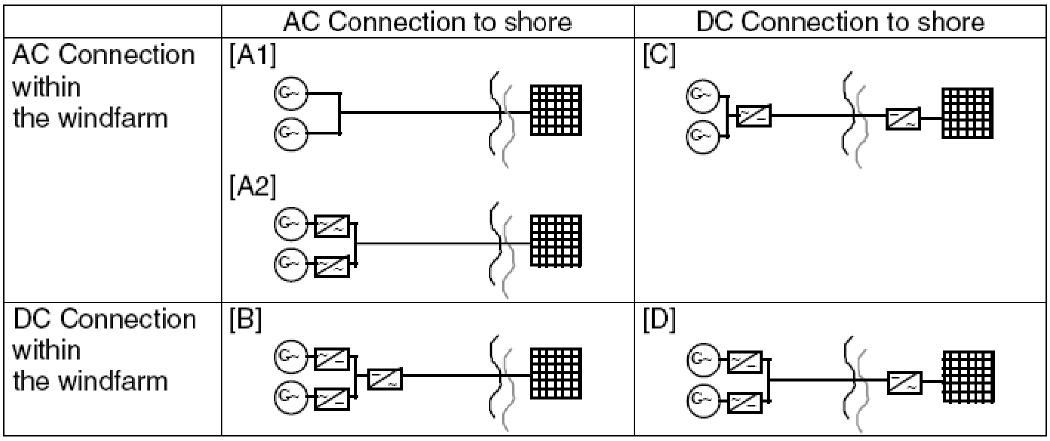


Figure 4.1.5 Basic grid connection options.

Options for components

In the following section the options for the components will be discussed. Although the generator is, in this project, regarded as part of the wind turbine it will be discussed here because of its implications for the grid connection.

The generator types commonly employed in wind turbines are the induction generator and the synchronous generator. The advantage of the induction type is its simplicity and corresponding low cost, but it requires reactive power. The synchronous generator, in combination with an AC-DC-AC link, allows for variable speed operation of the wind turbine which results in a higher energy yield (assuming constant lambda operation) and lower fatigue loading. The voltage level of the common generators for megawatt turbines varies from 460 V to 1.2 kV. A higher voltage level can be advantageous in order to reduce the cost of transformation to higher voltages for transmission.
Transformers are used to change the voltage level. A high voltage level is advantageous for power transmission because the losses (due to Ohmic resistance) depend on the square of the current; by increasing voltage level the current is decreased, for the same electrical power.

Several voltage levels can be used within an offshore wind farm. It is possible to employ a transformer for every wind turbine to bring the generator voltage level to the voltage level I. The power of a cluster consisting of a number of wind turbines can be collected and transformed to another voltage level II. The power of all clusters can then be collected at the connection point of the wind farm and prior to transmission to shore, transformed to voltage level III. The number of voltage levels will depend on the total power of the wind farm and on the cost of the transformers. The chosen voltage levels should be in accordance with European standards.

Switch gear, containing a circuit breaker, are necessary to deal with any short circuits. The application of switch gears at each turbine and/or at the collection point(s) must be determined by the requirements, in terms of availability and safety, of the owner of the offshore wind farm.

For the transmission lines one has to consider both the collection inside the farm and the transmission to shore. The options for the collection inside the farm are to use (submarine) cables or overhead lines. The substantial advantage of overhead lines is the relative (very) low costs compared to submarine cables (including laying costs). Perhaps offsetting this economic advantage is that their reliability in a marine climate might not be adequate, and it seems unlikely that overhead lines would be practical for very large turbine spacing. Furthermore, it should be checked whether the lines might present an obstacle during installation and maintenance activities and whether the required large tower height is advantageous in a system consideration.

AC versus DC technology

Transmission can be either AC or DC. AC transmission involves high dielectric losses (the isolation material acts as a capacitor); these losses are proportional to the cable length and the voltage. Three wires are necessary for AC transmission corresponding to the 3 phases. DC transmission requires expensive converters. For short distances AC transmission is the most cost effective option and for large distances DC transmission is preferable. The cross over point depends on the costs of the components involved and can be further investigated. HVDC (High Voltage DC) transmission systems have been increasingly used in recent years to transport electricity from remote energy sources to the distribution grid. At present the maximum capacity is 600 MW. BY 2015 1000 MW is expected to be feasible at approximately the same cable cost per km. Currently used generators operate with AC as well as the public grid. This means that, where an intermediate DC link is used, both AC/DC rectifiers and DC/AC inverters are required. The converter stations consist, amongst other items, of thyristor switches. They have to be placed in series because they can only switch a limited voltage (8kV). With developments in semi-conductor technology, it is expected that the voltage which can be switched by one thyristor will grow gradually. This means lower costs, at equal power, and lower energy losses. As alternative IGBT (insulated gate bipolar transistor) switches can be used which do not need reactive power.

Cluster layout

The design criteria for layout of the cables or lines within a cluster are the costs of the involved components and the reliability. A star connection results in the highest reliability compared to a circuit or chain connection. The higher capital costs for the extra cables for a star connection should be balanced with the higher energy yield.

- **Wind farm layout**

The wind turbines in a farm can be placed regularly in lines (rectangular) or in several sub clusters. A wind turbine which is placed inside the farm (and thus standing in the wake of another wind turbine) will experience a lower mean wind speed and a larger turbulence intensity. The larger turbulence results in larger fatigue loads. Different models exist to predict these wake effects.

In order to limit the power losses, wind turbines in an onshore farm are placed at a distance of 3 to 5 D (rotor diameters) from each other perpendicular to the prevailing wind direction; in the other direction the spacing is 8 to 10 D. For offshore wind farms it may be necessary to have a larger spacing. The reasons for this are threefold. Firstly, equalization between the mean wake velocity and the (unchanged) ambient wind speed outside the wake, needs a longer distance behind the turbine (because of the lower absolute turbulence intensity). Therefore offshore wind farms with the same spacing as onshore wind farms have lower aerodynamic cluster efficiency. Secondly, the relative increase of the turbulence intensity in the wake is larger in an offshore situation. According to the calculated increase of turbulence intensity, in the case of the Vindeby lay-out it is about 100 % (from 7 % above sea to 14 % in the wake); onshore the increase would be about 40 % (from 14 % to 19 %). Another reason to use a larger spacing is that in general the restrictions on the area available to the farm are less for an offshore situation. The lower losses due to a larger spacing should be balanced with the higher costs for the power cables (including laying costs and the power losses along these cables) inside the farm. The soil properties and variation of water depth at some specific sites may be such that the actual farm layout should be different from the ’optimum’ layout. A fourth reason is the overall economics with respect to the levelized production costs. Any OWECS suffers higher investment costs in comparison to an onshore farm, which favours larger turbine spacing. In order to determine the layout of an actual wind farm we should use a wind farm efficiency code in combination with a cost model.

4.2. Environmental and social issues

The most significant drawbacks associated with onshore wind energy, such as land use and amenity, are largely avoided when wind turbines are located offshore. However, this does not mean that offshore wind energy is devoid of any environmental impact.

Many of the minor environmental impacts associated with onshore wind energy may also be relevant offshore. Apart from the environmental impacts of carrying out construction work offshore, many of which are generic to offshore industries such as oil and gas and telecommunications, there are few issues, which are unique to offshore wind energy. One of these is underwater noise and vibration from operating turbines. As with the onshore wind energy, many of the impacts are of a socio-economic rather than truly environmental nature. They include issues such as potential interference with human activities such as fishing and radar.[24]

This part of the thesis is going to deal first with emissions savings and later on negative impacts.

4.2.1. Emissions savings

Numerous utility studies have shown that a unit of wind energy saves a unit of energy generated from coal, gas or oil, depending on the utility's plant. It follows that each unit of electricity generated by wind energy saves emissions of greenhouse gases, pollutants and waste products. The exact amount of emissions saved depends on which fossil plants are displaced by wind energy. In most of Europe this is coal, a situation still likely to continue for a few years. The reason for this is that almost all nuclear plant and combined cycle gas turbines operate at high load factors, to cover base load. This is the minimum load on the system, usually between 20 and 40% of the peak load. At higher loads other plant, mostly coal, are brought on line to cover demand. These plants are sometimes referred to as "load following". As wind energy has priority access to the grid its output contributes to that of the base load plant. The addition of wind therefore has the effect to displacing coal plant and hence the emission savings are those associated with coal plant, currently around 900g/kWh of carbon dioxide, plus oxides of sulphur and nitrogen and other chemicals. The next table (*see table 4.2.1*) shows these emissions; from various types of thermal plants. 10 GW of offshore wind, with a capacity factor of 30% will hence save around 23 million tons of carbon dioxide each year if coal plant is displaced, plus substantial quantities of other harmful pollutants. [25]

Technology	Coal	Oil	Gas
Stack emissions			
Carbon dioxide	830-980	670-750	380-420
Carbon monoxide	0,03-0,14	0,14	0,03
Sulphur dioxide	11-16	1,3-13	0
Nitrogen oxides	0,5-4,5	0,8-3,7	0,35-0,7
Methane	0,01	0,01-0,03	0,11-0,14
Particulates	0,2-0,5	0,4	Low
Waste products			
Ash	58-178	0,1	0
Gypsum	-	25	-

Table 4.2.1 Emissions from thermal plant, in g/kWh of electricity.

The economic savings due to the reduction of these emissions do not presently figure in economic assessments of wind energy. The external costs of fossil fuels sources, associated with the damage the emissions cause, may be difficult to quantify, but they are real. A review of several studies indicated that several assigned the external costs for coal fired generation at around 10€/MWh. [26]

Although the capacity of a gas plant is set to rise, nuclear closures are expected after the turn of the century, so coal is likely to continue to provide the bulk of the load following plant. Emission savings by renewables are therefore unlikely to change markedly, although country-specific analyses will be needed to establish exact numbers.

4.2.2. Environmental impacts of turbine installation

The effects of moving installation equipment to the site, the temporary disturbance of the seabed during construction and cable laying and the disturbance caused by maintenance vessels will all be site specific. These effects are generic to all offshore industries and are well understood and mitigation measures are available in many cases. For example, underwater bubble curtains can be used to prevent sound propagation during pile driving, if necessary. It is important during the site selection and initial scoping stage of the project to identify potential areas of conflict and minimize interference with other activities e.g. shipping, fishing and defense activity.

4.2.3. Turbine installation

A variety of different kinds of foundation can be used as they will be described in the next point 4.3. It is anticipated that gravity foundations require the seabed to be smoothed and covered with a layer of shingle. Monopiles require no sea bed preparation, however they are unsuitable where large boulders are present or the seabed is uneven. As it has been explained before, the cables from wind farms to the shore will mostly be buried, in order to protect them against damage from anchoring and fishing.

The environmental effects of both laying cables and installing foundations include the loss of habitat and possible direct loss of marine life during the installation process. There can also be disturbance from sediment movement and noise. It is important that any chemicals or oils used offshore are safe for the marine environment. It is recommended that any chemical or oils used be registered for use offshore.

4.2.4. Visual impact

The onshore wind energy industry has developed a very sophisticated battery of tools for qualitative and quantitative assessment of visual impact. These include:

- Mapping the zone of the visual influence (ZVI), to show how many turbines are visible from that location and how dominant they appear to be.
- Photo-montage techniques which place computer-generated images of turbines on a photographic image of the landscape.
- Animations, which show moving turbines superimposed on the landscape. A variation of this is the “fly through” technique which allows the viewer to “move” through a proposed development looking at the turbines from various angles.

These tools can be adapted for offshore projects. The accuracy of photomontage and video techniques was tested in a Thermie study on the Tuno Knob wind farm. The photographic techniques were shown to be successful in predicting a technically correct image, provided the scope of the image was not too wide. A wide panorama makes the turbines appear less tall as the viewer tends inadvertently to compare the height of the turbines with the width of the picture. Video methods were found to be unsatisfactory at long distances, due to the low-resolution achieved. [27]

Studies in Netherlands and Germany have shown that the visual impact is very small at a distance of 15 km from the coast. Thus the problem should not exist for plants located far away from the coast and should be accepted by local populations. The park, however, is very visible if placed at a distance of more than 8 km and disappears when the distance is about 45 km due to the curvature of the earth's surface, see *figure 4.2.3.*

Weather conditions must be also considered, such as the presence of fog, further reducing visibility of the wind farm. To reduce the risk of collision with ships or aircraft (the blade of a 3.6 MW turbine reaches a height of 130-140 m), it is intended to colour the blades of the wind turbine with specific colours, and in some cases it is also considered a lighting system of the nacelle. These solutions make the turbine more visible, not only to vessels and aircrafts, but also to the population, therefore the need for the wind farm to be further away from the coast.

Figure 4.2.2 Scroby Sands seen from the beach. The distance is 2.5 km with turbines of 2 MW, 80 m of diameter and the nacelle high is 60 m. As it can be seen in this picture the visual impact is important.

Figure 4.2.3 Graphic simulation of the wind turbine increasing the distance from the coast. It has to be taken into account that at a distance of 10 miles (16.09 km) the visual impactt is very low. Weather must also be considered as the fog and mist could further reduce the visual impact.

4.2.5. Impact on birds

The effects attributable to wind farms are variable and are species-, season- and site-specific. The effects can lead to displacement and exclusion from areas of suitable habitat and loss of their habitat. The scale of such habitat loss, together with the availability of other suitable habitats that can accommodate displaced birds, will influence the impact. There are several reliable studies indicating negative effects up to 600 m from wind turbines, i.e. a reduction in bird use of or absence from the area close to the turbines, for some species (e.g. whooper swan *Cygnus Cygnus,* pink-footed goose *Anser brachyrynchus,* European white-fronted goose *A. albifrons,* Eurasian curlew *Numenius arquata).* [28] Disturbance potentially may arise from increased human activity in the vicinity of the wind farms, e.g. maintenance visits, access facilitation via access roads, presence/noise of turbines. Few studies are conclusive in their findings, often because of a lack of wee-designed studies both before and after construction of the wind farm.

There is some indication that wind turbines may be barriers to bird movement. Instead of flying between the turbines, birds may fly around the outside of the cluster. The cumulative effects of large wind farm installations may be considerable if bird movements are displaced as a consequence. This may lead to disruption of ecological links between feeding, breeding and roosting areas. Wind farm design may alleviate any barrier effect, for example allowing wide corridors between clusters of turbines. Research and post-construction monitoring at several pilot sites will be necessary to determine whether and where this is an acceptable solution.

The wind energy industry is in its infancy offshore and, consequently, there has been little research into the impacts on birds. Nonetheless, there are useful studies underway, especially in The Netherlands and Denmark, again indicating a variable response that is both site- and species-specific. The proposals for large wind farms in shallow sea areas may conflict with the feeding distributions of seabirds, notably sea ducks if these are displaced as a result of disturbance.

Research and monitoring should be implemented by national governments and the wind energy industry, in consultation with relevant experts, to improve the understanding of the impacts of wind farms. This will be an iterative process that will inform decision-making, appropriate site selection and wind farms design.

4.2.6. Impact on marine life

Experience from the Vindeby and Ijsselmeer wind farms suggests they had a positive effect on fish populations. Both these wind farms have concrete gravity based foundations (which will be explained in the following point 4.3), which act as artificial reefs for seabed-dwelling organisms, thus increasing the amount of food available for fish. Monopile foundations will be less effective as artificial reefs and therefore few conclusions can be drawn from the experience of these early projects. Less is known about the effect of underwater noise and vibration marine life. Available information suggests that the underwater noise generated by offshore wind farms will be in the same range of frequencies as existing sources such as shipping vessels, wind and waves. Therefore the noise may merely contribute to the background level of low frequency noise present in the sea. Also it should be noted that the design of an offshore turbine and support structure is driven by the overriding objective of avoiding resonance, therefore vibration should be designed-out as far as possible, in order to prolong machine life. [29]

4.2.7. Effects of electromagnetic fields on fish

With the large scale developments of offshore wind power the number of underwater electric cables is increasing with various technologies applied. A wind farm is associated with different types of cables used for intra turbine, array-to-transformer, and transformer-to-shore transmissions. As the electric currents in submarine cables induce electromagnetic fields there is a concern of how they may influence fish. Studies have shown there are fish species which are magneto-sensitive using geomagnetic field information for the purpose of orientation. This implies that if the geomagnetic field is locally altered it could influence spatial patterns in fish. There are also physiological aspects to consider, especially for species that are less inclined to move as the exposure could be persistent in a particular area. Even though studies have shown that magnetic fields could affect fish, there is at present limited evidence that fish are influenced by the electromagnetic fields that underwater cable from windmills generate. Studies in the Baltic Sea have indicated some minor effects.

4.3. Foundations

The major challenge for offshore wind energy is cutting costs: undersea cabling and foundations have until recently made offshore wind energy an expensive option. New studies of foundation technology, however, plus megawatt-sixed wind turbines are now on the point of making offshore wind energy competitive with onshore sites, at least for shallow water depths up to 15 metres. Since offshore wind turbines generally yield 50 per cent higher output than turbines on nearby onshore sites (on flat land), offshore sitting may be quite attractive.
Even though the technology for offshore is currently based on onshore technology, there are a few important differences between the two. Offshore turbines tend to be much larger. Nowadays, turbines in the 5 to 7,5 MW are being developed. Offshore wind turbines have historically been installed on shorter towers (60 metres), as compared to onshore turbines. Different methods of access are needed for maintenance. Wind turbines tower bases usually have a landing for boat access and may have a helipad for helicopter access. It may be included a space for maintenance crews to take shelter if they are stranded due to changing weather conditions. Towers are designed for hydrodynamic loading from waves and currents in distinction to onshore towers. Offshore wind turbines may employ Condition Monitoring Systems (CMS) to identify electrical and mechanical problems before component failure. This allows the turbine to be serviced when weather conditions permit it, thereby decreasing unplanned outages and increasing availability. Offshore wind turbines may have redundant critical systems such as lubricating oil and cooling to provide higher reliability. Many offshore wind turbines have the generator step-up transformer located in the nacelle, rather than outside and adjacent to the tower. One of the big differences between onshore and offshore is the foundations. Unlike onshore turbines, these foundations will need to withstand loadings that are unique to the marine environment, including the impact of wave energy, ice, and the issue of water currents. All of these loads must be carefully factored into the engineering and planning of these structures. The design problem is not so much the ultimate load capacity of the foundation, but the accumulated deformations that might occur under cycling loading. More analyses must be done to ensure the structural soundness of turbine foundations.

In order to ensure that the operation of wind farms installed at hostile offshore sites will be reliable and cost effective, it is clearly essential that the wind turbines and support structures are designed and optimized taking proper account of the external conditions at the site, with respect to onshore. Over the last twenty years enormous progresses have been made with the development and validation of software tools which offer sophisticated and reliable representations of onshore wind turbines and are in use by the industry for design and certifications calculations. In parallel, there have been major advances in the methods used by the offshore engineering community for the design analysis of conventional offshore structures. Although there are obvious similarities between offshore oil and gas production platforms and offshore wind turbine structures, there are also several important differences. In the context of design calculations, an offshore wind turbine is much more influenced by wind loading and the design loads are considerably more sensitive to structural dynamic characteristics than in the case of oil and gas platforms. In addition, since offshore wind turbines are likely to be installed in relatively shallow water, there is considerable uncertainty in the calculation of hydrodynamic loading, both for fatigue and also extreme loads which may be driven by breaking waves.

In the next *figure 4.3.1* the different parts are indicated in which will be focusing the following pages. This image allows us to get an idea of how are the foundations. But before explaining the different types of foundations that exist it must be taken into account the different parameters that may influence its construction.

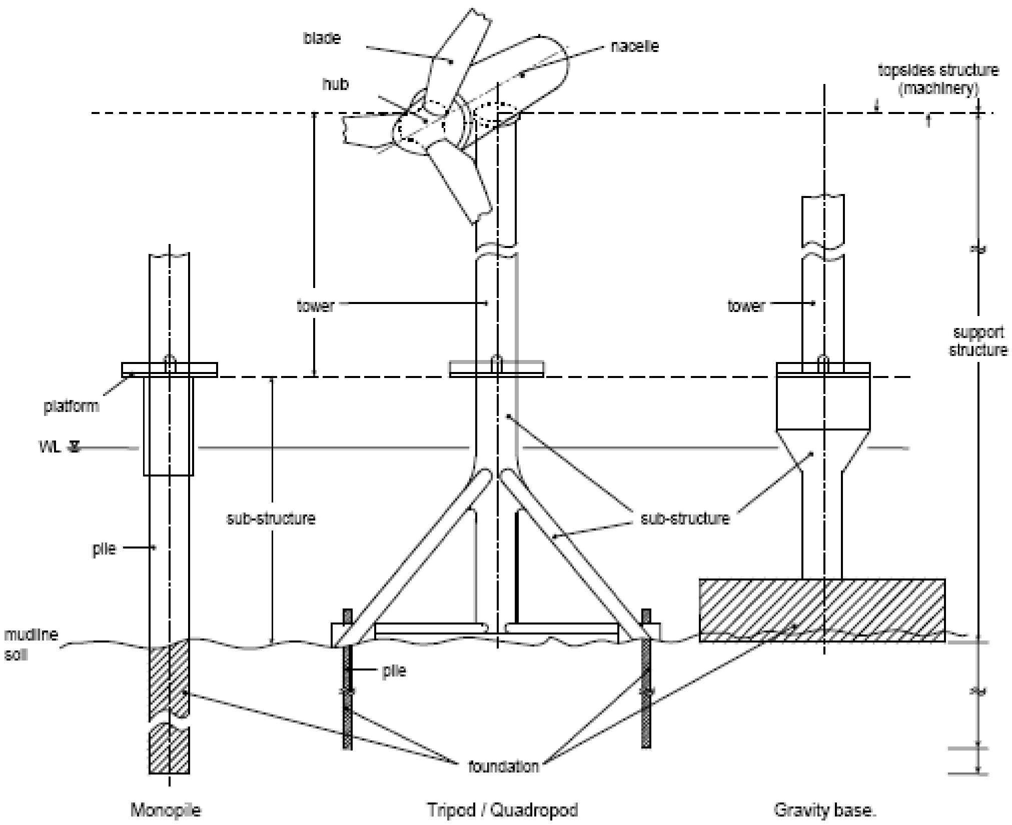


Figure 4.3.1 Typical wind structures and nomenclature.

4.3.1. Environmental loads

The onshore industry has developed a design construction according to the response of the static and dynamic loads. At the same time the offshore industry (e.g. oil platforms) has done the same for conventional marine structures. It is clear that the success of offshore wind technology can't dispense with the study of the interactions between the two main components. The whole system will bear two types of environmental loads: the aerodynamic load, which affects the rotor, nacelle and tower, and the hydrodynamic loads which primarily affect the support.

Ideally it could be used a single model for analyzing the whole system: rotor, nacelle, tower, support and foundation. In many cases this solution can't be used and is preferred to follow a different analysis: it is first studied the aerodynamics response of the rotor, nacelle and tower, while the rest of the system is represented as a boundary condition. Successively it is studied in detail the hydrodynamic response of the foundation and support, considering the aerodynamic response of the emerged part of the structure as an external load.

Some analysis carried out by Garrad (1005) and Kuhn (1998) have shown that seismic effects, possible presence of ice and currents may influence the load, while the type of foundation and high or low tide may condition the elastic response of the structure.

Concluding the two projects, it can be said that some characteristic parameters such as depth, the composition of the foundation and the height of the waves, have a certain influence on the support and therefore each wind farm requires its own design.

4.3.1.1. Wind

Many studies on wind conditions in European seas have been made since the early years of offshore development and thanks to that there are now large amounts of data. A part from the Weibull distribution, it is also known the velocity profile with height and its direction. All these issues were discussed in chapter 2.

4.3.1.2. Waves

The study of marine conditions is the same that was used for the offshore oil industry. The parameters of interest are the wave frequency and its height, which determines the strength and load effect on the structure. The biggest problems occur when the analysis is performed to shallow water where waves can be higher, thus generating higher loads than in normal conditions.

4.3.1.3. Ice

Many of the suitable sites for offshore are in the seas in northern Europe. In these areas it is possible that the installation is subjected to ice formation and this condition involves additional loads on the structure and foundations that should be taken into account during the design of the project.

4.3.1.4. Seafloor features

Generally the seabed can be perfectly horizontal, sloping, slightly tilted or too steep, and more or less fine sand alternating with layers of silt and clay. The consistency of the seabed has influence, for the supports that are oriented in the interior, in the length of support: for a sandy bottom bracket is caught by some 20 metres, whereas for a very rigid seabed might be sufficient for 11 to 12 metres. In both situations described above, different materials are used, and thus have a different cost of the support. For not so deep seabed and with strong currents, there is the possibility of a great movement of slag, and this is another aspect to be considered in the project due to this there may be a source of stress in the foundation. The effects produced by this situation are difficult to deduce a priori and therefore it is necessary to perform simulations. To study the interactions between the seabed and the structure in a column foundations, it is used the method developed by the offshore oil industry.

4.3.1.5. Site specific data

For a generic site it should be provided information relative to:

- Wind speed and direction.
- Wave height, period and direction.
- Correlation between wind and waves.
- Current's velocity and direction.
- Soil depth.
- Possibility of ice formation and its possible effects.
- Temperature and air density, salinity of the water, growth of the tides, etc.
- Composition of the seabed, slag.

In general all this information has to come from measures related to long periods of time. In the event that this information covers only a short period of time, it is needed more information to nearby areas.

4.3.2. The support structures for the wind

The supports are support structures for the wind turbine and ensure its stability. It has been developed several types of foundations and each lends itself to be used in different situations. The research has focused on various foundations: monopile and gravity based support structure (until 30 m, shallow water foundations), tripod tower and three legged jacket for transitional water (until 60 m) and others which will be described below. For deep water, we are still in the process of experimentation with the floating structure (up to 200 m, deep water foundations). The choice of the foundation depends on a number of factors and it is very important due to the fact that it represents a significant portion (20%) of the total of investment cost. Support structures for offshore wind towers can be categorized by their configuration and method of installation as described below. These foundations and associated water depths are shown in *figure 4.3.2.* The typical sizes for offshore foundations and their construction sequence are presented in *table 4.3.3*.

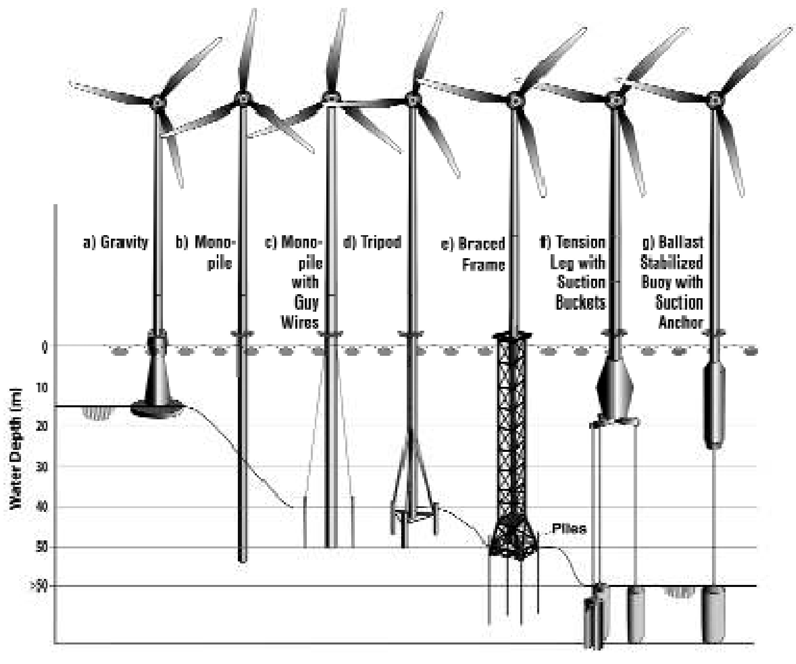


Figure 4.3.2 Foundation types and typical water depths.

Type of foundation	***Size (m)***	***Weight (ton)***	***Typical water depths***	***Construction sequence***
Gravity Base	*12-15*	*500-1000*	*0-15*	(a) Prepare seabed (b) Placement (c) Infill ballast
Monopile	*3-6*	*175-350*	*0-30*	(a) Place pile (b) Drive pile
Monopile with GuyWires	*3-6*	*175-350*	*20-40*	(a) Place pile (b) Drive pile
Tripod	*15-20*	*125-150*	*20-40*	(a) Place frame (b) Insert pile (c) Drive pile
Braced-Frame with multiple piles	*10-15*	*200-400*	*20-50*	(a) Place frame (b) Insert pile (c) Drive pile
Suction Bucket	*10-20*	*150-400*	*0-30*	(a) Place base (b) Suction installation
Tension Leg platform	*10-20*	*100-400*	*>50*	(a) Drive anchor pile or suction bucket (b) Float tension leg platform (c) Install anchor cables

Table 4.3.3 Basic sizing and construction sequencing for offshore wind turbine foundations.

I. Concrete gravity caissons

The first offshore pilot projects in Denmark and also the world, used concrete gravity caisson foundations. As it can be seen by the name, the gravity foundation relies on gravity to keep the turbine in an upright position. The Vindeby and Tunoe Knob offshore wind farms are examples of this traditional foundation technique. The caisson foundations were built in dry docks near the sites using reinforced concrete and were floated to their final destination before being filled with sand and gravel to achieve the necessary weight. The principle is thus much like that of traditional bridge building. The foundations used at these two sites are conical to act as breakers for pack ice. This is so necessary because solid ice is regularly observed in the Baltic Sea and the Kattegat during cold winters. Using traditional concrete foundation techniques the cost of the completed foundations is approximately proportional with the water depth squared (the quadratic rule). The water depths at Vindeby and Tunoe Knob vary from 2,5m to 7,5m. This implies that each concrete foundation has an average weight of some 1.050 metric tons. According to the quadratic rule the concrete platforms tend to become prohibitively heavy and expensive to install at water depths above 10 metres. Therefore, alternative techniques had to be developed in order to break through the cost barrier, as it will be seen below.

II. Gravity based support structures

Most of the existing offshore wind parks use gravitation foundations. A new technology offers a similar method to that of the concrete gravity caisson, explained before. Instead of reinforced concrete it uses a cylindrical steel tube placed on a flat steel box on the sea bed. A steel gravity foundation is considerably lighter than concrete foundations. Although the foundation has to have a weight of around 1000 tons, the steel structure will only weigh some 80 to 100 tons for water depths between 4 and 10 metres. If the structure is in the Baltic Sea, where pack ice protection is required, 10 tons have to be added. The relatively low weight allows barges to transport and install many foundations rapidly, using the same fairly lightweight crane used for the erection of the turbines. The gravity foundations are filled with olivine, a very dense mineral, which gives the foundations sufficient weight to withstand waves and ice pressure. The base of a foundation of this type will be 14 by 14 m (or a diameter of 15 m for a circular base) for water depths from 4 to 10 metres. (This is a calculation based on a wind turbine with a rotor diameter of 65 metres). The advantage of the steel caisson solution is that the foundation can be made onshore, and may be used on all types of seabed although seabed preparations are required. Silt has to be removed and a smooth horizontal bed of shingles has to be prepared by divers before the foundation can be placed on the site. The seabed around the base of the foundation will normally have to be protected against erosion by placing boulders or rocks around the edges of the base. This is also the case for the concrete version of the gravitation foundation. This makes the foundation type relatively costlier in areas with significant erosion. The cost penalty of moving to larger water depths is minimal compared to traditional concrete foundations. The reason is that the foundation base does not have to increase in size proportion to the water depth to lean against ice pressure or waves.

Figure. 4.3.4

III. Monopile

The use of this support is very common in the oil platforms offshore, and has thus achieved a great success for the 160 MW wind farm at Horns Rev. Monopile foundations have been used for offshore turbines in Denmark, the Netherlands and Sweden. The “monopile” concept is based on single piles that are driven into the seabed. Pile driving is a fast process, and piles are relatively inexpensive to produce. The current design philosophy for wind farms in water depths up to 20 m is based on the monopile with the installation methodology – driving, drilling or combination – depending on soil properties, water depth and contractors experience. Monopiles are a relatively compliant structure and hence are more difficult to design; uncertainties in ground conditions for example can result in a structure with a quite different structural frequency than designed for, with all the potential resulting problems of resonance induced dynamic oscillations. The monopile foundation is a fairly simple structure, consisting of several segments of steel and tight stacked one above the other to make a single stack, as shown in *figure 4.3.5*. This configuration provides high density and appears to be little influenced by the effect of slag or the scour effect. [30] Another great advantage is the fact that the installation of this structure does not require the preparation of the seabed. Monopile support gets to be put in the internal seabed, several metres deep, where it is fitted. This condition limits the horizontal movements (thanks to the pressure exerted by the surrounding soil throughout its length) and verticals (due to the friction that is developed along the surface). There are two methods used for the installation of the foundations. The first, driving, consists of putting the support at the selected point and keeping it upright. From the top, with a kind of hydraulic hammer, it is exercised a force pushing down the structure, digging in the area of the chosen measure. This method is quite simple, but obviously can only be taken if in the presence of sandy bottoms, otherwise it would be very difficult to penetrate the support on the seabed (think of a rocky bottom) and there may be risk of damaging the structure. The second method involves the drilling of the seabed, in order to make a hole where the support will be put. First, it is placed in the bottom of a hollow steel cylinder which serves to drive the auger and to contain the waste coming from the excavation (300-400 m^3 of material recovery), after this it comes the phase of the perforation. When the excavation reaches the desired depth, the auger is removed and the added support, filling the space between it and the excavation of cement. In the case of drilling, the bottom is rocky and the support is stuck at a lower depth than in the driving method, in which the seabed is sandy. Once the foundation is positioned, we proceed with the installation of the scour protection by a crane placed rocks around, controlling this process by sonar. The rocks can be transported from the coast with the use of large barges, and in some cases they stones of the drilling can be reused. Once it is placed the support and the scour protection, the installation of the wind turbine is next. The connection between the support and the tower of the turbine is produced by locking through a transition component which at the top presents a suitable platform to facilitate access to the structure (*see figure 4.3.6)*. Besides connecting the base with the tower, the transition element allows to adjust the inclination of the wind turbine in the case that the support is not perfectly placed. Once the tower is set, it is proceeded to install the nacelle, lift with a crane.

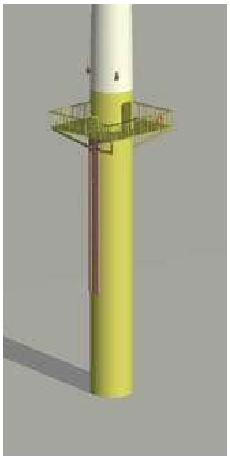


Figure 4.3.5 Monopile foundations

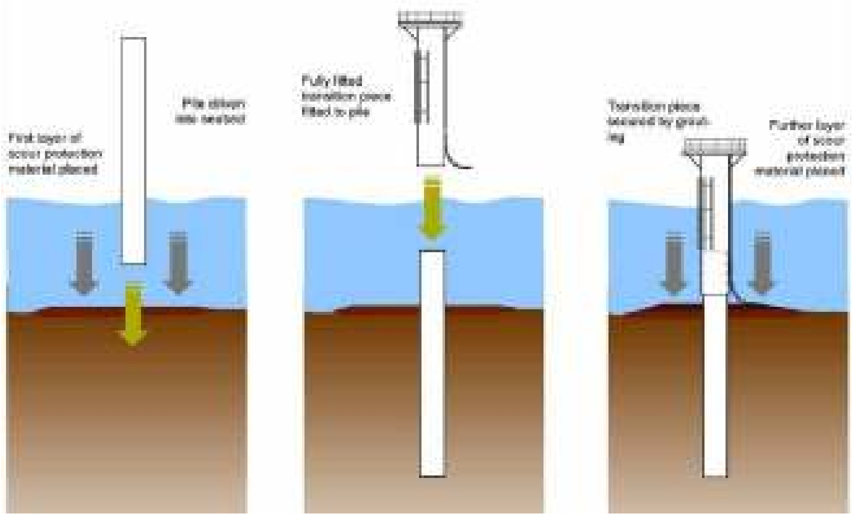
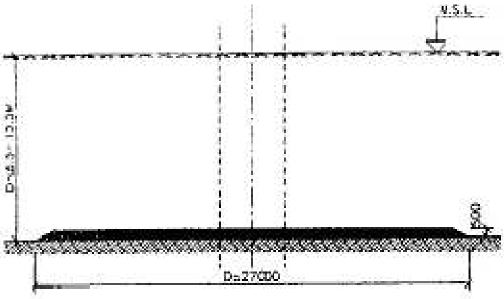
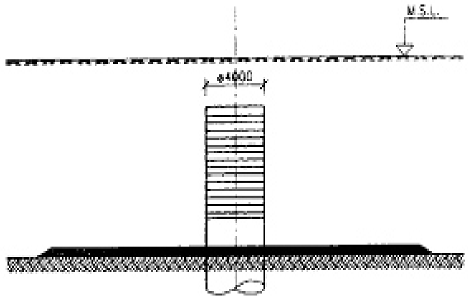
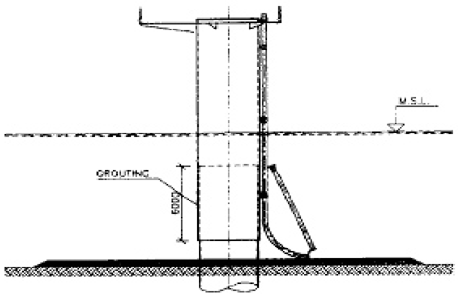
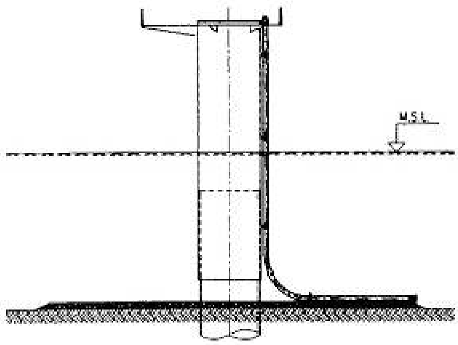
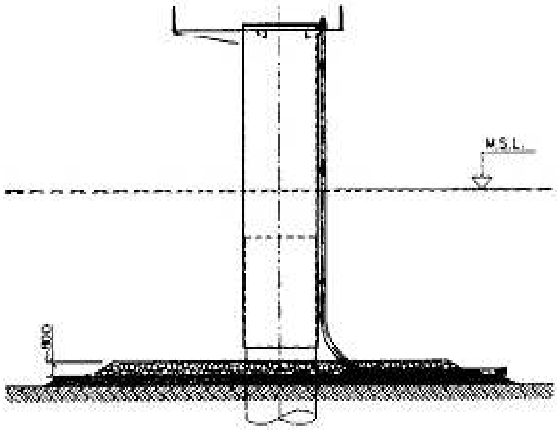
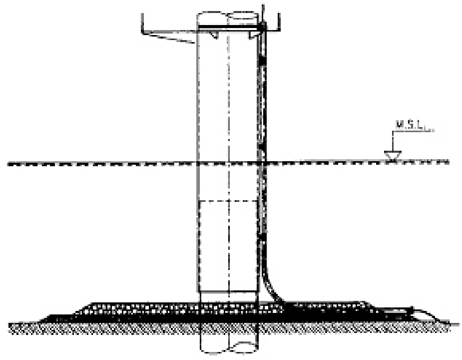
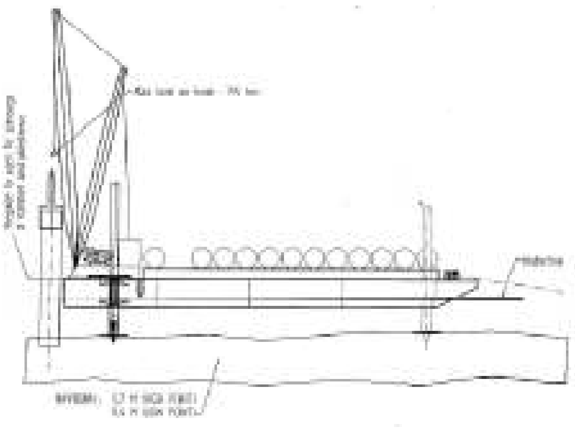
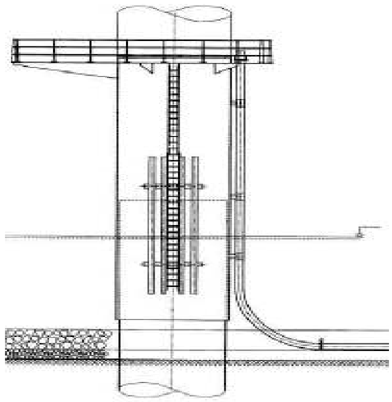


Figure 4.3.6 Sequence of steps to install the support, scour protection and the transition element.

The construction of a monopile foundation	
	
1. *A "mattress" of rock and stones is placed around the foundation to protect against erosion.* *- Thickness: ~ 0.5 m.* *- Stone diameter: 0.03-0.2 m.*	***2.*** *The monopile is driven through the mattress to the planned depth - approximately 25 metres.*
	
3. *The transition piece - complete with pre-installed features such as boat landing arrangement, cathodic protection, cable ducts for submarine cables, turbine tower flange, etc. - is cast together with the monopile. The transition piece makes it possible to raise the towers to a completely vertical position even if the foundation is not completely levelled.*	***4.*** *The cable ducts for the submarine cables are closed. The concrete is left to cure.*

	
5. The protective rock mattress is finished with an additional layer of rock and stones. - Thickness: ~ 0.8 m. - Stone diameter: 0.350-0.550 m.	***6.*** *Erection of the wind turbine and installation of cables to substation.*
	
7. *Pile driving. Specially designed barges, with a heavy duty hammer, are used to drive the monopile into the seabed.*	***8.*** *The transition piece is attached to the monopile in a special concrete casting process. The top rim of the transition piece is a flange that accommodates bolting of the turbine tower.*

One of the main problems of the monopile foundation is related to its flexibility, a problem that becomes even more important with increasing depth water and increased wind speed. If it is wanted to keep high rigidity of the structure when increasing the depth of water, the mass would increase with a cubic law (increasing length, diameter and thickness) and thus a first approximation would be that the costs would follow the same law. At the same time, the installation would require barges for the transportation and much larger hydraulic hammers that are not always available, and in any case would involve major increase in costs. For these reasons, these types of supports are used for shallow waters, varying between 5 and 30 metres. At the end of the useful life of the plant it is expected to cut the column of 2-3 metres below the seabed, leaving it where it is. It was decided to take this decision. This decision is taken because the mining operations of the foundation would be too complex and as a result of increased work load there will be a much greater environmental impact.

IV. Guyed monopile towers

The limitation of excessive deflection of a monopile in deeper waters is overcome by tying the monopile with tensioned guy wires.

V. Tripod

Where guyed towers are not feasible, tripods can be used to limit the deflections of the wind towers. For deeper waters, tripod support structures are being considered but the optimum solution is not yet certain and may well be a concept currently being brought into the field by offshore and coastal engineering specialists. There has already been one offshore wind turbine constructed on a tripod, the first wind turbine built at Nogersund in Sweden in 1990. However, this was a small turbine located in shallow water and hence unlike the structures to be built in the future. The typical structure is composed of three steel pipes, threaded by several metres of depth, connected to a central pylon with a larger section, which will build the tower. The components are usually connected with bars, forming a triangular structure, which also gives a high rigidity to the overall system, which is capable of transferring the full load (tower and turbine) to the tubes in the ground as forces of tension and compression. The diagonal bars crosses the column at a height of about 4 metres below the water surface at a variable angle (30 to 60 degrees) according to the depth of water (for very deep seabed angle it is larger, in order to vary the size of the base and ensure its stability, even at great depths). Compared with the monopile structure, it can stand the torque better through the base sitting on the seabed. Still comparing with the monopile solution, tripod structure has major complications when we talk about the plant design, and therefore it is expected that the manufacturing cost is higher. With increasing depth of the sea, the adaptability of this support must be verified, the fact is that in shallow waters, supports as monopile and gravity based are preferred, due to the weight and hence the cost of these structures is lower. Surely now it is the preferred solution for large power turbines and depths exceeding 25 metres. Its installation requires minimal preparation of the seabed.

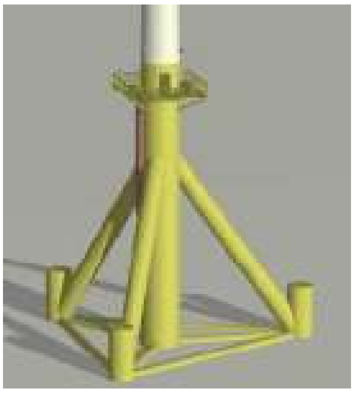


Figure 4.3.7 Tripod tower

VI. Braced lattice frame

A modification of the tripod frame, the lattice frame has more structural members. The jacket consists of a 3-leg or 4-leg structure made of steel pip that is interconnected with bracing to provide the required stiffness.

VII. Suction buckets

This design consists of a centre column connected to a steel bucket through flange-reinforced shear panels that distribute the loads from the centre of the column to the edge of the bucket. The steel bucket consists of a steel skirt extending down from a horizontal base resting on the soil surface. The bucket is installed by means of suction and behaves as a gravity foundation, relying on the weight of the soil encased by the steel bucket. The stability of the system is ensured because there is not enough time for the bucket to be pulled out of the soil during a wave passage. As the bucket is pulled up, a cavity is formed between the soil surface and the bottom of the bucket which creates a suction pressure that resists the uplift loads.

VIII. Floating tension leg platforms

At certain depths of 200-300m, the floating support seems to be the best solution from a technical standpoint and economically. In fact, it is probably the only structure in which the turbines would be installed in very deep areas. Like the other supports, the floating structure must support the weight of the turbine and the movements produced and keep them within acceptable limits. Over time, they have developed different possible configurations, many of

these are related to depths around 50 metres. Among which the most important has been studied by Henderson (2004), but the settings are designed for greater depths, as studied by Ushiyama (2003) and Butterfield (2005). It will take time, so that this technology reaches maturity, the full development could be achieved in some twenty years. The major complication is that of ensuring the stability of the structure, which is obtained by minimizing the induced oscillations of the waves and understanding the interaction between the support and the turbine. Precisely because of these complications it has not been able to identify yet what may be the best solution. In fact, with the knowledge acquired by the oil offshore, there are now available a range of systems, such as anchors, weights, ties and others, that would allow to have multiple solutions. The problem is that these have been developed for the oil industry that has great benefits and the cost is easily recovered, while the wind offshore needs the best solution to be compatible with its system of cost and profit.
These structures are floated to the site and submerged by means of tensioned vertical anchor legs. The base structure helps dampen the motion of the system. Installation is simple because the structure can be floated to the site and connected to anchor piles. The structure can be subsequently lowered by use of ballast tanks and/or tension systems. The entire structure can be disconnected from the anchor piles and floated back to shore for major maintenance or repair of the wind turbine.

4.3.3. Typical foundations

Foundations anchor the support structures to the seabed, and typically fall into the six types described below.

I. Gravity caissons

This type of foundation has been used for several offshore wind farms in Europe. For economical fabrication of gravity caissons one requires a shipyard or dry-dock near the site (*see figure 4.3.8*) so the massive foundation structures can be floated out to the site and sunk. Site preparation and placement required for gravity caissons typically involves dredging several metres of generally loose, soft seabed sediment and replacing it with compacted, crushed stone in a level bed. Special screeds and accurate surveying is required for this task.

Figure4.3.8 Gravity base foundation being constructed for Nysted Offshore Wind Farm at Rodsand, Denmark. *(Courtesy of Bob Bittner, Ben C. Gerwick, Inc.)*

II. Driven pipe pile

The driven steel pipe pile option is an efficient foundation solution in deep waters. The typical method of offshore and near-shore installation of piled structures is to float the structure (monopile, tripod or braced frame) into position and then to drive the piles into the seabed using hydraulic hammers. The handling of the piles requires the use of a crane of sufficient capacity, preferably a floating crane vessel (see *figure 4.3.9*). Use of open-ended driven pipe piles allows the sea bottom sediment to be encased inside the pipe, thus minimizing disturbance. The noise generated during pile driving in the marine environment might cause a short-term adverse impact to aquatic life, however, but because the number of piles is typically small, these adverse impacts are only short-term and relatively minor. Recent innovations in the pile driving industry, such as the bubble curtain, offer a way to mitigate noise impacts. A bubble curtain involves pumping air into a network of perforated pipes surrounding the pile. As the air escapes, it forms an almost continuous curtain of bubbles around the pile, preventing the sound waves from being transmitted into the surroundings.

Figure 4.3.9: Monopile 50 m (165 feet) long with a 4 m (13-feet) diameter being installed at the North Hoyle Wind Farm, UK. (Courtesy of RWE)

III. Post-grouted closed-end pile in predrilled hole

A closed-ended steel pipe pile is placed into a predrilled hole and then grouted in place. This option is used often for offshore pile foundations less than 5 m in diameter and offers significant advantages over the cast-in-place drilled shaft option, including advance fabrication of the pile, better quality control, and much shorter construction time on the water. This option requires a specially fabricated large diameter reverse circulation drill (*see figure 4.3.10*). It also requires handling and placement of a long, large-diameter pile, of considerable weight. Closed-end piles can be floated to the site and lowered into the drill hole by slowly filling them with water.

Figure 4.3.10 Reverse circulation drill.

IV. Drilled shafts or bored, cast-in-place concrete pile

The installation of bored, cast-in-place concrete pile (*see figure 4.3.11*) requires driving a relatively thin-walled (25 mm) casing through the soft sediment to the underlying denser material (if necessary to establish a seal), then drilling through and below the casing to the required base elevation. Bending resistance is provided by a heavy reinforcing cage using high strength, large diameter bars, with double ring, where necessary. The casing provides excavation support, guides the drilling tool, contains the fluid concrete, and serves as sacrificial corrosion protection. This approach requires a large, specially fabricated reverse circulation drill.

Figure 4.3.11 Construction of drilled shaft. From left to right, install casing and auger drill, place reinforcement cage, and pour concrete by tremie.

V. Composite "Drive-Drill-Drive" pile

This procedure requires an adaptation of existing drilling and piling techniques and involves a combination of drive-drill-drive sequence to achieve the design depth.

VI. Suction caissons

Like piles, suction caissons (*see figure 4.3.12*) are cylindrical in shape but have larger diameters (10 m to 20 m) and subsequently shallower penetration depths. These caissons are closed at the top. They are installed by sinking into the seabed and then pumping the water out of the pile using a submersible pump (*see figure 4.3.13*). Pumping the water creates a pressure difference across the sealed top, resulting in a downward hydrostatic force on the pile top. The hydrostatic pressure thus developed pushes the pile to the design depth. Once the design depth is achieved, the pumps are disconnected and retrieved. Suction caissons are expected to be particularly suitable for foundations in the type of soft cohesive sediments found around the U.S. coasts. These foundations cannot be used in rock, in gravel or in dense sand. Suction caissons are less expensive to install because they do not require underwater pile drivers. At the end of the life's wind turbine, a suction caisson can be removed completely from the seabed, unlike piled foundations. This provides room for recycling. General construction characteristics of the various foundation types are presented in *table 4.3.14.*

Figure 4.3.12: Suction caissons for an offshore platform being transported to site in the Gulf of Mexico. (Courtesy of E. C. Clukey).

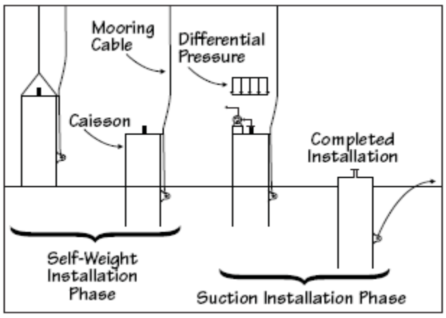


Figure 4.3.13 Installation of suction caisson.

Construction phase	*Gravity Base*	*Monopile*	*Tripod/Braced Frame*	*Tension Leg Platform*
Onshore fabrication	*On land and close to site to be economical*	*No constraint*	*On land and close to site to be economical*	*No constraint*
Transport offshore	*Float to site or on barge*	*Float to site or on barge*	*On barge*	*Float to site or on barge*
Pre-placement activities	*Seabed preparation required*	*None*	*None*	*None*
Placement	*Lift of float over*	*Lift and sink*	*Lift and sink*	*Lift and sink*
Fixing tower to substructure	*Bolt to substructure*	*Grout to pilling*	*Grout to tripod central member*	*Tie to tension cable*
Installation of tower and turbine	*Requires specialized cranes and large barges*	*No hindrance to lifting*	*Requires specialized cranes*	*No hindrance to lifting*

Table 4.3.14 Construction characteristics of offshore wind turbines foundations.

CHAPTER 5: Study of data and calculation method

5.1. From the North Sea to the Mediterranean

The countries bathed by the Mediterranean Sea have a high production capacity of offshore wind energy. This circumstance should be used to advise these countries in order to let them know, in terms of energy production, how many possibilities there are. By 2013, Germany hopes to have 1200 MW installed at sea, while in Denmark the aim is to have a capacity of 4000 MW installed offshore. Other European countries like the UK, the Netherlands and Ireland also begin to install wind turbines off their coasts, or, like France, have plans to do so.
Figure 5.1.1 shows the map with the bathymetry (study of underwater depth of lake or ocean floors) of the European coasts. It can be seen that the area corresponding to the North Sea (between the Netherlands and the United Kingdom), the north coast of France, Denmark, Germany and Ireland have excellent conditions for the installation of wind farms due to the fact that its depth is in all cases less than 100 metres. In fact, all offshore wind farms in the world, except for one located in Japan, have been settled in this area. It may be noted that the Mediterranean Sea also has excellent conditions for the offshore wind energy; especially on the coast of Tunisia, Libya, Greece, Italy and the Balkan countries.

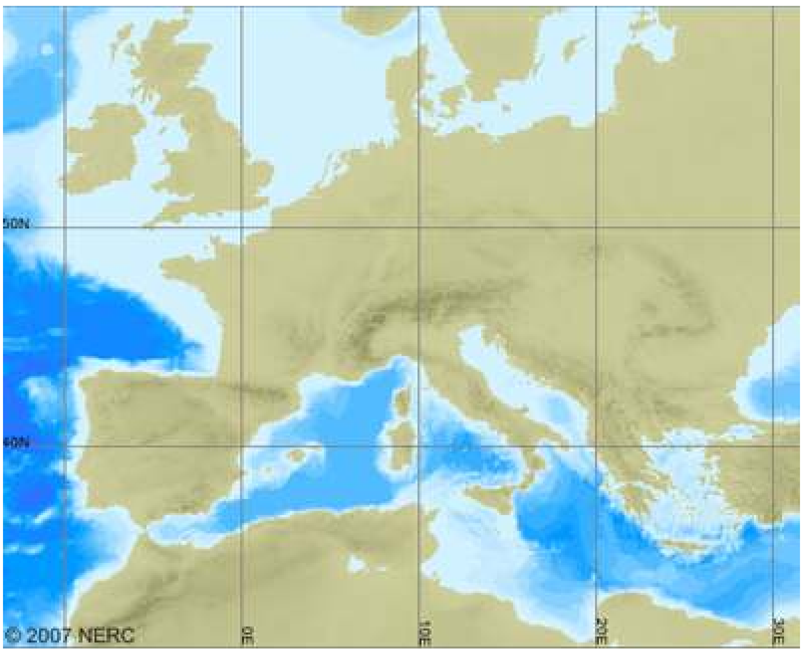


Figure 5.1.1 Bathymetry of the European coasts.

The locations of wind farms should always safeguard the marine ecosystems, conducting environmental impact studies and establishing protective and corrective measures for any possible condition to the environment where they are located. Currently the environmental impacts generated by offshore wind farms are very little or not known, being projects developed in public spaces for which no property rights or use are well defined. However, it can be deduced that the area where the wind farms will be installed will probably be closed to fishing to prevent damage to infrastructure and potential shipping accidents. Besides, the production of energy and noise can cause changes in the marine environment with implications for living organisms. As beneficial effects could place, those resulting from the artificial creation of a reserve in which the different species may shelter for fishermen and develop colonies on the artificial reefs created as foundations for the turbines. This could even increase the number of copies that will migrate later to other areas of the coast (*see point 4.2).*
Nevertheless, for offshore wind farms to end up being a reality in the Mediterranean the various public administrations will have to solve in the coming years, a number of aspects that are considered essential:

1. Defining property rights in the use of sea.
2. Establishing a strategic policy of using the area cost.
3. Studying in depth the possible conditions and benefits that large marine infrastructure can lead to the physical environment.

5.2. Current situation of the Iberian Peninsula

Spain has a great potential for offshore wind industry. According to a study by the European Commission, the country could have 25.52 GW of installed capacity in 2020, which will bend the onshore capacity. Despite its potential, offshore wind energy will not start in Spain. Therefore this thesis attempts to show that if a wind farm is conducted in Spain, it would greatly benefit, and in the future reduce CO_2 emission and thus be closer to meet the Kyoto Protocol. It would lead to less reliance on other energy sources such as oil.
Some European countries have taken the initiative. Currently, there are 38 offshore wind farms belonging to nine European Union countries. The United Kingdom and Denmark lead their implementation, with a share of 44% and 30% respectively. Countries such as Sweden, Germany and Norway have also built several facilities in its waters. According to the EWEA, the European offshore market will grow 75% in 2010. The recovery of this delay in relation to other countries could take several years. The most optimistic hope the first offshore wind

farms in Spain could start operating between 2012 and 2014. From Wind Energy Association (AEE) point to 2020 as a date that would have about 4000 MW of installed capacity.

In principle, the bases are established. The Government has regulated by Royal Decree the procedures and conditions for the implementation of such wind farms. Ministries of Environment, Rural and Marine Affairs (MARM) and Industry, Trade and Tourism (MICYT) have published the Environmental Strategic Study of the Spanish coast. In it, there are identified the areas that meet the favorable conditions for the installation of wind turbines.

The report assesses 4000 kilometres of coastline and includes the installation of 73 offshore wind areas, which are classified, as shown in the map (*see figure 5.1.2*), “exclusion zones” (in red), “suitable areas with restrictions” (yellow) and “suitable areas” (in green). Those responsible for the study say that in an exclusion zone projects may also occur and only be rejected if the environmental impact studies were negative.

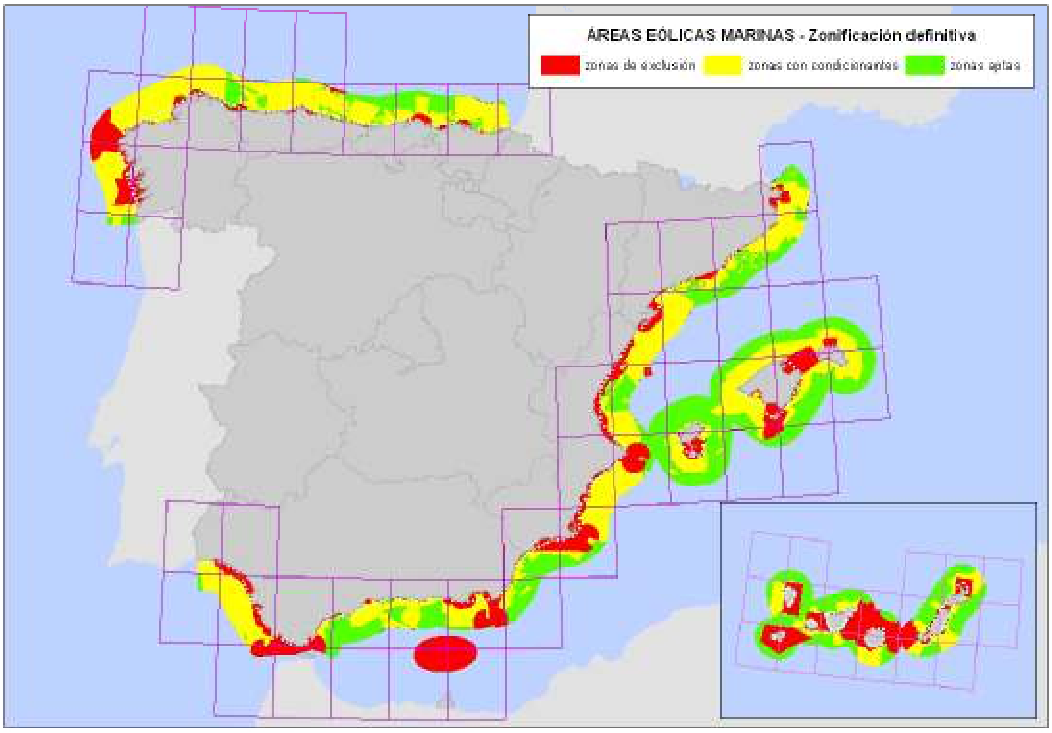


Figure 5.1.2 Map of the zoning of offshore areas.

Several Spanish companies in the renewable sector, and leaders in Europe and the world, such as Acciona, Capital Energy, Gamesa and Iberdrola have presented several projects. Such diverse areas of the coast, Galicia, Cadiz, the Canary Islands, Murcia and Tarragona are some of the possibilities mentioned. However, these proposals to develop offshore wind power have not gone beyond a statement of intent.

Several economic, environmental and administrative explain this delay of offshore wind energy in Spain. The costs of construction and O&M of wind farms at sea, as energy production, are higher than in onshore. The lack of electrical infrastructure to harness the energy produced is another major obstacle. In addition, there are still areas suitable for wind power expansion on solid ground, cheaper and cost effective.

The location of wind turbines is a key element. With the technology available today, the depth at which a wind farm can be installed must not exceed 20 metres. This factor limits to a few zones the placement of offshore wind farms. The continental shelf of the Spanish coast is generally characterized by its narrowness: four kilometres from the coast and more than 50 metres deep.

A possible solution could come from technological advances. The enterprise development sector resulting in higher performance models in terms of power and installation. Another possibility would be the floating wind turbines (*see point 4.3.2*), which have begun to be tested in some countries, like Spain. But the real advantage of these models may take several years.

5.3. Spanish Wind Atlas

IDAE (Instituto para la Diversidad y Ahorro de la Energía, i.e., Institute for the Diversification and Energy Saving) has considered necessary to develop a Spanish Wind Atlas with enough reliability to enable wind potential evaluations, including interactive access to the results through a Geographical Information System plug-in, whose scope is the whole National territory including inland waters and an additional coastal buffer of 24 nautical miles. The use of uniform criteria facilitates the comparison between the results obtained in different zones of the country. [31]

In the making of the Wind Atlas of Spain, a numerical weather prediction system has been applied to predict the long-term wind resource. Interaction with the topographical characterization of Spain has been taken into account, which has enabled the study without the need to carry out a specific measurement campaign. Besides that, real wind resource information has been used to validate the adopted simulation tool.

Conventional methods to study the wind potential in large extensions need a long and expensive measurement campaign, which involves installing several meteorological towers belonging to a homogeneous prospect network. Also, the conventional wind flow models are seldom precise in highly unstable wind regimes and topographically complex territories.

The modern mesoscale and microscale techniques offer a very effective solution to these problems: they effectively combine the use of a sophisticated atmospheric model, capable of reproducing mesoscale wind patterns, with a microscale wind model that responds to local terrain featuring. In this concern, studies of wind potential in large areas can be carried out at an acceptable resolution. It is necessary to emphasize that real in-situ wind measurements are not strictly necessary to obtain reasonable results, although met mast data is essential to confirm the forecasted wind potential in specific sites. In conclusion, atmospheric mesoscale-microscale modeling remarkably reduces cost and time to identify and evaluate potentially promising zones for developing wind projects.

This project designed by IDAE has been developed by Meteosim Truewind, a world-class leading company in development and research of new wind resource exploration techniques based on the mesoscale-microscale modeling system Mesomap. The first Mesomap was marketed by AWS-Truewind in the year 1999. In the last 10 years, it has been applied successfully in diverse regions belonging to more than 60 countries in five continents.

Following the described technique, the key target of this project has been fulfilled: to create a map of wind resource in Spain providing enough reliability to enable a first evaluation of the available wind potential.

5.3.1. Generation of wind resource maps

The MesoMap system generates the maps of wind potential in three steps. First of all, MASS (Mesoscale Atmospheric Simulation System) simulates the atmospheric conditions representative of a period of 15 years. Every simulation gives values of wind speed, among other meteorological variables (such as temperature, pressure, moisture, kinetic turbulent energy and heat flow) in three dimensions within the integration domain. These data are saved in hourly outputs. As soon as the simulations are completed, results are compiled in summary files, which constitute the input to WindMap model in the second stage of map making. The final stage is transforming these numerical results into maps, which is done with the help of the tools provided by Geographical Information Systems.

Both the average annual characteristics of the wind vector and the mean annual wind power density are products of the microscale model, downscaled from the results of the mesoscale model. This means that they are exactly the variables calculated by MASS in the whole three-dimensional mesh for every integration step. From wind speed and air density, the local wind power density is retrieved at every point.

The two main final products of the whole process are:

1. Maps of average wind speed and power density at different heights above ground (30, 60, 80 and 100 m).
2. Data files containing the distribution parameters of wind speed and frequency by direction.

The mapped speeds are compared to those coming from meteorological towers on the earth's surface or on the sea. In case significant differences are observed, final adjustments are performed.

5.3.2. Potential sites

- **Wind resource**

Knowing the wind or a wind resource area is crucial to choose the location of future wind farms, since with it we can deduce the production facility which, in turn, is closely linked to project profitability.

Carrying out a large-scale analysis we would be able to discard areas until the resolution is diminished. To perform this process, it is enough to know the average wind speed at the hub height of the wind turbines. It can be said from the analysis of the characteristics of the actual machines from the offshore wind farms that the height of the hub is about 80-120 metres above sea level. With the existing wind turbines and the results of the techno-economic analysis of foundations, it is appropriate to rule out a wind energy project if the average wind speed at hub height over sea level is less than 6 m/s. Between 2 and 8.5 m/s there is an uncertainty that would have to be discussed later on in the project. For wind values above 8.5 m/s it would provide a safety in the possible investment.

It is convenient, when designing a wind farm, to review the hub heights of wind turbines and the average wind speed limit established, as with experience these values could be modified.

At this moment of the project, it would be enough to consult different wind maps as the one shown in *figure 5.1.3* and *figure 5.1.4* for Spain. These are isoventa’s maps, i.e, isolines that separate equal wind speeds at a certain height, and therefore show the areas where might be possible to install an offshore wind farm.

Figure 5.1.3 Spain's offshore wind resource at 100m.

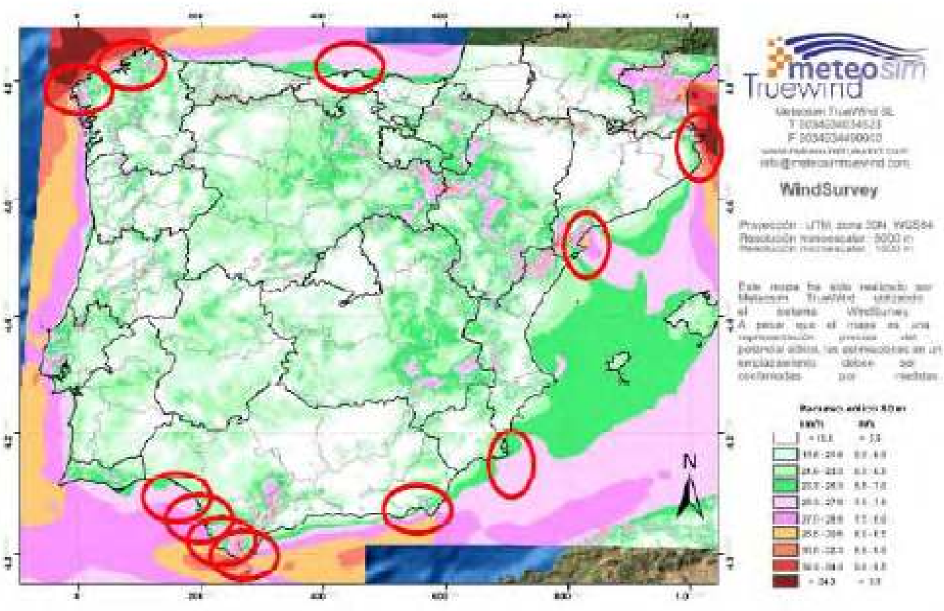


Figure 5.1.4 Spain's offshore wind resource at 80m.

Some red circles are shown in the figure above. These are the potential sites chosen to be studied in this project, which correspond to areas with greater potential compared to other possible areas.

- **Bathymetry**

Another aspect influencing the location of offshore wind farms is the bathymetry, as discussed above. It must be remembered that there is a currently restriction that prevents building offshore wind farms in areas with depths greater than 40-50 metres. With the advance of technology this restriction will decrease, so it is important when designing a new project to review existing technology at that time. For information on the bathymetry, it is sufficient with consulting maps as the one below (*see figure 5.1.5),* which shows the bathymetry of 10, 25, 50 and 100 m from the Iberian Peninsula. This information rules out areas with depths higher than the current limit (40-50 m).

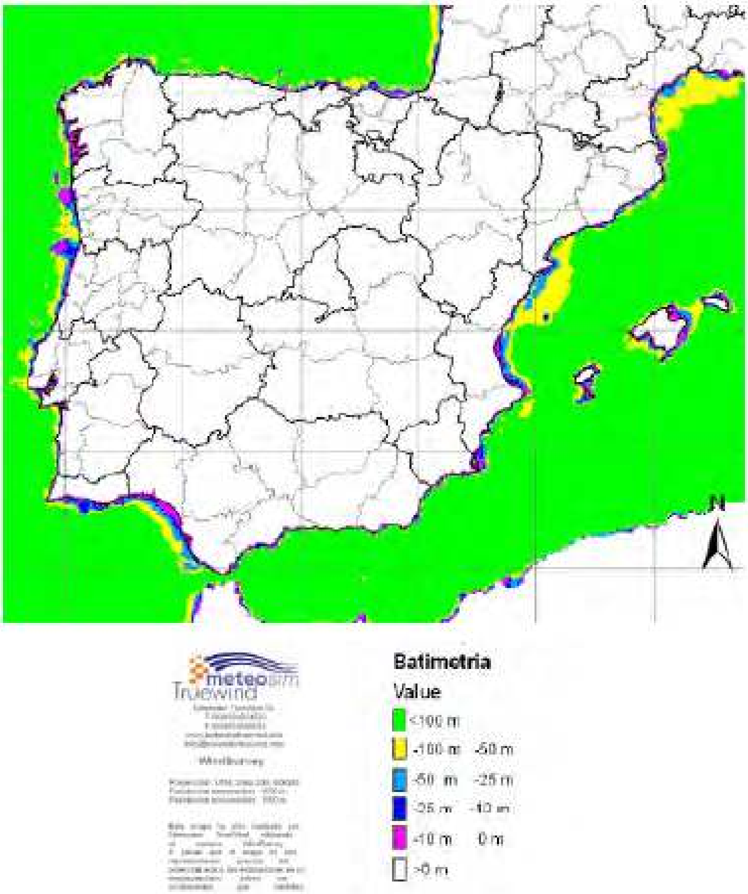


Figure 5.1.5 Bathymetry of the Iberian Peninsula.

This is the complete discarding of areas considered interesting at this point (according to the legislative and financial framework, including the zoning if existing, and the wind resource) or the reduction of the area of these zones. In the event that the installation was experimental, such as floating structures, this last restriction would not be taken into account.

- **Discharge capacity of the existing network**

For a wind farm to fulfill its function it is essential that the electricity generated could be evacuated by the existing infrastructure of the grid. The discharge capacity of the network in Spain is a critical point of the project, since many existing network infrastructures are saturated and cannot carry more electrical energy than lead today. Given the increasing demand for electricity and that part of the transmission and power distribution are not able to carry the new power produced, it has been created a plan of works and actions by the network operator, in the case of Spain REE (Red Eléctrica de España). It can be seen in the following *figure 5.1.6* the strengthening of the REE by the planning 2007-2016.

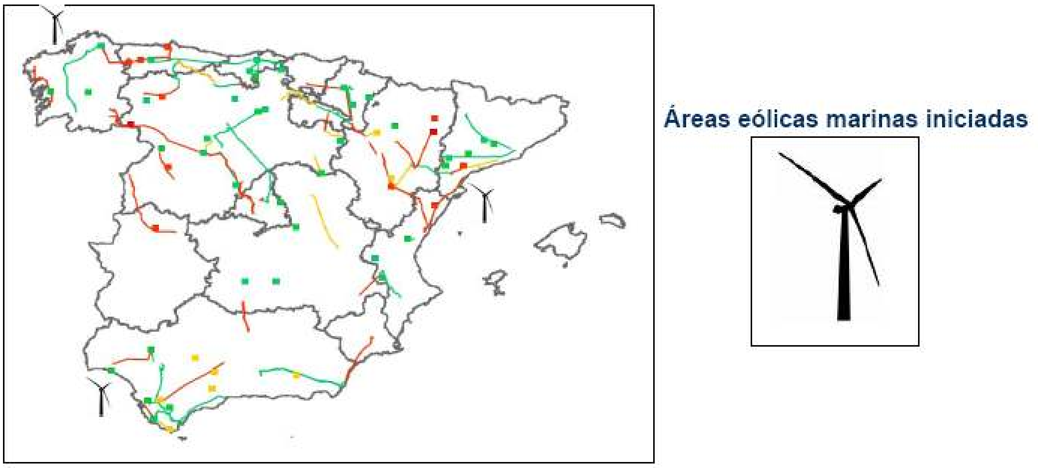


Figure 5.1.6 Planning electricity and gas sectors 2007-2016 and future AEE (Asociación Empresarial Eólica) activities.

Therefore, it must have to be done an analysis on the existence of evacuation capacity for the offshore wind farm in the year that is provided for its implementation, which will be function of the processing time and construction.

As it has been seen in the *figure 5.1.4* there are some potential sites in which offshore wind farms should be created. If we compared that figure with the one above, it can be seen that there is a match between them. This coincidence can be seen in the next *figure 5.1.7.*

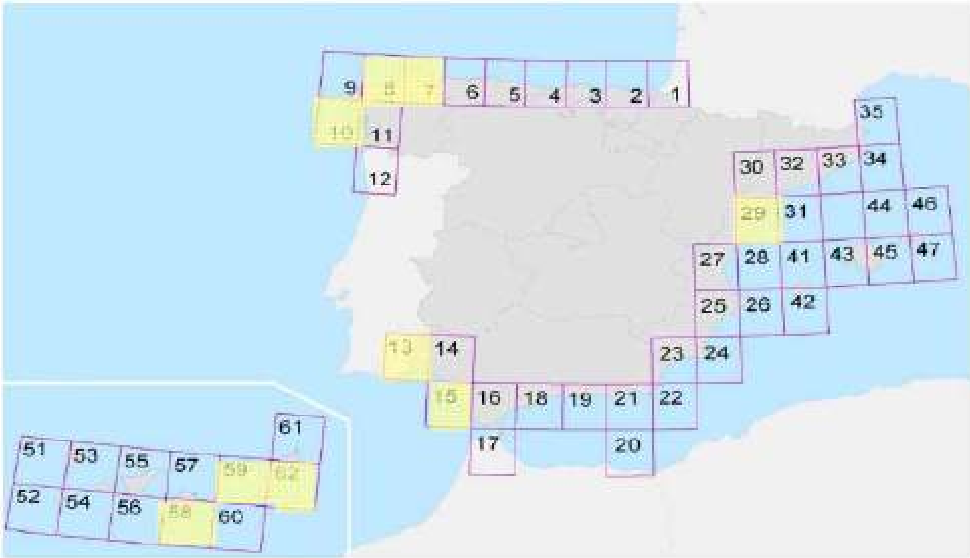


Figure 5.1.7 Areas coinciding with the areas requested [CENER].

The areas which will be focused on in this project are Galicia, Andalusia, Valencia and Catalonia. These are the chosen areas due to their bathymetry and their wind resource. Besides, there are the zones where the network is going to be improved. The next figures show the planning of electricity and gas sectors 2007-2016 and future AEE activities for each of the potential areas selected.

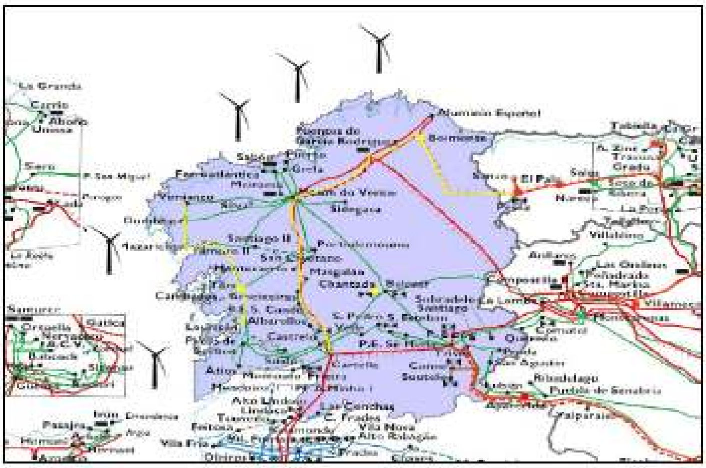


Figure 5.1.8 Planning electricity and gas sectors 2007-2016 and future activities for Galicia.

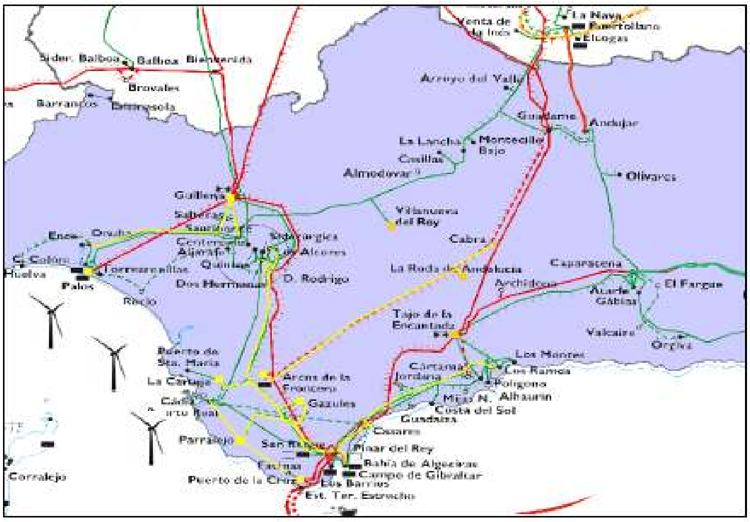


Figure 5.1.9 Planning electricity and gas sectors 2007-2016 and future activities for Andalusia.

Figure 5.1.10 Planning electricity and gas sectors 2007-2016 and future activities for Valencia and Catalonia.

5.4. Calculation method

5.4.1. Conditions and hypotheses

For the execution of this project we have had to assume certain conditions and assumptions due to lack of information:

- It has been considered that all the wind farm turbines receive the same wind speed and that they are at the same distance from the coast. It is generally assumed that they are under the same conditions for any variable considered.
- To know the depth of the wind farm a map of bathymetry has been used, as seen above. The only public available map is shown in *figure 5.1.5* and consequently the depth that has been taken for the calculations had to be an approximation.
- The network distance had to be also an approximation, and it has been decided the value of 4,5km.
- All the wind farms must have at least a power of 50MW for the Spanish government granted bonus when selling electricity.
- In terms of costs, references from previous projects have been taken.

5.4.2. Energy assessment

In this point it will be explained the procedure used to calculate the electricity production of an offshore wind farm.

Across the Spanish wind atlas, it has been possible to obtain data from the annual average wind speed at the heights of 80 and 100 metres, which correspond approximately to the heights of the wind turbine towers. The parameters k and c of Weibull distribution were also available and therefore it has been possible to calculate the probability that the wind blows at a certain speed, f(v). If this value is multiplied by the power generated by the turbine, at that speed ($\dot{W}$ (v)), by the hours in a year (assuming 8760 hours per year), it is obtained the gross energy generated by a wind turbine at a certain wind speed. [6]The function ($\dot{W}$ (v)) is different for each wind turbine, and is a feature which is given by the manufacturer. In the annexes the catalogues of the turbines selected and their respective power curves can be found. If we add the electricity production generated in the usable speed range of the turbine (for the speed range of cut-in and cut-out), it is obtained the gross annual electricity production of the wind turbine.

$$E_{gross}(v) = f(v) \cdot \dot{W}(v) \cdot 8760$$

$$E_{gross} = \sum_{cut\ in}^{cut\ out} E_{gross}(v)$$

The total net energy embedded in the network, which will therefore be sold, can be calculated taking into account losses which exist in the transformation from wind energy to electric energy and losses through the transmission line, considering the entire wind farm.

$$E_{net} = E_{gross} \cdot Nº \cdot Awf \cdot Na \cdot (1 - P_i) \cdot (1 - P_e)$$

- Nº: number of wind turbines.
- Annual availability of the wind farm (A_{wf}): it indicates the proportion of the annual average availability of wind turbines functioning at the park. Considering the results obtained from existing wind farms, it has been asssumed a value of 96% .[33,34,35]
- Network availability (Na): it takes into account the cases of network failure transferring its production accordingly to any damage and/or scheduled maintenance of the cab devilering primary energy, the reference value for this parameter is 99%.
- Interference losses (P_i): A wind turbie that is behind another draws less energy and there may be lower speed due to the wake that is formed, in other words, the aerodynamics of a turbine shadows over another. The value assumed is 5%.
- Electric losses (Pe): They are the energy losses through the transmission line, and could be quantified around 3% of the total energy transmitted.

It is also assessed at this point, the equivalent working hours of the park (E_h), obtained by dividing the brute power production by the rated power of the wind turbines, and the power factor of a wind turbine.

$$E_h = \frac{E_{gross}}{\dot{W}_n}$$

$$P_f = \frac{\sum_{cut\ in}^{cut\ out}[f(v) \cdot \dot{W}(v)]}{\dot{W}_n}$$

In this simulation it has been chosen three different turbines, these are: 2MW of Vestas, GE of 3,6 MW and 5 MW of Repower. As said before their respective catalogues will be found in the annexes.

5.4.3. Economic assessment

To assess the suitability of the investment it has been decided to adopt the method of the net present value (NPV), which evaluates the economic desirability of the park for 25 years, paying special attention to PBT (pay back time). The PNV is a standard method which defines the current value of a series of cash flows which are not added in a simple way, but discounted. It can be calculated as follows:

$$NPV = \sum_{j=-2}^{25} CF_{jdis}$$

$$j < 0 \quad CF(j) = -CI \qquad CF(j)dis = CF(j) \cdot (1+i)^{-j} \cdot (1+a)^{-j}$$

$$j > 0 \quad CF(j) = Sales - Costs \qquad \frac{\{[CF(j) \cdot (1+i)^j - Amm] \cdot (1-t) + Amm\}}{(1+j)^j \cdot (1+a)^j}$$

Where a, t, i are the indices of calculation (showing the discount rate, the tax rate and the rate of inflation respectively). CF is used to indicate the cash flow while Amm is depreciation. Later on there will be a more precise definition of these parameters.

The discount rate determines the present value of a stream of future earnings. Equal normalized earnings after taxes divided by present value, expressed as a percentage. The tax rate measures the burden of taxes and multiplies them by the discounted cash flow net and gives the contribution to be paid as tax. The inflation rate increases in the price of goods and services, usually annually. Depreciation is the distribution of the initial investment by the useful life, which is supposed to spread the constant line basis over the first 10 years of investment. In the following *table 5.4.1* are shown the values chosen for this project.

a	Discount rate	5%
t	Tax rate	38%
i	Inflation rate	3%

Table 5.4.1 Values adopted for the calculation of NPV.

It can be seen that in the formula to calculate the NPB the index j starts from -2. With the negative sign it indicates the years when there is no production. These are the years needed to build the park (this value is estimated from wind farms already built). In these first two years there are only disbursements that wil go to the cost of investment I_0. Since it is difficult to allocate the different costs for the two years of construction, it has been taken a 30% of I_0 for the first year and the remaining 70% for the second year.

1st year	j = -2	Payment 30% of I_0
2nd year	j = -1	Payment 70% of I_0
3rd year	j = 0	Start of production

Table 5.4.2 Starting procedure

The cash flow discounted determines the PBT, which represents the year when revenues reach to pay the expenses incurred by the investment cost and O&M, since the plant lifetime. Finally, it is possible to find the cost of energy production (Ec [c€/kWh]) through the research objective function, implemented in Excel, and it is found the energy value that cancels the NPV. This is a very useful parameter for comparisons between different electricity generating plants, and could be defined for any equivalent hours of operation. In practice, it is the selling price of power at the end of the plant life and involves no gain. The lower this value, the more attractive the production system is. Note that for calculating the production cost of power it should not be counted the revenue from the sale of green certificates.

5.4.4. Costs

The costs involved are the invesment costs, operating costs of the wind farm (called O&M) and decommissioning .[36,37] Investment costs include all costs that must be beared for the plant:

- Design costs: This category includes all expenses incurred in carrying out measurements of wind, detailed study of the seabed, feasibility studies, locating specific information and design itself. This cost depends on the size of the wind farm. For a park of 30 wind turbinesit has been estimated, also based on projects, a cost of 16 M€.

- Project management: This part of the cost is difficult to predict a priori, in this study it is assumed to be equal to 2,5% fo full cost of investment, based on feedback obtained from the parks built.

- Turbine: This price only includes the cost of the wind turbine (including the tower). The price of a single turbine can vary by manufacturer. In our study it has been made an average of the values found in literature.

Size of the wind turbine [MW]	Current price [k€]
2	1500
3,6	2963
5	3750

Table 5.4.3 Current prices of the different turbines used in this study.

- Turbine installation: The installation cost includes transportation by sea and by land, assembly of the different parts, connection with the tower and so on. For a wind farm comprising 30 units it could be assumed a value of 6.7M€. In fact, the cost for each wind turbine is about 215 k€, to which we must add a series of fixed costs which amount to 293,9 k€. In this study, the estimated values were adopted for parks that are up to 30km away. For shorter distances these values are also adopted, which is a choice that determines an increase of cost but can achieve more conservative results.

- Foundations: This item includes the cost of building the structure (C_{steel}), transportation and installation. The first entry is linked to the cost of materials and manufacture and can be calculated as:

  $$C_{structure} = m \cdot C_{steel} \cdot N^{o}$$

  Where m is the mass expressed in [tones] and Nº the number of support structures, which clearly coincides with the number of turbines. In this study monpile supports and tripods were considered, which are those that better suit intermediate depths: the first one has a base value of 2,25€/kg, while the second case, due to the increased complexity structure as the reference price was adopted 3.50€/kg. To determine the weigh of the structure and the turbine at different water depths it has been referred to a study found in literature and which we report these two different tables *[see table 5.4.4 and 5.4.5]* one for the monopile and the second for the tripod.

			Water Depth (m)				
Soil Type	**WTG**	**Weights (Te)**	**5**	**15**	**25**	**35**	**45**
Strong	**2 MW**	Pile Total	66,5	129,6	191,6	267,6	270,6
		Steel Total Weight	104,4	209,3	271,3	370,8	486,2
		Total Foundation Weight	110,1	215,5	277,5	377,5	493,7
	3,6 MW	Pile Total	107,3	189,8	285,5	378,2	515,1
		Steel Total Weight	165,5	293,1	388,8	481,5	618,4
		Total Foundation Weight	171,3	299,8	395,4	488,2	625,1
	5 MW	Pile Total	160,4	271,2	362,3	481,5	636,2
		Steel Total Weight	226,5	400,0	492,2	625,7	780,4
		Total Foundation Weight	233,2	405,8	499,2	632,2	786,9
Weak	**2 MW**	Pile Total	74,2	149,4	212,6	284,9	381,5
		Steel Total Weight	112,0	229,1	292,3	375,3	472,0
		Total Foundation Weight	117,7	235,4	298,5	402,0	498,6
	3,6 MW	Pile Total	119,0	213,9	291,3	390,8	529,6
		Steel Total Weight	177,2	317,2	394,6	494,1	632,9
		Total Foundation Weight	183,1	323,8	401,3	500,8	639,6
	5 MW	Pile Total	181,8	291,5	417,4	531,7	573,2
		Steel Total Weight	256,1	420,3	546,1	675,8	732,8
		Total Foundation Weight	262,3	426,1	551,9	682,3	765,1

Table 5.4.4 Weight support monopila as function of depth, depending on the foundation and the wind turbine.

			Water Depth (m)				
Soil Type	**WTG**	**Weights (Te)**	**5**	**15**	**25**	**35**	**45**
Weak	**3,6 MW**	Pile Total	/////	111,9	78,2	53,6	62,8
		Tripod Weight	/////	152	210	282,3	390,8
		Steel Total Weight	/////	367,6	391,9	439,6	557,3
		Total Foundation Weight	/////	400,1	424,5	472,2	589,9

Table 5.4.5 Weigh support tripod depending on the water depth.

Looking at the tables above, it can be seen that monopile represents the preferred solution for depth up to 25 metres, besides the media weight increases markedly and the adoption of tripod supports seems the preferable choice. 25 metres has been taken as the discriminating value for the choice of substrate and the development cost. One other consideration seems necessary: the table shows that by decreasing the hardness of the seabed, the structure must be driven to greater depths, thereby increasing the weight of the structure. For the feasibility analysis conducted in this study it will be always born in mind weak soil types in order to get more conservative results.The values of the table have been developed in order to find a simple algorithm in order to allow us to be able to calculate the weight of the support varying the depth and the size of the wind turbine. It has been taken as reference the 3.6 MW wind turbine, which has an intermediate power between those considered (2MW, 3.6MW and 5MW). In order to find the weights of the different turbines it has been necessary to introduce correction factors. The equations used in the study are given below:

$$\dot{W}_n = 3{,}6\ MW \qquad y = 10{,}098 \cdot x + 139$$

$$\dot{W}_n < 3{,}6\ MW \qquad y' = y - [0{,}8125 \cdot x + 60{,}691]$$

$$\dot{W}_n > 3{,}6\ MW \qquad y'' = y + [8{,}1778 \cdot x + 3{,}6792]$$

Where x represents the water depth in metres and y is the weight of the support in tones. The results obtained with the algorithm differ a 4-6% compared to those obtained experimentally; the error is considered acceptable. The installation cost includes transportation by land and seas, assembly of parts, installation of the support and protection of the slag. The cost to perform these operations could be quantified around 472,7k€/support where it is added a fixed fee of around 147k€. For a wind farm with 30 wind turbines, thus 30 supports, the total cost of installation of the foundations amounts to 14,33M€.

- Network connection: The cost of connection consists of two parts: a fixed amount of 477,05€ plus a fee which depends on the power of the wind farm and is equal to 69,638 €/MW.

- Transmission of the energy produced: Includes the cost of cables for the transmission of energy, amounting to 279,3 k€/km, for both onshore and offshore cables. This value must add up the cost for excavation and for accommodation of the cable underground, which amounts to 153,1 k€/km in the onshore part and 378,5 k€/km in the offshore part. The difference between the two situations is very high and reflects the real difficulties in conducting underwater operations. Furthermore, it must be added the cost to connect the wind turbines to the electric transmission grid, estimated at 279,3 k€/turbine.

- Transformer substation: The item includes the cost of the transformer substation and the related installation costs. The cost of a substation is around 4,3 M€, which includes the costs of transport and installation. An offshore transformer substation has a very high cost, around 13,1 M€, including transportation, installation and support. Since it has this high cost, the first wind farms, also favored by the proximity of the cost did not have the offshore substation. Therefore, the results will be more conservative.

- O&M: This cost includes costs that are incurred to ensure the proper functioning of the wind farm during its useful life. Their estimate is not easy and it is essentially based on information supplied by the constructors of other wind farms. These have shown high costs during the first year and lower costs for subsequent years. For offshore wind farms there are not available information for the last years of their lifetime. It has been assumed that the O&M costs will tend to increase at the end of their lifetime. In this study costs adopted are shown in the next *table 5.4.6.*

Guarantee (for the first 5 years)	1862,1 [k€/year]
O&M (except for the first year and the last 5 years)	1719 [k€/year]
O&M (for the last 5 years)	2148,6 [k€/year]

Table 5.4.6 O&M costs.

- Decommissioning: This includes all costs to be incurred for the removal and disposal of all parts of the plant at the end of its useful life. In this study, it has been assumed a cost of 394 k€/turbine, constant for both types of turbines used. The assumption does not weigh so much on the results for two reasons; this cost represents about 1% of the cost of electricity production and thus a small variation does not lead to major changes in the results. Moreover, the outlay for decommissioning is the 25th year of the lifetime of the plant and due to inflation and the discount rate its contribution to the discounted cash flow becomes more limited.

- Revenues: Obviously the revenue is obtained through the sale of electric energy produced. According to Royal Decree 661/2007 of the "Régimen especial" there are two alternatives for the remuneration of the electricity produced:

1. Sale regulated rate: Rate regulated + Accessories – Divert

2. Sale free market. Price 'Pool' + Bonus + Accessories - divert.

Complimentary reactive power versus continuity gaps (only existing parks) is maximum 0,39 c€/ kWh for five years until 12/2013. As our wind farm has to be built this is going to be discarded.

Regulated rate: It is single, independent of the power and the year of PEM € 75.68 / MWh (Year 2008), (> 20 years: 63.25 €/ MWh).

Wholesale market: The premium benchmark is 30,27€/MWh. Between the lower limits 73,66 €/MWh and upper 87,79€/MWh just for only 20 years.

In the offshore case it is only possible to sell the electricity to the market. And it is also introduced a maximum premium at the procedural level concurrency which is 17,3502 c€/kWh.

Therefore the selling price of electricity will be between the two limits described above. It has been assumed a value of 80,725 €/ MWh and as set out in the Royal Decree a premium of 17,3502 c€/kWh. This premium is only valid for the first 20 years.

CHAPTER 6: Results and conclusions

6.1. Results

This chapter will analyse the results obtained using the Excel program, taking into account all the parameters explained earlier in this study. Therefore 3 tables have been performed *[see tables 6.1, 6.2 and 6.3]* summarizing the characteristics of greater interest such as unit cost, PBT, NPV, net energy, specific cost, etc.

Galicia								
WT [MW]	**Depth (m)**	**M€/MW**	**Eqh [h/year]**	**Cp [%]**	**Net energy [GWh/year]**	**NPV [M€]**	**PBT [years]**	**ce [c€/kWh]**
2	30	2,25	2627,57	30%	138,07	1.412,37	6	17,82
2	37,5	2,28	2627,57	30%	138,07	1.366,13	7	18,05
3,6	40	1,72	3140,06	36%	297,00	5.866,61	4	11,11
5	45	1,43	2707,56	31%	355,69	7.285,71	4	10,59

Table 6.1 Result of the analysis depending on the turbine power in the area of Galicia.

Andalusia								
WT [MW]	**Depth (m)**	**M€/MW**	**Eqh [h/year]**	**Cp [%]**	**Net energy [GWh/year]**	**NPV [M€]**	**PBT [years]**	**ce [c€/kWh]**
2	50	2,38	4126,12	47%	216,82	4.026,80	4	11,94
3,6	50	1,77	4690,58	54%	443,66	10.955,50	2	7,63
5	50	1,45	4341,37	50%	570,32	14.820,48	2	6,72

Table 6.2 Result of the analysis depending on the turbine power in the area of Andalusia.

Catalonia								
WT [MW]	**Depth (m)**	**M€/MW**	**Eqh [h/year]**	**Cp [%]**	**Net energy [GWh/year]**	**NPV [M€]**	**PBT [years]**	**ce [c€/kWh]**
2	37,5	2,33	2694,98	31%	141,61	1.422,26	7	17,95
3,6	37,5	1,74	3186,64	36%	301,41	5.968,85	4	11,08
5	37,5	1,44	2783,41	32%	365,65	7.616,27	4	10,35

Table 6.3 Result of the analysis depending on the turbine power in the area of Catalonia.

As it can be seen on the results table above, electricity production is highly influenced by the area where the project is being undertaken. Thus it can be seen that the higher values of net energy correspond to Andalusia. For example, for the 5 MW wind turbine the net power output is 570,32 GWh/year, in contrast to the case of Galicia and Catalonia, always considering the same wind turbine, the values for the net energy produced are 355,69 and 365,65 GWh/year respectively. This is because in the region of Andalusia wind blows more strongly and this affects this parameter a lot.

The average wind speed in Andalusia is 9,6 m/s in contrast to both in Catalonia and Galicia which is 7,7 m/s, taking into account that these values are always an approximation and that these measures should be taken in the area to obtain better and real data.

If a wind farm is created in each area studied with a 5 MW wind turbine, it would be obtained 1291,67 GWh/year of net energy. This value represents 3,32% of total renewable energy and 0,43% of total energy consumed in Spain [31]. Therefore, if other similar wind farms are built this percentage may increase significantly and it could reduce the energy dependence that Spain has.

As for the total unit cost of installation, in general, for an offshore wind farm this value is approximately between 1,1 and 1,3 M€/MW for a farm with wind turbines with a capacity exceeding 1 MW.

If we refer again to the table of results, it can be seen that for 2 MW turbines the value obtained for the total unit cost is higher than that previously suggested. If it is done an average cost for all areas with 2MW wind turbines it is achieved the value of 2,31 M€/MW, which is significantly higher than 1,3 M€/MW. If we perform the same operation taking into account the 3,6 MW wind turbines it is obtained an average value of 1,74 M€/MW. But if it is done for areas with 5 MW wind turbines this value decreases to reach 1,44 M€/MW, which is more or less approximate to 1,1 M€/MW. Thus, it can be concluded that the more power a wind turbine has, the less the unit costs per turbine are.

Although in the area of Andalusia we have the highest depth (about 50 metres), always remembering that these values are an approximation due to the lack of public information for this data. This would be the best case despite having such depth, and consequently, it affects the structure weigh and cost. However, this is compensated by the high wind speed in this area.

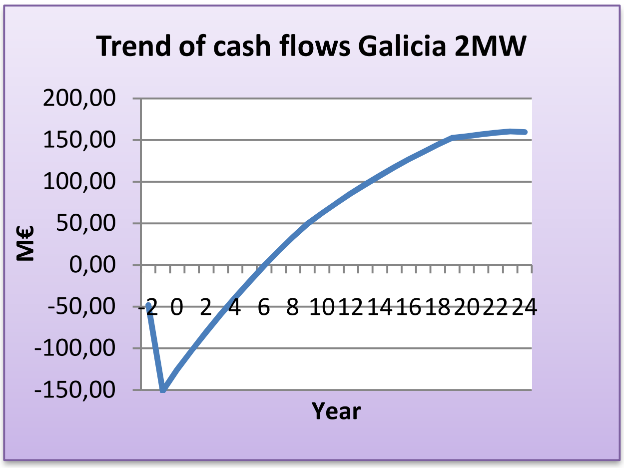
Despite all this, we cannot ensure the construction of wind farms in the respective areas, as they all have restrictions (as seen in the zoning map). It is therefore possible that precisely in those areas the wind farms studied in this project cannot be built.

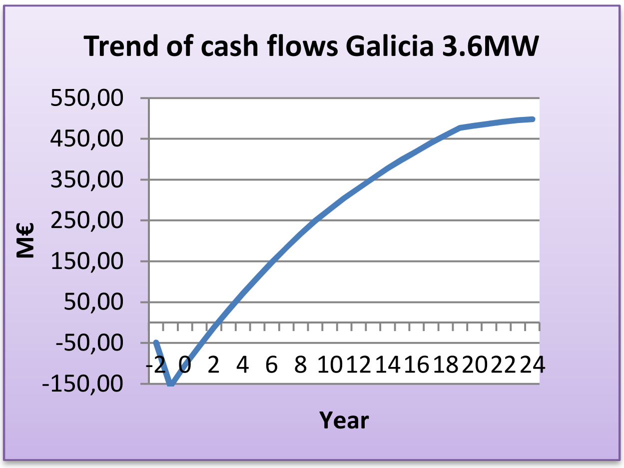
The time required by the wind farm to repay the investment is strongly influenced by weather conditions. A site that shows little windy conditions will be penalized and consequently the production of electricity will be limited. The windiest zone is Andalusia, thus it is the zone with lower payback times.

If you look at the payback time of the three areas, we still see that the better case is Andalusia with PBT of 4, 2 and 2 years with turbines of 2, 3.6 and 5 MW respectively. Although these PBT are perhaps too small, since it is highly unlikely to recover the entire investment in two years. It can also be concluded that the higher the turbine, in terms of power, the lower the PBT. This conclusion can be extended to the zones of Galicia and Catalonia.

The PBT can be calculated in the trend of cash flows' graphic, which is the year in which the NPB is zero. That means that it is in that year when we begin to recover our investment. In the next *table 6.4* the trend of cash flows of Galicia is shown.

Trend of cash flows of Galicia





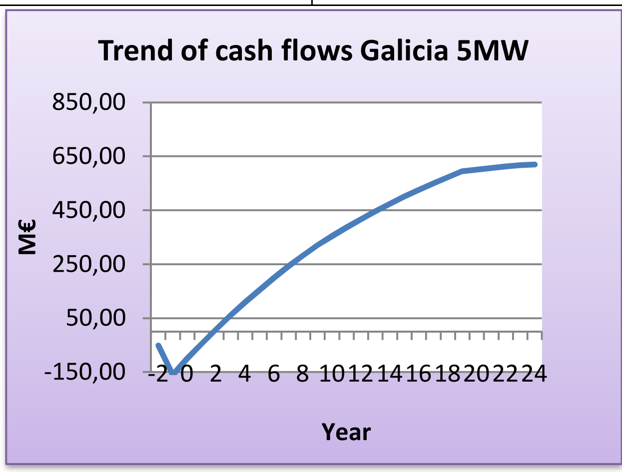


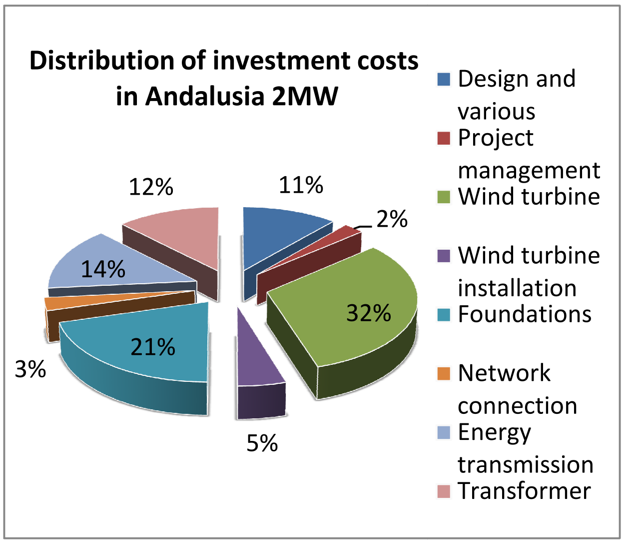
Table 6.4 Trend of cash flows in Galicia. Production from the year 0, and PBT value when the line cuts the abscissa.

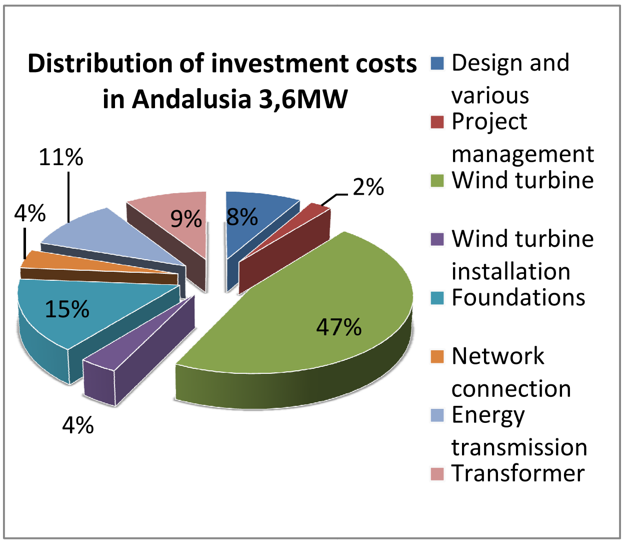
In that case the PBT is 7, 4 and 4 years for the wind turbines 2, 3.6 and 5 MW respectively. Having a high PBT could be considered critical, given the economic substance of the investment (150 M€). It is unlikely to invest in a plant that will only produce benefits after at least 10. The level of this operation will be too risky.

It can be noticed on the table above [*see table 6.4*] that in the last five years the curve of the cash flows has been less inclined: this is due to the increasing cost of 0&M at the end of the useful life of the wind farm.

Another interesting aspect to consider is the distribution of the investment, which can be seen in the next *table 6.5* for the case of Andalusia with the different wind turbines.

Distribution of investment costs in Andalusia





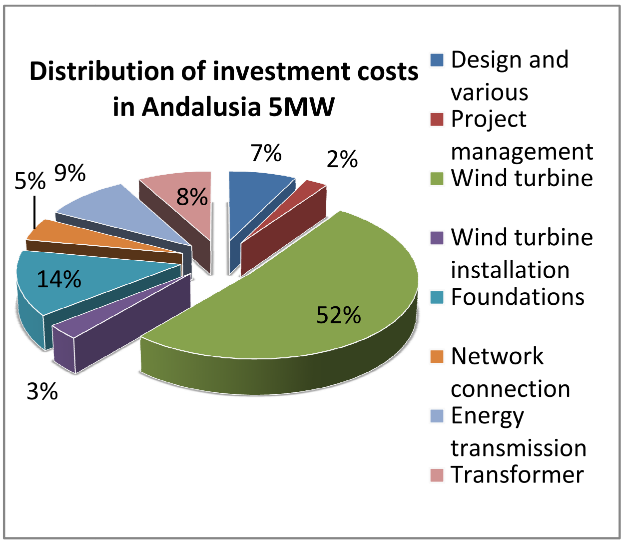


Table 6.5 Distribution of investment costs in Andalusia.

In the case of Andalusia, a large part of the investment goes to the wind turbine and the foundations with a percentage of a 53% in total in the case of the wind turbine of 2MW. Considering as well the installation of the wind turbine, that percentage would be up to a value of 58% of the initial investment. The remaining costs are distributed as follows: the highest percentages are for the transformer and the energy transmission with a 12 and 14% of the initial cost respectively. Another high value, with 11%, is for the design and data acquisition. This distribution closely resembles the distribution of existing parks.

With the turbine of 3.6 MW, just the wind turbine has a 47% of the investment. This value increases up to a 52% in the case of the 5MW wind turbine.

These considerations allow us to conclude that it is necessary to reduce costs of foundations and wind turbines, and consequently reduce the initial investment. This would allow wider dissemination of wind energy and its competitiveness with other types of plants to produce electricity.

As for PBT, the specific cost of energy production (ce), this parameter is strongly influenced by the wind conditions of the site. The most adverse conditions were found for the site of Catalonia, with a ce of 17,95c€/kWh with the 2MW wind turbine, very high considering that for an onshore wind farm the cost of energy production is around 10 c€/kWh.

Instead, for the area of Andalusia it would be obtained specific cost of production of 11,94 and 7,63 and 6,72 c€/kWh in the case of wind turbines with 2, 3.6 and 5 MW respectively.

In the last case, for Galicia we have the next specific costs 17,82 and 11,11 and 10,55 c€/kWh, always considering the three types of wind turbines.

The cost of energy production of a conventional combustion system, such as a combined natural gas cycle, is approximately 7,3 c€/kWh, of which a little less than 5’% is for fuel. To this it must be added the cost of externalities (price paid to buy the rights to emit CO_2), which is quantified at 3 c€/kWh. With a total up to 10-11 c€/kWh, it is still far below the 17,95 c€/kWh for Catalonia using the 2MW wind turbine.

The important fact is that the cost of production of energy for the CCGT is heavily influenced by fuel costs, which can fluctuate daily in an important way, and it seems that it is going to continue rising over the years. This is the prevision of the IEA, even though last year suffered a large drop in price.

It is also very important that subsides and helps in form of premiums of the Spanish Government will not decrease, since this would cause a great impact on the development of wind energy technology. At least it would be inconvenient for Spain, because in Spain it has not been built any wind farm yet, and therefore this technology is not so consolidated as in other countries. To be able to reduce the premiums of the State, costs of the wind turbine and the cost of foundations should be first reduced, which represent a high percentage in the investment, as seen above.

6.2. Conclusions

As the current energy model cannot be maintained, this means that, given the accumulating evidence on the expected depletion of fossil resources and the impacts of the current energy model, the transition to a new model has already begun. In addition to this depletion it should be taken into account the emission of gases that cause global warming. To prevent an increase in their emission, the international agreement of the Kyoto Protocol has been adopted, which aims at reducing six of these greenhouse gases that cause global warming.

The fact that Spain is a country heavily dependent on energy supply makes it even more interesting to develop renewable energy technologies, as wind offshore energy. Both Spain and Germany have reached high installation of power onshore, while states as Britain and Denmark are leaders in offshore wind technology. Since the ground available for onshore energy is reaching its limit in Spain, it is necessary to aspire to transfer this technology to the open sea.

Offshore wind farms are being designed to increase the installed power, now comparable to those of common plants that use fossil fuels. Current wind turbines are planned with three blades, with an adjustable tilt angle and asynchronous generator with a frequency converter. Technological developments tend to foster larger and efficient wind turbines, which will be installed on the open sea at tens of kilometers from the coast, where the visual impact would be almost nonexistent. The fact of taking advantage of offshore wind energy is related with the fact of exploiting these areas where wind conditions are better in terms of average speed. To achieve this it is necessary for engineers to focus on improving the foundations for great depths. The structures mostly used are the monopile ones, which use scour protection, and its installation is derived from the knowledge taken from the offshore oil technology. The transmission of energy occurs with the lines of AC, except for distances greater than 60 km when DC is used.

The spread of offshore wind farms will be determined by the designers' ability to reduce costs, especially in the turbines and the foundations. Having more efficient turbines positively affects the reduction of O&M costs, as they require less maintenance. This aspect is very important due to the fact that the farther away the wind farm is from the coast, the greater the O¬M costs will be, due to limited accessibility.

The mass-production of wind farms in series will make us gain more knowledge and data and the designing will be faster, reduce therefore investment costs and making this technology become more attractive.

In Spain, the bases are established, but for the effective development of offshore wind power, governments should accelerate the whole bureaucratic process and offer subsides to companies.

The risk of an investment in a plant of this type, using wind as energy source, is quite high, being this highly uncertain. But as it has been proof in onshore, the risk could be reduced if the data acquisition was carried out over a long period.

The conditions for the development and dissemination of this offshore area are all well-known. Now it is our choice to make it real.

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ANNEX

1. Maps of Galicia

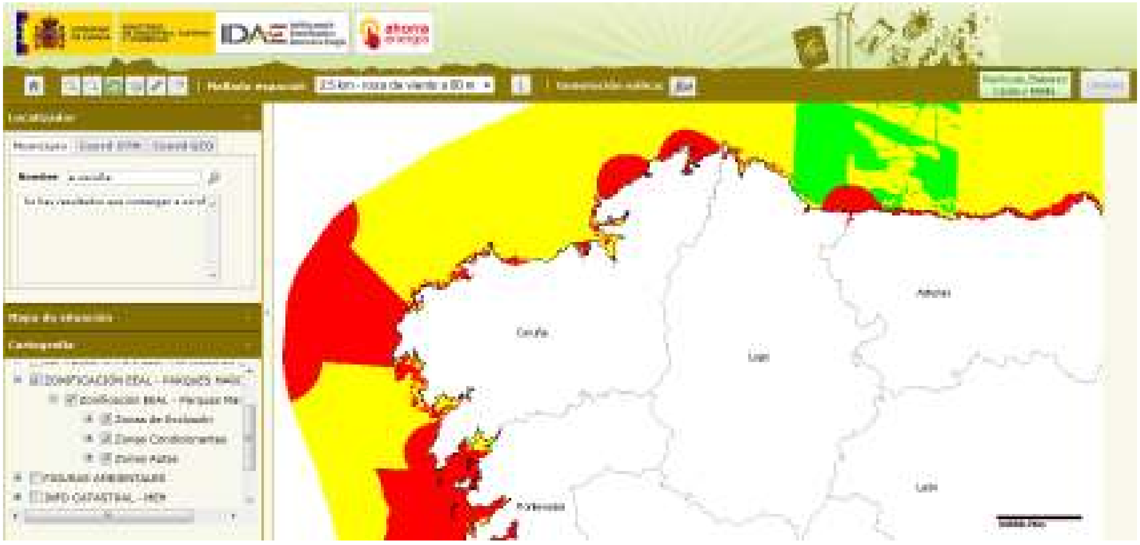


Figure A.1.1 Map of the zoning of offshore areas. In red exclusion zones, in yellow with restriction and in green suitable areas.

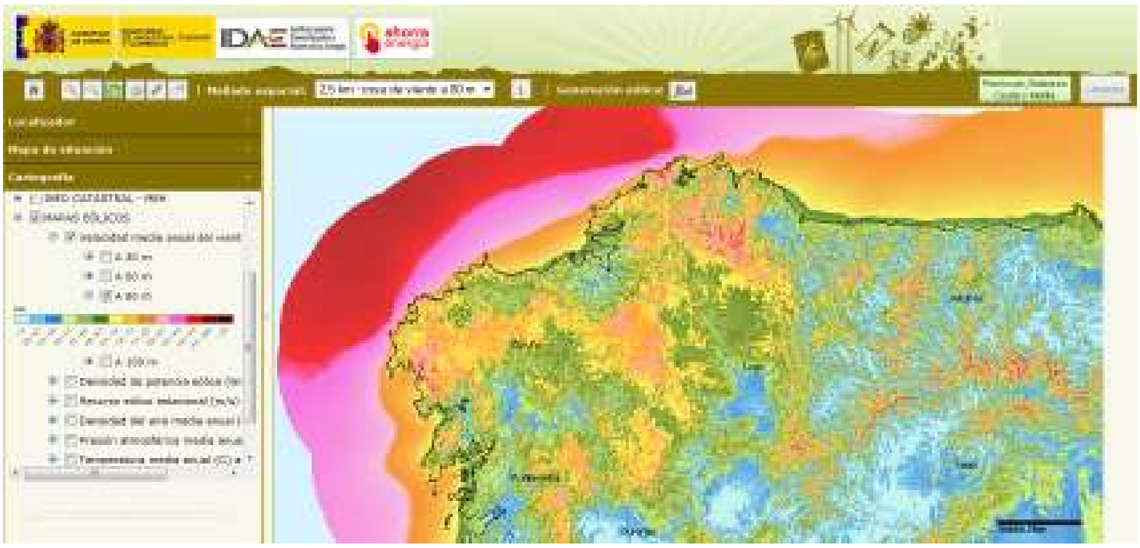


Figure A.1.2 Annual mean wind speed at 80 m [m/s].

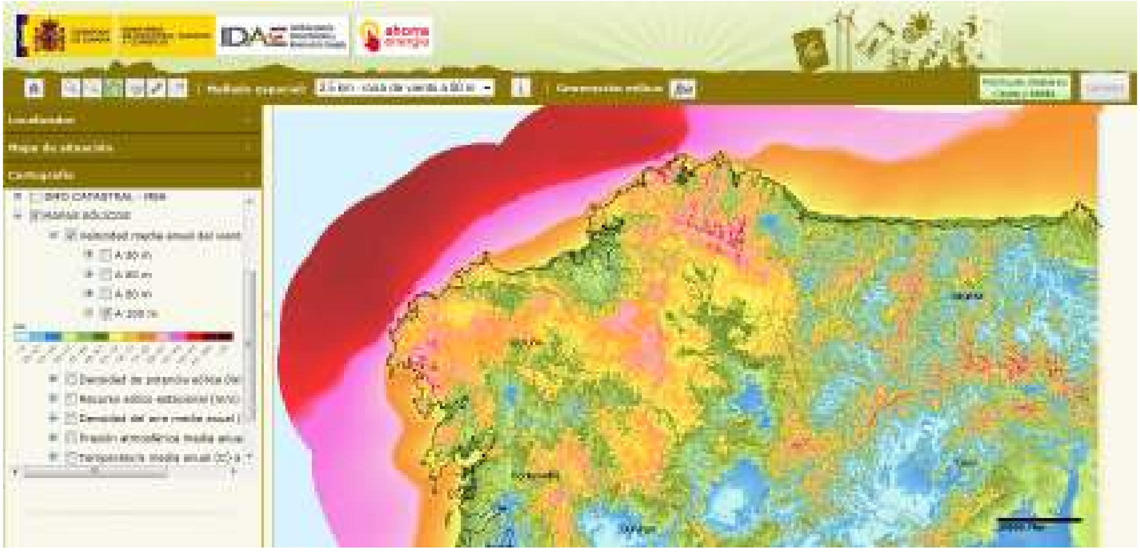


Figure A.1.3 Annual mean wind speed at 100 m [m/s].

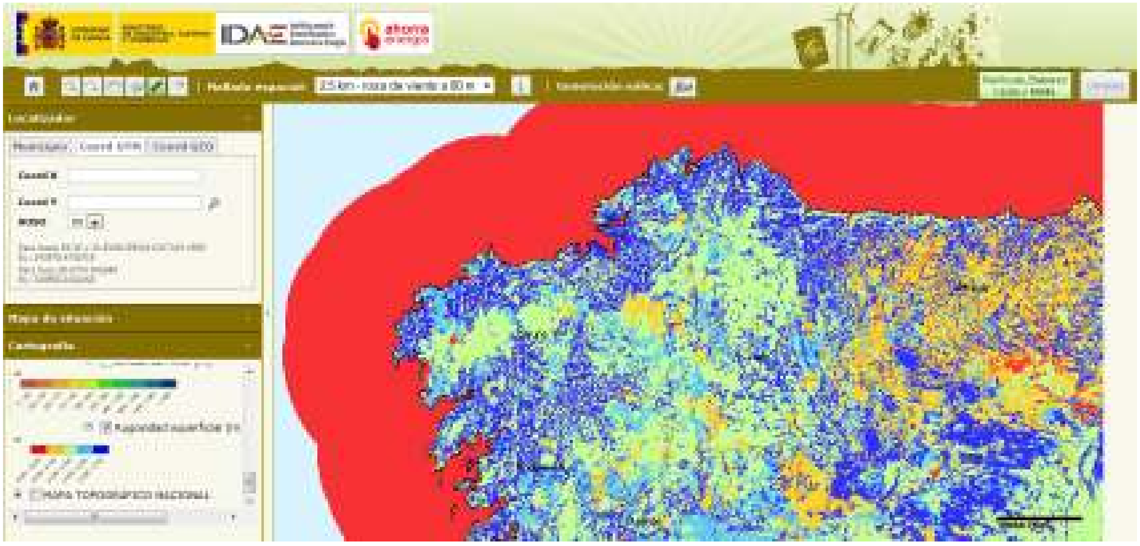


Figure A.1.4 Surface roughness [m].

Figure A.1.5 Protected natural areas.

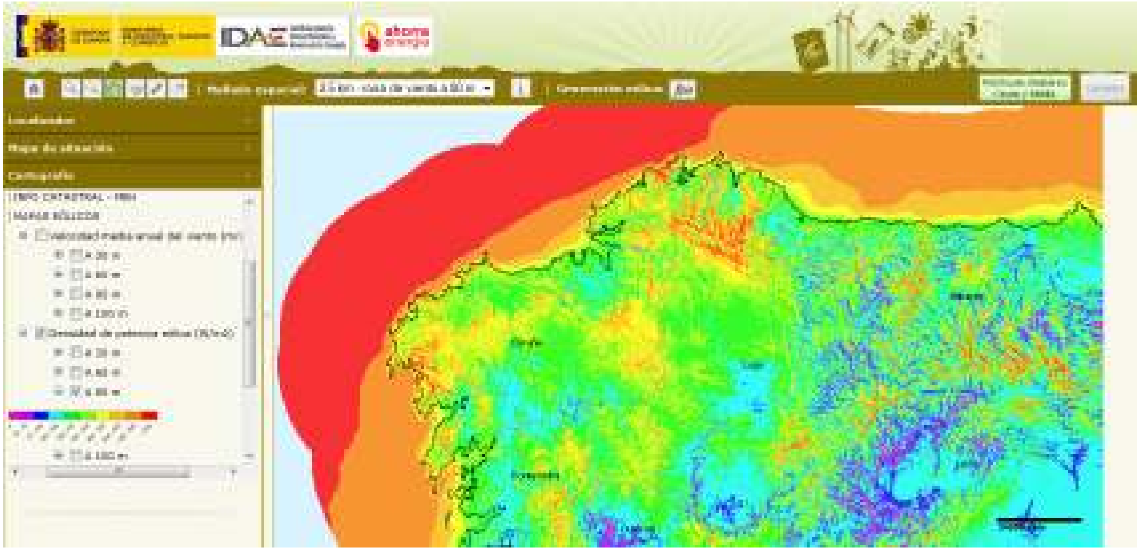


Figure A.1.6 Wind power density at 80m [W/m²].

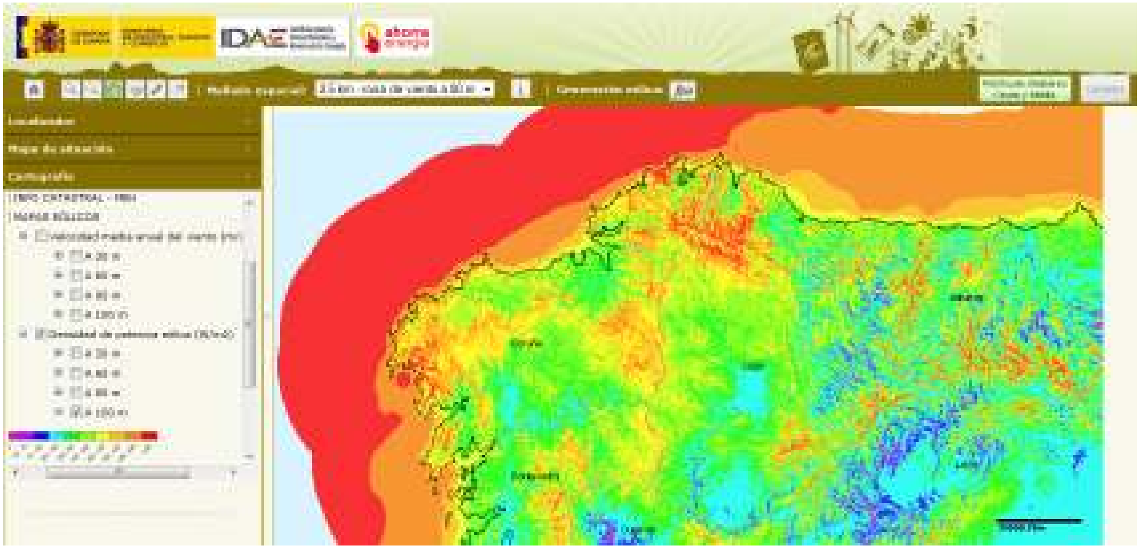


Figure A.1.7 Wind power density at 100m [W/m²].

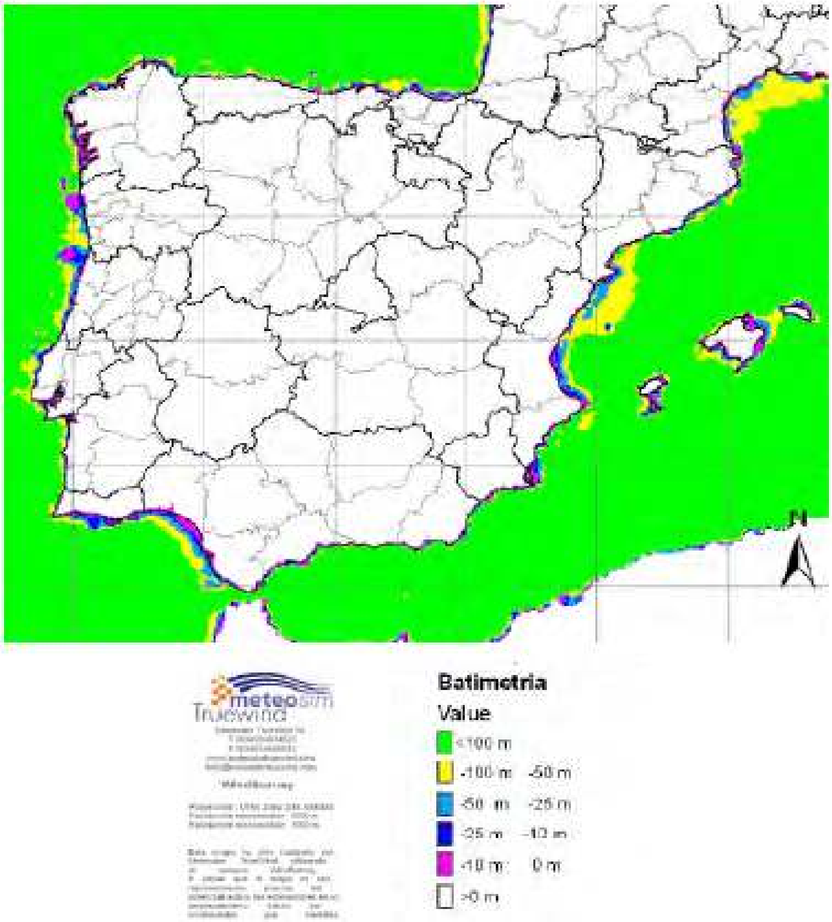


Figure A.1.8 Bathymetry of Spain. In the Galicia zone the depth is between 25 and 50m.

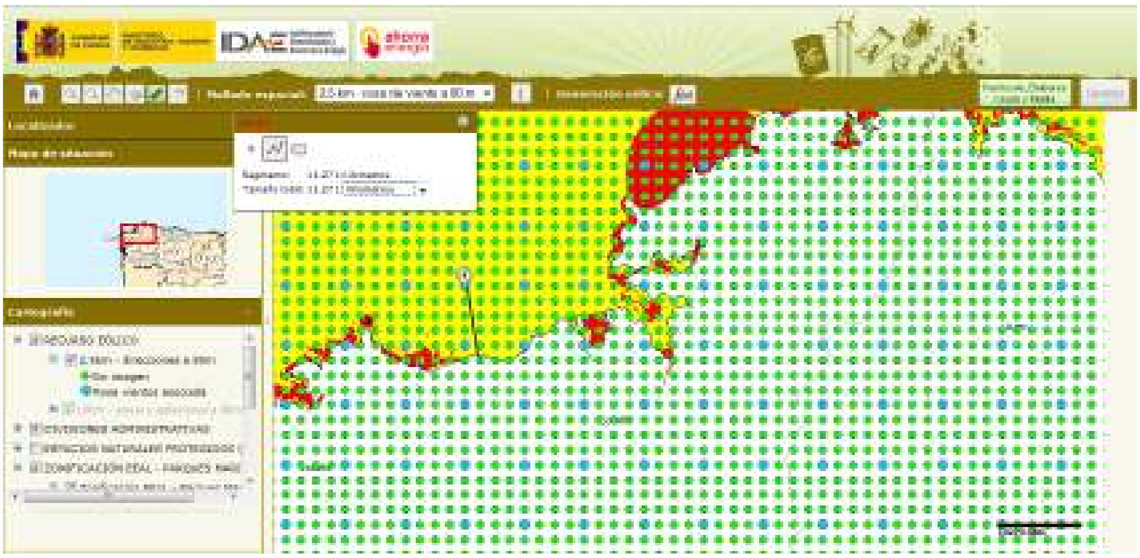


Figure A.1.9 Area chosen for the construction of the wind farm, which is at a distance of 11,271 km from the coast.

Figure A.1.10 Coordinates of the zone X: 43280,18571428571 Y:4823127,8266932275(UTM Zona 30 ED50).

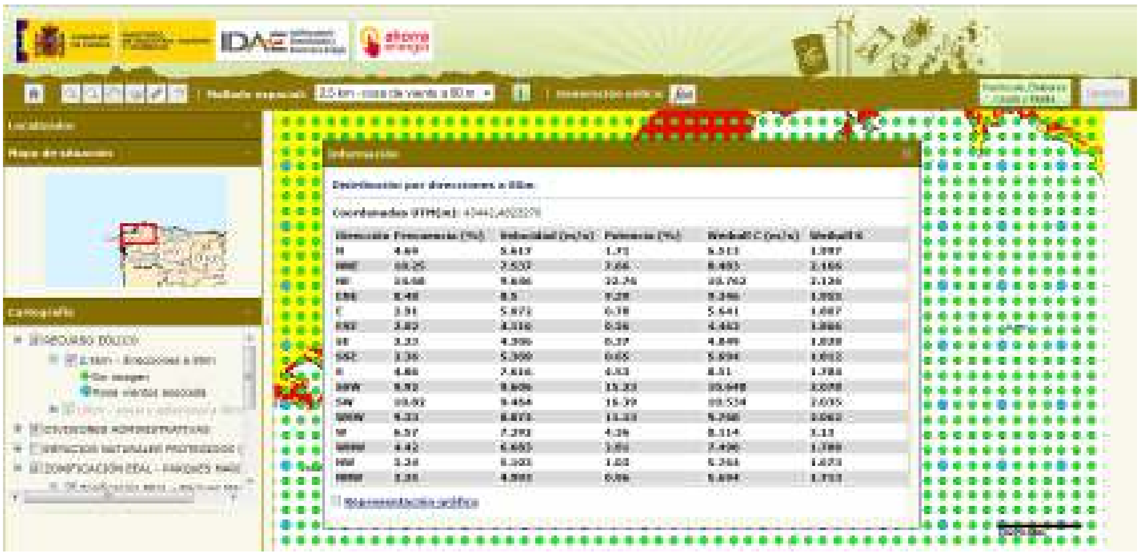


Figure A.1.11 Wind rose of the zone at 80 m.

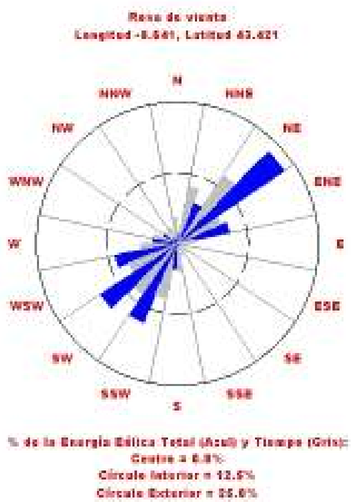


Figure A.1.12 Graphic representation of the wind rose.

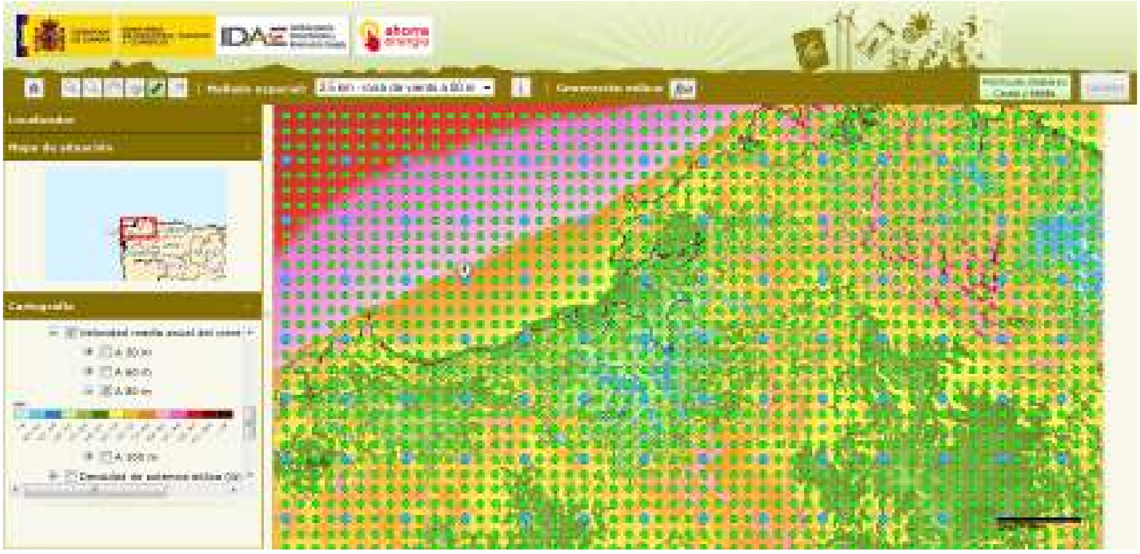


Figure A.1.13 Wind resource at 80m. In our study from 7,5 to 8 m/s.

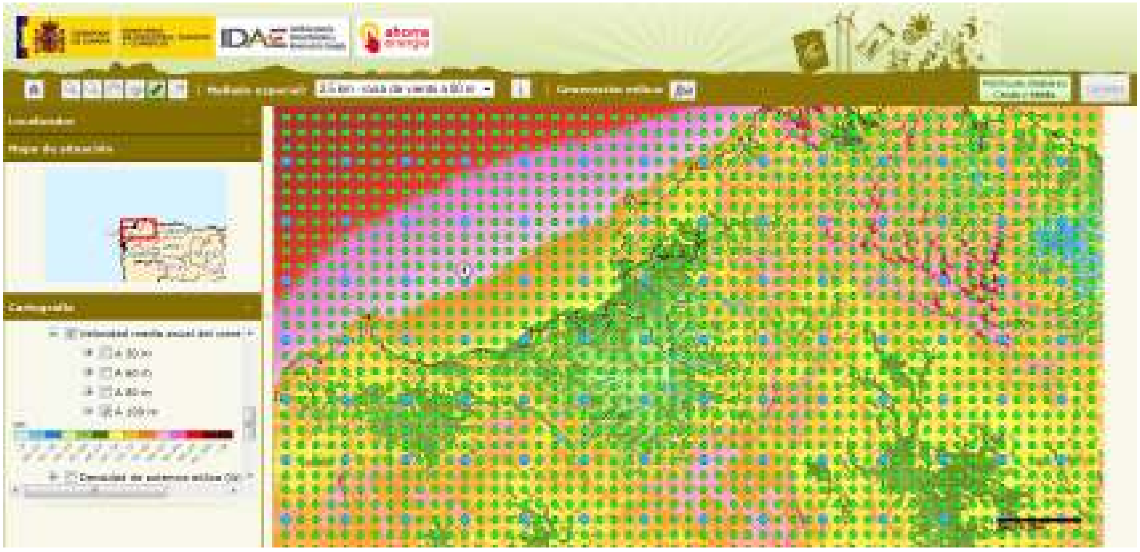


Figure A.1.14 Wind resource at 100m. In our study from 8 to 8,5 m/s.

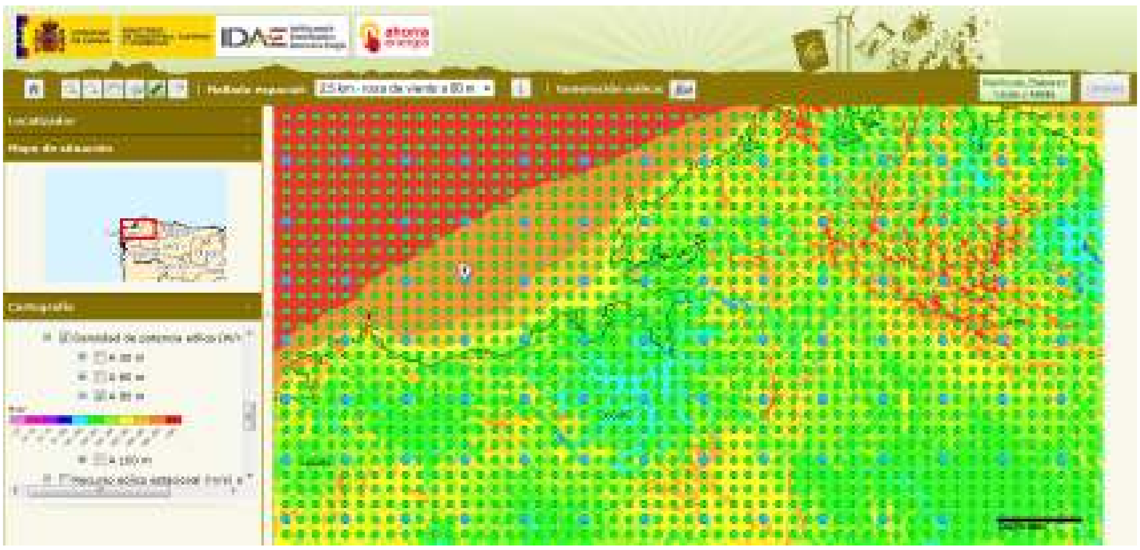


Figure A.1.15 Wind power density at 80m. In our study from 600 to 800 W/m^2.

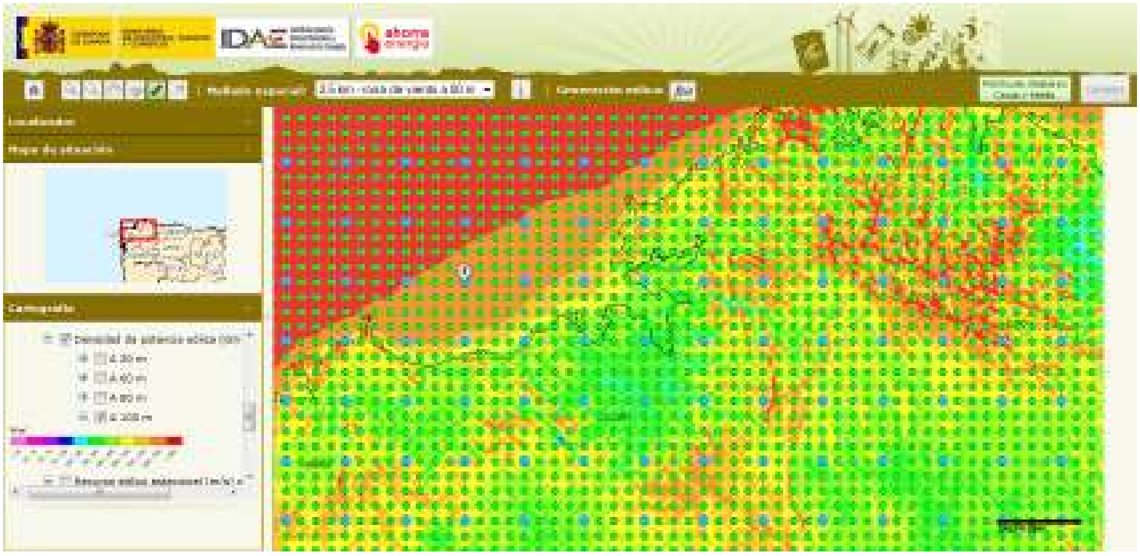


Figure A.1.16 Wind power density at 100m. In our study from 600 to 800 W/m^2.

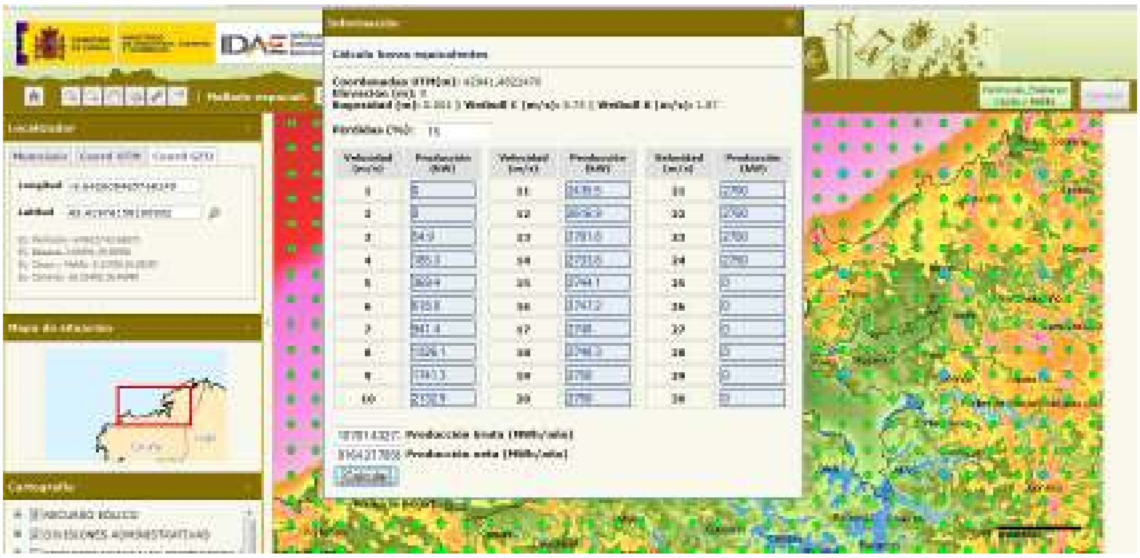


Figure A.1.17 Weibull parameters c and k with values of 8,75 and 1,87 m/s respectively.
Gross annual production 10.781,43 GWh/year with V66-2MW wind turbine.
Net annual production 9.164,22 GWh/year with V66-2MW wind turbine.
[Calculated with IDAE's program]

2. Maps of Andalusia

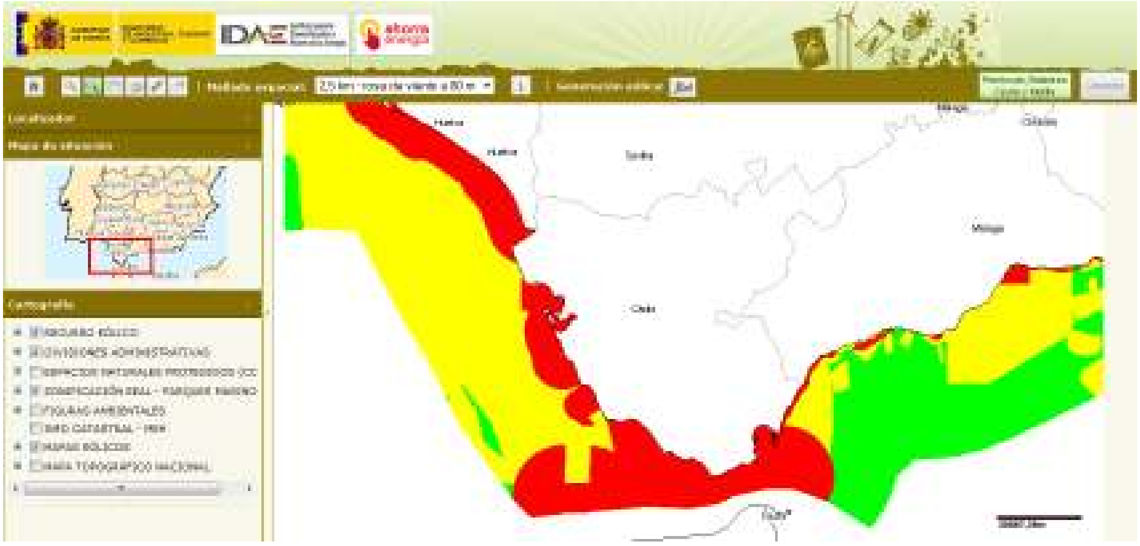


Figure A.2.1 Map of the zoning of offshore areas. In red exclusion zones, in yellow with restriction and in green suitable areas.

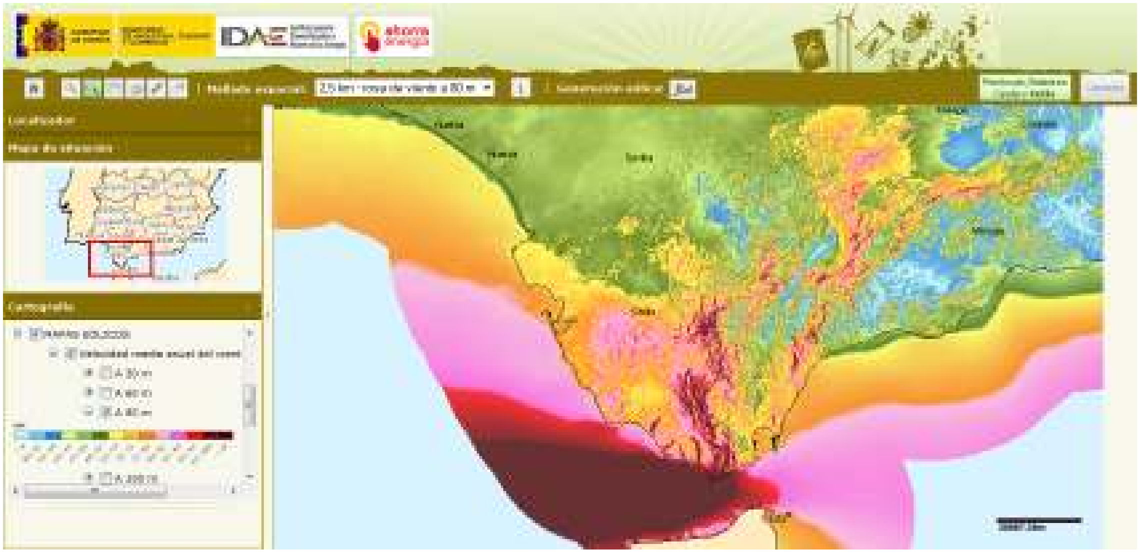


Figure A.2.2 Annual mean wind speed at 80 m [m/s].

Figure A.2.3 Annual mean wind speed at 100 m [m/s].

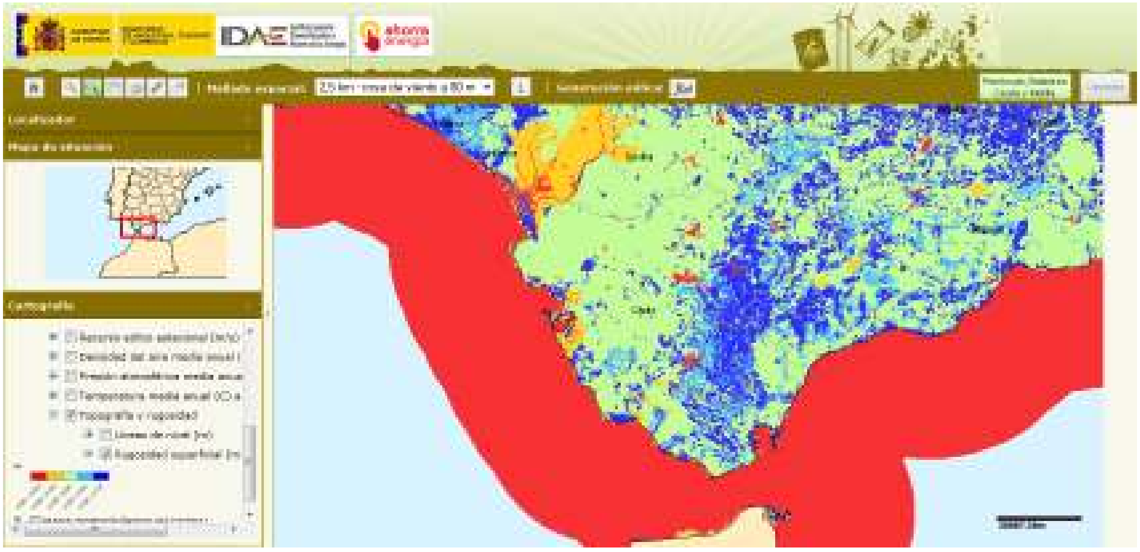


Figure A.2.4 Surface roughness [m].

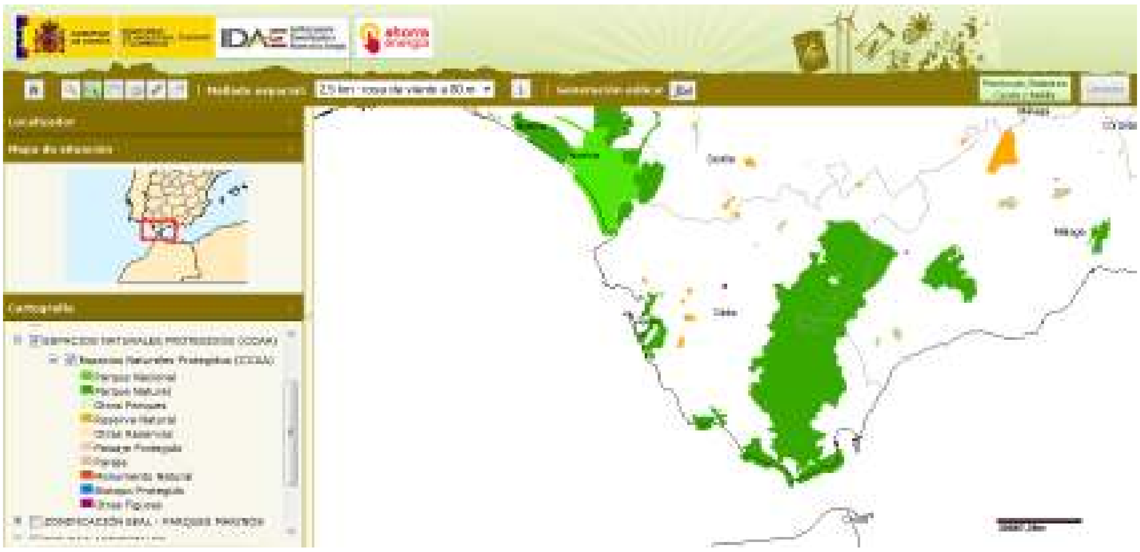


Figure A.2.5 Protected natural areas.

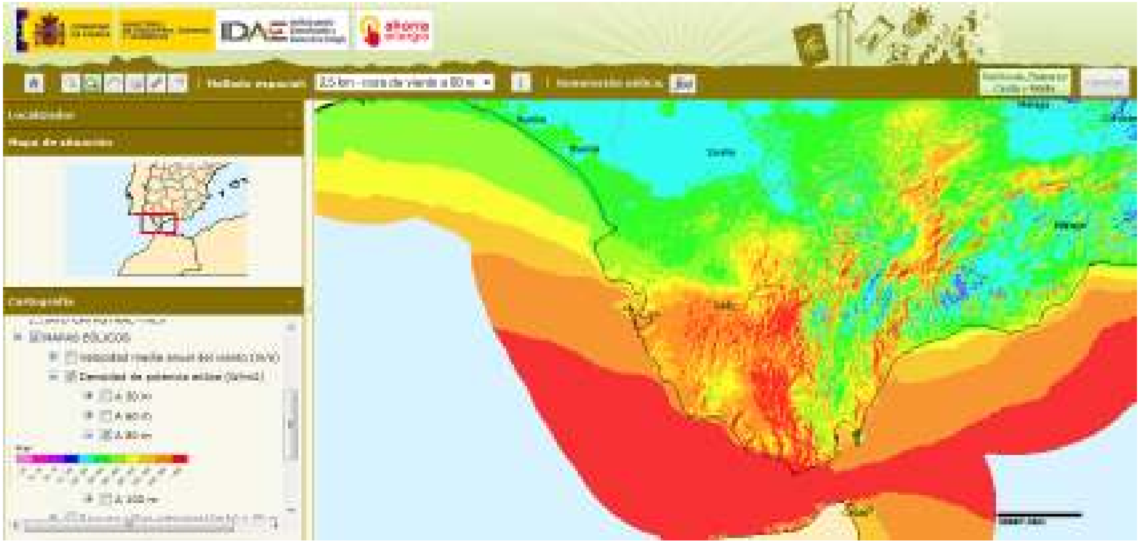


Figure A.2.6 Wind power density at 80m [W/m^2].

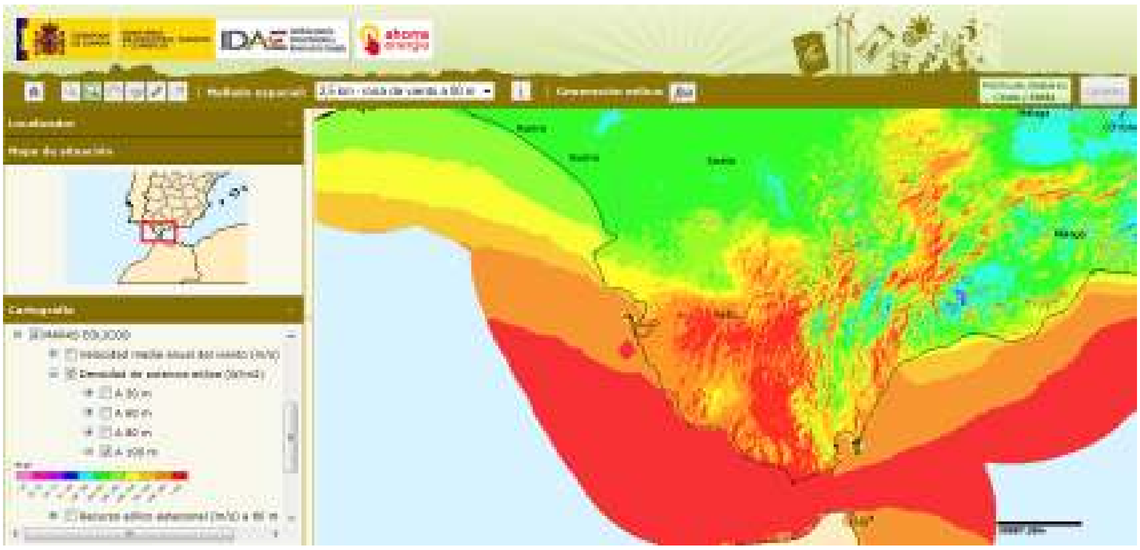


Figure A.2.7 Wind power density at 100m [W/m^2].

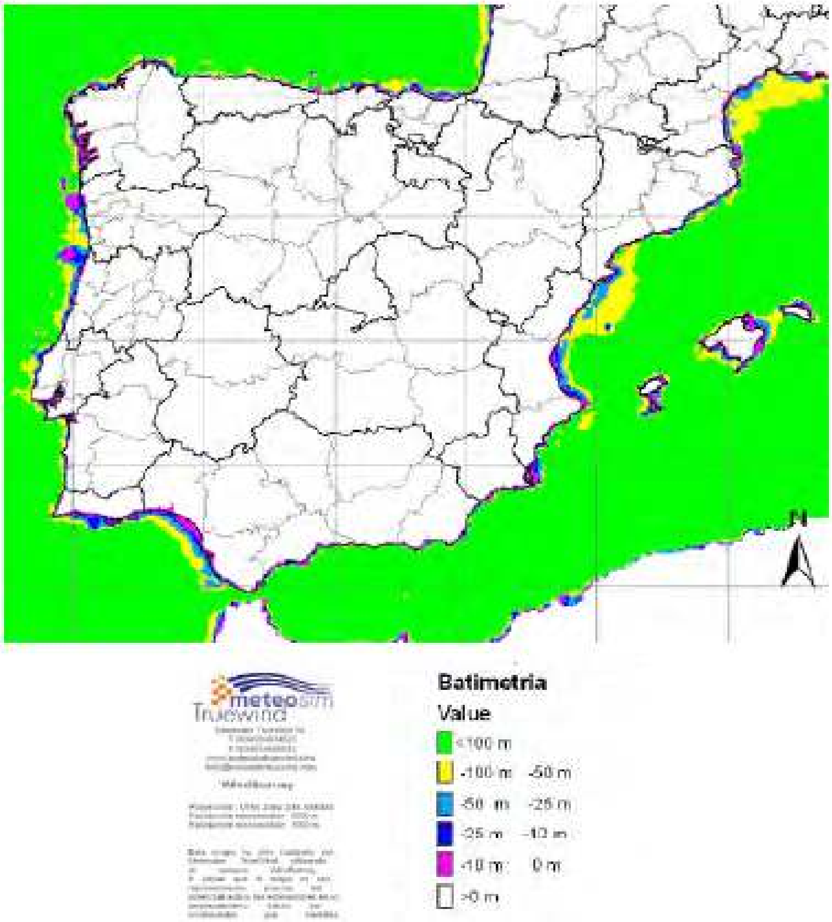


Figure A.2.8 Bathymetry of Spain. In the Andalusia zone the depth is between 25 and 100m.

Figure A.2.9 Area chosen for the construction of the wind farm, which is at a distance of 15,077 km from the coast.

Figure A.2.10 Coordinates of the zone X: 216943,22857142857 Y: 3998871,448207171 (UTM Zona 30 ED50).

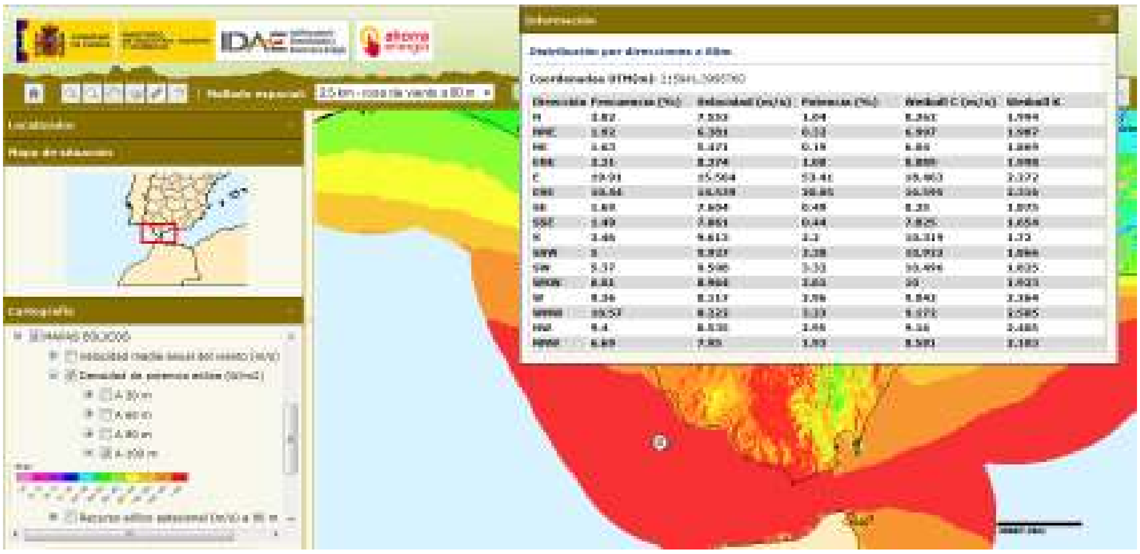


Figure A.2.11 Wind rose of the zone at 80 m. There is no graphic representation for this point.

Figure A.2.12 Wind resource at 80m. In our study from 9,5 to 10 m/s.

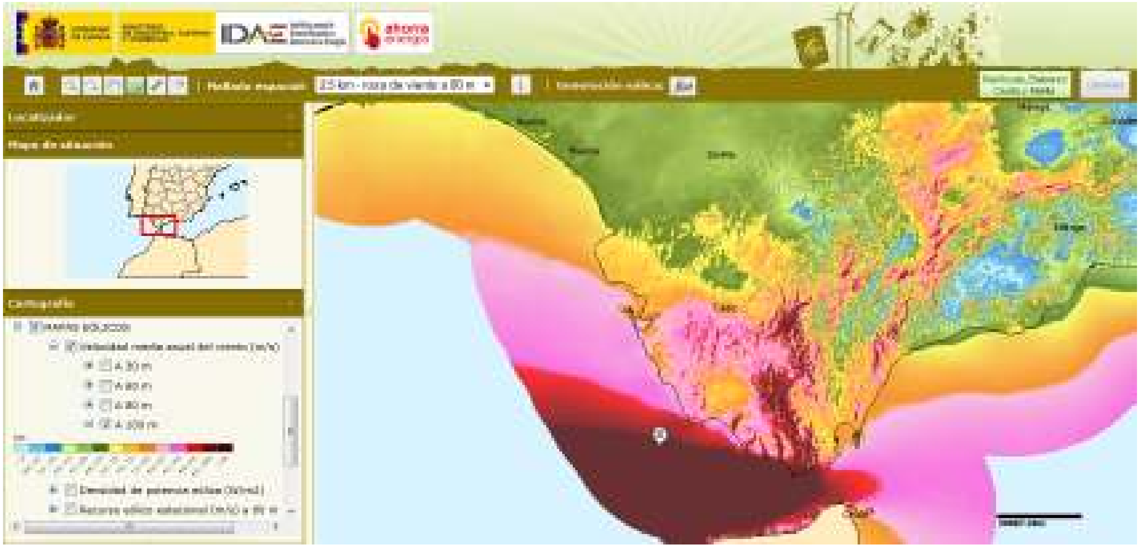


Figure A.2.13 Wind resource at 100m. In our study from 9,5 to 10 m/s.

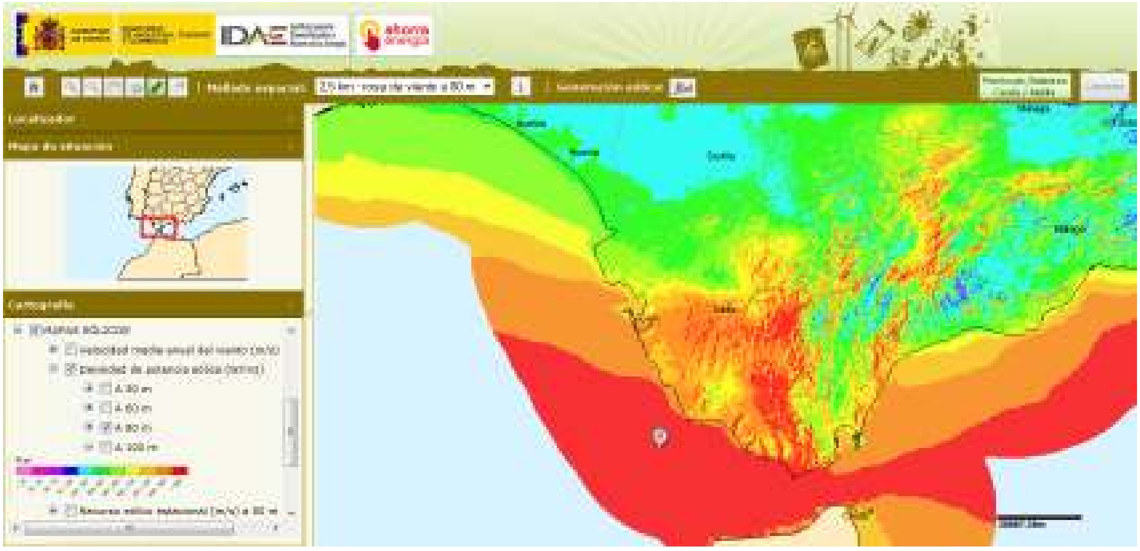


Figure A.2.14 Wind power density at 80m. In our study higher than 800 W/m^2.

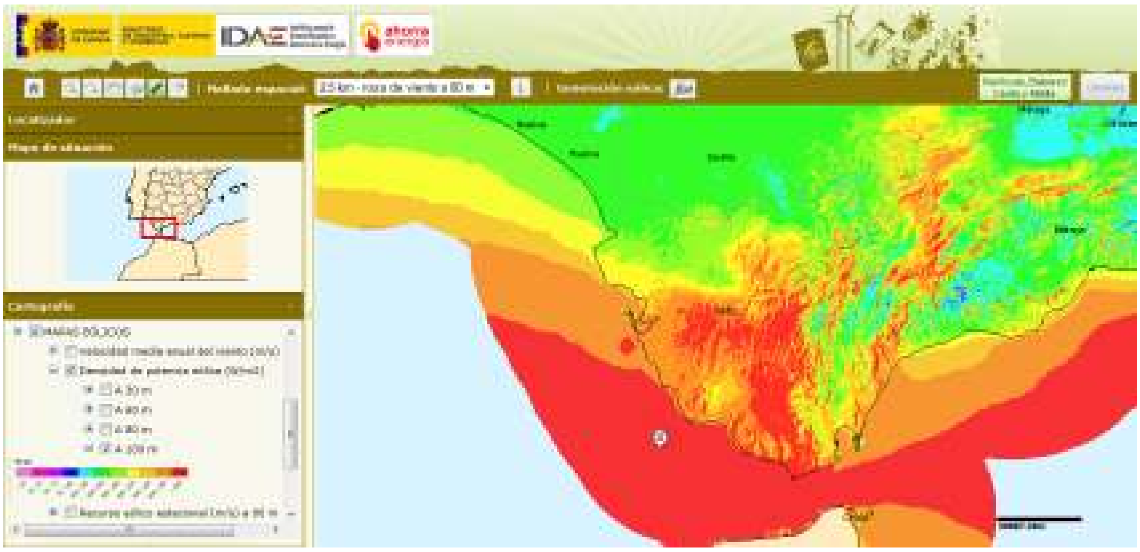


Figure A.2.15 Wind power density at 100m. In our study from higher than 800 W/m^2.

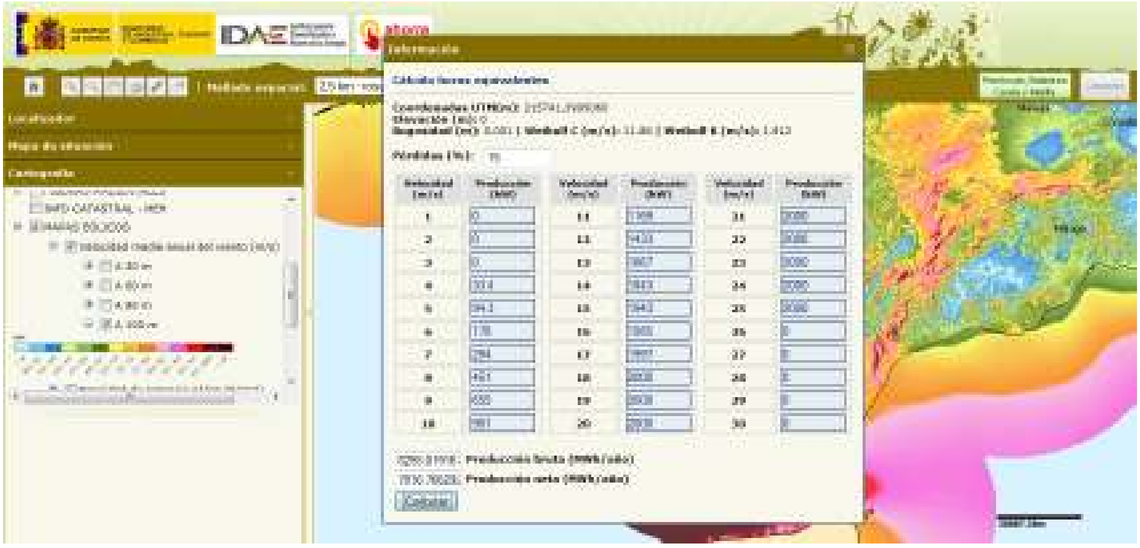


Figure A.2.16 Weibull parameters c and k with values of 11,86 and 1,912 m/s respectively.
Gross annual production 8.255,01 GWh/year with V66-2MW wind turbine.
Net annual production 7.016,76 GWh/year with V66-2MW wind turbine.
[Calculated with IDAE's program]

3. Maps of Catalonia

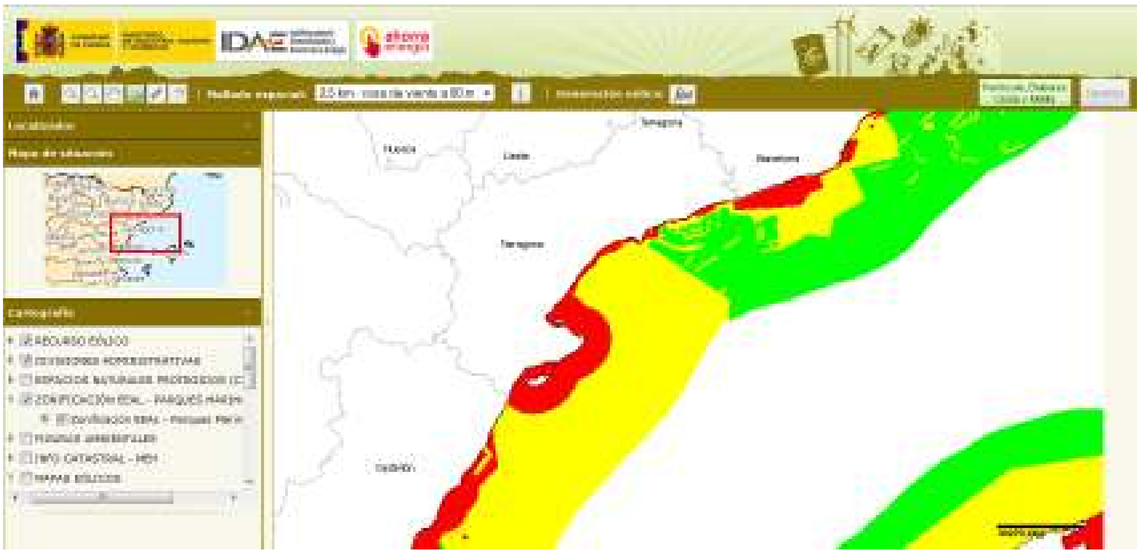


Figure A.3.1 Map of the zoning of offshore areas. In red exclusion zones, in yellow with restriction and in green suitable areas.

Figure A.3.2 Annual mean wind speed at 80 m [m/s].

Figure A.3.3 Annual mean wind speed at 100 m [m/s].

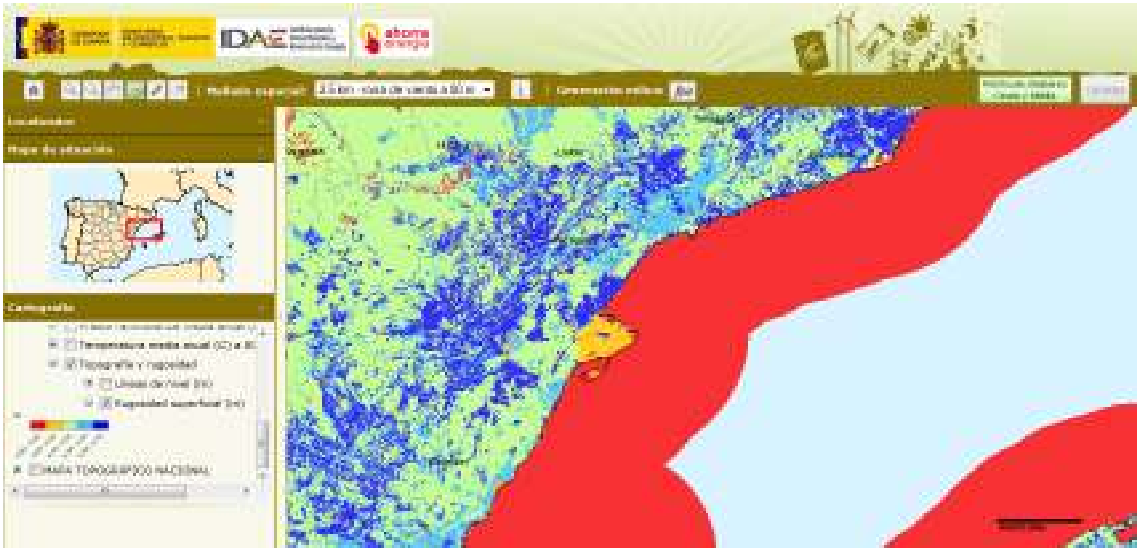


Figure A.3.4 Surface roughness [m].

Figure A.3.5 Protected natural areas.

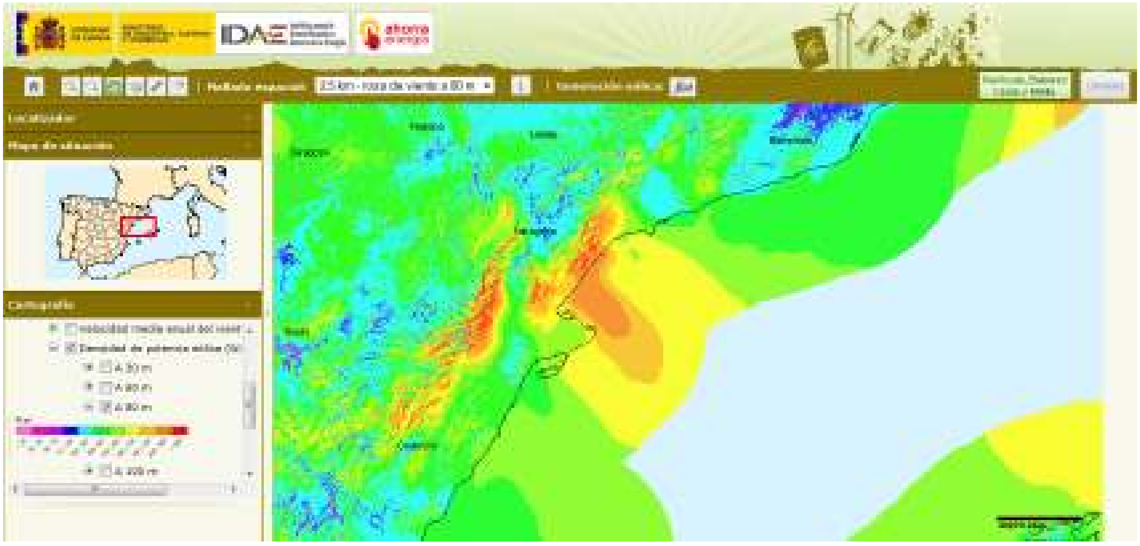


Figure A.3.6 Wind power density at 80m [W/m^2].

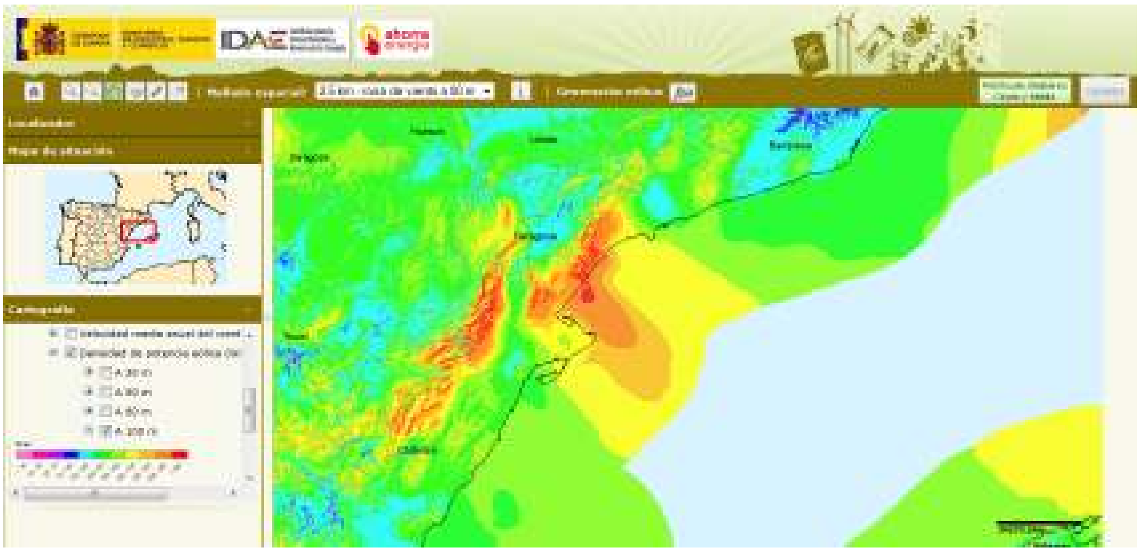


Figure A.3.7 Wind power density at 100m [W/m^2].

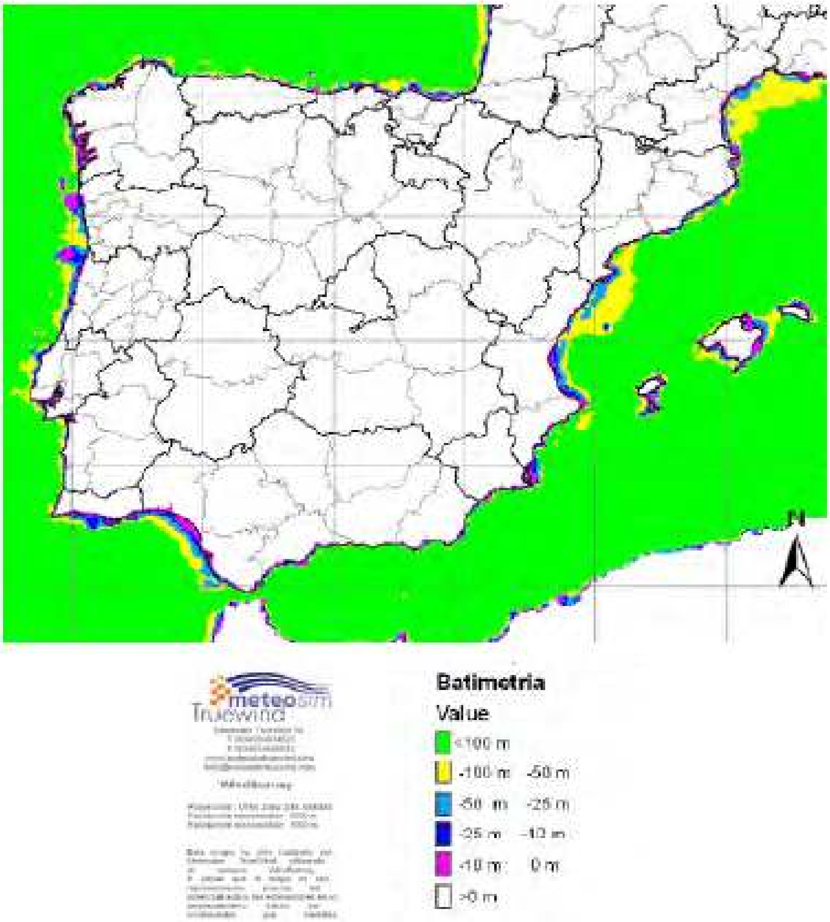


Figure A.3.8 Bathymetry of Spain. In the Catalonia zone the depth is between 25 and 50m.

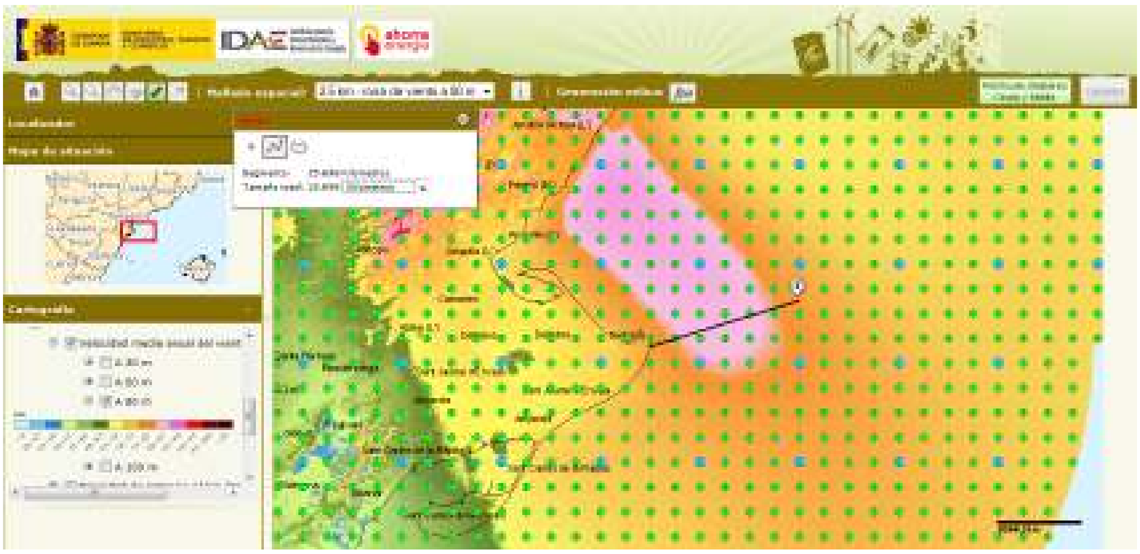


Figure A.3.9 Area chosen for the construction of the wind farm, which is at a distance of 15,696 km from the coast.

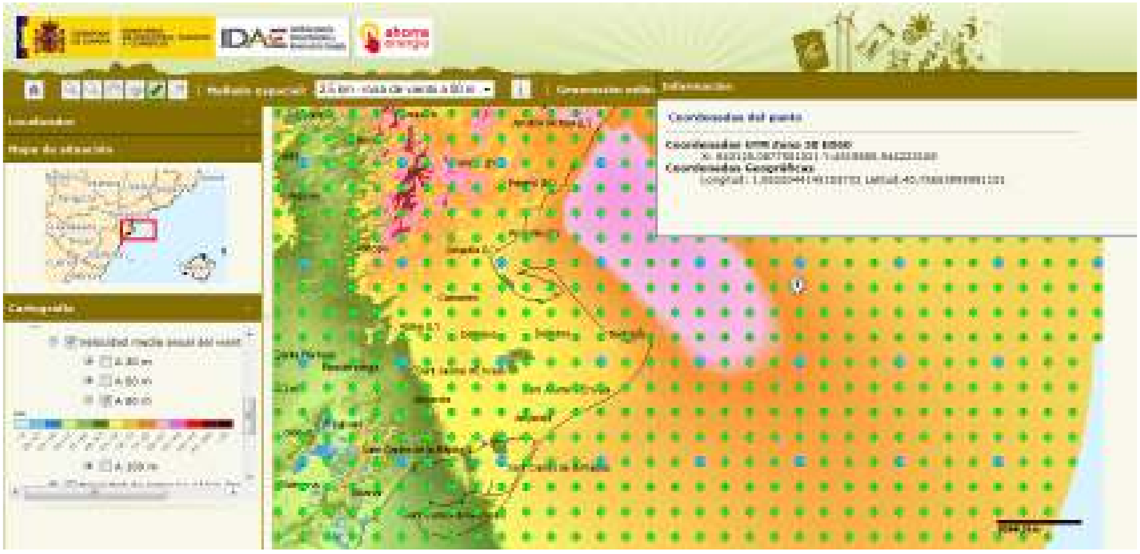


Figure A.3.10 Coordinates of the zone X: 843125,0877551021 Y: 4519885,944223108 (UTM Zona 30 ED50).

Figure A.3.11 Wind rose of the zone at 80 m. There is no graphic representation for this point.

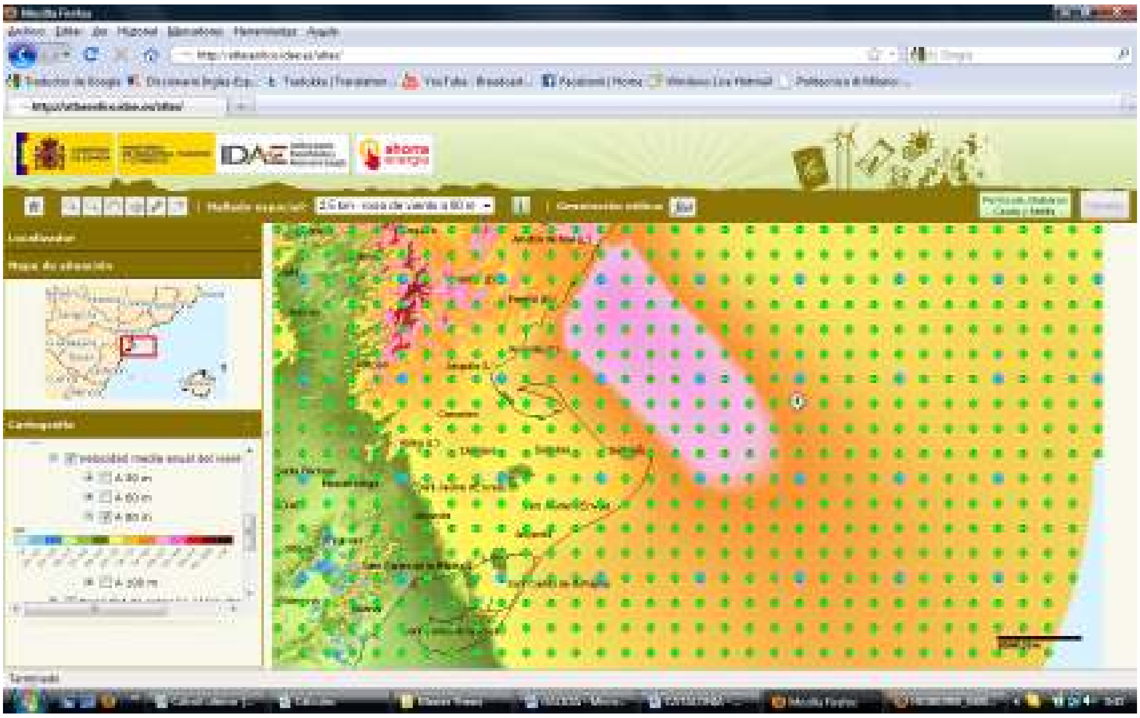


Figure A.3.12 Wind resource at 80m. In our study from 7,5 to 8 m/s.

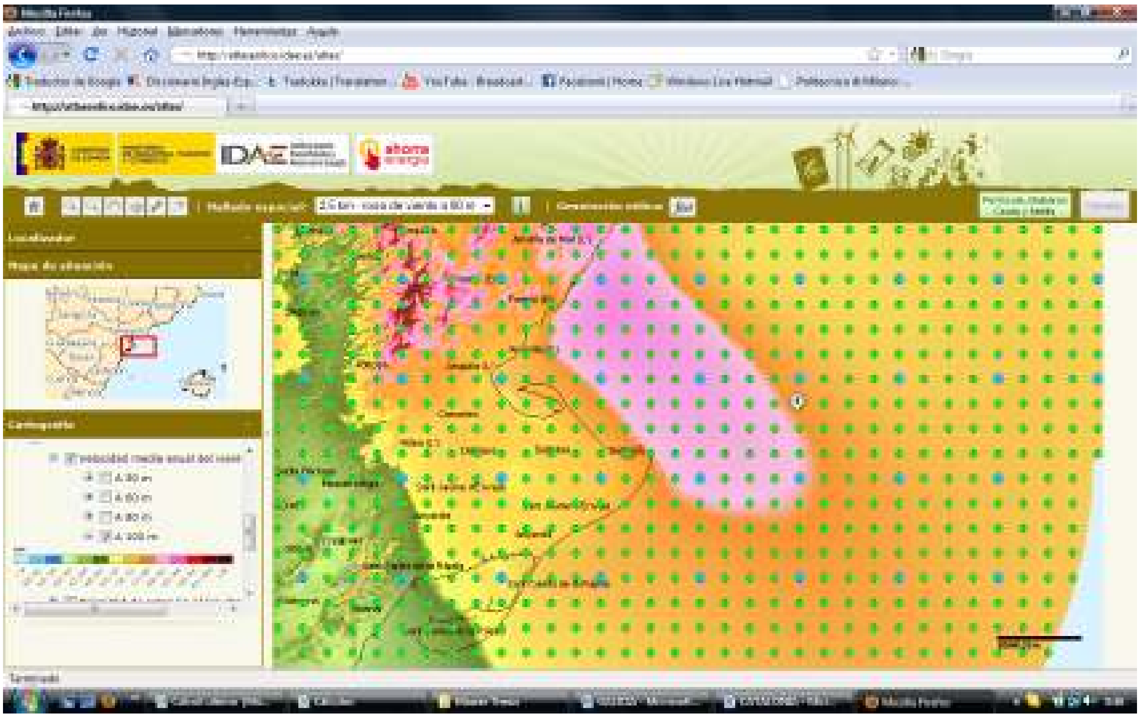


Figure A.3.13 Wind resource at 100m. In our study from 7,5 to 8,5 m/s.

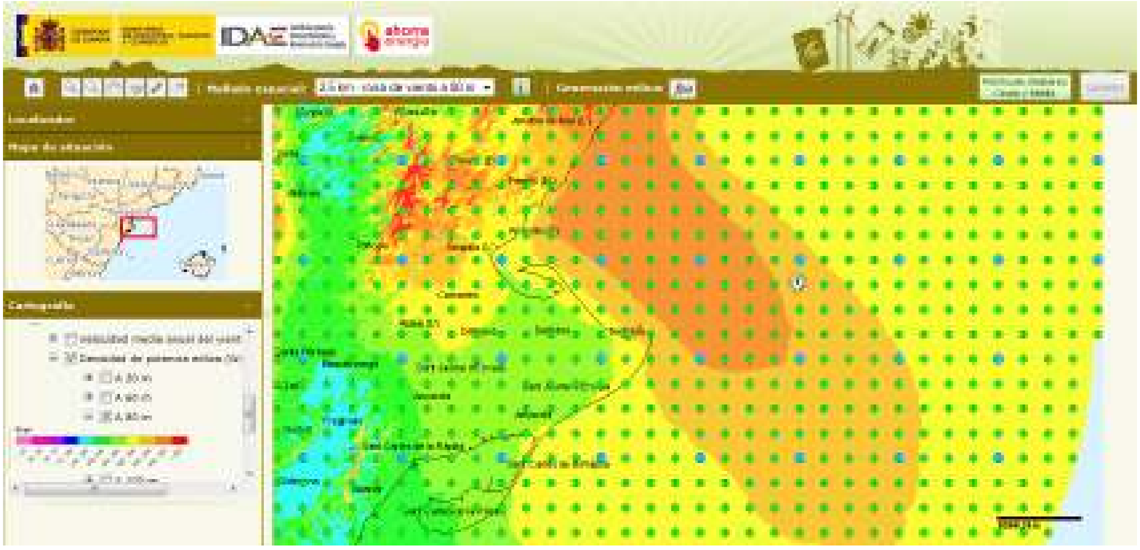


Figure A.3.14 Wind power density at 80m. In our study from 500 to 600 W/m².

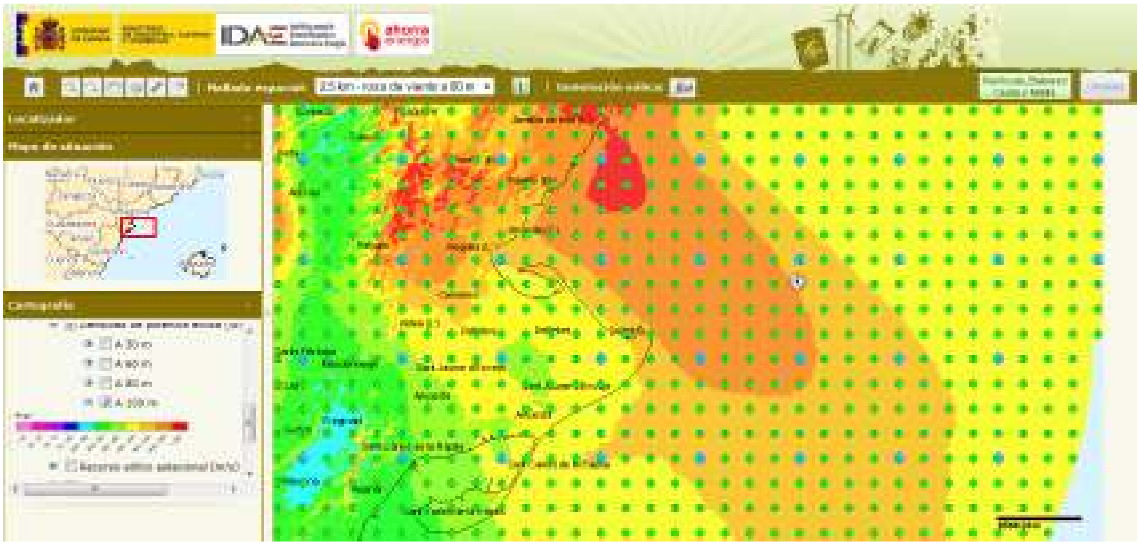


Figure A.3.15 Wind power density at 100m. In our study from 600 to 800 W/m².

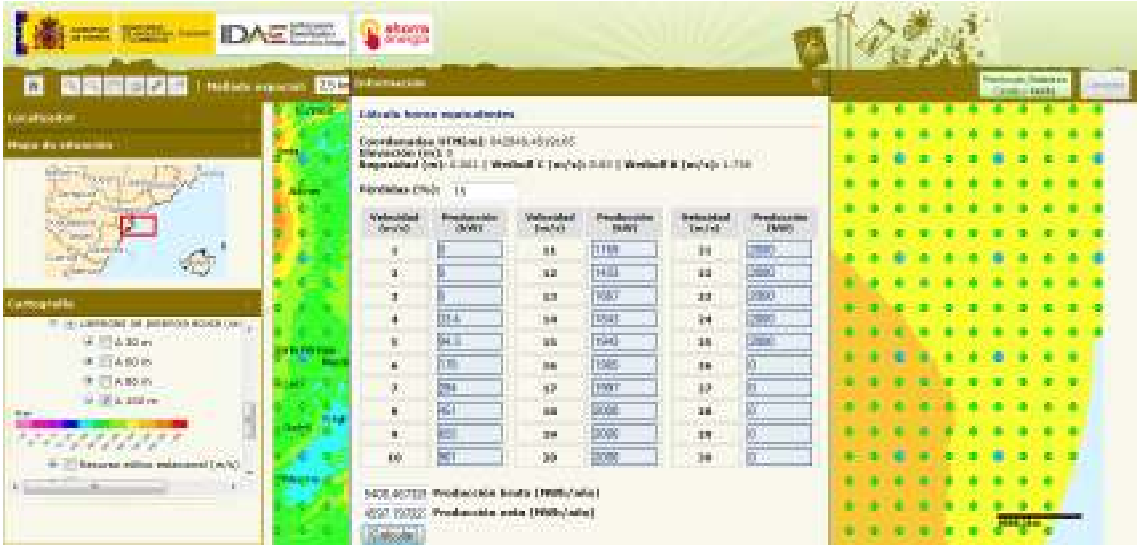


Figure A.1.17 Weibull parameters c and k with values of 8,83 and 1,736 m/s respectively.
Gross annual production 5.408,47 GWh/year with V66-2MW wind turbine.
Net annual production 4.597,19 GWh/year with V66-2MW wind turbine.
[Calculated with IDAE's program]

Vestas®

V66 – 1.75 MW & V66 – 2.0 MW (OFFSHORE)

with OptiTip® and OptiSpeed™

Offshore and onshore

There are two versions of the V66 turbine: a 2.0 MW model for offshore sites, and a 1.75 MW model for inland locations. Both versions feature a rotor diameter of 66 metres, hub heights of 60–78 metres, and, last but not least, the unique OptiSpeed™ system.

Vestas OptiSpeed™*

The V66 turbine is equipped with OptiSpeed™, a system that allows the turbine blades to rotate at variable speeds. OptiSpeed™ is a further development of the OptiSlip® system, which allowed the revolution speed of both the rotor and the generator to vary by as much as 10%. With OptiSpeed™, the revolution speed can now vary by up to approx. 60%.

OptiSpeed™ is an efficient solution because the converter only transforms the energy from the generator rotor, which is only a small part of the total energy generated by the system. The energy generated by the generator rotor is converted back into electricity suitable for the grid by the converter.

Thanks to the converter, the standard setting of the tubine prevents it from receiving reactive output from the electricity grid. However, it is possible to set the turbine to supply or receive reactive output, if required.

In short: OptiSpeed™ optimises energy production, especially in modest winds, and makes it easy to adapt the operation of the turbine to suit the parameters of the electricity grid, no matter how much the requirements from the electricity companies may vary.

Lower sound level

Sound levels are still of crucial importance when deciding on the placement of wind turbines in populous inland areas – often in places where wind speeds are not strong. Thanks to the low revolution speed of the V66 turbine in modest wind speeds, Vestas has taken yet another important step towards fulfilling requirements for a wind power solution with a low sound level. The V66 turbine also makes it possible to program the turbine sound levels before installation, so the operation of the turbine is tailor-made for the specific requirements of the chosen location.

Optimal pitch with OptiTip®

Just like all other Vestas turbines, the V66 is equipped with microprocessor-controlled OptiTip® pitch regulation, which ensures continuous and optimal adjustment of the angles of the blades in relation to the prevailing wind. The OptiTip® and OptiSpeed™ systems make it possible to optimise the solution to the often contradictory requirements for high output and low sound levels, depending on the location. On the V66 turbine, the pitch mechanism is fitted in the blade hub itself and contains a separate hydraulic pitch cylinder for each blade. These separate pitch cylinders also ensure triple braking safety, because one feathered blade is sufficient to stop the turbine.

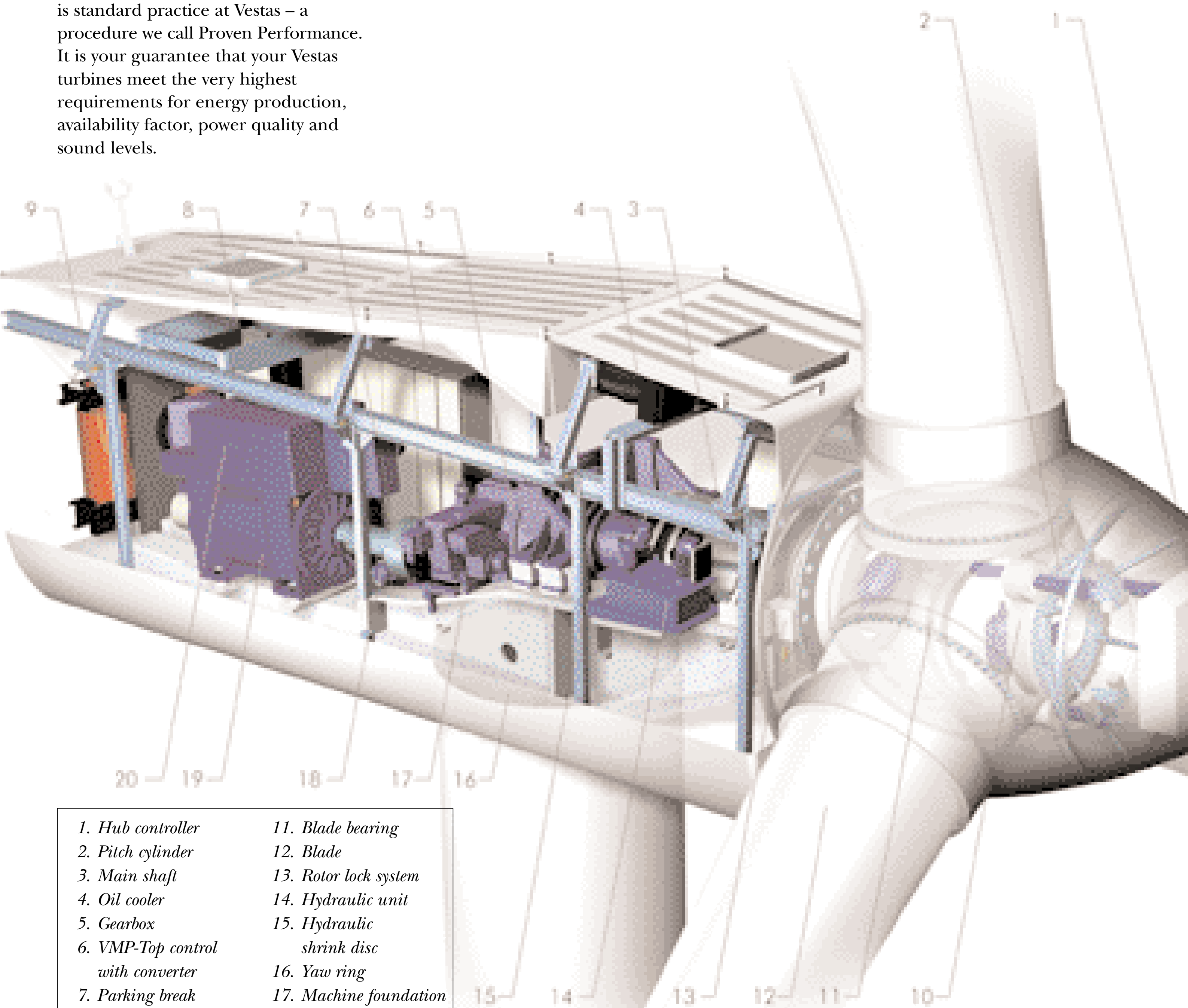
Lightning protection

Naturally, the new turbines are equipped with Vestas Lightning Protection, which protects the entire turbine from the tips of the blades to the foundations. The system conducts almost all lightning strikes harmlessly past the sensitive parts of the nacelle and down into the earth. As an extra safety measure, the delicate control units and processors in the nacelle are also protected by an efficient shielding system. The lightning protection system is an improvement of the system used on earlier Vestas turbines. Naturally, it has been thoroughly tested and conforms to both the DEFU recommendation and the applicable IEC standards.

*) Vestas OptiSpeed™ is not available in the USA and Canada

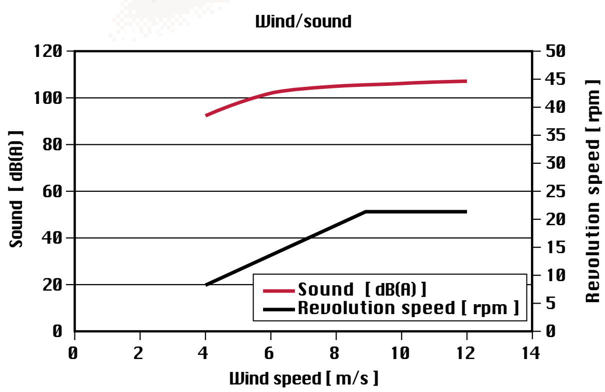
Proven Performance

We have spent many months testing and documenting the performance of the new Vestas turbines. When we were finally satisfied, we ran one last check by allowing an independent organisation to verify the results. This is standard practice at Vestas – a procedure we call Proven Performance. It is your guarantee that your Vestas turbines meet the very highest requirements for energy production, availability factor, power quality and sound levels.



1. Hub controller
2. Pitch cylinder
3. Main shaft
4. Oil cooler
5. Gearbox
6. VMP-Top control with converter
7. Parking break
8. Service crane
9. Transformer
10. Blade hub
11. Blade bearing
12. Blade
13. Rotor lock system
14. Hydraulic unit
15. Hydraulic shrink disc
16. Yaw ring
17. Machine foundation
18. Yaw gears
19. Optispeed™-generator
20. Generator cooler

The figure illustrates the relationship between wind and sound levels and the revolution speeds for turbines equipped with OptiSpeed™. It clearly shows the sound-level advantage of lower revolution speeds, as the turbine's measured sound level is approx. 15 dB(A) lower at 4 m/s than at 8 m/s. This is particularly important, as the sound from turbines is more disturbing at lower wind speeds.



ROTOR		
	V66-1.75MW	V66-2.0 MW (offshore)
Diameter:	66 m	66 m
Area swept:	3,421 m²	3,421 m²
Revolution speed:	21.3 rpm	21.3 rpm
Operational interval:	10.5-24.5	10.5-24.5
Number of blades:	3	3
Power regulation:	Pitch/OptiSpeed™	Pitch/OptiSpeed™
Air brake:	Feathered	Feathered

TOWER		
Hub height (approx.):	60 - 67 - 78 m	60 - 67 - 78 m

OPERATIONAL DATA		
Cut-in wind speed:	4 m/s	4 m/s
Nominal wind speed:	16 m/s	17 m/s
Stop wind speed:	25 m/s	25 m/s

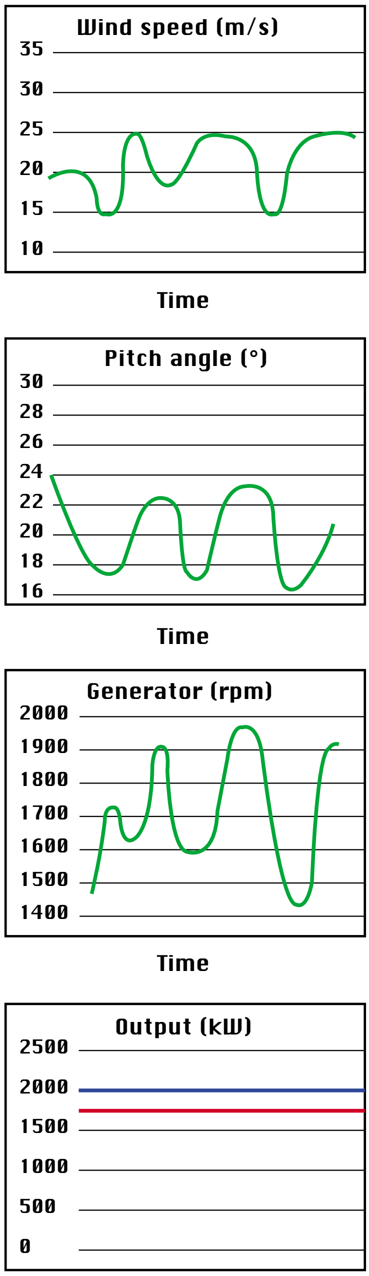
GENERATOR		
Type:	Asynchronous with OptiSpeed™	Asynchronous with OptiSpeed™
Nominal output:	1,750 kW	2,000 kW
Operational data:	50 Hz/60 Hz 690 V	50 Hz/60 Hz 690 V

GEARBOX		
Type:	1 planet step 2-step parallel axle gears	1 planet step 2-step parallel axle gears

CONTROL	
Type:	Microprocessor-based control of all the turbine functions with the option of remote monitoring. Output regulation and optimisation via OptiSpeed™ and OptiTip® pitch regulation.

WEIGHT (approx.)			
	(60 m)	(67 m)	(78 m)
Tower:	100 t	117 t	159 t
Nacelle:	57 t	57 t	57 t
Rotor:	23 t	23 t	23 t
Total:	180 t	197 t	239 t

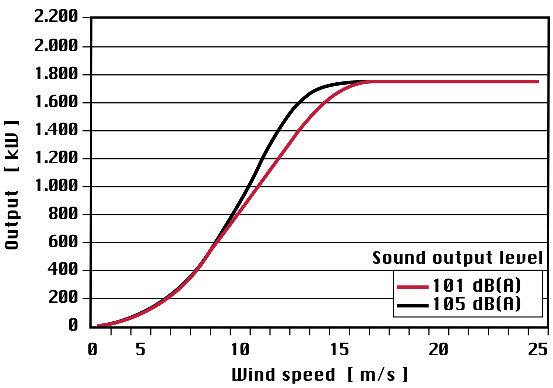
Actual measurements of Vestas V66-1.75 MW and V66-2.0 MW turbines with OptiSpeed®



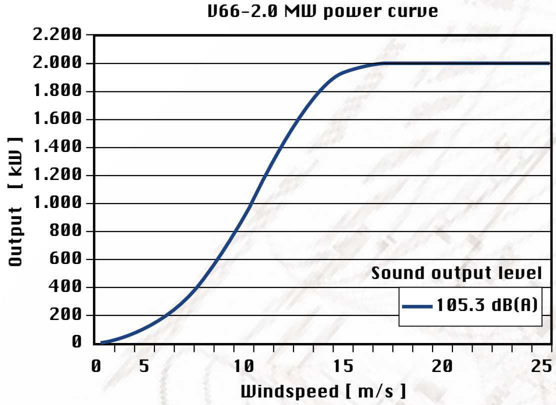
The sound output level can be adjusted by varying the revolution speed of the turbine as illustrated in the figure below. In practice, this means that the sound level recorded at a distance of 320 m (hub height 78 m), for example, can be reduced from 45 to 41 dB(A) – i.e. by more than half the recorded level.

OptiSpeed™ allows the revolution speeds of both the rotor and the generator to vary by approx. 60%. This minimises both unwanted fluctuations in the grid supply and the loads on the vital parts of the construction.

V66-1.75 MW power curves



V66-2.0 MW power curve



Profitable and flexible

To increase the performance of a wind turbine, simply increase its dimensions. That, at least, is the conventional way of thinking. And it must be said that it works, more or less. However, it is not enough simply to increase output – it is also a matter of building turbines that are better able to adapt to their surroundings, whether natural or man-made.

Using the unique Vestas OptiSpeed™ system, we have succeeded in designing a flexible turbine that adapts to its surroundings and exploits them to the full. OptiSpeed™ extends the number of potential sites for a wind turbine. For example, the sound level can be optimised to suit local conditions, and areas with modest wind are now becoming more attractive.

The external dimensions of the V66-1.75 MW and V66-2.0 MW turbines are the same as those of their predecessor, the V66-1.65 MW.

All the changes that have been made are inside the nacelle – and these are important changes. Thanks to the OptiSpeed™ system, we have managed to increase the turbine's production, improve areas such as power quality and sound level, and, at the same time, have increased its efficiency in modest wind conditions. At wind speeds as low as 4 m/s, the V66 turbines can exploit as much of the wind energy as at 8 m/s. This is something of an innovation.

If you value profitability and the ability to adapt, then you are sure to appreciate OptiSpeed™, and, of course, the V66.

Associated Companies

Vestas - Danish Wind Technology A/S
Smed Hansens Vej 27 · DK-6940 Lem
Denmark
Tel. +45 96 75 25 75
Fax +45 96 75 23 42
vestas-dwt@vestas.dk

Vestas - Scandinavian Wind Technology A/S
Smed Hansens Vej 27 · DK-6940 Lem
Denmark
Tel. +45 96 75 25 75
Fax +45 96 75 24 80
vestas-swt@vestas.dk

Vestas - International Wind Technology A/S
Smed Hansens Vej 27 · DK-6940 Lem
Denmark
Tel. +45 96 75 25 75
Fax +45 96 75 23 39
vestas-int@vestas.dk

Cotas Computer Technology A/S
Paludan-Müllers Vej 82 · DK-8200 Århus N
Denmark
Tel. +45 86 10 22 55
Fax +45 86 10 47 27
info@cotas.dk

Vestas - American Wind Technology, Inc.
19020 N. Indian Avenue, Suite 4-C
P.O. Box 278
North Palm Springs · Ca 92258
USA
Tel. +1 760 329 5400
Fax +1 760 329 5558

Vestas Deutschland GmbH
Otto-Hahn-Strasse 2
D-25813 Husum/Nordsee
Germany
Tel. +49 4841 971 0
Fax +49 4841 971 160
vestas@vestas.de

Vestasvind Svenska AB
Åkarevägen 17 · S-31132 Falkenberg
Sweden
Tel. +46 346 59050
Fax +46 346 59055
info@vestasvind.se

Vestas - Nederland Windtechnologie B.V.
Dr. Langemeijerweg 1 a
Postbus 63 · NL-6990 AB Rheden
Netherlands
Tel. +31 264971500
Fax +31 264971555

Wind Power Invest A/S
Smed Hansens Vej 27 · DK-6940 Lem
Denmark
Tel. +45 96 75 25 75
Fax +45 96 75 24 36
vestas@vestas.dk.

Joint Venture Companies

Vestas RRB India Ltd.
161, Sukhdev Vihar
New Delhi 110 025
India
Tel. +91 11 6838365
Fax +91 11 6835160
VRRB@gndel-vestas.global.net.in

Gamesa Eólica s.a.
Poligono Comarca 1 (Agustinos)
E-31013 Pamplona
Spain
Tel. +34 9 48 30 90 10
Fax +34 9 48 30 90 09
telemando.gamesaeolica@nexo.es

IWT - Italian Wind Technology, S.r.l.
Via Ariosto 12 · Zone Industriale
I-74100 Taranto
Italy
Tel. +39 099 4 606 111
Fax +39 099 4 606 333

With quality and care we use the wind to create competitive, environmentally friendly energy

Vestas Wind Systems A/S
Smed Sørensens Vej 5
DK-6950 Ringkøbing
Denmark
Tel. +45 96 75 25 75
Fax +45 96 75 24 36
vestas@vestas.dk
www.vestas.dk

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GE Energy

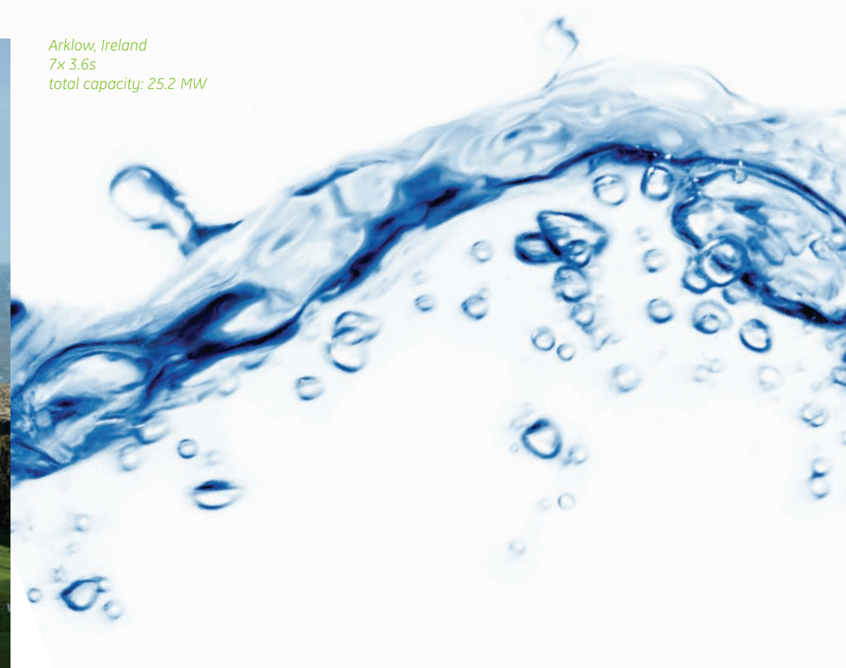
3.6 MW

Offshore Series Wind Turbine

ecomagination[SM]
a GE commitment

imagination at work

Arklow, Ireland
7x 3.6s
total capacity: 25.2 MW

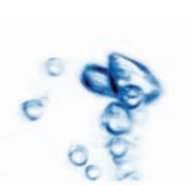


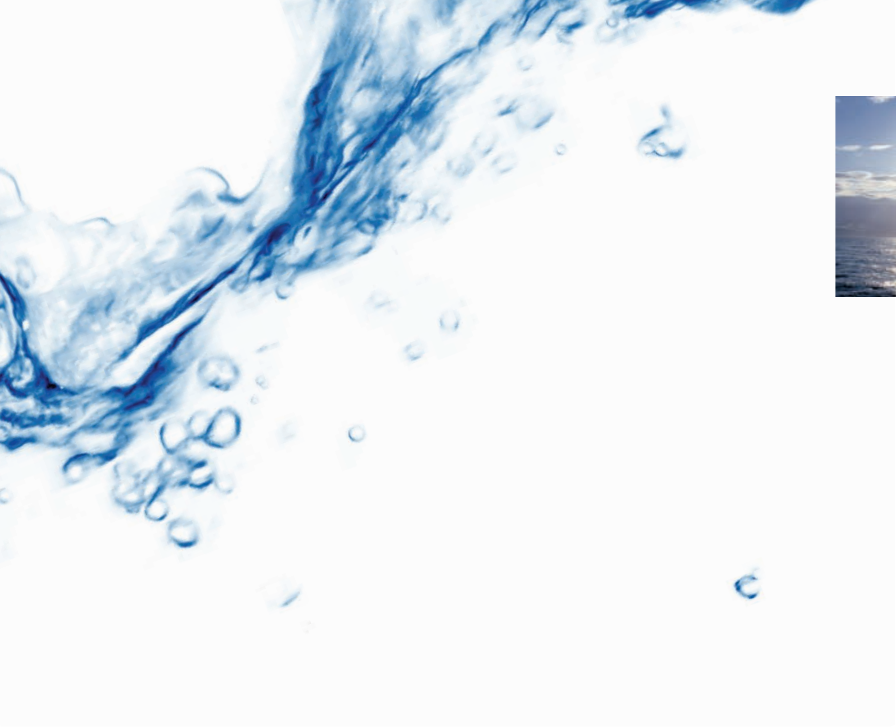
As the world's first commercially available wind turbine expressly designed for offshore use, our 3.6 MW series machine combines the best of our proven 1.5 MW technology with valuable expertise gained from building and operating two of the world's first multi-megawatt class off-shore wind facilities.

Engineered for high-speed wind sites and the harsh marine environment, our 3.6 MW machine features an exceptionally robust marinized design. Active yaw and pitch regulated with power/torque control capability and a double-fed asynchronous generator, it utilizes a distributed drive train design in which all nacelle components are joined on a common structure, providing exceptional durability. The generator and gearbox are supported by elastomeric elements to minimize noise emissions. The electrical container, located directly beneath the nacelle, houses the control panel, converter, switching systems and transformer. It also provides easy access for maintenance workers and protection against corrosion. Optional cranes simplify the maintenance process, higher-efficiency blades resist dirt and abrasion, and structural improvements enhance load absorption, allowing greater reliability and longer service intervals – an important cost-savings feature, considering the rigors of offshore power generation. The 3.6 MW offshore wind turbine also employs a variety of features inherent in GE's full line of wind turbines which range from 1.5 to 3.6 MW, for both on and offshore use. Special features include...

GE's Fleet-Wide Features and Benefits

Feature	Benefit
Variable Hub heights & rotor diameters	Provides versatility/adaptability to a wide variety of project sites
Variable Speed Control and Advanced Blade Pitch	Enables aerodynamic efficiency and reduces loads to the drive train, thereby reducing maintenance cost and providing longer turbine life
WindVAR (optional) (Wind-Volt-Amp-Reactive "WindVAR")	GE's unique electronics provide transmission efficiencies and enable harmonious function within the local grid
Low Voltage Ride-Thru (optional)	Allows wind turbines to stay on line generating power, even during grid disturbances.





Arklow, Ireland
7x 3.6s
total capacity: 25.2 MW

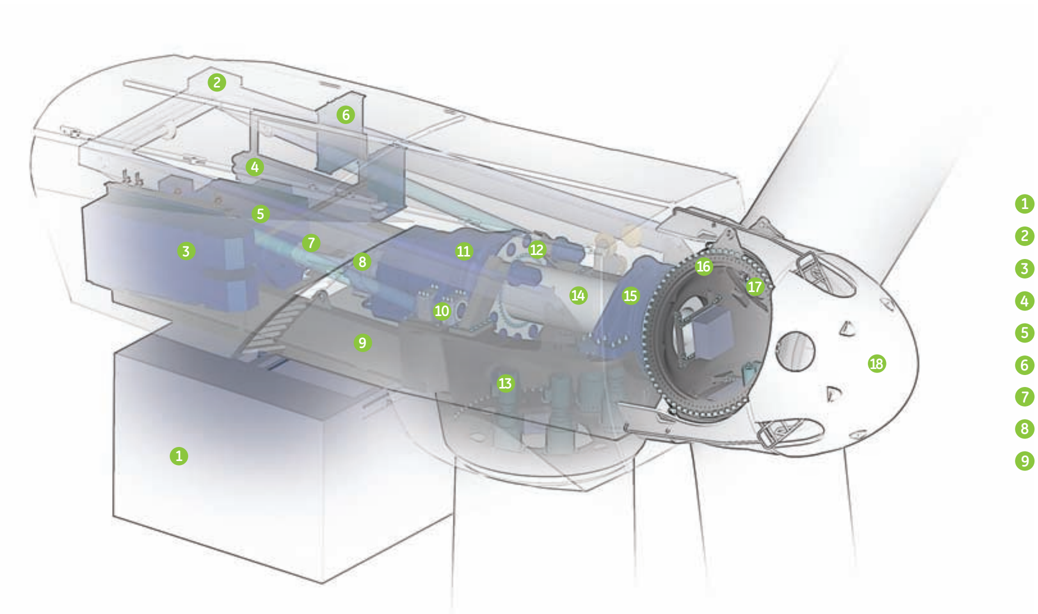
In support of future offshore wind energy development, in 2003, GE built and now operates the world's first commercial offshore wind facility utilizing its 3.6 MW offshore technology. Built as a technology demonstration and learning platform for offshore wind power, GE's 25-megawatt Arklow Bank Wind Park has been operating in the harsh conditions of the Irish Sea since June 2004. To date, valuable lessons learned have been abundant and are being integrated into GE's future wind technologies, with a focus on increased cost-effectiveness, reliability and safety.

Earlier, In year 2000, the world's first "megawatt-class" offshore wind farm, Utgrunden, was completed off the south east coast of Sweden. Designed, built and operated by our team, this knowledge base has been incorporated into our 3.6 MW offshore wind turbines.

As one of the world's leading wind turbine suppliers, GE Energy's current product portfolio includes wind turbines with rated capacities ranging from 1,500 to 3,600 kilowatts and support services extending from development assistance to operation and maintenance. We currently design and produce wind turbines in Germany, Spain and the U.S.

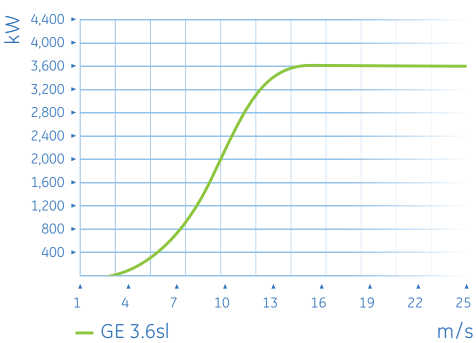
Arklow, Ireland
7x 3.6s
total capacity: 25.2 MW

Our facilities are registered to ISO 9001:2000. Our Quality Management System, which incorporates our rigorous Six Sigma methodologies, provides our customers with quality assurance backed by the strength of GE. We know that wind power will be an integral part of the world energy mix in this century and we are committed to helping our customers design and implement energy solutions for their unique energy needs. Every relationship we pursue bears our uncompromising commitment to quality and innovation.



1 Offshore container
2 Small gantry crane
3 Generator heat exchanger
4 Control panel
5 Generator
6 Oil cooler
7 Coupling
8 Hydraulic parking brake
9 Main frame
10 Impact noise insulation
11 Gearbox
12 Rotor lock
13 Yaw drive
14 Rotor shaft
15 Bearing housing
16 Rotor hub
17 Pitch drive
18 Nose cone

Power Curve



Technical Data 3.6sl

Operating data

• Rated capacity:	3,600 kW
• Cut-in wind speed:	3,5 m/s
• Cut-out wind speed:	27 m/s
• Rated wind speed:	14 m/s

Rotor

• Number of rotor blades:	3
• Rotor diameter:	111 m
• Swept area:	9677 m^2
• Rotor speed (variable):	8,5 – 15,3 rpm

Tower

• Hub heights:	Site dependent

Power control — Active blade pitch control

Design data

IEC 61400-1 ed2: Type class S*

Gearbox
- Three step planetary spur gear system

Generator
- Doubly-fed asynchronous generator

Converter
- Pulse-width modulated IGBT frequency converter

Braking system (fail-safe)
- Electromechanical pitch control for each blade (3 self-contained systems)
- Hydraulic parking brake

Yaw system
- Electromechanical driven with wind direction sensor and automatic cable unwind

Control system
- PLC (Programmable logic controller) Remote control and monitoring system

Offshore container
- Protecting converter, low voltage distribution panel, transformer and control system

Lightning protection system
- Lightning receptors installed along blades
- Surge protection in electrical components
- Lightning path to ground designed to protect main bearing
- Electrical container acts as a Faraday cage, protecting the equipment against lightning strikes

Offshore tower and foundation design
- Site-specific design: monopile, transition piece, and two-section tubular steel tower
- Transition piece incorporates safe access systems and medium voltage connections

* class 1 mean & extreme, class C turbulence per 61400-1 ed.3

Subject to technical alterations, errors and omissions.

www.gewindenergy.com

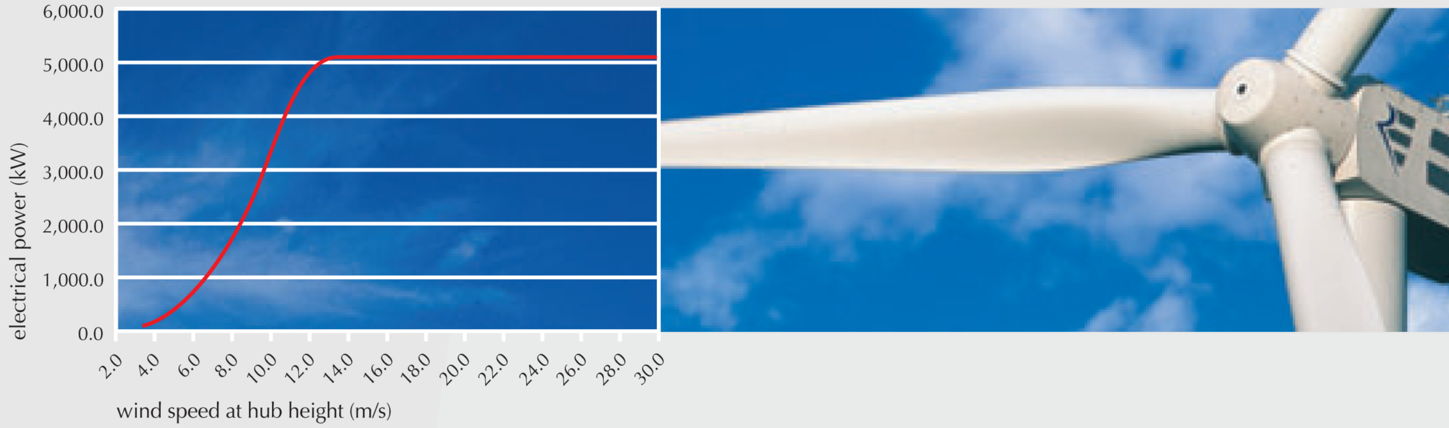
Proven technology in a new dimension

The REpower 5M takes our internationally renowned technology to a new dimension. Its innovative, detailed design reinforces our leadership in the provision of technical solutions. With a rated power of 5 megawatt and a rotor diameter of 126 metres, the 5M is one of the largest and most powerful wind turbines in the world. The 5M sets new standards for the economic viability of windfarms, especially in offshore installations.

Windfarms with turbines of this size achieve outputs similar to conventional power plants. This in turn puts high demands on the control and regulation system because optimised integration into the power grid is essential. In the 5M, REpower has once again shown how compatibility with the grid can be optimised. The 5M can be easily integrated into the grid, just like any other power plant of its size.

Due to its modular structure and logistical flexibility, the 5M is suitable for onshore and offshore installation. The offshore version is specifically designed to withstand extreme environmental conditions. This includes, for example, redundancy of key components to guarantee maximum availability, effective protection against corrosion and a permanent monitoring system.

Our comprehensive and efficient service ensures reliable and cost-effective operation of the 5M over its entire service life.



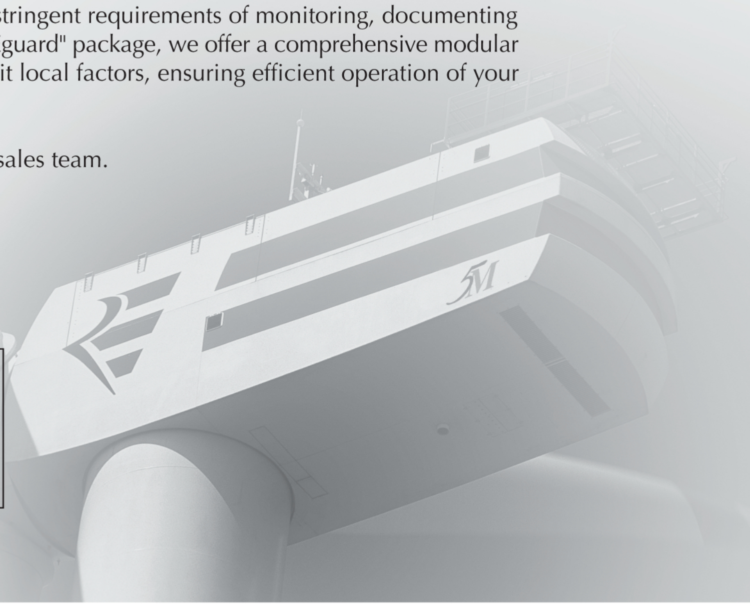
Powerful, economical, reliable

By choosing REpower turbines, you are selecting power plant technology of the highest quality. To ensure that your investment retains its value, we offer comprehensive after-sales service.

Our permanent system monitors your power plants 24 hours a day, 365 days a year ensuring the quickest possible response times of our local service teams. We also offer integrated service packages (ISP-onshore and OSP-offshore) that allow you to calculate your long-term operating costs.

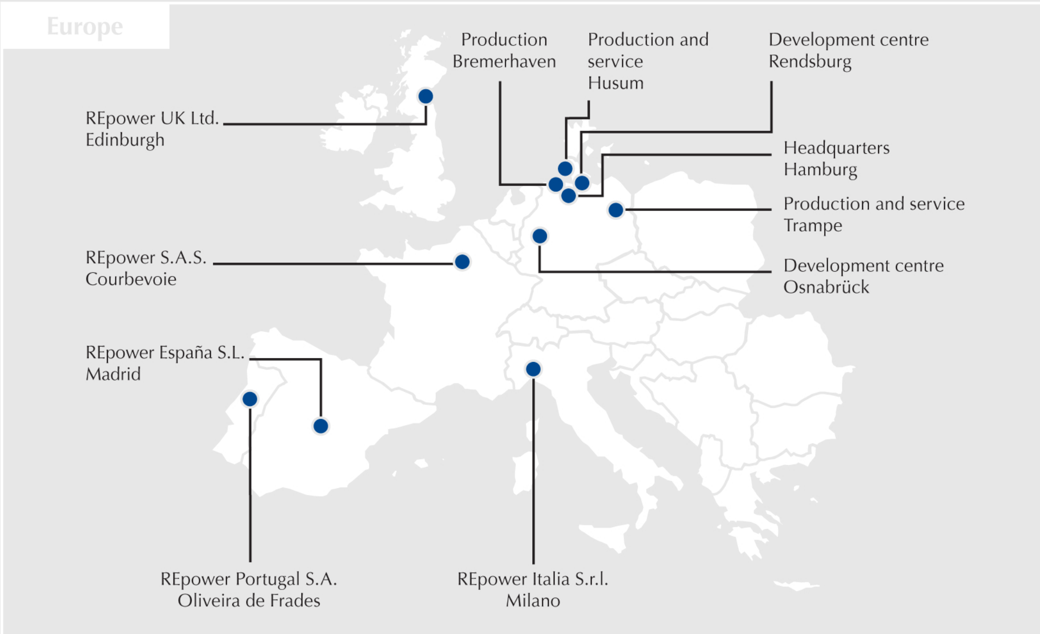
We are constantly upgrading our services to meet the increasingly stringent requirements of monitoring, documenting and optimising the operational behaviour of windfarms. With our "REguard" package, we offer a comprehensive modular windfarm management system that can be flexibly configured to suit local factors, ensuring efficient operation of your plant at all times.

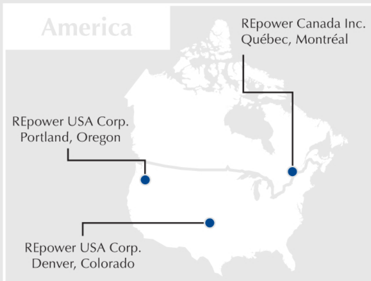
For more information, please refer to our brochures or contact our sales team.



03/2010

The REpower sales teams are always there for you.





Please visit our website: at **www.repower.de ▶ Company ▶ REpower Germany** or **REpower International** you can find the addresses of all our company sites.

	MM82	MM92	3.4M104	3.2M114	5M	6M
Rated power	2,050 kW	2,050 kW	3,370 kW	3,170 kW	5,075 kW	6,150 kW
Rotor diameter	82.0 m	92.5 m	104.0 m	114.0 m	126.0 m	126.0 m

REpower Systems AG · Headquarters · Überseering 10 · 22297 Hamburg · Germany
Phone: +49-40-5 55 50 90-0 · Fax: +49-40-5 55 50 90-39 99
E-mail: info@repower.de · www.repower.de

The 5-megawatt power plant
with 126 metre rotor diameter

Technical data

Design data

Rated power	5,075 kW
Cut-in speed	3.5 m/s
Rated wind speed	14.0 m/s
Cut-out speed	25.0 m/s onshore 30.0 m/s offshore
Type class	Offshore IEC IB, REpower S-Classes Onshore IEC IB, IEC IIA

Rotor

Diametre	126.0 m
Rotor area	12,469 m^2
Rotor speed	7.7 – 12.1 rpm (+15.0 %)

Rotor blade

Length	61.5 m
Type	GFRP shell construction, pre-bent

Yaw system

Type	Externally geared four-point bearing
Drive system	Gear motors with multi-disc brakes
Stabilisation	Disc brake with hydraulically operated brake shoes

Gear system

Type	Two helical planetary stage and one spur gear stage
Transmission ratio	i = approx. 97

Electrical system

Generator type	Double-fed asynchronous generator, 6-pole
Rated power	5,075 kW
Rated rotor voltage	660 V
Rated stator voltage	950 V
Rated speed	750 – 1,170 rpm (+15.0 %)
Generator protection class	IP 54
Converter type	Pulse-modulated IGBTs

Power control

Principle	Electrical blade angle adjustment - pitch and speed control

Tower

Type	Steel tube tower
Hub height	117 m onshore approx. 85 – 95 m offshore (depending on site conditions)

Foundation

Onshore	Reinforced concrete foundation, depending on site conditions
Offshore	Substructure suitable for actual site

Safety system

- Individually adjustable blades (electrically controlled) – fail-safe system
- Extensive temperature and speed sensing system including built-in redundancy
- Fully integrated lightning protection
- Automatic fire protection system
- Shielded cables protecting people and machinery
- Rotor holding brake with soft-brake function

Rotor bearing and shaft

- Double-supported distributed drive train with clear functional separation
- Bearing consisting of one movable bearing (CARB™) and one fixed bearing (spherical roller bearing) with optimised bearing housing and automatic for-life lubrication, ensuring excellent antifriction properties and prolonged service life
- The use of CARB™ bearings allows for axial shifts and inclination of the rotor shaft without causing damage

Rotor hub

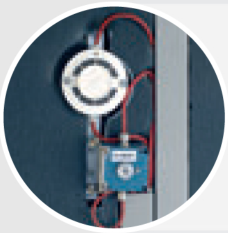
- Extremely low deformation due to compact design adjusted to power flow, with optimised integrated external pitch drives
- Generously dimensioned spinner allowing access to the hub in all weather directly from the nacelle
- Elastomer bearings of the battery boxes prevent damage due to acceleration peaks

Pitch system

- Virtually maintenance-free electronic system
- High-quality double-row blade bearing with hardened gears and automatic lubrication of track and gearing
- Protected against the elements by means of integrated deflector in the spinner
- Maximum reliability due to redundant blade angle detection by means of two separate measuring systems
- Fail-safe design with separate control and regulation systems for each rotor blade
- High-quality batteries in heated battery boxes; charge and status permanently monitored depending on the actual temperature

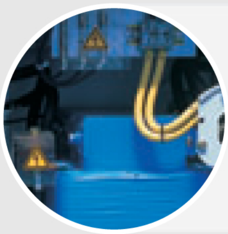
Rotor blade

- Load-optimised GFRP construction
- Lightning protection with multi-receptor system, including drain receptor in the blade tip
- Optional load and blade status monitoring system



Fire protection

- Fully automated fire protection system with active signals (for smoke and aerosols) and smoke detection in the nacelle, the switch cabinets and the transformer room (for early fire detection)
- Automatic nitrogen multi-point fire extinguishing equipment protecting the electrical components
- Carbon dioxide and ABC fire extinguishers for manual fire-fighting in the tower and nacelle

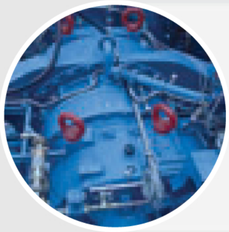


Electrical system

- optimised integration of the complete system into the nacelle
- Reliable protection against humidity and salt through cooling with air to air heat exchangers
- Low transmission loss as components are located close to each other
- Components mounted on elastomer bearings, reducing structure-born sound and vibration

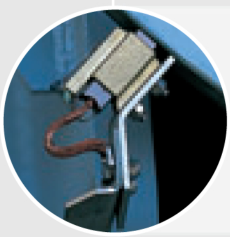
Tube Tower

- Characteristic frequency of the tower is above rotating frequency of the rotor (rigid design) and ensures minimum stress in tower and machine
- No restrictions regarding speed range of unit, as there is no risk of frequency interference
- Excellent component safety due to T- and L-flanges and load-optimised door opening



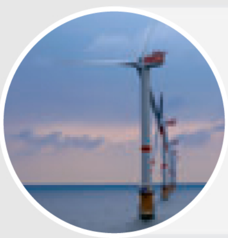
Gear system

- Two helical planetary stages and a double helical spur gear stage ■ Net torque transmission via slip-on gear design ■ Dimensioned ac requirements regarding service life and smooth running ■ optimised efficiency
- Elastomer bearing of torque multiplier for effective structure-borne sound insulation and gear-protecting compensation of peak loads
- Low temperature level due to efficient oil cooling system with oil/air heat exchanger
- Electric and mechanical system for optimised lubrication during normal and idle operation
- Excellent oil quality due to reliable filtering with minimum mesh size of 6 µm with triple-stage oil filtering system



Lightning protection

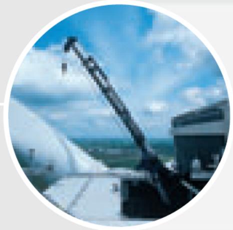
- Lightning protection concept based on zones, meeting the stringent requirements of IEC lightning protection class I and the GL regulations, with internal and external lightning protection ■ Outer lightning protection by means of multiple receptors located in the rotor blades and the lightning rod at the weather mast ■ Reliable protection of bearings due to defined lightning conduits
- GFC coupling for the galvanic insulation of the generator system from the gear system
- Overvoltage arrester protecting the electric system ■ Reliable protection of the generator by means of insulated bearing bushings



Environment

- No leakage of lubricants at hub or nacelle, due to
  - labyrinth packing in spinner
  - grease and oil collecting pans integrated in nacelle
  - coaming edges in nacelle panelling and
  - oil pan below azimuth gearing
- Closed central lubrication system of blade bearings ■ Shielding of all relevant cables to protect workers and machine
- Very low noise level

ording to REpower gear regulations, meeting the most stringent

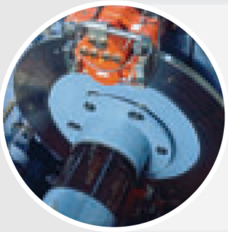


On-boa
- Fully
  - unr
  - grea
  - high
  - grea
- Flexi

Azimuth / Yaw system
- Externally geared four-point bearing, driven by generously dimensioned high-quality gear motors with multi-disc brakes
- Hydraulic holding brakes relieve the drives when idle and stabilise the nacelle
- Minimum load on drives due to low friction at four-point bearing and minimum brake pressure during tracking

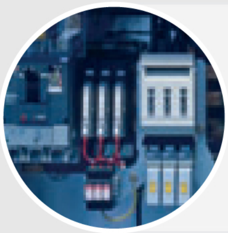
Serviceability
- Ample space in nacelle for ergonomically optimised and reliable service
- Hub easily accessible in all weather conditions witho
- If necessary, the unit can be easily and safely dismantled as drive train components are flange-mounted and the electric connectic
- Permanent status monitoring and reliable early detection system combined with optimised maintenance schedule based on condi

d crane
ydraulic marine crane ■ All necessary maintenance work can be completed with on-board equipment due to:
tricted swivel range
each
load capacity
lifting heights
e operation with remote control ■ Option for transport of people with caged platform

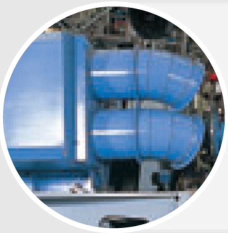


Holding brake
- Secure holding of rotor via generously dimensioned disc brake
- Soft-brake function with delayed hydraulic actuation protects the gear system

Transformer
- Use of cast resin and dry-type transformers with excellent ecological properties
- Fully enclosed assembly with air to air heat exchanger
- Reduced weight and fire risk
- Output voltage adjustable between 20 and 33 kV



Converter
- Low conversion loss and high total efficiency as converter output is limited to maximum 20 % of the overall output
- Redundant system with 4 modules aligned in pairs allows for continuous operation even in the event of a module failure
- optimised frame construction minimizes vibration and oscillation



Generator
- Yield-optimised variable speed range
- Fully enclosed generator with air/air heat exchanger
- optimised temperature level in generator, even at high outside temperatures
- Low-voltage operation allows for the use of tried and tested series components without the need of additional switching equipment
- Excellent safety as insulation is dimensioned for 20 kV

Corrosion prevention
- Special multi-layer coating according to DIN EN ISO 12944
- Highly effective additional coating of the tower and foundation area
- Protected installation of all electrical components in nacelle
- Cooling and ventilation of components through heat exchangers
- No intake of humid or salty air into the nacelle

t having to leave the nacelle ■ Excellent accessibility of all components ■ Guards mounted over all rotating components ensure safe servicing
s are equipped with plug-type connectors ■ Easy handling of heavy components due to sturdy folding crane located in the nacelle
on monitoring system ■ Helicopter descent platform for offshore installations ensure accessibility to the unit even in adverse weather conditions