From the sustainability of wind energy
A Global approach to wind power

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Abstract

As most renewable energies strive to reach maturity, wind power is growing at 29% a year and it is expected to do even better in the future. The industry of wind energy is therefore becoming one of the most promising solutions to the current world energy concerns. This report aims to assess the sustainability of the extensive use of wind energy in regard to five criteria.

First, even if reduced by geographical or technical factors, the overall availability of the wind resource does not threaten the expansion of the wind industry. Second, the decrease of green house gases emission and the security of supply are interesting gains brought by wind energy. It thus seems profitable to the society to invest in supporting systems since this industry is not cost competitive yet. Third, limited negative social impacts and positive effects for local populations participate to the overall public acceptance of wind turbines installation. Fourth, environmental impacts can either be mitigated or avoided, which is a condition to the sustainability of a specific wind farm project. Fifth, the technological possibilities push further away the limits of the wind industry, enhancing its sustainability.

On the whole, we therefore conclude that the use of wind energy in an extensive way is sustainable.

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Chapter One: Introduction

1.1 From Renewability to Sustainability

In 2001, solar, wind, and tide energy all together accounted for only 0.1% of world total primary energy supply (TPES) and 0.5% of renewable supply (I.E.A, 2003, p.3). Nevertheless, although still among the marginal renewable energy sources, the world installed wind power generation is constantly increasing. Thus, it raised more than then-fold between 1992 and 2002. Compared to 2001, installed wind capacity worldwide grew by 29% (7200 MW) in 2002. This increase is mostly concentrated in Europe where was situated 75% of the world installed capacity base in 2002. The same year, wind power accounted for 4% of total German electricity generation and 17% of total Danish power generation. (B.P., 2004)

This rapid increase in wind energy use must be accompanied by detailed studies of its consequences. In other words, it should be asked if wind power is really a good solution to our current energy concerns. Indeed, with developing as well as developed countries using more and more energy, we can anticipate an increase of energy use by a factor of five by the year 2025 (W.C.E.D., 1987, p. 14). According to Brundtland (1987, p.14), the planet could not stand such a scenario, especially if we continue to rely upon non-renewable fossil fuel. More recent concerns regarding climatic changes tend to reinforce this idea.

Indeed, “climate change” has been a key word of world environment concerns for the last twelve years. During two important conferences held in Rio de Janeiro and Kyoto in 1992 and 1997 respectively, all the participating governments agreed to reduce green house gas emissions (GHG), which are said to be responsible for global warming. To meet this objective, the most expected action programme was the implementation of renewable energies. However, in many European Union's Directives or academic papers, it is hardly defined what are renewable energies. Some of those documents only define it as including wind, solar, hydrogen, and biomass energies, where some others say that it is green energy. Therefore it seems important to define precisely this term in order to focus on wind energy, one of these renewable energies.

First of all, renewable energies do not emit much GHG compared to conventional energy sources such as coal and oil. Since the concern on global warming is increasing, these less-emitting sources are expected to grow.

Secondly, renewable energies use natural resources that do not die out, such as hydroelectric power, tidal power, geothermal power, wind power, solar energy, fuelwood, biomass conversion, and solid waste. In comparison, conventional energy plants cannot work forever because they depend on natural sources that have been produced in a long time period. It is impossible to produce these resources in a short time.

The third point is that renewable energy sources are generally more dispersed or universally available. Solar panels can be built wherever there is long day-light time and wind turbines can be erected in any windy place but oil, coal, and natural gas cannot be extracted everywhere. They have to be purchased.

However, renewable energy sources can carry their limitations since they cannot all be effectively exploited and may also present social or even environmental disadvantages. Hence, a broader concept had to be developed in order to assess the viability of a certain theory, politic, or in the present case, technology. The notion of sustainability has therefore been chosen for this report as a frame to analyse the possibility of developing wind energy. Indeed, the constant growth in wind energy production, as mentioned earlier, made it an interesting subject to account for its sustainability.

1.2 The objective: assessing the sustainability of wind energy

The aim of this report is therefore to analyse the pros and cons of the use of wind energy in a multi-disciplinary perspective in order to decide if this energy source should be seen as a sustainable alternative and thus used in an extensive way. Prior to this, a brief review of the use of wind mills over time will be done in order to realise the historical importance of this energy source. Then, to draw any conclusion regarding sustainability of the wind industry, our vision of this concept will be defined and a review of different perspectives of sustainability will be done, which will allow us to demonstrate our own position.

Sustainability of wind energy will then be analysed in regard to five general aspects. We will first look at the geographical and technological limitations of the use of wind turbines. The objective here is to demonstrate if the wind industry is sustainable in regard to the availability of the resource. Thus, this section will include a detailed explanation of the wind formation and of its physical characteristics, allowing to understand the distribution of winds on the planet. The capability of wind energy to supply the world-wide electricity needs will hence be assessed. Technological requirements, descriptions, and limitations of wind turbines will also be furnished.

Second, economics of the industry will be explained to conclude if wind energy is cost competitive and if not, if it is profitable to subsidise it. If one of these conditions were fulfil, it would advocate for the economical sustainability of wind energy. Therefore, the factors determining wind electricity price and the cost competitiveness of the industry will be analysed. Then, it will be explained why the industry should be subsidised and ways of doing so will be proposed. The pros and cons of two policy systems, the feed-in and the green certificate systems, will finally be discussed.

Third, the direct effects of the industry on people will be assessed regarding its visual disturbance, impact on local dynamism and its development. Here, sustainability will depend on the possibility for the industry to arouse public acceptance.

Fourth, the environmental costs will be defined. Those will first include the global effects on ecosystems for onshore and offshore wind farms. A particular attention will then be drawn to the impacts on birds, followed by solution proposals. The problems of erosion, noise, vibration, and electromagnetic fields and their mitigation actions will also be explained. In this chapter, sustainability of the wind industry relies upon its capability to avoid or solve the environmental impacts it induces.

Fifth, a look to the future developments of the technology will allow us to see if today's limitations can be overcome to make wind power sustainable. This will concern the possible improvements to the turbine structure in itself, the storage possibilities and the evolution of turbines towards hybrid structures, especially wind and water power hybrids.

Finally, a conclusion of the sustainability of wind energy will be drawn regarding the pros and cons developed in the five disciplinary chapters. Some more conditions to achieve sustainability of the industry will also be proposed.

Chapter Two: History of windmills

2.1 Evolution of windmills through time

There have been many different “mills” throughout history, including water powered, animal powered and wind powered. The first windmills to appear in Europe were the 12th century “post mills”(See Figure 1), named due to their upright post in which four blades were mounted at right angles to each other. The “smock mills”(See Figure 2) were the next in design, and as the name suggests these looked like a giant dress-like agricultural costume. These mills were different from post mills as their blades were made to rotate and face the wind. “Tower mills”(See Figure 3) were the next step in mill design and structure. The stone and brick used for the previous mills was discarded and wood was used to create the tower. As the name suggests it was a large circular tower with four blades facing the wind at the top. (Telnet Web Development and Darrell Dodge (1),2001)

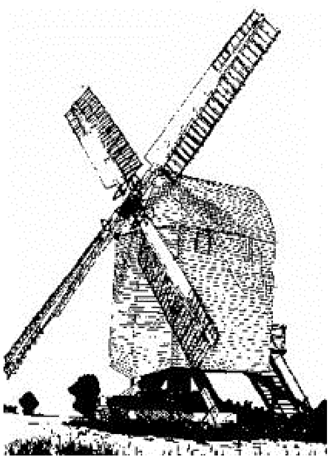

Figure 1: Post Mill

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Figure 2 : Smock Mill

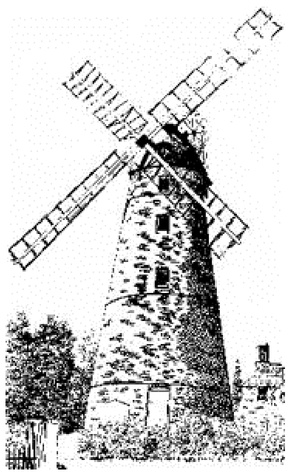

Figure 3 :Tower Mill

The use of windmills spread rapidly over Europe during the 13th and 14th centuries. They were generally used for grinding grain, moving water or powering machinery. As time advanced so did the structure and design of the windmills. Modern day windmills are generally called “wind turbines” as they are mainly for producing electricity.

2.2 The development of modern wind turbines

In the early 18th century there was a dramatic shift from the use and research of wind energy to the use of steam engines and fossil fuels. The steam engines, which burnt fossil fuels, were more compact, easily transportable, and did not rely on areas of strong winds. They produced more power and were more reliable for providing a continuous supply of power. This made them more appealing to use than windmills. (Telnet Web Development and Darrell Dodge (2), 2001).

Despite many industries turned from using wind energies, some continued the research. One industry figure was Charles F. Brush (See Figure 4) who kept up the research on wind mills, as he believed they were a more environmentally friendly way to produce power. Brush’s research and determination lead to the construction of the first large electricity generating wind turbines in 1888. They were built and constructed in Cleveland, Ohio, USA. A few people began to follow this example and started research of their own.

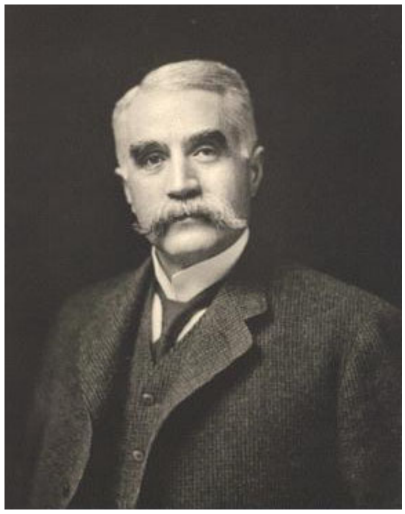

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Figure 4 :Charles F. Brush

By the end of World War One, these electricity output wind turbines had spread over to Denmark and many other European countries. However, due to the still steady up-rise of fossil fuels, many wind turbine operators went out of business. The first major offshore mass producing wind farms were built by the Russians in the Caspian Sea in 1931. Many other countries, such as Denmark, America, UK, and Germany saw how successful these were and constructed similar offshore wind farms. (D.W.I.A. (1), 2003).

Today, issues surrounding the use of renewable energy sources make the development of wind power more accurate than ever before. In most places over the world there is access to wind farms that are generating electricity and energy to power the schools, homes and factories.

Chapter Three: Defining sustainability

3.1 Strong and weak sustainability, two views of a single concept

The first attempts to give a clear definition of sustainable development might come from the Brundtland's Report "Our Common Future" published in 1987. It stated that it is a "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs (W.C.E.D., 1987, p.43)". Though quite a broad statement, this definition has the quality of linking environmental protection to economical growth. Nevertheless, according to Schaltegger *et al*. (2003, p.22), those two disciplines don't carry the proof that sustainability is the objective to reach. Thus, ethical reasons are behind any postulate for sustainability.

Hence, two opposite views of sustainability have been developed, each one based on different values. On one side, strong sustainability argues that economical value, or manufacturing capital, cannot substitute natural capital. For some adherent of this ideology, the reason is that economic capital cannot replace all the roles a certain resource occupies in its ecosystem. Therefore, only renewable resources should be exploited (Schaltegger *et al.*, 2003, p.23).

Even if showing different basic principles, the deep ecology movement can also be seen as a strong sustainability type of ideology. According to the Norwegian philosopher Arne Neass who came first with the name deep ecology in 1972, every living being has an intrinsic value that must be conserved. Thus, humans shouldn't exploit natural resources if it's not to satisfy their vital needs. Deep ecology claims for a profound change of the values supporting our developed western world. Quality of life must not mean to possess more, but to be able to do great with less (Naess, 1984, in Katz *et al.*, 2000, p.x-xi).

On the other side, weak sustainability is advocated by adherents of economical growth and maintains that the value of nature can be replaced by economical value. This means that today's technological developments, if they can serve future generations, should be encouraged, even if harmful to the environment. (Rennings, 1997, pp. 47-48) (Schaltegger *et al.*, 2003, p.23). Such an idea certainly does not recognise any intrinsic value to the ecosystems. On the contrary, it sees the living as utilitarian material for human growth.

3.2 A frame supporting economical growth

The Brundtland's Report brings some more reservations to weak sustainability while supporting it. According to it, "the accumulation of knowledge and the development of technology can enhance the carrying capacity of the resource base (W.C.E.D., 1987, p.44)". This means that today's resource exploitation is compatible with sustainability as long as it allows relieving future environmental pressure. Therefore, sustainable development relies upon technology, which needs resources to develop. But for development to stay sustainable, the "system-wide effects of exploitation" have to be taken into account (W.C.E.D., 1987, p.45).

In an energy perspective, this means that in addition to improve energy efficiency and distribution, we must assess environmental impacts of an energy source before using it, that is, in order to ensure that the costs do not exceed the benefits (W.C.E.D., 1987, p.61). To this, we would add that the costs, economic, social or environmental, even if smaller than the benefits, could threaten the sustainability of the technology. Therefore, each cost has to be considered in itself and not only as a part of the total cost.

Moreover, as Brundtland (W.C.E.D., 1987, p.62) proposed, ecological and economic considerations have to be integrated in the decision process. As for the case of energy efficiency, those two perspectives aren't necessarily in opposition. Thus, this example reinforces the support given by Brundtland to the possibility of a sustainable economical growth. Indeed, it is often believed that the energy expenses follow the economic growth, but some countries, like Japan, have managed in the past in maintaining a low energy consumption while growing economically (Uno, 1995, p.39).

A third point supporting the benefits taken from economic growth is brought by the example of past economical crises, like the slow down of economic expansion and stagnation in world trade experienced world-wide but especially in developing countries in the 1980's (W.C.E.D., 1987, p.36). Indeed, this event has shown how harmful a slow economical growth for the environment can be. As described by Brundtland (W.C.E.D., 1987, pp.35-36), economical pressure, particularly in developing countries, lead to a "considerable increase in human distress and overexploitation of land and natural resources to ensure survival in the short term". Therefore, the economical slow down resulting of a deep ecology transformation of the system could also create supplementary stress on the environment.

Nevertheless, development is also limited by environmental degradation (W.C.E.D., 1987, p.35). This fact forces us to conclude that an agreement between deep ecology and wild economical growth has to be reached. But the deep ecology platform does not leave any space for anything in-between. Indeed, accepting deep ecology basic principles such as the intrinsic value of every living being carries unavoidable consequences. That is, we must protect each being as we protect humans. It is not sufficient to decrease our consumption to accomplish this; we must go back to a very simple way of life with a much smaller population.

3.3 The difficulty of following the deep ecology idea

Even if we believe in the intrinsic value of life and are ready to modify our own behaviours in order to live as much as possible according to this philosophy, social changes required by deep ecology can only be accomplished if every human being on earth is ready to do the same. This change in philosophy and behaviours of every individual cannot escape the notion of desire. Indeed, desire appears as a major opponent to the reduction of consumption advocate by deep ecology. To transform our criteria of what is a good life, our desires must also change. But according to Maskit (2000, p.215) this discussion lacks in Naess's writings. Thus, Maskit states that we now have to make the bridge between reason and desire. He says that where Plato thinks desire can be restrained, Naess simply sees desire as something that can go away (Maskit, 2000, p.221). The existence of desire might be what makes the profound changes asked by deep ecology so far from reality. Nevertheless, Maskit's (2000, pp.225-226) idea is that we need preliminary policy changes to stop the creation of environmentally destructive desire and to help people struggling with those desires to adopt a reasonable behaviour.

3.4 Definition of sustainability chosen for this report

Our point here is that so deep change will not occur overnight. Deep ecologists are aware of that. Advocating or not for weak sustainability will not change the fact that economical growth is something we will have to deal with, at least until world-wide values have changed toward deep ecology and we have argued that this can be long. This means that while working on a transformation toward deep ecology, we still need to find solutions for a weak sustainability scenario. We demonstrated that if economical growth is in complete opposition with the notion of intrinsic value of life, it is still compatible with that of sustainability.

Now that the theoretical angle to assess the sustainability of wind energy has been chosen, concrete evaluation criteria still have to be defined in order to realise this exercise. Sustainable development is known to merge economic, social, and environmental fields into an integrated single perspective (Schaltegger *et al.*, 2003, p.21). Our evaluation criteria will therefore concern these three areas to which we will also add the technological sphere. The chosen criteria are based on the description of sustainable development proposed by the Brundtlant report, the experience of the Canadian hydro electricity company *Ontario Hydro* (Howes, 1997, p.310-323), and on Uno's view of sustainability in a Japanese context (Uno, 1995, p.200-216).

First, in the technological perspective, it is essential to ask if wind energy has the potential to be used in a maximised and efficient way (Howes, 1997, p.312). Is wind really an important source of energy? Have we reached the technological roof? Is it a global solution to our energy shortage or only a local one? As mentioned by Howes (1997, p.312), renewability of the resource itself is essential to account for the sustainability of the studied energy source. This also means that in order to be sustainable the resource must not be limited.

Then, having recognised the importance of economical growth, sustainability requires that wind energy provides financial gain in order to maintain its exploitation (Howes, 1997, p.312). To achieve this, it either has to be cost competitive or to be subsidised. However, the industry should only be subsidised by the state if it is profitable to the society.

On a more social scale, sustainable wind energy would take the well being of people into account. Uno (1995, pp.201-216) insists on the fact that this notion must include the environmental impacts. If those are limited, the level of well being is enhanced. On the other hand, economical well being also has to be considered. It is necessary that wind energy does not enhance world poverty, which would tend to reduce “people’s capacity to use resources in a sustainable manner” (W.C.E.D., 1987, p.49). Therefore, it has to support local dynamism, to create jobs, and concentration of the wealth that it generates has to be avoided. To these social preoccupations, we would finally add the psychological well being, which is represented by the social acceptance of wind energy.

With the dependence of economy and society on the biosphere (Schaltegger *et al*., 2003, p.21), the fourth criteria, environmental impacts, is an unclear one. Indeed, with the theoretical definition of sustainability selected above, a sustainable energy source must tend to reduce environmental damages but not necessarily avoid them totally (Howes, 1997, p.312). However, some impacts are unacceptable. Thus, the overall integrity of the ecosystems has to be maintained. It must be remembered that species, even though living being, are not renewable once extinct (W.C.E.D., 1987, p.46).

Thus, these criteria can be used as questions asking “Is wind energy sustainable?”, As mentioned before, a negative answer regarding some of these criteria, for instance the existence of technological limitations, would only level down the sustainability, where other negative answers, e.g. concerning major economical restriction, could by themselves lead to a conclusion of unsustainability.

Chapter Four: Availability of the wind energy resource

4.1 Criteria for the technical sustainability of wind energy

In a very technical matter, the sustainability of wind energy depends on the availability of the resource. Thus, the purpose of this chapter is to investigate if the wind resource available for the production of electricity is big enough to sustain the development of the wind energy industry on the long run. It will also be explained how the specific distribution of this resource over the earth's surface and the technological problems associated with building, operating, and overall efficiency of wind turbines affect the size of the usable resource.

4.2 The Geography of wind

4.2.1 Where does the wind come from?

Wind is defined as the horizontal movement of air relative to the earth's surface. The main drive of this movement is the sun. In fact wind energy is an indirect form of solar energy. It's estimated that 1 to 2% of the solar radiation that reaches the earth is converted into wind, representing something between 1.74 to 3×10^{15} W, an almost unlimited resource.

Generally winds result from an unequal heating of different parts of the earth's surface. Because the earth's surface heats up at different rates, air temperature varies too. Differences of temperature cause differences in pressure. These appear because warm air is light and will rise to the upper parts of the atmosphere. It creates an area of low pressure on the ground, where the cold air is heavier and will descend from higher parts of the atmosphere, creating an area of high pressure. This difference in pressure across distances is called a "pressure gradient". Wind speed is directly dependent on the pressure gradient.

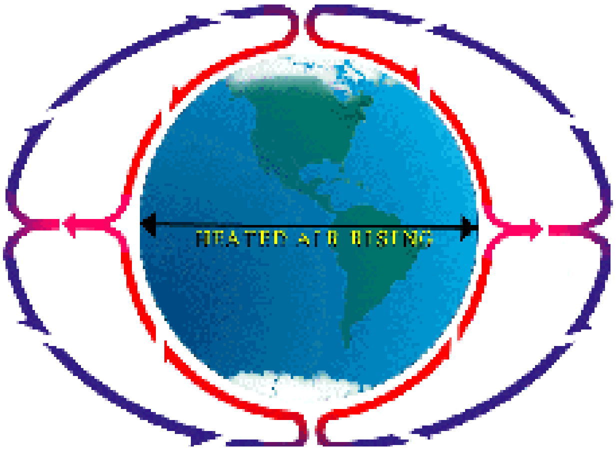

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Figure 5: Basic model of wind pattern on earth

Air heated at the equator rises into the upper atmosphere, travels as jet stream to the poles where it cools, sinks down, and is pushed by the pressure gradient back to the Equator.

There are different causes of the unequal heating of different parts of the earth's surface, but the main one is simply the shape of the planet. As shown in figure 5, this spreads the energy received from the sun on an increased surfaced as you go from the equator (where there is maximum heating), to the polar regions where there is no light for half of the year.

In fact this is not the way in which wind circulates in the atmosphere because the whole system is disturbed by other factors that will result in very complicated wind patterns. These factors are:

- the spin motion of the earth (Coriolis deflection);
- the tilting of the earth, which shapes the seasons;
- the presence of large bodies of water and land, which warm and cool at different rates creating a disparity in the atmosphere above;
- the differences in temperature between lowlands and highlands.

4.2.2 The Global wind circulation

The wind movement in the Northern Hemisphere will first be discussed. Hot air rises from the equator, creates a low-pressure area, and flows towards the North Pole. The upper wind flow is deflected to the right by the Coriolis effect (see Figure 6), which causes it to pile up and move from west to east. The piled up

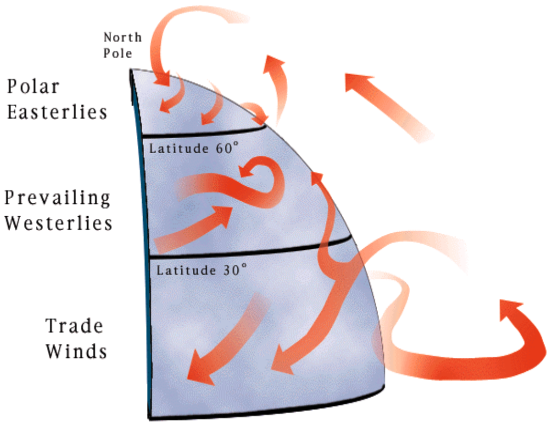

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Figure 6: The Coriolis effect on the global wind circulation

Once the air has begun to move like in Figure 5 (surplus heat to the poles and surplus cold to the equator) the Coriolis force comes into action and complicates everything.

air cools, creating a high-pressure area, and sinks; as it accumulates on the surface, it flows towards both the equator and North Pole. The air moving toward the equator is influenced by the Coriolis effect and moves from the Northeast, and because of its direction is called the Northeast trade winds[1]. The poleward moving air also moves to the right and is called the prevailing westerlies. The third wind belt develops as cold polar air sinks and moves south, is deflected to the right, and is therefore called the polar easterly. The same air pattern occurs in the latitudes of the Southern Hemisphere, except that the deflection of the wind is to the left rather than right[2].

The zones that separate these three major wind belts are also identified.

1. Near the equator is a region called the doldrums. A more explanatory, if less colourful, name is the intertropical convergence, for it is there that the trade winds of both hemispheres meet. It is known for its extremely low pressure, frequent thunderstorms, and very calm wind.
2. At about 30^0 is a high-pressure area where the trades and westerlies diverge and go toward the equator and pole, respectively. It is an area with little wind but unlike the doldrums, there are no cloud formations, just blue skies and warm temperatures.

[1] Wind is classified according to the direction from which it is blowing.

3. The third zone lies at about 60° latitude, and is called the polar front. Its location varies with the seasons, since the polar front moves south in winter and north in the summer. The cold polar easterlies meet the warm prevailing westerlies in this zone, and because of the extreme differences in pressure, dramatic weather conditions and winds occur. (Cislunar Aerospace, 1997)

Roughly speaking, trade winds occupy the area between 0° (the equator) and 30° degrees latitude; prevailing westerlies are in the area between 30° and 60°; and polar easterlies occupy the region between 60° and 90° (the poles). Moreover, the whole system is compensated at high altitudes by the jet stream, which is generally westerly, with wind speeds that can exceed 300 mph. Finally, the tilting of the earth makes all this complicated system to move annually from north to south and back.

4.3 Regional and local wind patterns

On a regional scale, the different rates in which land and sea warm and cool create a very specific air circulation called monsoons. At a more local scale the same phenomenon creates periodical winds, the sea breezes (see Figure 7). These are very important in wind power generation because they offer very reliable wind speeds.

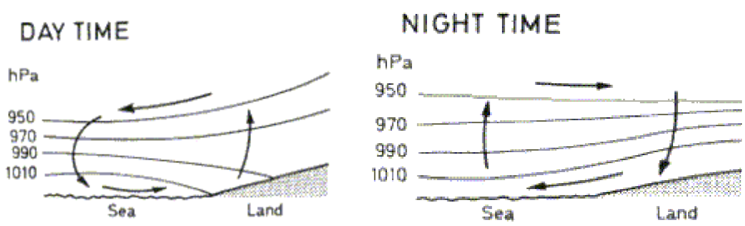

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Figure 7: Creation of sea breezes during day and night time.

Also, on the local level the cooling air along the slopes of a mountain causes drainage winds, also called mountain or gravity winds. As the air becomes

[2] In the Southern Hemisphere the trades are called the Southeast trade winds.

heavy, it flows downhill producing the mountain breeze. The valley breeze is the uphill counterpart of the mountain breeze. These happen when the sun heats the valley walls and mountain slopes during the morning hours, making the air next to the ground to rise along the slopes. (See Figure 8)

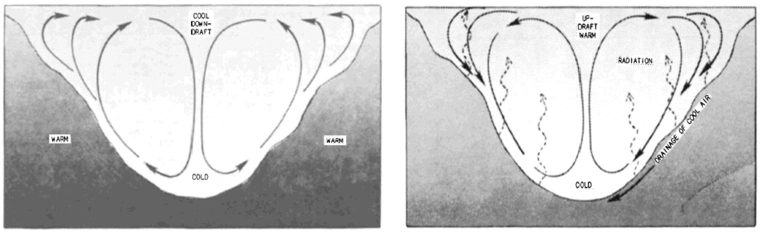

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Figure 8: Mountain and valley breezes

Other local air circulations important for power generation are the “Glacier winds” and the “Foehn winds”. Some other air movements can have very destructive effects on wind turbines such as Ereddies and Turbulence.

4.4 From wind to wind energy; some physical characteristics of the wind

The graph in Figure 9 was created using “the power of the wind formula” $P = 1/2\ \rho\ v^3\ \pi\ r^2$, which, among others, takes into account ρ (the density of dry air: 1.225 kilograms per cubic metre), r (the radius of the specific rotor measured in metres) and π (=3.1415926535...). The formula shows that the power (P) of the wind measured in Watt (W), depends strictly on the cube of the velocity (v) of the wind measured in metres per second (m/s).

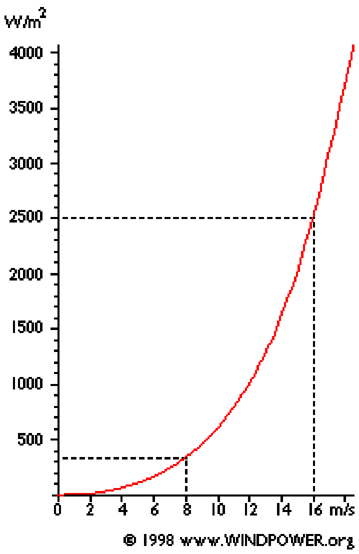


Figure 9 : The power content of the wind at different speeds

The energy content of the wind varies with the cube of the average wind speed, e.g. if the wind speed is twice as high it contains 2^3 = eight times as much energy.

The graph shows that at a wind speed of 8 metres per second we get a power (amount of energy per second) of 314 Watts per square metre exposed to the wind (the wind is coming from a direction perpendicular to the swept rotor area). At 16 m/s we get eight times as much power, i.e. 2509 W/m^2.

On the other hand, the power coefficient describes which fraction of the power in the wind may be converted by a wind turbine into mechanical work. It has a theoretical maximum value of 0,593, sometimes called the Betz coefficient, but rather lower peak values are achieved in practice (35-40%, although fractions as high as 50% have been claimed). Moreover, wind speed, and hence power, vary directly with height above ground. They increase at the greatest rate over hilly or mountainous terrain and at the least rate over smooth terrain. (Gipe, 1993, p. 37)

Considering their physical characteristics, winds can be divided into geostrophic and boundary layer winds. The geostrophic wind is found at altitudes above 1000 metres above ground level, where the air flow can be considered largely free of surface influences.

At lower altitudes, the effect of earth's surface can be felt. This part of the atmosphere is known as the boundary layer. The properties of the boundary layer are important to understand the turbulence experienced by wind turbines. In the lowest part of the boundary layer (up to 100m) surface winds are found, which can be very turbulent. These winds provide the power for today's wind turbines.

Turbulence is the deciding phenomenon separating geostrophic and boundary winds. The boundary layer effect can also affect wind turbines at a microscopic level, because it increases the friction between the air and the airfoils, reducing the overall performance. Turbulence refers to fluctuations in wind speed on a relatively fast time scale, typically less than 10 min. It is generated mainly by two causes: the friction with earth's surface, and the thermal effects caused by air moving vertically. Turbulence intensity clearly depends on the roughness of the ground surface and the height above the surface. However, it also depends on topographical features such as hills and mountains, especially when they lie upwind, like well as more local features as trees and buildings. It is also influenced by the thermal behaviour of the atmosphere (the warmer air is more turbulent than the cooler one). (Burton, *et al*. 2001, p.17) Wind turbines can be damaged by excess turbulence and their lifetime also decreases because of internal vibration caused by this phenomenon.

4.5 The Wind energy resource

4.5.1. Mapping of wind energy potential at global and local levels

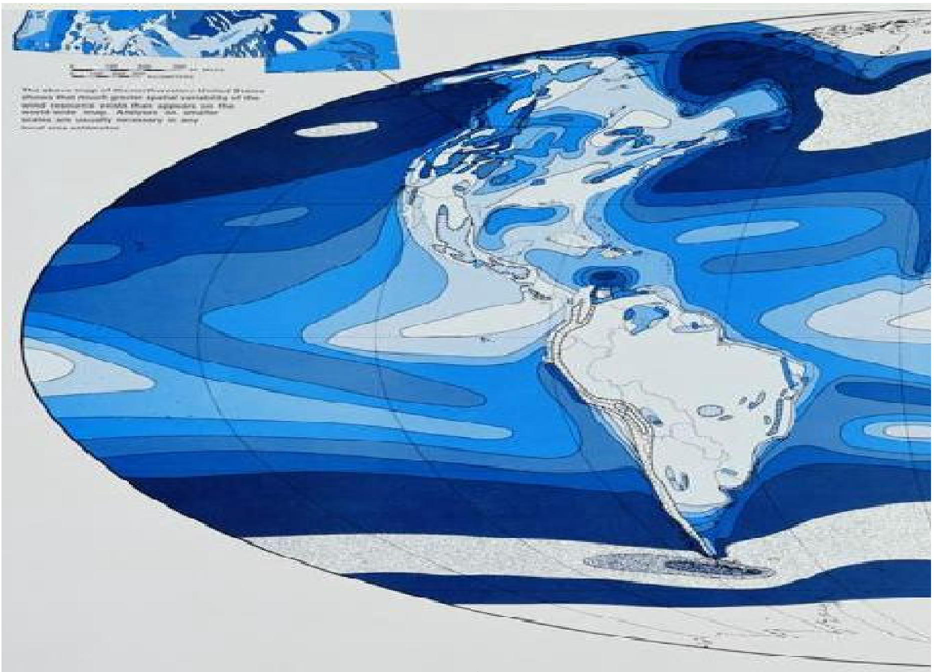
Now that we can estimate the amount of energy that can be used from the wind, and already knowing the global and local wind circulation, we can calculate and map the areas in which wind is a major energy resource. The "world-wide wind energy distribution estimates" map can be seen in figures 10 and 11.

Table 1: Classes of wind power density at 10 m and 50 m [(a)].

WindPower Classes	**10 m (33 ft)**		**50 m (164 ft)**	
	Wind Power Density (W/m^2)	**Speed [(b)] m/s (mph)**	**Wind Power Density (W/m^2)**	**Speed [(b)] m/s (mph)**
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

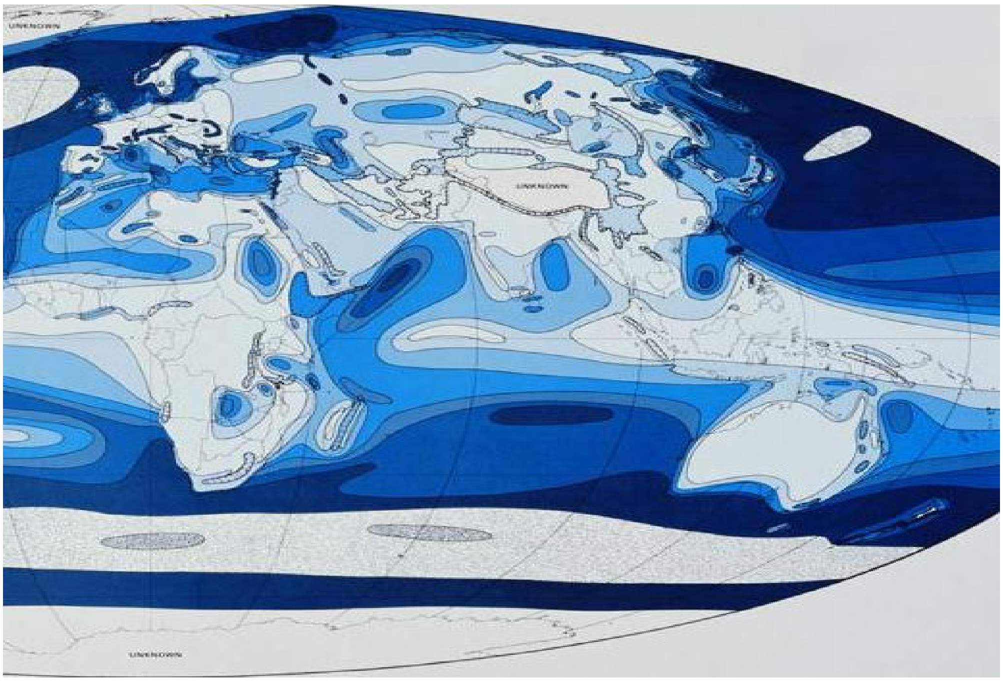
Table 1 presents the speed of each wind power class. These should span two power densities. For example, Wind Power Class = 3 represents the Wind Power Density range between 150 W/m^2 and 200 W/m^2. The offset cells in the first column attempt to illustrate this concept.

The following figures (10 and 11) illustrate de distribution of the wind classes on Earth. It can be seen that the wind energy resource increases from almost zero (white) to seven (dark grey). However, the white stripe surrounding Antarctica and the white areas in the middle of the oceans are especially rich wind resources.



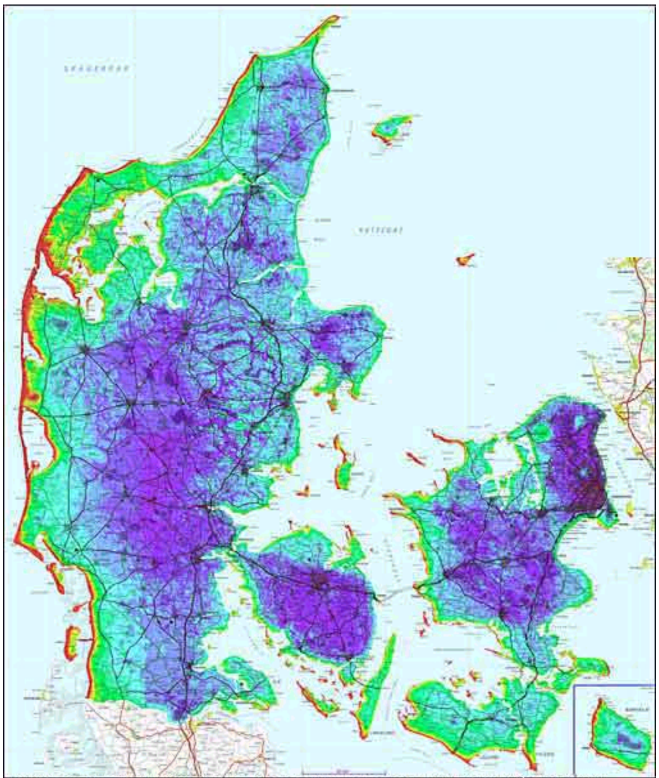
source: www.bergey.com

Figure 10 : Wind resource in the Western Hemisphere



source: www.bergey.com

Figure 11: Wind Resource in the Eastern Hemisphere
(Maps Courtesy of US-DOE and NREL)



source: www.windpower.org

Figure 12: Mapping at a local level

This unique map of Danish wind speeds takes local terrain into account. We can see that West and Southwest are the predominant winds in Denmark, since West and Southwest facing coastal sites have by far the highest energy content of the wind.

The map is actually a very high resolution map, where the area of the whole country (44,000 km^2 area) was divided into 1.1 million squares 200 by 200 m each (220 by 220 yards), and the mean wind speed was calculated for each square km. (D.W.I.A. (2), 2003)

Legend:

W/m2	m/s
>510	
510 - 460	7.5
460 - 410	
410 - 360	
360 - 310	6.7
310 - 260	
260 - 210	5.7
<210	

Not like the global maps, which can be used more like guidelines in determining the right areas for installing wind turbines, the wind map shown in Figure 12 was developed to assist the Danish municipalities in their planning work (zoning) for wind turbines. Calculating such a detailed wind map of a large area was an enormous task: The map was made on the basis of extremely detailed digital maps at the scale of 1:25000. However, it is still not sufficient for locating a wind turbine, since it was generated mechanically, without detailed verification in the terrain.

4.5.2 Assessment of the capability of wind energy to supply the electricity needs of nations on all continents

Returning to the global wind energy resource map, we can see that wind with usable classes of potential is pretty much spread on almost all the surface of the earth. With the exception of inland areas and the equatorial belt, over 80 % of the earth's surface have wind speeds over class two (5,1 m/s annual average). Unfortunately the remaining 20% incorporate most of human population and their electricity needs. There are also some exceptions where the wind sweeps over densely populated areas with great electricity demand.

These areas are: N-W Europe; S-E Asia; Japan; Central and western part of the USA. These combining factors explain why these regions are more advanced than the rest of the world in the usage of wind power, but there is also great hope in the immense offshore potential, which surrounds every continent:

- Europe: excellent wind and siting conditions in the North sea, and on all the Atlantic coast; good wind conditions in the Mediterranean basin; also very good conditions on the eastern part of the Black Sea and Caspian Sea.
- Asia: Southern tip of the Arabic Peninsula and the surrounding seas; Gulf of Bengal; all the Pacific Rim area.

- Australia: very good potential on all surrounding seas; excellent resources for Tasmania and New Zealand.
- Africa: good potential even inland in the great Sahara desert, and on all surrounding seas, with the exception of the equatorial areas; also very good to excellent potential in South Africa.
- South America: poor resources onshore (except in the southern part of Patagonia plain), but excellent to very good conditions offshore (without those calm equatorial areas).
- North America: excellent potential offshore, on all coasts.

4.6 Harvesting the wind

4.6.1 Technical considerations in siting wind turbines

As seen previously more than just maps are required when considering siting a wind turbine. A series of factors must be taken into consideration, beginning with the local characteristics of the wind and the measurement of the actual wind resource that can be used. Looking at nature itself is usually an excellent guide to finding a suitable wind turbine site. Trees and shrubs in the area give a good clue about the prevailing wind direction and force. Moving along a rugged coastline, it is easy to notice that centuries of erosion have worked in one particular direction.

Meteorological data, ideally in terms of a "wind rose" calculated over 30 years, is probably the best guide, but this data is rarely collected directly on site. There are many reasons to be careful about the use of meteorological data, because precise measurement of wind speeds, and thus of wind energy, is not as important for weather forecasting as it is for wind energy planning. Wind speeds are heavily influenced by the surface roughness of the surrounding area created by obstacles (such as trees, lighthouses or other buildings), and by the contours of the local terrain. Obstacles can decrease wind speeds significantly, and they often create turbulence in their neighbourhood.

Therefore, it is best to avoid major obstacles close to wind turbines, particularly if they are upwind in the prevailing wind direction. The decrease in wind speed depends on the porosity of the obstacle[3]. A building is obviously solid and has no porosity, whereas a fairly open tree in winter (with no leaves) may let more than half of the wind through. In summer, however, the foliage may be very dense, so as to make the porosity less than, say one third.

When siting a wind turbine, one can consider using at his advantage two positive phenomena: the tunnel effect and the hill effect. The first means that, even if the general wind speed in open terrain may be, 6 metres per second, for example, it can easily reach 9 metres per second in a natural "tunnel". Placing a wind turbine in such a tunnel is one clever way of obtaining higher wind speeds than in the surrounding areas. To obtain a good tunnel effect the tunnel should be "softly" embedded in the landscape. In case the hills are very rough and uneven, there may be lots of turbulence in the area.

On hills, wind speeds are higher than in the surrounding area. This is due to the fact that the wind becomes compressed on the windy side of the hill and once the air reaches the ridge, it can expand again as it soars down into the low-pressure area on the lee side of the hill. (D.W.I.A. (2), 2004) In both cases if there is much turbulence it may negate the wind speed advantage completely, and the changing winds may inflict a lot of useless tear and wear on the wind turbine.

[3] Porosity is defined as the open area divided by the total area of the object facing the wind

There are of course other factors to be considered in the siting of wind turbines like:

Grid Connection : Obviously, large wind turbines have to be connected to the electrical grid. For smaller projects, it is therefore essential to be reasonably close to a 10-30 kilovolt power line if the costs of extending the electrical grid are not to be prohibitively high. (It matters who has to pay for the power line extension).

Grid Reinforcement : The electrical grid near the wind turbine(s) should be able to receive the electricity coming from the turbine. If there are already many turbines connected to the grid, the grid may need reinforcement.

Soil Conditions : Both the feasibility of building foundations of the turbines, and road construction to reach the site with heavy trucks must be taken into account with any wind turbine project. (D.W.I.A. (2), 2004)

There are also the inevitable issues related to the environment the aesthetics, zoning laws, neighbours complains etc. (these are to be discussed further away in this paper), but taking into account only the local characteristics of the resource, the criteria for siting a wind turbine may look like this:

Siting Criteria for Wind Turbines, Utility Scale (over 500kw)

(New England Wind Power Siting Workshop held in Boston on October 24, 2001.)

Ideal:

- Common and indistinct landscapes: lack of variety in topography and vegetative cover ;Sparsely settled area; but not unsettled or wild ;
- Working landscape characterised by logging practices, or earth resources extraction;
- In or adjacent to a major industrial area.

Possible

- Lower ridgelines in moderately settled area;
- In or adjacent to an area characterized by strip development.

Difficult

- Ridgelines near distinct or very high peaks.

4.6.2 Wind turbines, how do they work?

Wind turbines transform wind energy into electricity, but like all technology, turbines come in all shapes and forms. There are two great classes of wind turbines: Horizontal and vertical axis machines.

source: www.ece.umr.edu

Figure 13 : "Eggbeater"

Vertical axis wind turbines (VAWTs): The Darrieus machine being the most common, it is characterised by its C-shaped rotor blades which make it look a bit like an eggbeater (see Figure 13). It is normally built with two or three blades.

The basic theoretical advantages of a vertical axis machine are:

1. The generator, gearbox etc, may be placed on the ground, and the turbine may not need a tower.
2. No yaw mechanism to turn the rotor against the wind.

The basic disadvantages are:

1. Wind speeds are very low close to ground level.
2. The overall efficiency is not impressive.
3. The machine is not self-starting
4. The machine needs guy wires.
5. Replacing the main bearing for the rotor necessitates removing the rotor on both a horizontal and a vertical axis (more or less tearing the whole thing down). (Gipe, 1993)

Horizontal axis wind turbines (HAWTs): They are more common. Today all grid-connected commercial wind turbines are built with a propeller-type rotor on a horizontal axis. The wind changing direction, all HAWTs have some means for keeping their rotor into the wind, separating them in two subclasses: upwind and downwind turbines.

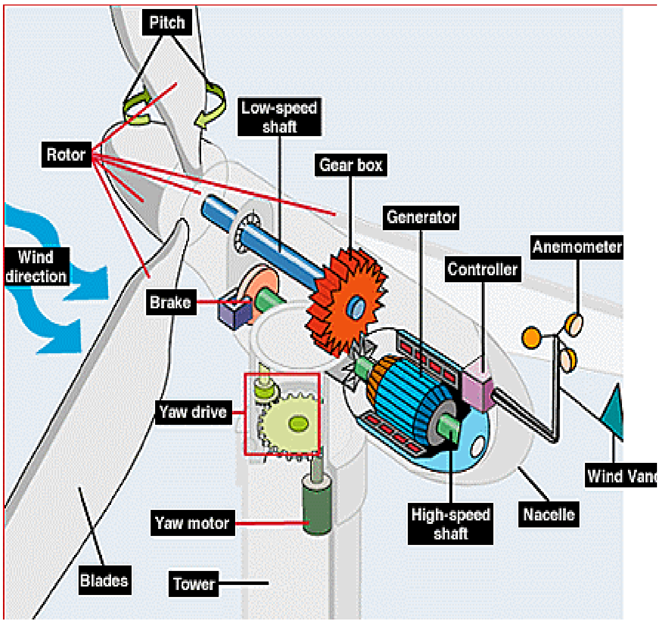
- Upwind machines have the rotor facing the wind. The basic advantage of upwind designs is that it avoids the “wind shade” behind the tower. On the other hand, there is also some wind shade in front of the tower. Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly. The basic drawback of upwind designs is that the rotor needs to be made rather inflexible and placed at some distance from the tower. In addition, an upwind machine needs a yaw mechanism to keep the rotor facing the wind.

- Downwind machines have the rotor placed on the lee side of the tower. They have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. For large wind turbines this is a somewhat doubtful advantage, however, since cables are needed to lead the current away from the generator. The cables, hence have to be untwisted when the machine has been yawing passively in the same direction for a long period of time, which requires a yaw mechanism.

A more important advantage is that the rotor may be made more flexible. This is an advantage both in regard to weight, and structural dynamics of the turbine. Therefore, downwind turbine may be built somewhat lighter than an upwind one. However, the basic drawback is the fluctuation in the wind power due to the rotor passing through the “wind shade” of the tower. This may give more fatigue loads on the turbine than with an upwind design.(D.W.I.A. (2), 2003)

4.6.3 Description of the upwind HAWT[4]

The nacelle contains the key components of the wind turbine, including the gearbox, and the electrical generator.



source: www.eere.energy.gov

Figure 14 : Internal Design

The rotor blades capture the wind and transfer its power to the rotor hub. They are designed much like a wing of aeroplane.

The hub of the rotor is attached to the low-speed shaft of the wind turbine.

The low-speed shaft of the wind turbine connects the rotor hub to the gearbox. The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate.

The gearbox has the low-speed shaft to the left. It makes the high-speed shaft to the right turn approximately 50 times faster than the low-speed shaft.

The high-speed shaft rotates with approximately 1,500 revolutions per minute (RPM) and drives the electrical generator. It is equipped with an emergency mechanical disc brake.

The electrical generator is usually a so-called induction generator or asynchronous generator.


source: www.religiousconsultantion.org

Figure 15 : External design

[4] Also known as the Danish design

It's power is usually between 500 and 4,200 kilowatts (kW).

The electronic controller contains a computer, which continuously monitors the condition of the wind turbine and controls the yaw mechanism. In case of any malfunction, it automatically stops the wind turbine and calls the turbine operator's computer via a telephone modem link.

The hydraulics system is used to reset the aerodynamic brakes of the wind turbine.

The cooling and heating unit contains an electric fan which is used to climate control the electrical generator. In addition, it contains an oil-cooling unit, which is used to cool the oil in the gearbox.

The tower of the wind turbine carries the nacelle and the rotor. It may be either a tubular (See Figure 15) or a lattice tower. Tubular towers are safer for the personnel, but the advantage of lattice towers is that they are cheaper.

The anemometer and the wind vane are used to measure the speed and the direction of the wind. The wind turbine's electronic controller starts the wind turbine when the wind speed reaches approximately 5 m/s and stops it if the wind speed exceeds 25 m/s.

The yaw mechanism uses electrical motors to turn the nacelle with the rotor against the wind. The electronic controller senses the wind direction using the wind vane and operates the yaw mechanism.(D.W.I.A. (2), 2004)

4.6.4.Technological limitations and unsolved problems of wind turbines

As seen previously, the Benz law and the aerodynamics of the turbine reduce the energy that can be extracted from the wind to almost 1/3 of the original resource content. Furthermore, the turbine will generate electricity only in the wind speed interval between the cut in and cut out speeds (from 3 to 25 m/s),. Unfortunately, as the turbine reaches full operating load around 10 m/s, it will use inefficiently the very common low wind speeds, and will keep the same power output as the wind speed increases, missing out on the increase in power of the wind. In most cases, the turbine will extract less than 10 % of the energy contained in the wind.

One could ask “is size everything when considering wind turbines?”, and the answer seems to be yes. Indeed, with increased size, the turbine produces cheaper electricity, has better wind conditions and less turbulence. However, besides the economical limits of building such giants, manufacturer are begging to encounter technical issues too. On land the limit has been set by the E-112 prototype at Magdeburg, Germany. This 4.5 MW direct drive turbine has a rotor diameter of 112.8m and a 10m synchronous ring generator. Future giants will be built only for testing purposes as the transport costs of their enormous parts makes prohibitive their commercial siting onshore.

The main advantages in building big offshore wind turbines are in the usage of enormous cranes; the fact that there is no need for new expensive infrastructure; and the regulations that are pretty lax. Therefore, it will not be a great surprise when turbine sizes double offshore in the decades to come. The problem is that the deeper the water, the more expensive the construction will be. Until now a single offshore farm, Blyth Harbour, with an excellent wind resource, has gone beyond the 7 m dept limit, which seem to be the economical limit for the concrete foundations. Although there are plans for even deeper foundations (30 m), this depth, or 7m, is considered by most experts to be the technical limit in siting a turbine.

Onshore, wind turbines present problems. The first one is that potentially good sites are already crowded and it is almost impossible to build new ones before tearing the old ones down. Siting a new wind farm inland is a hair-raising business because of all the regulation needed. The problem is that some of the aerodynamics concerning energy production are largely unknown, resulting in self destroying vibrations and inefficiency of the turbine. The pulsation in power output and the negative effect of turbines on weak electrical grids are well documented, but the need for some backup generation is also an important drawback.

The CO_2 emitted during fabrication and siting is another negative factor. Fortunately, as the technology evolves the CO_2 payback time can reach just 3 months, but smaller and badly sited wind turbines will take years to pay back the energy invested. These old often garage built wind turbines are the ones that give wind turbine technology a bad name. They are noisy, visually intrusive and most of all, there are so many of them (See Figure 16). One single modern turbine (See Figure 17) could replace 100 of these.

source: shop.ecoiq.com

Figure 16 : Cluster of wind turbines

source: www.spirit-lake.k12.ia.us

Figure 17 : Single wind turbine

Other problems created by turbines and still waiting to be resolved are the interference, with radio and TV broadcast, and the parasitic signal they "provide" to sensitive radar station (both military and civilian). There are also "minor problems" regarding breaking apart propellers in high wind and also flying debris, especially ice, but there has not been death due too mechanical failure of turbines. However plenty of fatalities and injuries during siting and maintenance operations of some privately owned turbines (especially home built ones) have occurred. Electrocution has also claimed the life of some of these enthusiasts.

4.7 Conclusion on the technical sustainability of wind energy

The total wind energy resource is virtually unlimited, many times more than the electricity needs of the entire planet, but some factors limit the usage of this immense resource. The main and local wind patterns create areas with different wind energy resource potentials and unfortunately the best areas are over oceans and seas. Moreover, the remaining inland resource is heavily fragmented and degraded by topography, vegetation, and buildings. It is estimated that less than 1 % of the entire resource can be used because of geographical factors.

Additional reductions to the potential energy resource are due to the theoretical and technical limitations of the wind turbines. This reduction is estimated at 90 % of the usable energy resource. However, it can be assumed that, considering the importance of the starting resource, the usable resource remaining (even in the worst case) is still capable of supplying the expansion of wind industry.

Chapter Five: Economics of wind energy

5.1 Criteria for the economical sustainability of wind energy

As previously mentioned, wind energy is said to be the fastest growing renewable energy in the world. Almost 40,000 MW of wind turbines were installed at the end of 2003 in more than 50 different countries. The growth of wind energy is impressive, especially in Europe where about 28,000 MW of wind power is installed. Growing indeed, but is the wind industry able to support itself economically? If it is not, should the state subsidise it to allow it to continue its growth? In this regard, we try here to demonstrate that wind energy is economically sustainable if it fulfils one of the two following conditions. First, it should be cost competitive compared to conventional energy sources. If it were, this would be an important incentive to develop it further so that it can reach its full potential on the energy market. Second, in the case where wind energy is not cost competitive and needs to be subsidised to compete in the market, it must be profitable for the society to promote it. Indeed, the investment of state's funds to promote the wind industry has to bring gains to the society in return, financial, social, or environmental ones.

Therefore, this chapter will demonstrate to which extent wind energy is cost competitive and what are the principles making it profitable to subsidise it. In this regard, examples of supporting systems will be presented.

5.2 Costs of wind energy

5.2.1 Factors affecting the wind electricity price

"There are no absolutes in energy prices. No single number can be assigned to the price of wind energy." (European Commission, 1999, p.65) We should start from this viewpoint when analysing the economical perspectives of wind energy. Production costs will vary greatly from a wind turbine to another, mainly because of some key factors.

Among these, as explained in chapter 4, wind speeds are crucial to the efficiency of energy production, stronger wind making blades turn faster, thus producing more electricity. Wind speeds depend on the sites where wind turbines are installed and as seen in the previous chapter, the energy of wind varies with the cube of its speed. Therefore, a small variation of wind speed induces a large difference of energy production and thus, of production costs (A.W.E.A, 2004, p.2).

On the other hand, production costs of wind energy have been decreasing for almost two decades due to improvements in turbine design making them more efficient. For example, the American Wind Energy Association (A.W.E.A.) mentions that “a modern 1.65 MW turbine generates 120 times the electricity at 20 times the cost of an older 25 kW turbine”, reducing by more than three folds the costs per kW (A.W.E.A., 2002, p.2). Coming development of the industry such as improvement of the storage capacity will also participate to diminish the costs. This will be discussed in chapter 8.

Moreover, larger wind farms appear to be more economical that the smaller ones. This is due to the spreading of the transaction, operation, and maintenance costs over more kWh with a larger project. Thus, the energy cost of a 51 MW wind farm will be 61% that of a 3 MW wind farm (A.W.E.A., 2002, p.2).

5.2.2 Costs description

As assessed by a report from The Danish Ministry of Environment and Energy about installation costs of wind turbines, the prices of wind turbine projects differ individually (Danish Energy Agency, 1999). However, the main installation costs are always shared among a number of variables such as: the cost of the turbine itself, the planning and development, the site foundation, the construction, the roads, the grid connection, and the legal fees. The operation, maintenance, and insurance costs, and the charges for the use of the electricity grid figure among the ongoing fees. (S.E.I., 2004, p.4)

In general, the initial investment for a 1MW wind turbine project is about 1.1 million EUR (S.E.I., 2004, p.4). As shown in table 2, the most expensive part of the investment is the construction costs of the turbines themselves, accounting for 80 % of the total installation cost[5].

Table 2: Average cost of a typical 600 kW turbine project (Danish Energy Agency, 1999)

Component	Average DKK (600kW)
Turbine ex-works[5]	3 146 000
Foundation	149 000
Grid connection	288 000
Electrical Installation	20 000
Tele communication	14 000
Land	103 000
Roads	39 000
Consulting	36 000
Finance	20 000
Insurance	94 000
Total	3 909 000

Operation and maintenance costs depend on some variables. For instance, operation costs depends on the period of working time. The costs of operating a new wind turbine are relatively low, but as the time passes, costs increase. As shown in table 3, according to statistical surveys done by Risø National Laboratory using a model for annual operation and maintenance costs, the percentage of the total investment attributed to operation and maintenance costs rises as wind turbines become older (Danish Energy Agency, 1999, p.19). Operation and maintenance costs are divided into parts such as services.

[5] Ex-work means that no site work, foundation, or grid connection costs are included.

consumables, repair, insurance, administration, lease of site (Danish Energy Agency, 1999, p.19).

Table 3: Annual operational and maintenance costs in % of the investment in the wind turbine (Danish Energy Agency, 1999, p.19)

Machine Size	Year 1-2	Year 3-5	Year 6-10	Year 11-15	Year 16-20
150 kW	1.2	2.8	3.3	6.1	7.0
300 kW	1.0	2.2	2.6	4.0	5.0
500-600 kW	1.0	1.9	2.2	3.5	4.5

5.2.3 Cost comparison with other energy sources

Since the 1980s, the cost of wind energy decreased by approximately 90% and is expected to continue to lower down with the constant growth of the industry (A.W.E.A., 2002, p.1). Data from 1996 comparing the levelized[6] cost of wind energy to that of other energy sources are shown in table 4. It should be noticed that wind power, without the addition of subsidies, has a cost level situated in the same range than conventional energy sources, such as coal or gas. According to the same data, nuclear power appears to be much less competitive. Furthermore, it has to be mentioned that the gas price has increased since that time to reach 15 to 20 USD cents/kWh, while wind energy cost slightly decreased. (A.W.E.A., 2004, p.1)

Table 4: Levelized cost of different energy sources

Fuel	Levelized cost (1996) (USD cents/kWh)
Coal	4,8-5,5
Gas	3,9-4,4
Hydro	5,1-11,3
Biomass	5,8-11,6
Nuclear	11,1-14,5
Wind	4,0-6,0

[6] Include all capital, fuel, and operating and maintenance costs associated with the plant over its lifetime and divides that total cost by the estimated output in kWh over the lifetime of the plant.

However, Risø National Laboratory presents a different scenario. According to it, wind power production costs are situated around 4 EUR cents/kWh, where coal and natural gas would respectively cost around 3 and 3,8 EUR cents/kWh. (Morthorst, 2004, p.11) Another cost assessment done by the Belgian Ministry of Energy and Sustainable Development (Pauwels and Streydio, 2000, p.18) also conclude that wind energy is not fully cost competitive. It compared wind electricity production onshore/inland, onshore/on coast, and offshore[7] to conventional fuels. The first column of table 5 presents the basic production costs, demonstrating that even onshore/on coast production in Belgium is not price competitive compared to coal, gas and nuclear power.

Table 5: Production, external and total costs of different energy fuels (Pauwel and Streydio, 2000, p.18).

Fuels	Production cost	External cost	Total cost
		EUR cents	
Nuclear	3,1	0,1	3,2
Gas (CHP)	3,2	1,0	4,2
Coal	3,4	2,4	5,8
Wind onshore/inland	7,8	0,3	8,1
Wind onshore/on coast	4,5	0,1	4,6
Wind offshore	5,8	0,1	5,9

Therefore, it appears that in the majority of the presented scenarios, wind energy cannot compete in the market with traditional energy sources without the help of financial support. Except in the A.W.E.A. data, wind energy is not price competitive at the moment.

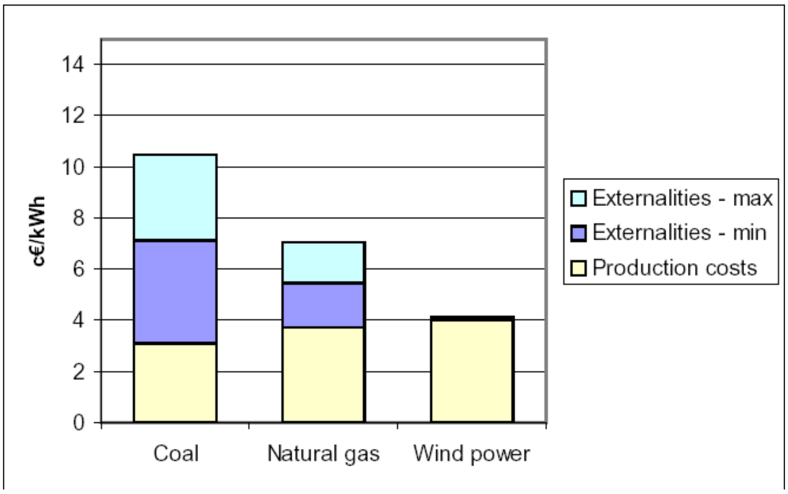
[7] Calculations were done considering working times of 1800, 2600, and 3250 hours, respectively, the turbines functioning at 20% of their nominal value the rest of the time. The estimated depreciation rate is 5% per year for 20 years of activity.

5.2.4 Factors improving competitiveness of wind power

Several factors could improve the price situation of wind energy. First, some ways of improving wind power efficiency have already been demonstrated. These included the choice of a site presenting high wind speeds, the improvement of the technology and the increase of the wind farms size.

Second, it should be noted that the wind energy sector is highly capital-intensive. It needs an important investment prior to produce any benefit, meaning that the industry is very sensitive to the interest rate charged for this investment (A.W.E.A., 2004, p.2). It seems that the wind turbine technology is still seen by potential lenders as a novel and risky one, at least among American investors (A.W.E.A., 2002, p.3). It therefore receives less favourable financing. Apparently, if the wind industry would receive the same financing than a typical natural gas project, its production costs could decrease by nearly 40% (Ryan and Kahn, 1996, in A.W.E.A., 2004, p.2).

Third, according to the A.W.E.A., "the cost of wind energy is dropping faster than the cost of a conventional generation" (2004, p.2). This will tend to increase the competitiveness of the wind industry in the coming years.



source: Morthost, 2004, p.14

Figure 18: Production costs plus externalities for wind power and conventional plants

Fourth, actual cost calculation do not include external costs such as environmental and health costs. However, it seems that considering externalities, wind power would already be highly economically competitive. Indeed, figure 18 shows how the very low external costs of wind power makes its total cost much lower than that of coal or gas.

The second and third columns of table 5 allows to draw a similar conclusion. Indeed, due to high external costs of coal and gas, wind energy produced on the coast of Belgium can compete with these two fuels. However, nuclear power stays the more competitive energy source. (Pauwels and Streydio, 2002, p.18)

Therefore, it can be assumed that even if not all data assess the actual cost competitiveness of wind energy, the addition of externalities makes the industry highly competitive compared to conventional energy sources.

5.3 Why subsidising the wind industry?

5.3.1 Overall EU Policy

In "An Energy Policy for the European Union" published in 1995, European Commission set its agenda to meet energy policy objectives. The three main objectives presented were to improve the competitiveness of renewable energies, the security of supply and the protection of the environment (European Commission, 1995, p.6). Renewable energies are seen as important tools to achieve these objectives. Since the competitiveness with conventional energy sources such as oil, coal, and gas is crucial to the promotion of renewable energies, some financial support schemes are implemented within EU member states. They are discussed later in this chapter.

To achieve these agendas, the European Union introduced directives concerning renewable energies. In Directive 2001/77/EC, the European Parliament says that, “the promotion of electricity produced from renewable energy sources is a high Community priority […] for reasons of security and diversification of energy supply, of environmental protection and social and economic cohesion” (European Parliament and the Council, 2001, p.1). As the purpose of the Directive is “to promote an increase in the contribution of renewable energy sources to electricity production in the internal market for electricity and to create a basis for a future Community framework thereof”, they force member states to encourage consumption of electricity produced from renewable energies and publish a report of the state of national targets every five years. The Directive also made it necessary to increase transparency so that consumers can recognise the difference between electricity produced from renewable and non-renewable sources. This could be achieved by introducing green certificate system. However, the Directive do not handle energy saving. Meyer criticises the Directive 96/92/EC on the same problem (Meyer, 2003, p.667).

In 2001, Commission of the European Communities published an action program, which aims to propose a decision of European Parliament and the Council of Europe. In the paper, renewable energies are seen as tools to reduce CO_2 emission by setting the target of 12% of all energy production (European Commission, 2001, p.27).

5.3.2 Green house gas emission concerns

In 1992, five years after the publication of the Brundtland’s Report, United Nations Conference on Environment and Development[8] was held in Rio de Janeiro, Brazil. The main argument in the conference was to establish “Sustainable Development”, which was first defined in the Brundtland’s Report.

[8] The conference is also called “the Earth Summit” due to the fact that prime ministers and presidents from more than 180 countries were at the same table.

Another five years after the Rio summit, the world summit on environment was held in Kyoto, Japan. Through the summit, the protocol that forces signing states to reduce green house gases (GHGs) emissions was assigned. States that signed and ratified the protocol should reduce certain amount of GHGs, namely Carbon Dioxide (CO_2), Sulphur Dioxide (SO_2) and Oxidised Nitrogen (NO_x), according to the negotiation held during the summit. The main tool that would be used for reduction is the increase use of renewable energy as well as some mechanisms between signing states i.e. Clean Development Mechanism, Joint Implementation and GHGs Emission Trade. To achieve the aim, a number of actions were taken over the years, at the national and the inter-governmental levels.

In 2002, World Summit on Sustainable Development took place in Johannesburg, South Africa. After the discussion, member states of the European Union and some other countries[9] jointly declared "The Way Forward On Renewable Energy". In the document, they express their huge concern about renewable energy use and their commitment to implementation. Further, they set necessary policies to adopt the use of renewable energy. The European Union has already set its action plan as a common strategy (European Commission, 1997, p.6).

Therefore, environmental protection is also among the main subjects in EU directives. The current objective of preventing climate change induces the support of renewable energy sources (European Wind Energy Association, 2003, p.6). In "Energy for the Future: Renewable Sources of Energy - White

[9] These countries are; Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Iceland, Latvia, Lithuania, Malta, New Zealand, Norway, Poland, Romania, Slovakia, Slovenia, The Alliance Of Small Island States, Switzerland and Turkey.

Paper for a Community Strategy and Action Plan" published in 1997, European Commission claims that the aim of the strategy is "to ensure that the need to promote these energy sources is recognised in new policy initiatives, as well as in full implementation of existing policies" (European Commission, 1997, p.7). It suggests financial measures such as:

- Flexible depreciation of renewable energies investments
- Favourable tax treatment for third party financing of renewable energies
- Start up subsidies for new production plants, Small and medium enterprises, and new job creation
- Financial incentives for consumers to purchase renewable energies equipment and services.

These measures have been achieved by different means. For instance, private investors in Denmark can receive subsidies from the government on the form of reduced taxes. The incomes from wind turbines are taxed in the same way than other investments, but the first DKK 3000 sold are not imposed, and only 60 % of the remaining income is taxed as usual. By doing so, many citizens could be involved in investing in small wind turbines.

Moreover, in the case of the fourth measure, the promotion of renewable energies is effectively achieved by co-operating with consumers. Consumers, in other words, the public, should participate in decision-making processes, and thus determine which direction their society is heading for. Lowering the actual price of electricity from renewable sources can contribute to this object.

Finally, taxes will play a significant role in the promotion of renewable energy when they are put on conventional oils, coal, and gases in the form of environmental taxes. It is believed that electricity companies and other private companies should pay taxes for every unit of CO_2 emission, thus encouraging the use of electricity from renewable, and reducing the global emissions.

5.3.3 Security of supply as a wind power advantage

Security of supply has been one of the main concerns in energy policy since the 1970s when two oil crises shook the entire world. The amount of oil supply decreased, and consequently the price of oil was set higher. Many countries, such as the United States, Japan and Denmark, changed their energy policy towards building nuclear power plants in order to cover the loss of oil and to secure the supply of energy. However, Denmark chose to promote renewable energies after civil movements against nuclear energy during the 1970s and 1980s. In 1985 a political agreement was made so that public energy planning would be done without nuclear energy (Danish Energy Authority, 2003). Renewable energy sources appear to be more reliable and should therefore be promoted. Moreover, in some regions like India, the building of wind turbines meets the need to cover energy shortage (European Wind Energy Association, 2003, p.6).

Therefore, the fact that wind power appears to be a more reliable energy source than conventional fuels advocate for its promotion. In that sense, investment of state's funds to promote wind industry brings considerable gains to the society.

5.3.4 Conclusion on the economical sustainability of wind energy

Economically, it seems that the wind industry is not yet fully competitive with conventional energy sources. However, it has been demonstrated that it is profitable for the society to subsidise it. Actually, it can be said that the polluting energies, mostly in regard to their GHGs emission rates, are indirectly subsidised because externalities are not considered in the cost calculation. If they were, or if wind energy were directly subsidised, wind industry would become fully competitive.

This would bring environmental gains to the society. Promoting the use of a nearly competitive and mature energy source such as wind can also be socially and financially profitable because it would increase the security of the energy supply. For these reasons, we consider that it is useful to support wind energy so that it is economically sustainable. The coming examples show different ways of supporting the wind industry.

5.4 Examples of financial supporting systems

5.4.1 Danish Policy on energy as a case study

There are two main categories of policies that are related to electricity from wind power: those concerned with prices and amounts in a market, and those concerned with wind turbines. The former is described in the Energy Supply Act of 1999. The latter is observed in the Environmental Protection Laws, land-use planning, and building legislation.

When investors build wind turbines, they have to follow local planning acts and to meet the country council requirements levels of noise, safety and quality of their technology. These approvals are set by The Danish Energy Agency and Risø National Laboratory.

Denmark is one of the most “renewable energy” minded country. Since 1980, a constantly increasing number of wind turbines have been built and these can produce 17% of the gross energy consumption (B.P.,2004). In the latest energy policy presented in 2003 (Danish Energy Authority, 2003, p.1), the Danish energy policy focused on:

- An open and international energy market
- Liberalisation of energy market
- Cost-effective management of environmental concerns
- Security of supply

The Danish Energy Authority declares that, it is its "responsibility […] to lay down guidelines for the best possible production and distribution of energy, having consideration for such issues as security of supply, cost-efficiency and international commitments (Danish Energy Authority, 2003)". Their objective is in parallel with EU policies.

Governmental supports are implemented to investment costs, production costs, and R&D activities. The two main systems concerning production costs are the fixed price system and the green certificate system (fixed quantity system). The former is introduced in states such as Denmark, Germany and Spain, though Denmark changed its system in 1999 to green certificate system by passing the Bill on Energy Supply. As Hvelplund (2001) and Meyer and Koefoed (2003, p.600) point out, it seems that Denmark had gone in a wrong direction. Here we will compare the two systems.

In Denmark, production subsidies have been changing the last 5 years. As Meyer and Koefoed (2003, p.605) say, the years 2000, 2001 and 2002 are the transition period of the subsidy system to distinguish old and new wind turbines. A production subsidy of DKK 0.60/kWh was paid for wind turbines built or under contracts before 1999, and then for a specified number of working hours or until they become 10 years old. From 2000 until 2003, the subsidy diminished so that 0.33/kWh was paid, but wind turbine owners would also receive the income from sales of green certificates. However, as the Danish government postponed its full implementation of green certificate system until 2003, subsidies of DKK 0.10/kWh were added, so that the total subsidies reached DKK 0.43/kWh. After 2003, the subsidies were abolished and the income of wind turbine owners would then come from the sales of green certificates. However, the Danish government postponed the implementation once again until 2005 due to the concern that Danish certificate market is too small to stabilise certificate prices. Since "old" turbines owners can receive financial help from the government, a rush of wind turbines installations started in 2000.

The two following sections discuss two different regulatory and supporting systems concerning electricity coming from renewable sources.

5.4.2 Feed-in system (fixed price system)

For more than a decade, fixed price system has been effectively working in Denmark as well as in Germany and Spain. In this system, a minimum price is guaranteed by the government for electricity generated from renewable energy. This is a long-term contract so that wind turbine manufacturers and owners could easily obtain bank financing for investment. In Germany for example, the country having very good coastal sites where enormous amounts of electricity can be produced due to plenty of wind, prices are set at EUR cent 9.54/kWh for the first five years, and at EUR cent 6.48/kWh for the rest of working years (Hvelplund, 2001, p.110). In Denmark, in addition to the fixed price system, renewable energy investment subsidy was introduced in 1979.

As Hvelplund (2001, p.7) describes, prices of electricity from renewable sources are set politically, while the produced quantity is determined by the market. Since electricity prices are set by the government, wind turbine manufacturers and owners can increase the amount of wind turbines that will be sold by decreasing their sales prices (Hvelplund, 2001, p.56). This is possible because the electricity price is assured under this system, which could be a strong incentive for people to invest in wind turbines.

Despite these good points, there are some problems concerning this system. First of all, fixed price system is criticised because it does not follow market principles. If electricity is something one can buy and sell in a market, then prices are naturally set by this market. However, as Hvelplund explains, what is trade in a market under fixed price system is not electricity but "amounts of electricity" (Hvelplund, 2001, p.22). The amounts will change according to the demand and the supply. Hence in a sense, this system also conforms to market principles.

The second problem is that some wind turbines, especially those built in a windy place, can receive too much subsidies compared to other wind turbines since subsidies do not go with technological developments (Meyer and Koefoed, 2001, p.598, Hvelplund, 2001, p.19). Therefore, the state is loosing money because it subsidises some producers more than what they really need and want to install wind turbines. This is one of the reasons why the Danish government made the decision to change the supporting system, together with the diminution of governmental budgets.

5.4.3 Green certificate system (fixed quantity system)

In this system, electricity companies have to buy a certain proportion of electricity generated from renewable sources. The government sets this proportion. Prices of green certificates are set in a market by selling and buying green certificates which guarantee that the electricity are from renewable sources. One certificate corresponds to 1 MWh of electricity production. On a green certificate, information such as the production plant, date of issuing, energy source and technology should be specified. The Danish government has set that 20 % of the electricity should be supplied from renewable sources by 2003 (Meyer and Koefoed, 2003, p. 601). Prices of green certificates are at minimum DKK 0.10/kWh, and at maximum DKK 0.27/kWh. Since the price fluctuates between these two politically set prices, it can be said that in this system, the market does not fully determine the price. If electricity companies on behalf of the consumers fail to buy obligatory quota of electricity generated from renewable sources, they have to pay DKK 0.27 /kWh for the amount they did not buy to the system operator, who control green certificate markets. Contrary to the fixed price system, the only way electricity producers increase their income from the sales of electricity in fixed quantity system is increasing prices of certificates (Hvelplund, 2001, p.56).

Compared to fixed price system, fixed quantity system is said to be more market conforming, because green certificates are traded following market principles, which is impossible in fixed price system. Danish Energy Authority mentions that "it is essential that the future electricity market can use more market-oriented mechanisms to ensure cost-efficient development of renewable energy production (Danish Energy Authority, 2003)".

As Meyer and Koefoed point out, the Danish government's decision to shift from the fixed price system to fixed quantity system was made because they thought the latter could be a standard in the EU at that time (Meyer and Koefoed, 2003, p.600). However, since the EU negotiations allowed each member state to choose the regime which better suits to its situation (European Parliament and the Council, 2001, p.3), countries such as Germany and Spain kept their fixed price system.

5.4.4 Advantages and disadvantages of each system

Both systems have advantages and disadvantages. In an early stage of development, every new technology needs financial supports on the form of subsidies. An advantage of the fixed price system is that it can contribute to new technologies development. Since the price is fixed, wind turbine owners can sell more electricity if they can lower the production costs. This is also promoted by the fact that the quantity of the electricity production is determined by the market, so the motivation of wind turbine owners is generally high because they can gain more profits if they produce more.

However, as technologies and industries mature, governments consider cutting subsidies because these technologies are already next to competitive with other technologies. We saw that in some situations it is the case for wind energy compared to fossil fuels.

If there is a big market to trade goods, market principles can work effectively. Fixed quantity system might work in international electricity markets. But in these markets, competitiveness of the technology should be the same in each country and consequently developments in technologies should also be more or less the same. Looking at current situations in Europe from this perspective, it can be said that establishing international electricity markets is difficult, because technology developments and the type of electricity resources are different in many countries. Denmark, Germany and Spain are leading countries in wind energy, while eastern European countries have used less wind energy.

Another problem in green certificate system is its unfairness. Since the price of green certificates determined by the market is applied to all wind turbines, there is no price differentiation. Wind turbine owners in coastal sites, where there is generally plenty of wind, can benefit from the sales of green certificates, while owners in poor inland sites cannot.

Similar to this, in fixed price system, wind turbine owners in good sites are overcompensated because the fixed price is applied to all wind turbines. As good windy places are soon used, this situation does not promote new investors, but it also favour the installation of new wind farms on the most efficient sites. Thus, by putting a stop to the fixed price system, the Danish government wish to stop investors to build turbines in poor places.

However, the German government introduced different prices according to sites and resources in 2000 (Hvelplund, 2001, p.42). By doing so, competition between turbines is promoted. As a result, the production cost is lowered and the amount of electricity coming from renewable sources increases.

Finally, favourable regulatory systems can promote renewable energies, especially wind energy due to its high technological developments. These regulatory systems should be politically and economically stable in order to promote renewable energies. Therefore, the industry becomes more efficient, improves its competitiveness and as a result, becomes self promoted.

During the last two decades, Danish energy policy had a big success with renewable energies, especially wind energy. The installation capacity rose enormously and the amount of renewable energies in the total energy supply increased. However, the Danish political change seems to increase the uncertainty of energy policies. This situation is criticised by Meyer and Koefoed (2003, p.605), who argue that it could lead to the unsustainability of renewable energies.

Chapter Six: Social impacts

6.1 Criteria for the social sustainability of wind energy

The public approbation to the construction of a wind farm is becoming more and more essential to the realisation of such projects. Many example of social opposition had lead to the cancellation of wind farm construction. The public support or lack of support can totally change the direction of wind farm plans. However, if there is public support the wind farms are usually developed in the area. Therefore, sustainability of wind energy in regard of social impacts implies the public support and acceptance.

6.2 Aesthetic value

6.2.1 Factors influencing visual impact

Wind turbines are tall in structure and can have a blade length of up to 30m. This may have a visual impact on the landscape. To some people a wind farm may appear intrusive or ugly. Precursors that influence an individual's opinion on windmills could be:

- the social and historical value a person places on the proposed site
- the environmental value an individual places on reducing pollution and CO_2 levels
- an individual's knowledge of technologies and alternatives for producing energy in an environmentally friendly way.

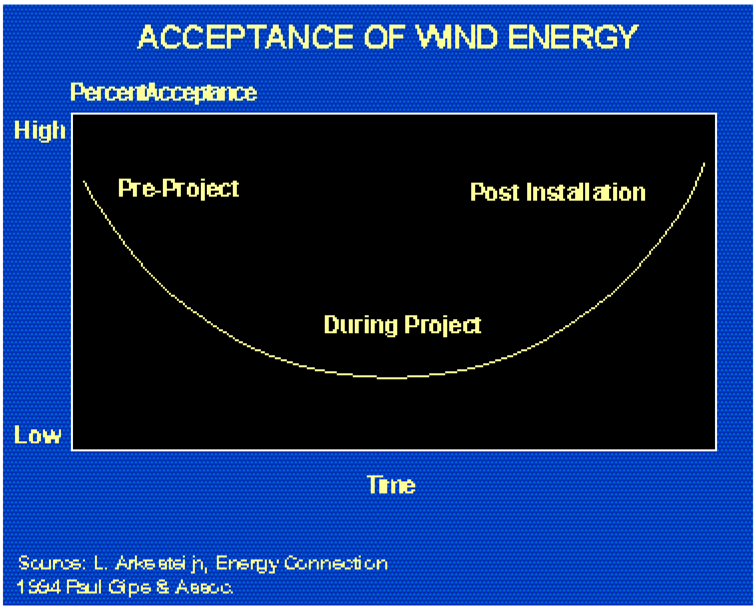
In Altamont Pass, California (See Figure 19), it was found that visual intrusion of wind turbines is the public's greatest concern. As a result extensive design and architectural planning went into making wind turbines aesthetically pleasing. Surveys were conducted and the general consensus was that the turbines should all be the same in structure. The surveys concluded that they must :

- be proportional to one another in height
- turn the same way
- be the same colour
- have all mechanical parts hidden from view.

source: www.safewind.org

Figure 19 : Altamont Pass

6.2.2 Public acceptance



source: Gipe, 1995

Figure 20: Public acceptance of wind energy over time

Surveys showed, (See Figure 20) however, that many inhabitants in areas where wind farm projects are in place are at first resistant to the thought of having a wind farm in their back yard. This is know as the NIMBY syndrome (Not In My Back Yard) in which people are in principle in favour of wind energy, as long as there is no wind turbine around their house. During the construction stage, which is the most disturbing, residents hate the thought of wind farms.

After the wind farms have been running and producing electricity the inhabitants find that they are not as intrusive as they first thought.

Moreover, people living close to wind farms (within 20 km) like the areas they live in, mentioning the peacefulness (28%), scenery (26%), rural isolation (23%) and friendly people (20%) as particular strengths. When asked to say what the shortcomings are, most commonly mentioned are a lack of amenities (20%), poor public transport (18%), and lack of jobs (8%). Just five people (0.3%) spontaneously mention wind farms as a negative aspect of their area. (Gipe, 1997)

6.2.3 Lighting

The lighting on the wind turbines can increase their visual disturbance. Wind turbines that stand over a certain height must have lights, reflectors or some sort of visual device that can be seen from the sky. If a wind turbine is higher than 120 metres it has to have a reflector and a tipped rotor blade (See Figure 21). This means that the end of the blade has to be tipped red so that it is visible during the day, and a reflector so that it is visible at night.

source: www.religiousconsultation.org

Figure 21: Tipped wind turbine

source: www.menzelphoto.com

Figure 22: Light on the hubs of wind turbines

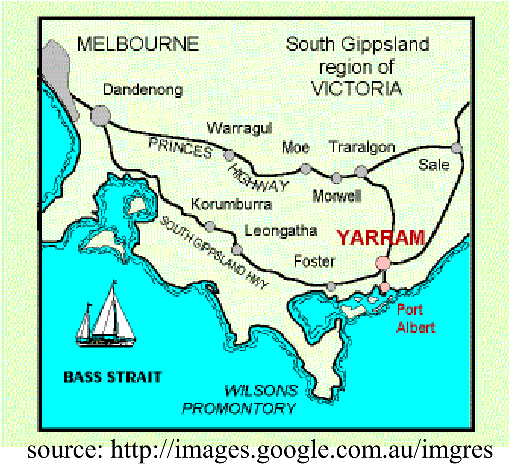
However, there are possibilities of minimising the lighting effects. Indeed, operators should douse security lighting at their wind plants and substations, and the lights at the hubs of the taller turbines (See Figure 22) to decrease the contrast between the wind plant and the night time landscape of rural areas where wind turbines are typically installed. Night-time security lights are non-essential and can be activated as needed by motion detectors such as those used by Southern California Edison in light sensitive environments.

6.2.4 Other installations

On most wind farms there are a few small buildings that contain equipment such as transformers, tractors, cables, etc. It was these buildings that people of Carland Cross, Wales, found visually intrusive. To rectify this problem the public approached the builders. Now all buildings in wind farms are to be constructed out of traditional materials to make the buildings look like traditional cottages, instead of ugly warehouses. Making these buildings more attractive is a concept that has been taken on by other wind farm promoters to quickly gain acceptance. Nowadays newer designs of wind turbines, such as the new Danish design, have all transformers and cables inside the tower of the wind turbine, making extra storage buildings no longer necessary.

6.2.5 Case study

A case study of visual intrusion is shown in Gippsland, Victoria, Australia. A project is in place to build a wind farm along the southern coast (See Figure 23). Residents of the area are angry because the windmills will obstruct their views and cut property prices by up to 25%.



source: http://images.google.com.au/imgres

Figure 23: Gippsland, Victoria

Environmental campaigner Phil Honeywood said, "one of Australia's best assets is our coast. Having 30-40 storey high wind turbines that are visible from 30 km away will be detrimental to the coastline's character." Wilson's Promontory is a nature reserve situated near where the wind farm is proposed to be built. Thousands of people from all over the world are attracted to the promontory annually for its native flora, fauna and breathtaking scenery. When the farm will be built, 61 turbines will be visible from the promontory, which is expected to result in a drop in tourism. Honeywood add that "areas as scenic as these should be protected from wind farms." He asks, "Why build them here when there are effect alternatives elsewhere?" (The Age Company Ltd, 2004)

6.3 Shadow flicker

Shadow flicker occurs when the sun passes behind the hub of a wind turbine and casts a shadow over neighbouring properties. When the blades rotate, shadows pass over the same point causing an effect called, "shadow flicker." Shadow flicker within houses occurs if a wind turbine is close enough to and of a specific orientation with, a nearby house. Close neighbours of wind farm projects occasionally raise shadow flicker as an issue. (Gipe, 1995)

The flickering effect from the wind turbines depends on the time of year (which determines how low the sun is in the sky) and on the time of day. Moreover, there is less or sometimes no shadow flicker when there is vegetation or other obstructions between the turbines and the house. This is also true, if windows facing a turbine are fitted with blinds or shutters, or if the sun is not shining brightly enough to cause shadow from the turbine.

Fortunately, with the help of computers, we can predict accurately the probability of when and for how long there may be flickering effect. Using computers to calculate the sun height, angle, wind speed and time of day to avoid the flickering allow to solve this problem by turning off the wind turbine for a certain number of hours of even days. Doing these calculations, we may not know in advance when the wind will blow or what the wind direction will be, but using astronomy and trigonometry, a "worst case" scenario can be computed. This worst case is a situation where there is always sunshine, when the wind is blowing all the time, and when the wind and the turbine rotor keep tracking the sun. (Energy Efficiency and Conservation Authority, 1995)

6.4 Job creation

Wind energy is associated to job creation mainly in the manufacturing sector, but also locally during the construction stage. For example, a typical 5 MW wind farm will cost about 5.5 million EUR to build, of which 1 to 2 million EUR will be spent locally. It will provide 50 construction jobs for 6 months and 2 long term, sustainable jobs. (S.E.I., 2004).

However, the wind farm will reduce the need to import and produce about 60,000 tonnes of oil or 95.400 tonnes of coal, thus cutting jobs in this sector. Nevertheless, investing in renewable energy, using energy and materials more efficiently, and designing products to be more durable and repairable will generate more jobs than continuing to invest in extractive industries and fossil fuels.

Moreover, we consider that the local employment effect will favor the public acceptance of a wind farm construction in the area.

6.5 Security of supply and local advantages

When considering energy production in general, a major risk is associated to the security of supply. As assessed in the preceding chapter, the wind industry as the advantage of not presenting this risk, the wind being a renewable resource.

Moreover, renewable energy is often related to decentralisation, which means that the electricity production is done not in a central power plant, but in locally placed plants such as wind turbines and solar panels. This is due to the fact that they use resources that can be acquired locally and because electricity generators or heating factories can be placed in every small region. Many wind turbines in Denmark are private-owned, which means that the electricity they use is self-sufficient. An example of this can be found in Samsø Island, which lies to the east of Jutland. On the island, all the consumed energy is produced by means of wind turbines, including onshore and offshore, solar panels and biomass plants[10]. The example of Samsø Island demonstrate that decentralisation allows a community to use only renewable energy but also to increase its dynamism by the industry created around this objective of self-sufficiency.

6.6 Conclusion on the social sustainability of wind energy

Some positive and negative social impacts related to the use of wind energy have been described. First of all, wind turbines may affect the scenery of the nature by their visual intrusion and the shadow flickering effect. Noise, that will be assessed in the next chapter, also has effects on humans. Such negative

[10] On a calm day when wind turbines cannot produce enough electricity, they import it from the main island, while they export on a windy day.

impacts can induce public reluctance toward wind farms which, if turns into opposition, can threaten the project. However, for a wind farm to be approved, the public needs to be involved in the planning and construction process. Positive effects for the locality can also encourage people to support the project. Indeed, the use of renewable energies, especially wind and solar energy that is available locally, can lead to the independence of communities. Using local resources will affect the local economy in creating jobs and promoting local companies and initiatives (Elliott, 2000, pp.261-274). We therefore consider that the temporary aspect of the public opposition together with the local positive effects of the industry make wind energy socially sustainable.

Chapter Seven : Environmental costs

7.1 Criteria for the environmental sustainability of wind energy

Starting from Brundtland's definition of sustainability, the wind industry, in order to be sustainable, must not modify the actual state of the environment so that future generations will still be able to fulfil their needs. Of course, the use of wind energy does induce environmental impacts, which will be described in this chapter. However, we consider that as long as these effects can be avoided or mitigated, the whole industry stays sustainable. Nevertheless, in the cases where important environmental effects cannot be minimised, the sustainability of a wind turbine site is not anymore possible, even if technical and economical features make it very profitable.

In this chapter, potential environmental impacts will be described. If real problems, their solutions will be proposed in order to conclude if major environmental concerns threaten the sustainability of wind energy. If one of these impacts would miss a viable solution, a verdict of unsustainability would follow.

7.2 Global impacts on ecosystems

7.2.1 Onshore wind farms

The building of the wind turbines facilities and of the roads necessary to construction and maintenance as well as the damage done to the land during the construction phase are responsible for the removing of a certain proportion of the vegetation of the area. For instance, the proposed Maiden Wind Farm in USA (549 wind turbines) estimates at 414 and 128 acres of native habitat temporarily and permanently destroyed, respectively. Consequently, a loss of wildlife habitat, an alteration of wetland and riparian functions, a reduction in plant diversity, and a change in plant community functions are expected. As the vegetal cover is modified, risk of bringing new noxious weed species is also to consider.

Nevertheless, these consequences can be minimised by revegetating the habitat as quickly as possible with native species. It is also important to control weed invasion by cleaning the construction vehicles before driving them on site and by controlling noxious weeds that have established (U.S.D.E., 2002). Moreover, since wetlands are particularly sensitive areas, wind farm construction should avoid taking place on these lands. It has to be considered that any impact on the vegetal cover of the area will also affect the wildlife inhabiting this ecosystem.

However, it should be noted that in most cases wind farms are built in areas extensively used for agriculture. As a result, the used land generally presents a poor vegetal diversity, meaning a weak environmental value (Externe, 2004).

Another environmental concern onshore goes to bat mortality, which present higher rates than what was thought before. This is especially true for species migrating south. For example, at the Mountaineers Wind Energy Center in West Virginia a mortality rate of 70 bats per turbine per year as been estimated. In the first two years of operation of the wind plant in the Cumberland Mountains of eastern Tennessee, it is an average of 30 bats per turbine that were killed.

The problem seems to be associated with migration. The hypothesis is that bat would not use echolocation continually while migrating. This could be a matter of energy saving or a consequence of the greater flight speeds reached during migration. Such speeds would make the echolocation system less efficient. Therefore, that kind of impact could be avoided by placing wind farms elsewhere than on bat migratory routes. Since most bat species do not appear to migrate over open ocean, offshore wind parks present advantages (Safewind.info, 2003).

7.2.2 Offshore wind farms

Some impacts on marine ecosystems result of construction and decommissioning of the wind farms. Among those, underwater noise and vibration would be associated with pile driving. It is believed that the implied sound levels would only generate short-term startle response followed by habituation (Knudsen *et al.*, 1992,1994; Westerberg, 1999, in SeaScape Energy, 2002, p.130). Fish may also temporarily avoid the pile driving area up to a distance of 1000 metres (SeaScape Energy, 2002, p.132). The slow increase of pile hammering would induce a gradual avoidance of the area by the fish, thus preserving their hearing (SeaScape Energy, 2002, p.143). Marine mammals are also likely to show short-term avoidance of the work area (SeaScape Energy, 2002, p.146-153).

A second impact would be related to mobilisation and redistribution of sediments in the water column as well as mobilisation of soil contaminants. This could induce impacts on fish, shellfish, and benthic communities (SeaScape Energy, 2002, p.97-128).

While operating, elasmobranches may respond to the electromagnetic fields generated by cabling. It has been demonstrated that they would tend to avoid them or be momentarily attracted by them (Gill and Taylor, in SeaScape Energy, 2002, p.137). This effect can be mitigated by insulation and burial of cables (SeaScape Energy, 2002, p.143). Moreover, disturbance could still be caused by underwater noise and vibration. Although general habituation to continuous noise generated by the operating turbines as been observed before (Westerberg, 1999, in SeaScape Energy, 2002, p.139). This might also be true for marine mammals, which have been observed while migrating past noise generating oil and gas drilling platforms (Vella *et al.*, 2001, in SeaScape Energy, 2002, p.153).

Moreover, a potential change in the lower trophic level due to change in the sedimentation processes around the turbines would induce effects on fish populations (SeaScape Energy, 2002, p.107-128). Finally, permanent loss of sea bed habitat will be experienced by the benthic communities at the emplacement of the turbines (SeaScape Energy, 2002, p.108). Potential impacts on fish could also arise if a wind farm would be put on a spawning or nursery ground (SeaScape Energy, 2002, p.125-127). However, the submerged section of the wind mills may be colonised by various seaweeds and invertebrate (Vella *et al.*, 2001, in SeaScape Energy, 2002, p.108) thus creating new habitat for fish populations. They will tend to gather in those areas, profiting of the enhanced food resource and of the safety of the wind farm's waters compared to those of the open ocean.

7.3. Impacts on birds

7.3.1 Types of potential impacts

In a global perspective, Tingley (2003, p.9-23) describes three main potential effects of wind turbines on birds. Firstly, the most assessed impact is the risk of collision with the turbines. The birds can hit a non-moving part of the turbine or the spinning rotor blades. They may also be caught in the strong pressure wave generated after the passing of a blade. This last form of collision is called wake collision and can induce disorientation, physical collision with the turbine or falling on the ground or water of the birds.

Secondly, the disturbance effect is also considered. It is due to the noise of the wind turbines, to their visual amenity and to the increase human activity in the area. This can lead to the avoidance of the area, although species can possibly habituate to the new environment. Through avoidance behaviour, the disturbance effect has two major impacts: 1- the indirect loss of habitat and 2- the creation of a barrier to flight patterns. The former will be observed if essential resources not uniformly distributed are situated in the disturbed and therefore avoided area. Consequently, larger wind farms could cause larger losses of habitat. Moreover, a diminution of available resources can lead to reduced breeding success and increased mortality. The latter occurs if individuals start flying around the wind farm instead of through it. This will happen if the wind farm intersects a major migratory route or the daily home-range movement of species. Although reducing collision risks, such behaviour induces extra stress and energy expenses.

Thirdly, a direct loss of habitat or a habitat alteration occurs if the wind farm is built upon or physically alters the habitat. Direct loss of habitat happens on the surface where wind turbines facilities are built. On the other hand, alteration can present positive aspects such as habitat creation for the birds themselves (perches) or for their feeding resources. Indeed, as mentioned earlier, in offshore cases invertebrates and fish will tend to colonise the submerge base of the wind turbines, resulting in a reef effect. Nevertheless, as previously said, an increased frequentation of the wind farm could result in an increased risk of collision with the turbines.

Finally, another factor having direct effect on birds is related to the lighting of the turbines. Aviation lights are known to disorientate birds, mainly nocturnally migrating passerines, and thus to alter their course. Bad weather reducing visibility enhance this effect.

7.3.2 Specific impacts on birds onshore

The collision risk with onshore wind turbines has often been assessed. Indeed, in California, the sadly renown Altamont Pass and its 5000 wind turbines are responsible for the death of 1000 birds per year. Half of these are raptors, mostly red-tailed hawks (*Buteo jamaicensis*). However, 24 golden eagles (*Aquila chrysaetos*), a protected species, are also killed each year. This puts the mortality rate of these turbines at 0.19 birds per turbine per year. California wind industry argue that the repowering of the wind farms, while reducing the number of turbines in activity, would decrease de number of birds killed. However, the National Renewable Energy Laboratory (USA) has concluded that this would occur only if the area occupied by wind parks is also reduced (Gipe, 2004).

Another example of collision risk onshore comes from wind farms located on the coast in the Strait of Gibraltar. A study about soaring-bird mortality notes that "wind turbines are often arranged in rows, along the coasts of mountain ridges" (Barrios and Rodriguez, 2004, p.72). In such places, soaring-birds use the strong air currents to go uphill. Therefore, wind turbines present a risk of collision or mortality to birds, but only at certain wind speed. Therefore, the authors propose that the turbines related to the highest collision rates should be turned off when wind speed lead to dangerous flights (Barrios and Rodriguez, 2004, p.79-80)

However, another study conducted by De Lucas *et al*. (2004) in the same area demonstrated that the presence of turbines does not affect bird abundance and that soaring-birds detect and avoid the turbines, even better when they are functioning. The mortality rate in this wind farm was therefore practically nil. This can be explained by the fact that the area of the wind farm wasn't used as a feeding, roosting or breeding place, but only as a passageway. However, since birds can detect and avoid the turbines, a long row of turbines can act as a barrier to daily travel or migratory routes. The authors suggest that making shorter turbines rows, more easily avoidable, could reduce this effect (De Lucas *et al*., 2004, p.403-405).

Regarding the disturbance effect and indirect habitat loss, Larsen and Madsen (2000) have assessed the effects of wind farm and other physical elements of human origin (wind breakers, roads, …) on the pink-footed geese (*Anser brachyrhynchus*) during its wintering and spring staging. They found out that wind turbines placed in cluster generated more important avoidance than those placed in rows. This resulted in a reduction of the field area available to geese. The authors then suggest that lines of turbines and smaller clusters, creating less avoidance, would minimise habitat loss (Larsen and Madsen, 2000, p.762).

7.3.3 Specific impacts on birds offshore

Until now, a very few studies have been conducted regarding the real effect of offshore wind farms on birds. Tingley (2003, p.34) mentions that the risk of collision depends on the number of birds travelling through the wind farm vicinity, their flight height and their avoidance of the turbines and blades. These factors are site-specific and species-specific and must therefore be studied for each proposed or actual wind farm site.

However, evidence of bird collisions with offshore wind turbines have been assessed in the past. A study conducted at Blyth Harbor in England found mortality rate for shoreline wind farms of 0.75 to 5.2 birds per turbine per year. Although those numbers seem high, collisions represent only 0.01% of all bird flights through the wind farm (Parkinson, 1999, in Tingley 2003, p.36). In Osterbierum, Netherlands, this proportion has been found to be of 1.1% (Winkelman, 1992, in Tingley, 2003, pp. 38-39). However, it was observed that the number of collision tend to decline over time, suggesting habituation for local populations (Percival, 2000, in Tingley, 2003, p.36). It is also assessed that most of the collisions occur during nights with poor flight or visibility conditions (e.g. strong headwinds, fog, rain, new moon) (Winkelman, 1992, in Tingley, 2003, p.38). Finally, since migration altitude is highly variable from species to species, place to place, and dependant on weather conditions, this factor cannot be considered as influencing collision risk in general. However, observation of high migration altitude in particular areas could decrease the collision risk in those specific locations (Tingley, 2003, pp.40-41).

Concerning the disturbance factor, a study conducted at the Tunø Knob wind farm (Denmark) by Guillemette *et al*. (1998, p.50) found no variation in the abundance of common eider (*Sometaria mollissima*) related to the presence of the standing towers or revolving rotors. However, they did find out that the eiders avoided flying and landing within 100 metres of the wind farm. This has the positive effect of reducing the collision risk, but apparently eiders do not avoid to feed in the area, getting there by swimming. Indeed, according to Tingley (2003, p.42) “no study to date has documented any negative impacts of wind farms to bird populations as a result of acting as a barrier to movement”. Nevertheless, he also mentions that negative effects could be found when bigger farms will be studied.

Finally, Tingley (2003, p.42) notes that direct habitat loss is rarely documented as having a significant impact on offshore bird populations. However, loss of habitat could temporarily result of the construction phase interfering with food supply communities.

In order to reduce those potential impacts on birds, wind farm planning should avoid heavily used sites. These can be areas of feeding, roosting, mating, staging, daily travelling, moulting, and migrating. Since bird sensitivity is species-specific and site-specific, no standard avoidance distance from those sites can be determined. The distance has to be defined in avian surveys prior to each project (Tingley, 2003, p.47).

7.3.4 Solutions to impacts of onshore and offshore wind farms on birds

First, Tingley (2003, pp.48-49) offers proposal of offshore wind farm configurations which could also apply to onshore cases. He mentions that minimising the number of turbines decreases the risks for birds flying through the wind farm. The effect of the installation of bigger multi-megawatt wind turbines is still poorly known. While bigger turbines have slower rotors that birds are more likely to see and avoid, collision risk may also be increased by the larger size of the turbine, the larger swept area, and the very fast moving blade tips. However, given a set total output of a wind farm, a few large multi-megawatt turbines could present a lower impact than many smaller turbines (Tingley, 2003, pp.52-53).

Moreover, the turbines should be arranged according to the actual use of the site by the birds and the size of the wind farm. Based on Winkelman (1992, in

Tingley, 2003, p.48) Tingley (2003, p.48-49) proposes the following configuration:

1- Small wind farm with local birds: one dense cluster so that the birds keep away from it, avoiding collision risks.
2- Large wind farm with local birds: several dense clusters spaced far enough apart to avoid barrier effect.
3- Small wind farm with migrant birds: lines of turbines parallel to migration direction or an open cluster to avoid barrier effect.
4- Large wind farm with migrant birds: broken down lines or clusters to avoid barrier effect for birds flying perpendicularly.

Second, visibility of the turbine could still be enhanced. Birds being able to see in the ultra violet wavelength, research is currently done toward the possibility of using UV paint to make the turbines more visible. However, the development of patterns diminishing the motion smear (inability to distinguish quickly moving objects) seems even more promising (Tingley, 2003, p.53).

Third, the bad hearing capacity of birds is also a problem. Experimenting of blade whistles is currently done. This could allow birds to hear the turbines from far enough to avoid them before the motion smear makes the blades less visible (Tingley, 2003, p.54).

Fourth, giving the fact that “lighting of tall structures is strongly associated with massive mortality events of birds” (Richardson, 2000, in Tingley, 2003, p.54), a less risky way of lighting turbines for aviation purpose has to be found and applied. It seems that white strobing lights with the fewest flashes per minute would be preferable (Tingley, 2003, pp.54-55).

Finally, it should be admitted that once a wind farm is built, particular turbines associated with greater collision risk has to be turned off during high-risk periods (e.g. nights during migration), moved or even decommissioned. If the complete site present high mortality rate, it should be turned off at night, during inclement weather, and during period of peak migration (Tingley, 2003, p.56).

7.4 Erosion

Erosion is the wearing away of the earth's surface sediments by any natural process. In this case it is the natural process of wind, but the main culprit for wind erosion is human induced. In some areas where wind turbines are not sited or constructed properly, then erosion can occur.

As turbines are situated in windy places there is a higher risk of erosion at their base. The wind is strong and blows hard against the base of the wind turbines, so any loose soil and sediments are weathered away, leaving pits and rills and the base of the turbine exposed to more wind. Dust from the wind turbines can also be a great nuisance to nearby residents, farmers and weather forecasters.

Erosion is a major problem during the construction of a wind turbine. As the loose soils are more prone to weathering away, the wind turbines need to be constructed quickly and efficiently to avoid long periods of time where the dust is open to the wind and easily eroded. Indeed, during that stage there is a lot of sediment suspended in the atmosphere, which is blown over long distances by the wind to settle somewhere else. These dust clouds can cause disruption to farms and farmers. The dust can settle on newly planted crops, choking the new shoots. As the dust can be quite thick it can make it harder for the farmers to gauge the direction of the weather. The dust needs to be removed straight away and spread elsewhere out of the direct wind path. Erosion can also be a concern in certain habitats such as the desert, along coasts and where hard-packed soil surface could be disturbed by the wind. (Gipe.P, 1996).

Wind companies can reduce the risk of serious erosion by: minimising the amount of earth disturbed during construction, principally by eliminating unnecessary roads; avoiding construction on steep slopes, allowing buffers of undisturbed soil near drainage and at the edge of plateau's; assuring revegetation of disturbed soils, and designing erosion-control structures adequate to the task. The single most reliable technique for limiting erosion is to avoid grading roads in the first place.

On flat onshore wind farms there is virtually no erosion due to the fact that they are generally concealed from the wind. However, a small amount of erosion still occurs during construction, which is dismissed and causes major damage to nearby flora and fauna. (Gipe, 1996).

source: www.wind-works.org

Figure 24 : Gully from wind farm

A short case study of the problem of wind erosion due to the ill construction of wind turbines is apparent in the Tehachapi Pass, USA. In this Pass there are many factors that contribute to the erosion, such as rainfall, slope length, and cropping .

The erosion levels are high in this area. The slopes are long (See Figure 24) and allow runoff (See Figure 25) ample time to accelerate and heighten the problem. The rill and gully erosion, seen in the Tehachapi Pass cuts deep into the surface of the landscape .

source: source: www.wind-works.org

Figure 25: Close up of gully

More galling than the erosion itself is the abuse of the resource it represents, because accelerated erosion is unnecessary and can be avoided. Once the rills and gullies form they should be treated immediately otherwise the erosion will accumulate at a very fast rate. (Gipe, 1996).

Erosion is a poorly known problem of wind farms but an important one. Environmental impact assessments should take it into account. However, as stated before, proper installation could greatly lessen the effect of erosion.

7.5 Noise

7.5.1 Onshore

Noise is defined as any unwanted sound. The effect of noise on people can be classified into three general categories:

1) Subjective effects including annoyance, nuisance, and dissatisfaction
2) Interference with activities such as speech, sleep, and learning
3) Physiological effects such as anxiety, or hearing loss

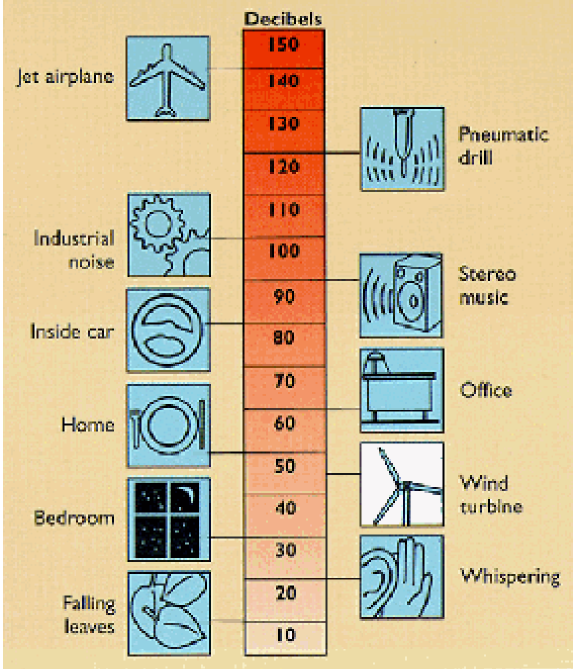
Wind turbines are often sited in rural or remote areas that have a corresponding ambient noise character. Furthermore, while noise may be a concern to the public living near wind turbines, much of the noise emitted from the turbines is masked by the background noise of the wind itself.

The sources of noise emitted from operating wind turbines can be divided into two categories: 1) mechanical and 2) aerodynamic. The primary sources of mechanical noise are the gearbox and the generator. Mechanical noise is transmitted along the structure of the turbine and radiates from its surfaces. Turbines have been made quieter by putting a rubber cushioning or pillow between all the mechanical parts to avoid this friction so that less noise is generated. Aerodynamic noise is produced by the flow of air over the blades. Efforts to reduce aerodynamic noise have included the use of lower tip speed ratios, lowering of blade angles, and modification of the speed operation.

There are four types of noise that can be generated by wind turbine operation: tonal, broadband, low frequency, and impulsive:

1) <u>Tonal</u>. It is caused by wind turbine components such as meshing gears, generator, cooling fans, and auxiliary equipment.
2) <u>Broadband</u>. It is often caused by the interaction of wind turbine blades with atmospheric turbulence, and also described as a characteristic "swishing" or "whooshing" sound.
3) <u>Low frequency</u>. Associated with downwind turbines (turbines with the rotor on the downwind side of the tower). This is caused when the turbine blade encounters localized flow deficiencies due to the flow around a tower.
4) <u>Impulsive</u>. This is caused by the interaction of wind turbine blades with disturbed airflow around the tower of a downwind machine.

The main source of noise comes during the construction stage of the wind turbine. When there is a lot of heavy machinery such as tractors, cranes and trucks moving parts of the wind turbine around to get it erected as quickly as possible. However, while operating, modern wind turbines are nowadays very quiet (See Figure 26).



source: http://www.safewind.org/wind_FAQ_final.htm

Figure 26: Decibels of a wind turbine

While another concern could be the noise effect on animals, studies conclude that the wildlife inhabiting the area are not affected by the noise of the wind turbines. Some animals have a higher level of hearing than humans. It is only during the construction stage that the animals seem disorientated due to all the machinery moving around, but there is no long-term effect on them. (University of Rhode Island, 2004)

7.5.2 Offshore

With the offshore wind turbines noise is not a direct problem. No inhabitant can be disturbed and it does not directly effect the marine life. During the construction stage where there is more movement of ships and heavy machinery there is more noise generated but, as seen before it still have little to no long term effect on the marine life.

7.6 Vibration

One of the main problems that affect some marine mammals is the vibration at the base of the wind turbines, which is an indirect effect from the noise. The noise from the spinning of the rotor blades vibrates down the tower of the wind turbine and into the base under the sea level. The bases of wind turbines are either made up of steel or concrete. When the noise vibrates down the tower it decreases in intensity.

The effect this has one some marine life is that it can, if strong enough, disturb their navigation. Some marine animals such as turtles, dolphins and some fishes use sonar wavelengths to navigate on migratory routes or to breeding sites. If disrupted too much they can loose all orientation and become separated from their pod/school and the chances of survival are made much slimmer, especially if they are already an endangered species such as the Loggerhead Turtle (*Caretta caretta*) and Sperm Whale *(Physeter macrocephalus)* (Safe Wind, 2003). With the onshore wind turbines, vibration still occurs but there is no effect on the surrounding environment.

7.7 Electromagnetic fields

7.7.1 Offshore

The production and conduction of electricity can produce electromagnetic fields. The fields are generated around cables that conduct electricity from wind turbines to the consumer. The monopoly cables are the ones that produce the higher electromagnetic field. These cables are suspended above the seabed from the base of the offshore wind turbines. Even though they are not very high they are intrusive, and disturb and disorientate some marine life.

There are many marine animals that rely on sonar for navigation, for example some turtles, sharks and dolphins. Many species of rays can detect electromagnetic fields generated by prey buried and hidden in the sea bed. The emission of electromagnetic fields by the electric cables can disturb the senses of the rays, making them vulnerable to their prey because they cannot detect them. The cables threaten the survival of marine animals that rely on sonar navigation. Not only can they be more vulnerable to their prey but their navigation on migratory routes and to breeding sites is also disorientated. For sharks such as the Gummy Shark (*Mustelus antarcticus)*, which are already endangered by the commercial fishing industry, the cables could eventually mean extinction. (Safe Wind, 2003)

Other marine animals which are affected by the presence of electromagnetic fields include eels and some cetaceans. Evidence from the Baltic sea suggests that the movement of eels can be disrupted by the presence of the electromagnetic fields generated by the monopole cables. (Balloch, 2004)

Eels are naturally attracted to monopole cable electromagnetic fields, with higher fields being more attractive. Meanwhile cetaceans can become disorientated by high electromagnetic fields. This can change the ecosystem around the base of the wind turbines, adding eels to the equation but losing the cetaceans from disorientation. However, the electromagnetic field generated is not usually high enough to seriously damage cetacean species. As previously mentioned, the insulation and burial of cables can greatly diminish the electromagnetic field intensity and hence its effects.

7.7.2 Onshore

With onshore wind turbines there is no effect of electromagnetic fields on the animals. However there is a disturbance in the airwaves. The rotating blades can interfere with signals from TV and radio radar waves. There is not a huge disturbance along the airwaves, however enough to cause some static. Radar interference from the movement of the turbine blades causes a problem for nearby radio stations, residences and farms. These effects are largely undocumented, however they are taken into account by the military on an international scale. The movement of rotor blades can intercept with the radar signals from low flying planes. (Balloch, 2004)

7.8 Conclusion on the environmental sustainability of wind energy

It seems that all potential environmental impacts of wind farms can either be avoided or mitigated. Indeed, the more direct way to minimised them is simply to avoid to install wind turbines over particularly sensitive areas such as wetlands or migratory routes. In some cases, habitat loss is difficult to avoid, but it may be compensated by habitat creation, as it happens with the reef effect. Some other effects like erosion and electromagnetic fields can be easily mitigated by an efficient construction diminishing the amount of earth disturbed and by the insulation and burial of the cables, respectively. Finally, a major environmental concern goes to the effect on birds. Number of solutions to that problem were proposed, such as adopting better wind farm configuration, increasing the visibility of the turbines, and turning off the turbines during more risky periods. Therefore, it can be concluded that wind energy is environmentally sustainable.

Chapter Eight : Future developments

8.1 Enhancing the sustainability of wind energy

As seen in the previous chapters, wind energy can be influenced in a negative way by limitations in the usage of the wind resource and sometimes by the lack of competitiveness compared to the conventional energy producers. This part of the project intends to show how the continuous improvement in the wind turbine technology, storage and the usage of hybrid technology can overcome these limitations before they can affect the sustainability of wind energy on the long term.

8.2 The future evolution of the wind turbine

Wind turbines are expected to evolve in two different ways: the small privately owned generators will develop more in reducing cost and maintenance needs, and the utility grade turbines will grow larger more powerful and cheaper to operate (especially offshore).

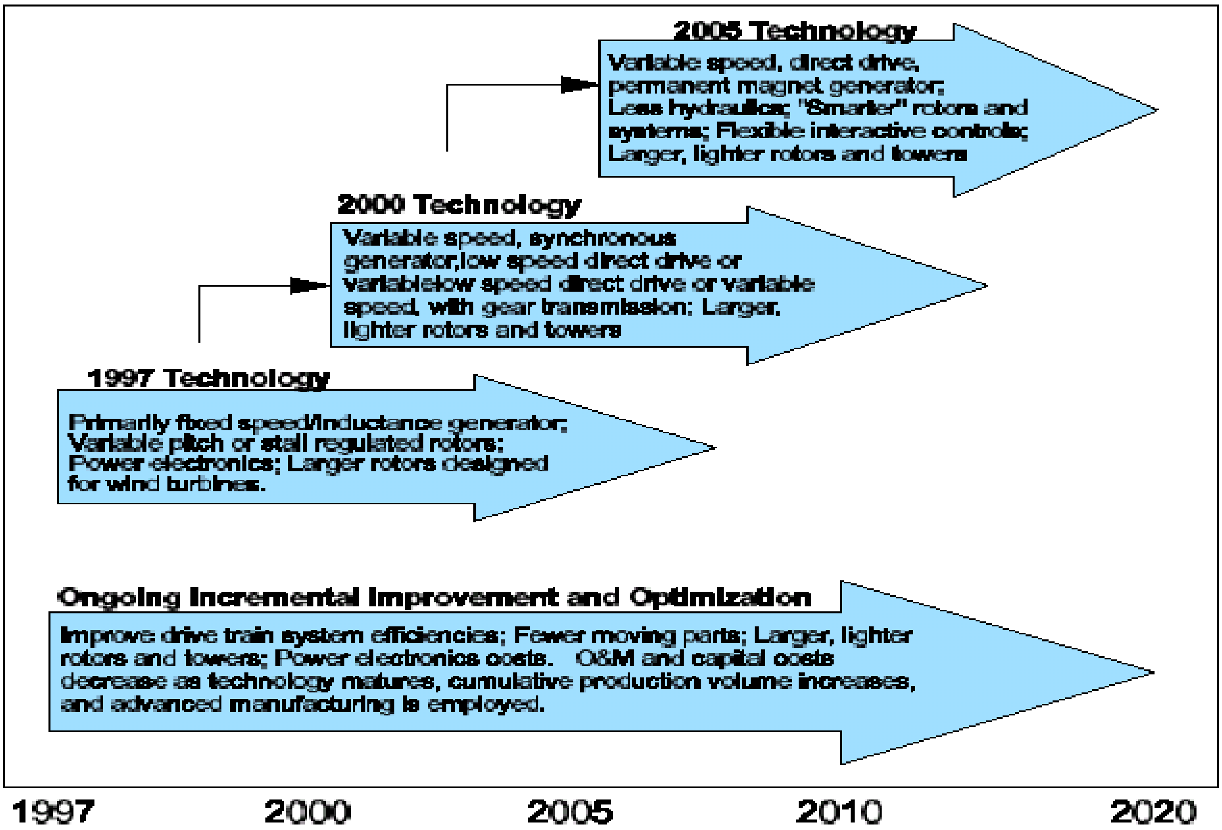


Figure 27: Future improvements of wind turbine technology.

As shown in figure 27, there is a great expectation in new component developments underway now that will significantly change the materials usage patterns. Generally there are trends toward lighter weight materials, as long as the life-cycle cost is low. Specific development trends in turbine components are discussed below:

Rotors: As the rotor size increases on larger machines, the trend will be toward high strength, fatigue resistant materials: composites involving steel, glassfiber-reinforced-plastic (GRP), and carbonfilament-reinforced-plastic (CFRP).

Gearboxes: The step-up gearbox used on large turbines today is expected to be replaced in many future machines by "AC-DC-AC cycloconverters". Large "epicyclic gear boxes" used in large ships may continue to be the drive system for some large turbines.

Nacelles: Simplification and innovation to reduce total weight

Towers: Pre-stressed concrete is a material that is starting to be used in greater amounts in turbines, especially in offshore or near-shore applications. Concrete in towers has the potential to lower cost, but may involve nearly as much steel in the reinforcing bars as a conventional steel tower. (Ancona, D. and McVeigh, J., 2001)

8.3 Is storage a real problem for wind energy?

The output from the turbines can vary very much in a day or during the same year (See Figure 28) and this variation does not always coincide with the electricity demand of the grid. This is not a big problem when wind energy can easily be backed up by other power sources on peak load. As the proportion of wind in electricity generation grows, the problem of "storing" excess electricity and using it when it is in demand will grow as the grids must remain stable.

Already stand alone systems face the challenge of somehow storing the excess electricity produced in periods of good winds, and using that excess energy at peak consumption or whenever the turbine cannot deliver enough power. Usually this is done with the help of batteries, but this kind of storage continues to be an economic burden in life-cycle assessments of autonomous applications. Issues such as short life-span, weight, initial cost, low energy density and transition to localised mass production all point to a continued need for research and development. But there are other solutions to this problem :

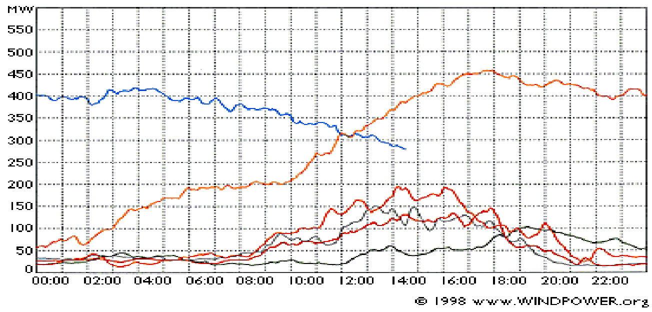


Figure 28 Week of electricity output from the 650 MW of wind turbines installed in the Western part of Denmark.

The blue curve (top left) shows the power output on 25 June 1997, while the orange curve (top right) shows the output the preceding day.

Electrical power consumption was 2,700 MW and wind was supplying 270 MW i.e. 10 per cent of the electricity consumption.

A flywheel consists of a wheel whose heavy weight resists sudden changes of speed, extensively used in car engines. Less commonly known is that they have energy densities hundreds of times that of lead-acid and other chemical batteries and can store and discharge energy often and rapidly. By rotting a flywheel in an minimum-friction environment, it can store energy. Flywheel storage systems operate at speeds exceeding 60,000 revolutions per minute (rpm). They last ten times longer than batteries, use no hazardous chemicals, tolerate nearly any temperature, and require less maintenance than batteries. Consequently, depending upon the application, they have a long potential life of 20 to 40 years. (Toolbase services, 2004)

Hydrogen has great potential as an energy source. Unlike petroleum, it can be easily generated from renewable energy sources like wind. The theory is simple: produce hydrogen when you have excess wind, use it in a fuel-cell when the wind is not strong enough. Fuel cell technology and electrolysis are pretty mature technologies, so the only problem is how to store the hydrogen between these two processes.

Here are some ideas like:

- Metal Hydride Tanks : Act similar to a sponge soaking up water.
- Compressed Hydrogen : Hydrogen can be compressed into high-pressure tanks.
- Liquid Hydrogen : Liquefies at -253^{o} C.
- Chemically Stored Hydrogen : The hydrogen is combined in a chemical reaction that creates a stable compound containing the hydrogen.
- Glass Microspheres : The glass spheres are warmed, increasing the permeability of their walls, and filled by being immersed in high-pressure hydrogen gas. But these are often energy consuming and difficult to use.
- Carbon Nanotubes are a new idea. They are microscopic tubes of carbon, two nanometres across, that store hydrogen in microscopic pores on the tubes and within the tubes structure. Research on this promising technology has focused on the areas of improving manufacturing techniques and reducing costs. As carbon nanotubes move towards commercialisation, these technologies can assure that 60 to 70% of the storage facility weight is actually H_2, not like 10% or less like in the other cases.

A very interesting proposition is also to use the actual tower of the wind turbine to store the hydrogen. This may seem a foolish idea but it could actually work, and is potentially cheaper than all the others technologies. (Kottenstette, R. and Cotrell, J., 2003)

There are also other ways to store excess electricity:
The Pumped storage requests two reservoirs and an big altitude difference. Water is pumped up to the top reservoir at night, when demand for power is low or whenever the energy production is higher than the consumption. When there is a sudden demand for power, the water rushes down the tunnels to drive the turbines, which drive the powerful generators. The water then collects in the bottom reservoir, ready to be pumped back up later. These kind of systems are already in use, and can react in just 12 seconds, the biggest ones providing over 1320 megawatts. (Darvill, A., 2003)

Japan already invests in storing energy in this way, by using the altitude differences between the mountains and the surrounding sea. As Denmark reaches its goal (50% wind energy by 2050), it should consider storing the excess wind energy produced in the winter, using the high altitude differences encountered in some of it's Scandinavian neighbours, especially Norway, which already has lots of reservoirs suitable for this purpose.

Watching a European weather map, it may be seen that at any given day, that there is an almost stable ratio between electricity usable wind and non-usable winds (too strong or too weak). The problem with wind energy is that all the generating facilities are crowded in some good sites and that on small area wind varies strongly each day. As wind turbines become more efficient and could use more varied wind speeds, they could be spread on large areas therefore ensuring that there will always be enough power coming from some wind farms in Europe.

The system may require a better interconnectivity between national grids and a more efficient way to transport electricity at high distances. However, there is still a great possibility of overall reducing cost (no more expensive storage facilities, and no more stand-by generating facilities), ensuring that there would not be blackouts even in the worst cases (like a storm stopping all the wind production of Denmark). Nevertheless, on a regional grid heavily dependent on wind (over 50%), there could be still some problems as low voltage lines aren't stable enough to variations in power output, resulting in undesired fluctuations.

8.4 Hybrids

There is another alternative to storage, and this has been used extensively on stand-alone systems: hybrids. The concept of hybrids involves two or more electricity sources backing each other. Photovoltaic cell backing up the wind turbine when winds stop, and a diesel generator backing the other two is actually the most common case, although this is not the only one.

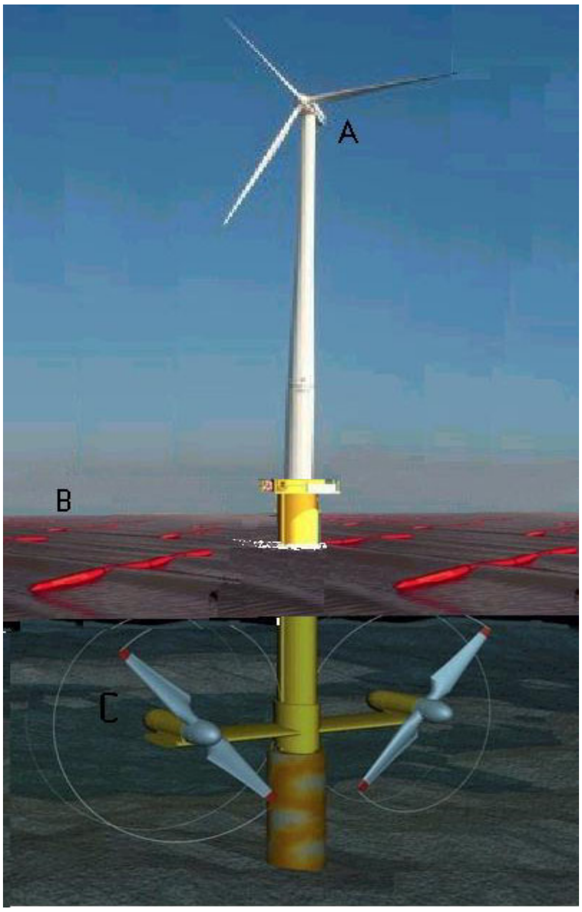
Onshore applications usually involve the grid as a backup system, although stand alone systems can provide a constant output of electricity without the use of batteries. As wind energy gets a bigger share in the generating market, hybrids will have to appear on a larger scale, so that the electricity can be reliable and continuously provided even on regional or local scale. If you can use it, small hydro is an excellent option as you can turn the turbine on and off really fast. Other renewables can be used on large scale where the local conditions make it possible (solar, biogas, geothermal), but the presence off small fossils burning power station cannot be excluded in hybrids.

Offshore, more abundant resources can complement wind. It has long_been recognised that in the seas and oceans there are vast quantities of energy. Sea water is much more dense than air, about 800 times more dense, and therefore the energy is more concentrated than in wind. Thus, a tidal or an ocean current of a certain speed (usually measured in metres per second) will have much more energy than a breeze of the same speed. One way to use the tidal currents has been to build a large barrier across an estuary. This had important environmental impacts, but the Seaflow project has at least demonstrated the viability of generating electricity from tidal flows.

There is also a lot of energy on the surface of the oceans and seas. A long-standing challenge is how to capture this energy and convert it into useful electricity. Finally we may have a practical solution.

A way of doing so is to mount a two-bladed turbine on the seabed in a region known to have significant currents. The minimal requirements are currents flowing at 2.25 to 2.5 metres per second (4.5 to 5 knots), with a depth of water of 20 to 30 m. Two pairs of rotating blades, the rotors, are mounted on a single steel underwater tower. The flow turns the blades of the rotors which convert the energy into electricity with generators that are mounted behind the rotors. The whole unit can turn to face the oncoming flow, for example to turn with the changing direction of the tide (blades rotors and generators are the same type as those in wind turbines) (See Figure 29). One significant benefit of marine current turbines is that their energy output is easily predictable. A single unit could produce 600 kW (Marine Current Turbines, 2004). Even the old VAWT's may make a spectacular return underwater, using tidal power of low speeds.

The Pelamis is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. It measures 150 metres long by 3.5 metres in diameter. The Pelamis is anchored so that it is free to move to face nose-towards oncoming waves. As waves travel down the length of the machine each section forces the hinged joints to bend. This movement is resisted by hydraulic rams, contained within a Power Conversion Module, which pump high-pressure hydraulic fluid into an accumulator. This provides a smooth flow of fluid to a hydraulic motor which is coupled to a generator to provide electricity. The machine consists of three Power Conversion Modules, each rated at 250 kW, giving a maximum power output of 750 kW (similar to a modern wind turbine). An Environmental Impact Analysis, completed by independent agencies,



A Typical utility scale wind turbine, with its own power transformers and grid connection.

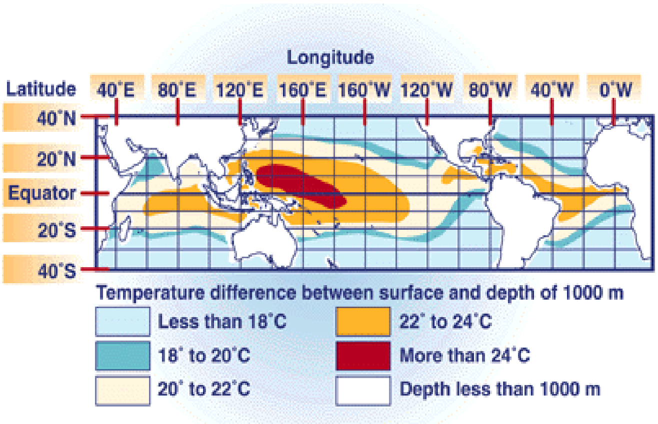
B ”Pelamis” farm, using the same grid connection and transformation station than the wind turbine. The turbine also serves as anchor reducing further the costs. (can be replaced by platforms with flotors providing extra electricity, and structural stiffness.

C The “Sea floor” turbines, share with the wind turbine the same technology as in blades gears generation, and also they use the same support, transformation stations, and grid connection cable.

These hybrids can provide 10-15 Mw/ per instaled unit and all the technology shown is separately already in use). In warm and deep waters, the hybrids wind turbine can be used to support the pipes and cables of an oceanic thermal energy convertor (OTEC).

Figure 29: Combined wind, tidal currents and waves hybrid power generating system (computer graphics)

showed that these technologies do not offer any threat to fish or marine mammals. (Ocean Power Delivery Limited, 2004)



source: www.solarenergyltd.net

Figure 30: The energy potential of the tropical ocean.

Commercial Ocean Thermal Energy Conversion (OTEC) plants must be located in an environment that is stable enough for efficient system operation. The natural ocean thermal gradient necessary for OTEC operation is generally found between latitudes 20^0 N and 20^0S.

Within this tropical zone are portions of two industrial nations- the USA and Australia- as well as 29 Territories and 66 Developing Nations. Of all these possible sites, tropical islands with growing power requirements and a dependence on expensive imported oil are the most likely area for OTEC development.

OTEC, or Ocean Thermal Energy Conversion, is an energy technology that converts solar radiation to electric power. OTEC systems use the ocean's natural thermal gradient to drive a power-producing cycle. As long as the temperature between the warm surface water and the cold deep water differs by about 20°C, an OTEC system can produce a significant amount of power. If less than 0,1% of the energy stored in tropical waters could be converted into electric power, it would supply more than 20 times the total amount of electricity consumed in the United States on any given day (see Figure 30). (N.R.E.L., 2004)

8.5 Conclusion on the technological possibilities for wind energy

Wind turbine technology is continuously developing and improving in its aerodynamics and in the usage of new materials. This allows to create more efficient and long lasting turbines. The continuous improvement of the turbines and the shift in building offshore and bigger wind farms are all signs that the cost of wind electricity will reduce further.

Improvements in storage technology and in the way in which wind farms and electricity grids are being developed will reduce the need for backup systems, and create the possibility of self regulating energy systems even if wind is the major electricity source. The use of hybrids also increases the possibility of building wind farms in areas with poorly developed grids. It could be the way to economically implement wind turbines in deeper waters, so to get in the areas with excellent wind resource.

Chapter Nine: Conclusion: Is wind energy sustainable?

9.1 A Brief look upon the future

Anyone who tries to predict how the future is going to look, will usually guess some bits, but mostly get everything else wrong. Hollywood is of course the mass producer of such failures but scientist aren't far behind. Knowing these risks we will try to find the future of wind energy, starting from known facts:

1. The electricity needs of the world are increasing at an accelerating rate, as new industrialised nations like India and China with immense economical potential get into gear.
2. The resources of oil are still estimated at 35 years, but this figure begins to lose its stability and declines as the new findings cannot keep up with the increasing demand. This creates pressure and results in market prices reaching all time highs predicted to stay like that for some months, despite many attempts to keep them under control.
3. The climate is becoming more unpredictable each year, and even the most stubborn governments will have to face the truth: Climate change is happening, and faster than expected. So the world will need to reduce CO_2 emissions, without stalling the economic growth.
4. As other renewable energies strive to reach maturity, wind is growing at a staggering 29% a year and it is forecasted to do even better in the future.

Considering the facts, the World Energy Council (W.E.C.) predicts worldwide wind capacity to reach up to 72 GW by 2010 and 180 GW by 2020. W.E.C. also considers an "environmentally driven scenario" that would have a much faster growth if national policies were adjusted. That scenario predicts that the world will generate 470 GW of wind power by 2020. (Ancona and McVeigh, 2001)

If the WEC predictions are maybe a little bit too optimistic, we still have to face the reality of a very fast growing technology. However, there is still time to find out whether or not we are heading on the right path with wind energy. In other words, this brings us back to our starting question, i.e. knowing if this energy source, even though renewable, is sustainable.

We are aware of the fact that the following conclusions might seem subjective in the sense that they are not based on calculations. They are rather built on our own visions of sustainability criteria for each discipline that has been studied. Moreover, the reader will notice that in many aspects sustainability of wind energy can be achieved, but only under some conditions. An attempt to propose these limitations will be done.

9.2 Sustainability in regard to wind distribution and technological developments

As explained, one to two percent of the solar energy received by the earth is transformed into wind. Because of the specific patterns of wind circulation and some local characteristics, this energy is not evenly spread, resulting in areas with different average wind potential classified from one to seven.

We saw that modern wind turbines can use wind energy over class three. Unfortunately most regions with this kind of potential are over seas and oceans. For now, technological limitations make the settling of wind turbines in those regions nearly impossible. The area of the remaining good sites is also heavily reduced by different factors mostly related to human activity. Moreover, the technical characteristics of wind turbines reduce further the amount of energy that can be extracted. Actually, the installation of wind turbines offshore over seven metres deep makes the costs prohibitive. However, technological improvement*s* and the growing of the market could overcome this problem. Also, given the importance of the potential resource, those limitations to the exploitation are not significant.

This means that the expansion of wind energy is not threatened, at least on the medium term. Therefore, since wind energy can be seen as an important energy source that can still expand with further technological developments, we consider that, in this regard, it is sustainable.

9.3 Economical sustainability of wind energy

As stated in chapter three, we believe that the wind industry, in order to be sustainable, must produce sufficient financial gains to maintain its exploitation. This can be achieved by two different means. First, if wind energy production is cheap enough to compete with other energy sources, it could be able to take its place in the market and would be self-sufficient. Second, if not cost competitive, the industry can be supported by the state. However, this should only be done if it is profitable to the society.

We demonstrated that despite the American Wind Energy Association's opinion, the wind industry is not yet fully competitive. Considering production cost only, conventional fuels such as coal and gas are still cheaper to use and are therefore favoured. However, their external costs are very high. If these were included in the price calculation, wind energy appear to have a comparable competitiveness. Furthermore, the actual absence of green taxes can be seen as an indirect subsidy to the polluting energy sources.

The climate change and green house gases emission are currently reaching a high level of concern in the European Union. Thus, politics are switching toward the support of renewable energies, particularly the wind power technology due to its degree of maturity. On the other hand, the security of supply assured by wind energy is also a major advantage. This point becomes even more important when considering expected fossil fuel shortages.

Therefore, if wind energy is not cost competitive in its actual state, we consider that it is profitable for the society to support its growth. In a first time, we thus conclude that wind energy is economically sustainable since it fulfils one of the two stated conditions.

In a second time, during its early developing period governmental supports can be implemented in the form of direct production subsidies or investment subsidies. In a second stage of development, governments, for instance in Denmark, point out the fact that the industry could be more independent and become part of the liberalised market. However, in countries like Denmark the introduction of full market mechanism by trading green certificates in the renewable energy sector could lead to an uncertain situation. Indeed, Danish market alone might be too small for trading certificates. Also, the different turbine efficiencies in the country (mostly depending on their locality) makes the income of the producers more unstable. On the other hand, it encourages the settling of wind turbines on the best sites, increasing the overall efficiency of the industry.

If green certificate system does not seem to be optimal in a small market situation, the most successful system, at least at this developing stage of wind industry, seems to be the fixed price system, even though it also has some disadvantages. First, it is an additional cost to the state budget. Also, the difference of efficiency of the wind turbines, depending on the area, creates over-compensation for the more efficient producers, increasing state's expense without bringing extra benefits. Nevertheless, German and Spanish experience have demonstrated that their wind industry can still be sustainable under that fixed price system. Furthermore, the German system, fixing a few different prices depending on the efficiency level, appear to be a viable solution.

9.4 Sustainability of wind energy in a social perspective

However, as mentioned before and as concluded during the First national conference in defence of the landscape against the construction of wind farms (Terra, 2004), wind farms can present negative impacts for the traditional land use and for the environmental value of their location. They can also affect negatively some local initiatives supporting sustainable development, such as tourism. If the wind industry doesn't pay attention to these critics, its development could be slowed down by the negative public opinion. We believe that educating people about the necessity of using renewable energy sources could favour the public acceptance of the industry. Indeed, the main driver in acceptance of wind turbines by the public is their positive aspect for the environment. Moreover, the "Not In My Back Yard" (NIMBY) syndrome can be diminished by involving local population in each step of a wind farm construction. This includes to first propose the idea to the community before going on with the project. The proposal should even be done before the wind possibility tests.

Nevertheless, the perception of a wind farm tend*s* to improve after it has been constructed and that the population has got used to it. Hence, people's concerns should be listened and answered to, but on the long run, even a negative starting opinion doesn't necessarily threaten the feasibility of a wind farm project. Moreover, as mentioned in Eyre (1997, p.173), human sensitivity to noise, visual amenity or electromagnetic interference don't represent threats to sustainability of wind energy because they don't affect ecosystems nor future generation who could easily deal with eventual problem by simply decommissioning the turbines.

In another perspective, the achievement of wind energy sustainability should also participate to the improvement of people's financial situation. Reducing poverty is a condition for people to use resources in a sustainable way. The fact that the wind industry is creating jobs and increases the local development and dynamism hence accounts for its sustainability and promote public acceptance.

9.5 Environmental sustainability of wind energy

It has been demonstrated in chapter five that the potential environmental effects of wind farms can either be avoided or mitigated. Specific ways of doing so have been proposed. Thus, the disturbance occurring during the construction stage (modification the habitat, noise) are temporary and can be minimised. Effects on birds and bats can also be diminished by a careful selection of the wind farm sites. Developing optimal wind farm configurations will diminished the loss and fragmentation of the habitat for the wildlife in general. Lastly, some impacts such as vibrations are not of so great concern while other, like electromagnetic fields and erosion can easily be mitigated. Therefore, environmental impacts aren't in opposition with the sustainability of wind energy.

However, in order for this statement to stay true, some actions need to become the norm in the wind industry. First, the number of authors conclude that given the high site-specificity of environmental effects, deep studies and environmental impact assessments have to be conducted prior to any wind farm project (Barrios and Rodriguez, 2004, p.80; De Lucas *et al*., 2004, p.405; Tingley, 2003, p.85; Guillemette *et al*., 1998, p.57). The results of those researches should be placed in first position in the decision making of a wind farm location, size and configuration. For now, as Tingley (2003, pp.50-51) notices, the wind resources, sea depth and benthic substrate (in offshore cases), and proximity to the energy grid, still take precedence over environmental effects. In this regard, the First national conference in defence of the landscape against the construction of wind farms (Terra, 2004) calls on the wind industry to be more environmentally rigorous. Basic professional ethics should weight more than the possibility of increasing profits.

Of course, the economical costs of these environmental measures are important. For some ill-sited wind farms it could lead to the unsustainability of the project. Given the technological possibilities and the important unexploited wind resources, environmental mitigation is not likely to threaten the overall sustainability of wind energy.

Moreover, the reader will notice that emissions of acid gases and green house gases resulting from wind turbine production and installation hasn't been assessed in this report. According to Eyre (1997, p.173), these emissions couldn't be used as a threat to the sustainability of wind energy. Indeed, wind power could generate the electricity to feed the production of its turbines therefore having a neutral and even negative gas emission balance (as long as a turbine produces more electricity than what is consumed for its construction, which is already the case).

9.6 A technological future to support sustainability

Wind energy could be a solution to the energy problems facing the planet (global climate change, incoming shortage of fossil fuels, increasing demand). But in a perspective of sustainable development, the resource must not be limited. For this industry to continue its growth and to become one of the primary energy source*s*, the future has to bring some much-needed improvements in the technology.

First, wind energy generation could be improved by the modification of the wind turbine design so that they could use more classes of wind speed. Thus, they could occupy less favourable sites, increasing the amount of exploitable areas. Transport and storage of electricity also need to be improved. Usage of new storage technologies including hydrogen are already being developed. This would make the output from wind generators more continuous and predictable, and reduce impact on electricity grids.

However, the usage of hybrids appears to be a promising solution, saving money and making wind energy connectivity possible even on poor grids with no storage capacity. Offshore hybrids could also push wind energy generation further into the seas and oceans, passing the seven metres depth limit. The incredible potential of offshore winds (classes of energy over 5, and little turbulence) could therefore be exploited, making the resource almost unlimited and hence supporting the sustainability of wind power.

9.7 Wind energy: a sustainable solution

It appears that the extensive use of wind energy as a solution to the current energy concerns could be sustainable. Nevertheless, conditions to sustainability have been assessed. Thus, even if the resource in the actual state of technology is important enough to support the industry's development, the achievement of the huge technological possibilities could make the resource almost unlimited.

At the economic level, it is environmentally and socially profitable to financially support the wind industry while it is not cost competitive. Some governments (e.g. Denmark) already think that wind industry is ready to enter the liberalised market, with a favour going to green certificate market. However, it seems that on small market a fixed price system should be maintained.

In the social sphere, the fact that wind industry participates to local development advocate for its sustainability. Moreover, its limited real impact on the local population could help to overcome the public hesitation.

Lastly, it is essential to push further the research about the potential environmental impacts. The results of studies and environmental impact assessments have to become the first priority when setting a new wind farm or rethinking an old one.

We would finally mention that as long as the sustainability of a wind farm project has not been assessed, it seems right to affirm that it shouldn't be subsidised out of funds designed to promote sustainable development (Terra, 2004). These funds should rather be used to finance research. Tingley (2003, p.87) proposes that small experimental wind farms should be built and intensively monitored to assess their environmental impacts. Once the studies completed, these farms should be decommissioned. A second step in this extensive research would consist in building one or two medium to large wind farms. If carefully sited, these farms wouldn't have to be disassembled afterwards. In the continuity of Tingley's proposal, we would add that the experiments conducted in these wind farms should also study impacts on local human populations as well as technological innovations.

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