# LIFE-CYCLE ASSESSMENT OF A SPANISH WIND FARM

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ABSTRACT

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The theme of this thesis is the environmental effects, energy and raw-material consumption of a wind farm. The study focuses on the manufacturing and production line of a wind turbine, in other words, the beginning phases of the whole life-cycle of a wind farm.

The most meaningful phases during the life-cycle of a wind farm, considering their environmental effects and energy consumption, were examined in a research about an Italian wind farm that functioned as the basis for this study. In this thesis, the collected material and data from the earlier research was utilized and used in calculating the environmental effects of a Spanish wind farm, which acts as case study in this study. The aim of the study was to broaden the earlier study, which focussed mainly on presenting the results without going through investigating the methods such as the phases of a life-cycle assessment.

The investigating methods for these two studies are mainly similar when calculating the ecoprofile of electricity. The ecoprofile and also theconsumption of raw-materials natural resources, in the most meaningful phases of the life-cycle were investigated in this study. As a difference to the earlier study, the usage of MIPS-calculation was used when estimating the environmental effects of different raw-materials. Raw materials that produce mass quantities of worn, natural resources, abiotic as well as water and air, were calculated, which also creates the image of the amount of materials used to produce the product, in other words, the product eco-backpack

Based on the results, the conclusions can be drawn that materials affect most decisively the environmental impact of wind farm construction and energy use. The results suggested the use of concrete and steel as raw material to be responsible for most of a wind farm's environment, energy and natural resource consumption. In the future, plant planning can therefore be focussed on these factors when wanting to improve the eco, -and energy efficiency of a wind turbine and an entire wind park. This study did not deal with the ways of improving the eco-efficiency of materials or the change of production methods, but it provides starting points for planning those remedies.

Keywords: wind energy, wind power plants, life cycle analysis, eco-efficiency,
MIPS, material input

Lahden ammattikorkeakoulu
Ympäristöteknologian koulutusohjelma

HEINONEN, NINA & ZOUHIR, MEHDI: Espanjalaisen tuulivoimapuiston elinkaariarviointi

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TIIVISTELMÄ

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Tämän opinnäytetyön aiheina ovat tuulivoimapuiston ympäristövaikutukset sekä energian ja raaka-aineiden kulutus. Opinnäytetyö keskittyy tuuliturbiinin tuotantovaiheeseen, toisin sanoen, tuulivoimapuiston elinkaaren alkuvaiheisiin.

Tuulivoimapuiston elinkaaren ympäristövaikutusten ja energiankulutuksen kannalta merkittävimpiä vaiheita on selvitetty italialaista tuulivoimapuistoa koskevassa tutkimuksessa, joka on toiminut myös tämän tutkimuksen pohjana. Tässä opinnäytetyössä hyödynnetään tuossa aiemmassa tutkimuksessa kerättyä materiaalia ja lukuarvoja ja niitä käytetään laskettaessa tutkimuskohteena olevan espanjalaisen tuulivoimapuiston ympäristövaikutuksia. Työn tarkoitus on myös laajentaa aiempaa tutkimusta, joka keskittyi lähinnä esittelemään saadut tulokset käymättä läpi tarkemmin varsinaisia tutkimusmetodeja, mm.elinkaariarvioinnin vaiheita.

Sähkön ekoprofiilin laskennassa tutkimusmenetelmät ovat näiden kahden työn osalta osin samankaltaiset. Myös tässä työssä selvitetään 1 kWh:n sähkön tuottamiseksi saatu ekoprofiili ja lisäksi elinkaaren merkittävimpien vaiheiden raaka-aineiden luonnonvarakulutus. Erona aiempaan tutkimukseen tässä, on MIPS-laskennan käyttäminen eri raaka-aineiden ympäristövaikutusten arvioinnin välineenä. Raaka-aineiden massamäärien tuottamiseen kuluneet, luonnonvaroista abioottiset sekä vesi ja ilma, on laskettu, mikä luo myös käsitystä tuotteen aikaansaamiseksi käytettyjen materiaalien määrästä, eli toisin sanoen tuotteen ekologista selkärepusta.

Tulosten perusteella on tehty johtopäätöksiä tuulivoimalan rakentamisen ympäristövaikutuksiin ja energiankäyttöön ratkaisevimmin vaikuttavista materiaaleista. Tuloksista on voitu päätellä betonin ja teräksen käytön raaka-aineena olevan vastuussa suurimmasta osasta tuulivoimapuiston ympäristövaikutuksia sekä energian ja luonnonvarojen kulutusta. Täten voidaan tulevaisuuden laitos-suunnittelussa keskittyä näihin tekijöihin, kun halutaan parantaa tuulivoimalan ja koko tuulivoimapuiston eko- ja energiatehokkuutta. Tässä työssä ei käsitellä noita keinoja parantaa ekotehokkuutta materiaaleja tai tuotantotapoja muuttamalla, vaan tarjotaan lähtökohtia noiden keinojen suunnitteluun.

Avainsanat: tuulienergia, tuulivoimalat, elinkaarianalyysi, ekotehokkuus, MIPS, materiaalipanos

## CONTENTS

# 1 INTRODUCTION

Taking a closer look into the production line of a product, in this case a wind turbine and a wind farm, and examining the usage of raw-materials and energy, can the major factors that affect the results of the entire production line or even the whole life cycle of the product be found. When these factors are found, and their impacts are known, it is easier to make conclusions and design new solutions of how to improve the environmental friendliness (or greenness) of the product. This can be achieved e.g. by improving the material and energy efficiency of the product. This study aspires to find those major factors.

Wind energy production and building new wind farms in order to benefit from renewable energy sources, has increased rapidly during the last decades. This study is about the environmental impacts of a wind farm. ScienceDirect magazine's publication of the Energy performances and the life cycle assessment of an Italian wind farm-study functioned as a pattern for this study. Hence, in the text, it is often referred to as “the earlier study”. In that study, it was discovered that manufacturing and installation are the most significant life-cycle phases of the wind farm, and therefore the main energy consumption, the usage of natural resources and other environmental impacts are included in these early life-cycle phases.

This is why this study continues from the results and investigates, which materials and other factors make the life-cycle phases the most significant. After discovering those main factors, it is easier to focus on improving the energy efficiency of the wind farm production through material management and product development. In addition, this study contains a similar ecoprofile of the electricity research like that of the Italian wind farm, but in this case, for a Spanish wind farm.

Briefly, it focuses on investigating the main factors from materials and life cycle phases that have a major role in the environmental impacts of the wind farm, and provides an ecoprofile of electricity.

Although the methods of life-cycle assessment have been generally described in Chapter 5, the MIPS-calculation (Material Input per Service Unit) has been, however, used as an investigating method (for environmental impacts), mainly due to its simplicity and the lack of more in-depth and available amount data that is usually requested in order to execute a detailed life-cycle analysis. A precise life-cycle assessment would have been more time-consuming for this project as well. Although the main title refers to a Spanish wind farm and its environmental assessment, the results of this study can be applied to several similar wind farms, which use similar techniques and raw-materials. It is worth mentioning that the material data for this case study wind farm was collected from the case study of the Italian wind farm. Thus, in the text, the situation of the wind energy in many countries (such as Finland) has been spoken about.

This project was executed in the College of Industrial Engineering in Barcelona, Spain. It was done as a joint project as follows:

The following chapters have been written by Nina Heinonen:

- 1. Introduction
- 2.4. Wind power in Finland
- 3. Wind turbine technology (except 3.2)
- 4. Life-cycle analysis in general
- 5.1. Case study: General framework
- 5.3. Case study: Building works
- 5.4. Case study: Operation and maintenance cycles
- 6. Environment and energy analysis of the wind farm
- 8. Conclusion

The following chapters have been written by Mehdi Zouhir:

- 2. Wind energy in the world (except 2.2)
- 3.2. Wind farms
- 5.2. Case study: Manufacturing of wind turbines
- 5.5. Case study: Transports
- 5.6. Case study: Decommissioning phase
- 7. Ecoprofile of electricity

# 2 WIND ENERGY IN THE WORLD

## 2.1 Wind energy in the world

Thousands of wind turbines are currently operating in various parts of the world, with a total capacity of over 159.2 GW at the end of 2009, and Europe takes part in 48% (end of 2009). Countries interested in developing wind energy are still undergoing initial investment (commissioning of wind farms that did not exist before). In fact, the installed capacity grows continuously but at different rates in different countries, and ranks the states by installed capacity gives a result of moving one year to another. Nevertheless, current figures show that the largest investor countries are the Western countries (America and Europe), but Asia, with India and China, began to take an important position.

TABLE 1: Installed windpower capacity (MW) in the world (Wikipedia 2010)

| # | Nation | 2008 | 2009 |
|---|---|---:|---:|
| - | European Union | 65,255 | 74,767 |
| 1 | United States | 25,170 | 35,159 |
| 2 | Germany | 23,903 | 25,777 |
| 3 | China | 12,210 | 25,104 |
| 4 | Spain | 16,740 | 19,149 |
| 5 | India | 9,587 | 10,925 |
| 6 | Italy | 3,537 | 4,850 |
| 7 | France | 3,426 | 4,410 |
| 8 | United Kingdom | 3,288 | 4,070 |
| 9 | Portugal | 2,862 | 3,535 |
| 10 | Denmark | 3,164 | 3,465 |
|  | **World total (MW)** | **121,188** | **157,899** |

Wind energy in our atmosphere is much greater than the global energy consumption. A serious study revealed the potential of wind power onshore and near-shore to 72TW annually, equivalent to 54,000 million tons of oil, what is more than five times the energy use of today's world in all its forms.

The exploitation of wind power will be then limited by economic and environmental factors. Wind energy is a renewable energy which is inexhaustible human civilizations' time scale.

Wind energy is the sector that has the best record in the classification in the multi-criterion study *"Review of solutions to global warming, air pollution, and energy security"*. A wind turbine does not consume fresh water; it is a clean energy that doesn't reject directly carbon dioxide or sulfur dioxide, or fine particles, or long-lived radioactive waste, or any other type of pollution in air or water. It does not require pesticides, does not induce thermal pollution. It has a small surface footprint and has a very low impact on biodiversity, almost negligible. It is becoming available almost everywhere, in a decentralized manner.

The United States became the first country in terms of installed capacity in 2007 (almost 5,300 MW of new wind power capacity) and first in the world for total power in 2008 (with over 25,000 MW). The wind power is up 42% of installed production capacity in first position before the fired gas power stations.
This record pace of installations continues, especially as the wind energy is the subject of a consensus, particularly in the economic stimulus package enacted by President Barack Obama.

China has set the goal to get 15% of its electricity from renewable sources by 2020, and has set targets in terms of renewable energy in its core businesses of energy production. In 2008, the installed wind capacity in China amounted to 12,200 MW. The country provides, also for next year, a further doubling of installed capacity.

India is the fifth global market for wind power with about 10,000 MW installed in late 2008. Suzlon, its main industrial operator, has become one of the world's leading manufacturers.

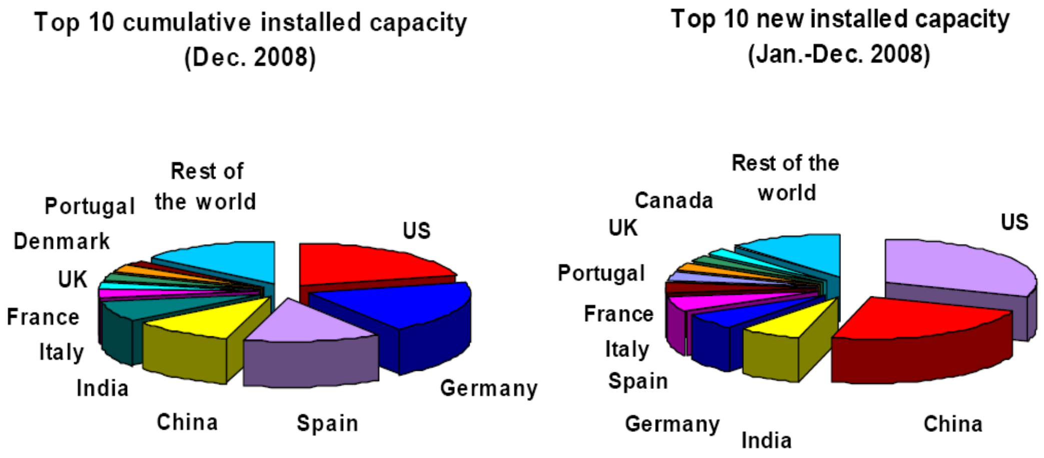


FIGURE 1: Installed capacity of wind power (Global World Energy Council 2008)

## 2.2 Wind power in Spain

Wind energy in Spain is a source of renewable electricity. At 31 December 2009 the wind power capacity was 19,148.80MW (18.5% of the national electric system capacity) during the year covering 13% of electricity demand, making it the fourth country in the world in terms of installed capacity, behind Germany, U.S. and China. In addition, since 2009 it is also the third source of energy after overcoming generated by coal.

The most important producers of wind power in Spain are:

| | |
|---|---|
| Iberdrola | 25.5% |
| Acciona | 20.9% |
| NEO Energia | 8.3% |

TABLE 2: Installed windpower capacities (MW) in Spain (Wikipedia 2010)

| **Rank** | **Autonomous Region** | **2008** | **2009** |
|---|---|---:|---:|
| 1 | Castile and León | 3,334.04 | 3,882.72 |
| 2 | Castile-La Mancha | 3,415.61 | 3,669.61 |
| 3 | Galicia | 3,145.24 | 3,231.81 |
| 4 | Andalusia | 1,794.99 | 2,840.07 |
| 5 | Aragon | 1,749.31 | 1,753.81 |
| 6 | Valencian Community | 710.34 | 986.99 |
| 7 | Navarre | 958.77 | 961.77 |
| 8 | Catalonia | 420.44 | 524.54 |
| 9 | La Rioja | 446.62 | 446.62 |
| 10 | Asturias | 304.30 | 355.95 |
| 11 | Basque Country | 152.77 | 152.77 |
| 12 | Murcia | 152.31 | 152.31 |
| 13 | Canary Islands | 134.09 | 138.34 |
| 14 | Cantabria | 17.85 | 17.85 |
| 15 | Balearic Islands | 3.65 | 3.65 |
|  | **Spain total (MW)** | **16,740.32** | **19,148.80** |

In 2005, the Government of Spain approved a new national law with the aim of reaching 20,000MW of production in 2012. The Spanish energy plan foresees generating 30% of its energy from renewable energy to reach 20.1GW in 2010 and 36GW in 2020. It is expected that half of this energy comes from the wind sector, with thereby avoiding the emission of 77 million tons of carbon dioxide into the atmosphere.

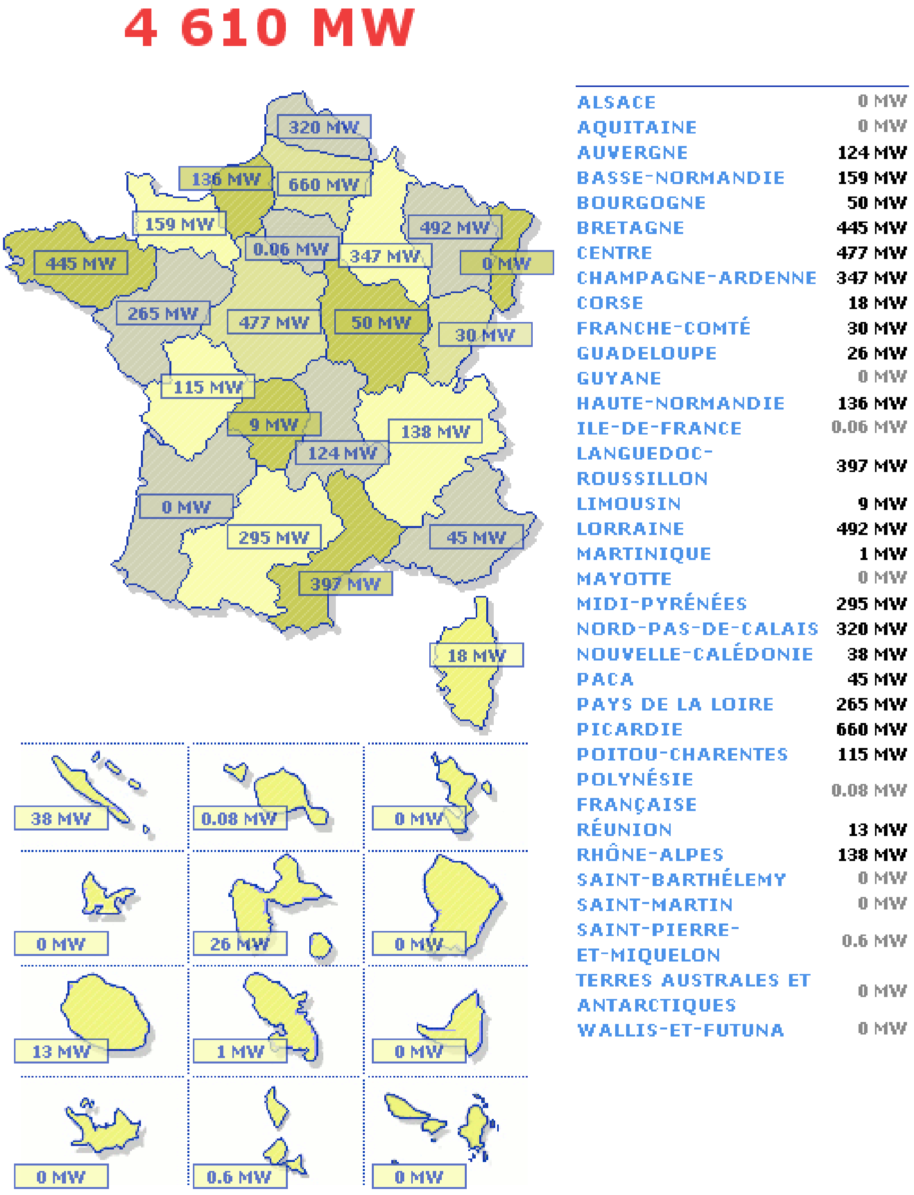
On February 24, 2010 at 11:20am, there was the historical maximum instantaneous production with 12,902MW, being the record for wind energy production and the maximum power generation with 270,420MWh of electricity produced.

*(IDAE, Instituto para la Diversificacion y Ahorro de la Energía 2010)*

## 2.3 Wind power in France

Second wind resource in Europe after the United Kingdom, France is trying to fill the backlog, so it has a significant wind potential. The proposed offshore wind farm on both sides (Atlantic Ocean and Mediterranean Sea) is currently under study. According to EDF, “among the renewable, wind power has the greatest potential for development and represent a majority share in the production of renewable energy. The wind will make its contribution in the independence of

France in energy”. EDF have to buy electricity from wind power for more than double its cost, what is against the advice of the Commission for Energy Regulation, makes wind energy investment attractive. The stated goals for wind power are 10,000MW in 2010 (6,000-9,000 windmills).

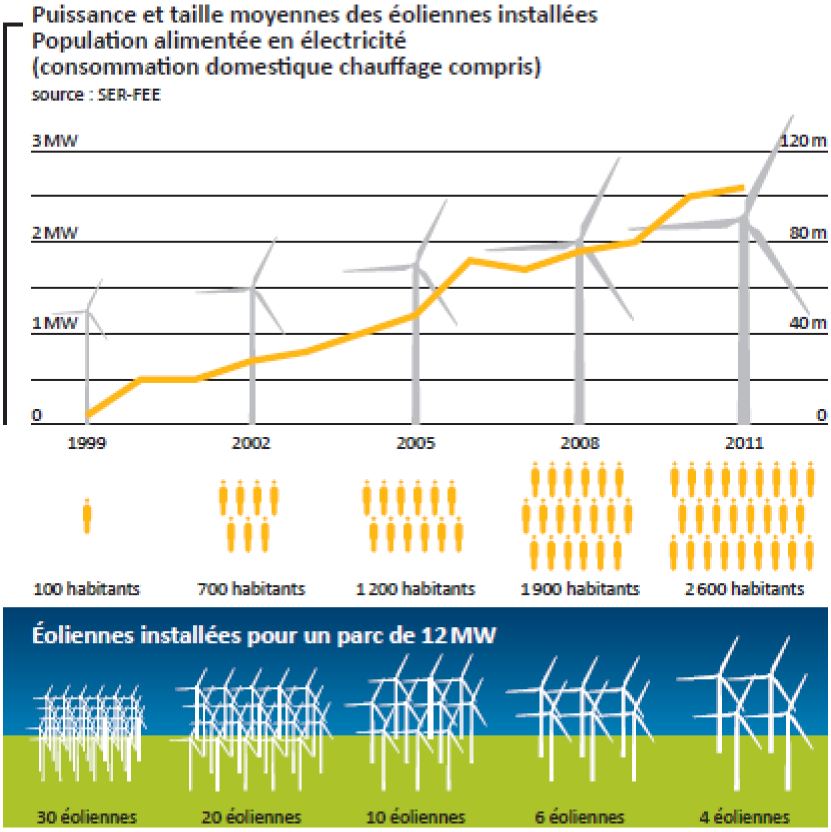


| | |
|---|---|
| ALSACE | 0 MW |
| AQUITAINE | 0 MW |
| AUVERGNE | 124 MW |
| BASSE-NORMANDIE | 159 MW |
| BOURGOGNE | 50 MW |
| BRETAGNE | 445 MW |
| CENTRE | 477 MW |
| CHAMPAGNE-ARDENNE | 347 MW |
| CORSE | 18 MW |
| FRANCHE-COMTÉ | 30 MW |
| GUADELOUPE | 26 MW |
| GUYANE | 0 MW |
| HAUTE-NORMANDIE | 136 MW |
| ILE-DE-FRANCE | 0.06 MW |
| LANGUEDOC-ROUSSILLON | 397 MW |
| LIMOUSIN | 9 MW |
| LORRAINE | 492 MW |
| MARTINIQUE | 1 MW |
| MAYOTTE | 0 MW |
| MIDI-PYRÉNÉES | 295 MW |
| NORD-PAS-DE-CALAIS | 320 MW |
| NOUVELLE-CALÉDONIE | 38 MW |
| PACA | 45 MW |
| PAYS DE LA LOIRE | 265 MW |
| PICARDIE | 660 MW |
| POITOU-CHARENTES | 115 MW |
| POLYNÉSIE FRANÇAISE | 0.08 MW |
| RÉUNION | 13 MW |
| RHÔNE-ALPES | 138 MW |
| SAINT-BARTHÉLEMY | 0 MW |
| SAINT-MARTIN | 0 MW |
| SAINT-PIERRE-ET-MIQUELON | 0.6 MW |
| TERRES AUSTRALES ET ANTARCTIQUES | 0 MW |
| WALLIS-ET-FUTUNA | 0 MW |

FIGURE 2: Monitoring wind energy production by the Environment and Energy Management Agency – ADEME (28/05/2010)

In 2009, according to a survey of CREDOC, 72% of French people (59% in Ile-de-France where residents say they feel less involved) would support a wind farm construction in their municipality. On 28% of opponents to such implantation, half say they are against for reasons of landscape and 8% because they fear being bothered by noise. Membership is higher in small municipalities. A study had earlier shown that the existing wind farms are massively supported. (ADEME 2010)

In 2009, additional 1,036 MW of wind power have been connected to the French network. In late 2009, the park is widely distributed across the territory, approaching the 4,600MW, of which only a marginal share in the FOD (0.8%), with a production of 7.6TWh, or 1.5% of electricity national consumption. But five regions (Picardie, Lorraine, Brittany, Central and Champagne-Ardenne) are better equipped with 55% of the installed power.



*Translation:*

- *Power and mid-sized wind turbines installed*
- *Population supplied with electricity*
- *(Domestic heating included)*
- *Habitants: Residents*
- *Installed windmills for a 12MW's wind farm*
- *Eoliennes: Wind Turbines*

FIGURE 3: Evolution of wind turbines and wind farms in the last decade

The objectives of the *Grenelle Environment* in 2020:

- Over 20 million tonnes of oil equivalent of renewable energy, it is at least 20% of renewable energy consumption of 2020's France
- Wind energy is essential to achieving this goal: it accounts for one quarter of 20 million tonnes of oil equivalent
- For wind power: 25,000 MW wind power, including 6,000 MW offshore wind turbines, it is about 8000, including 2,000 already installed.

The most important wind power producers at the end of 2009 in France are:

| | | |
|---|---|---|
| Enercon | 1007 MW | 21.1 % |
| Vestas | 937 MW | 19.7 % |
| Repower | 829.6 MW | 17.4 % |
| Nordex | 912 MW | 19.1 % |
| Gamesa | 320.93 MW | 6.7 % |

*(Syndicat des énergies renouvelables (Etat des lieux du parc éolien Français,* www.enr.fr/*); ADEME: Agence de l'Environnement et de la Maîtrise de l'Energie (http://www2.ademe.fr/); France Energie Eolien)*

## 2.4 Wind power in Finland

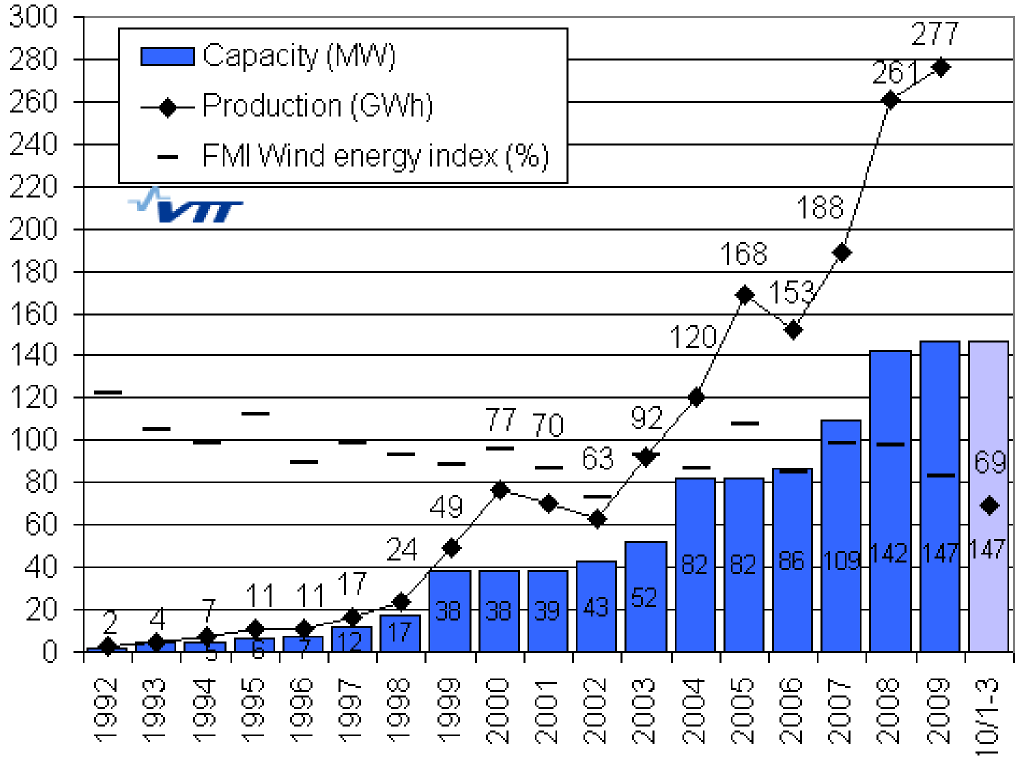


CHART 1: Wind power production and capacity in Finland 1992-2009 (VTT 2010)

For a widescale construction of wind power, Finland has been a slightly more unfavourable area when compared to the other northern countries. However, the unbuilt wind power potential is still great. (Wikipedia 2010)

The development of wind power capacity in Finland in the recent years has been minor compared to the progress in the world. The wind power capacity in Finland in February 2010 was 147 MW, and there were 118 wind turbines installed. In 2009, the amount of the electricity produced by wind power was 275 GWh. It covers approximately 0, 3 % of the whole Finnish electricity consumption. (Tuulivoima Suomessa 2009, VTT 2010)

According of wind power production statistics, in 2008 by the Technical Research Centre of Finland (VTT), the markets of wind turbines in Finland have been practically divided between six manufacturers. The market leader in the end of the year 2008 (143MW) was domestic Winwind with its 39 % share. Its share has increased since 2006 when Siemens was the market leader with its 32% share (in 2008 the share was 20 %). Enercon had the share of 20 %. The Vestas-corporation (including NEG MICON, NORDTANK & WINWORLD) had 14 % share. Harakosan had the share of 4% and Nordex had the smallest share of 3 %. In addition, there is a Finnish wind power company Windside that that has specialized on wind turbines that work under hard conditions, and sells these mainly abroad. (Holttinen & Stanberg 2008, Holttinen 2006)

In 1988 formed Suomen Tuulivoimayhdistys ry operates as trusteeship organization of wind power industry in Finland. In 2008, wind power was produced by Suomen Hyötytuuli Oy (share of 22 %), Lumituuli Oy, Tunturituuli Oy (2%), PVO-Innopower Oy (26 %), Energiapolar Oy and Propel Voima Oy (2%), Leovind (17%), Haminan Energia (2%), SaBa Wind (6%), VAPO:s wind power (5%), ViaWind (4%), Vattenfall electricity production (2%), Kotkan Energia (1%), Ålands Vindkraft (2%) and Ålands Vindenergiandelslag (4%) and others (5%). Many wind power companies are collaborative companies of the largest electricity producers or distributors. In 2009, there were two companies in Finland that manufactured wind turbines suitable for detached houses. Eagle Windpower produces traditional small scale windmills and Windspiral produces the ones rotating round their own axis.

Wind power production increased until 2000. The growth of production is explained by the increase of production capasity until 1999. This was because the wind conditions of a year and the growth of installed capasity affected the wind power production. Therefore, when the years 2000, 2001 and 2002 were not so windy as the earlier years, and the capacity remained almost constant, the production of wind electricity decreased. The same phenomenon was perceived in 2005 and 2006 when wind conditions were weaker than earlier year and therefore the production was lower than year before as well.

The amount of output in installed wind power capacity has increased rapidly also in Finland over the last few years. The early installed output of wind power capacity has increased from 1991 level of 173 kW into 3 MW of 2008.
(Tuulivoima Suomessa 2009)

The wind conditions, the ground form and a long shoreline create desirable conditions for large scale production of wind power in Finland. In addition, it is possible to set up wind farms even in the scale of thousands of megawatts in the broad shoals of Finnish sea areas. (Suomen Tuulivoimayhdistys ry 2008)

Wind power in Finland is placed mostly on coastal areas, constantly along the land and the centers of electric consumption. 25 % of Finland wind power production was produced in Aland in 2008. Electricity from the wind was mostly produced in Western Finland (31%) and secondly most in Aland (24%). The share of Aland and Lapland increased compared to 2007.

Researches that have been made by VTT show that the production potential in offshore areas can be even 15 TWh, but it demands new foundation technology and building new transit network capacity.

Additional potential of yearly production of wind power on coast and archipelago areas is estimated 2-3 TWh and in the fell areas of Lapland 0.5 TWh. This could be executed with the current network. However, in Lapland the road and network is very sparse and therefore most of the potential areas are too far to be economically profitable to implement. In addition, most of the fell areas are part of national parks, nature conservation or wilderness regions, or nationally significant landscape regions.

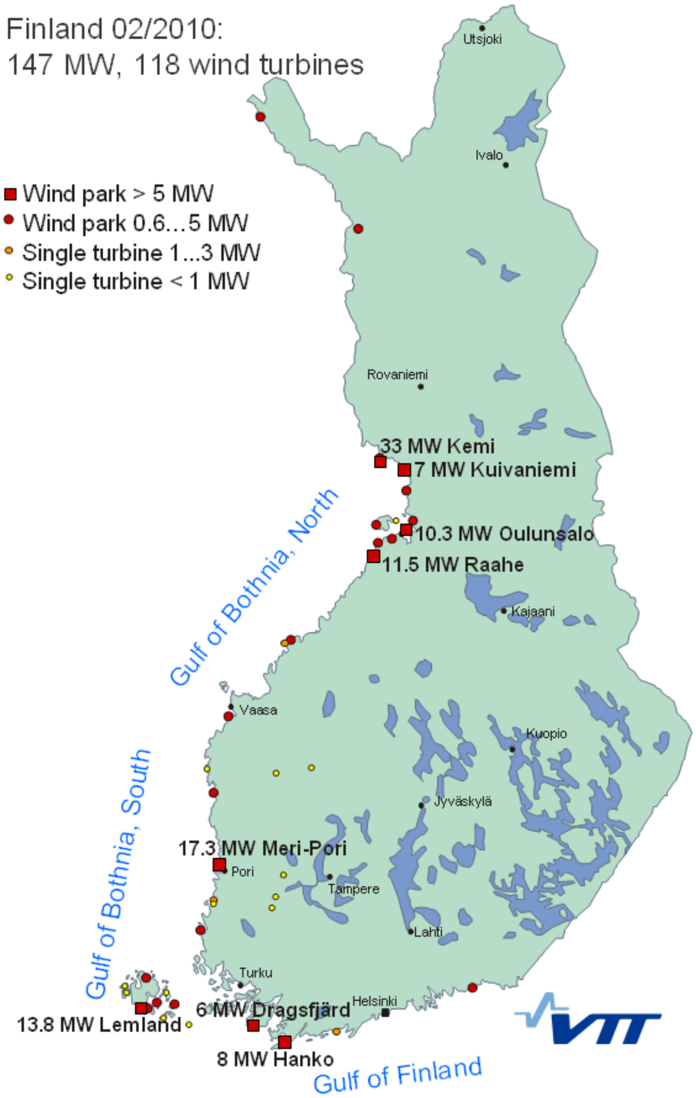


FIGURE 5: Wind power plants in Finland in February 2010 (VTT 2010)

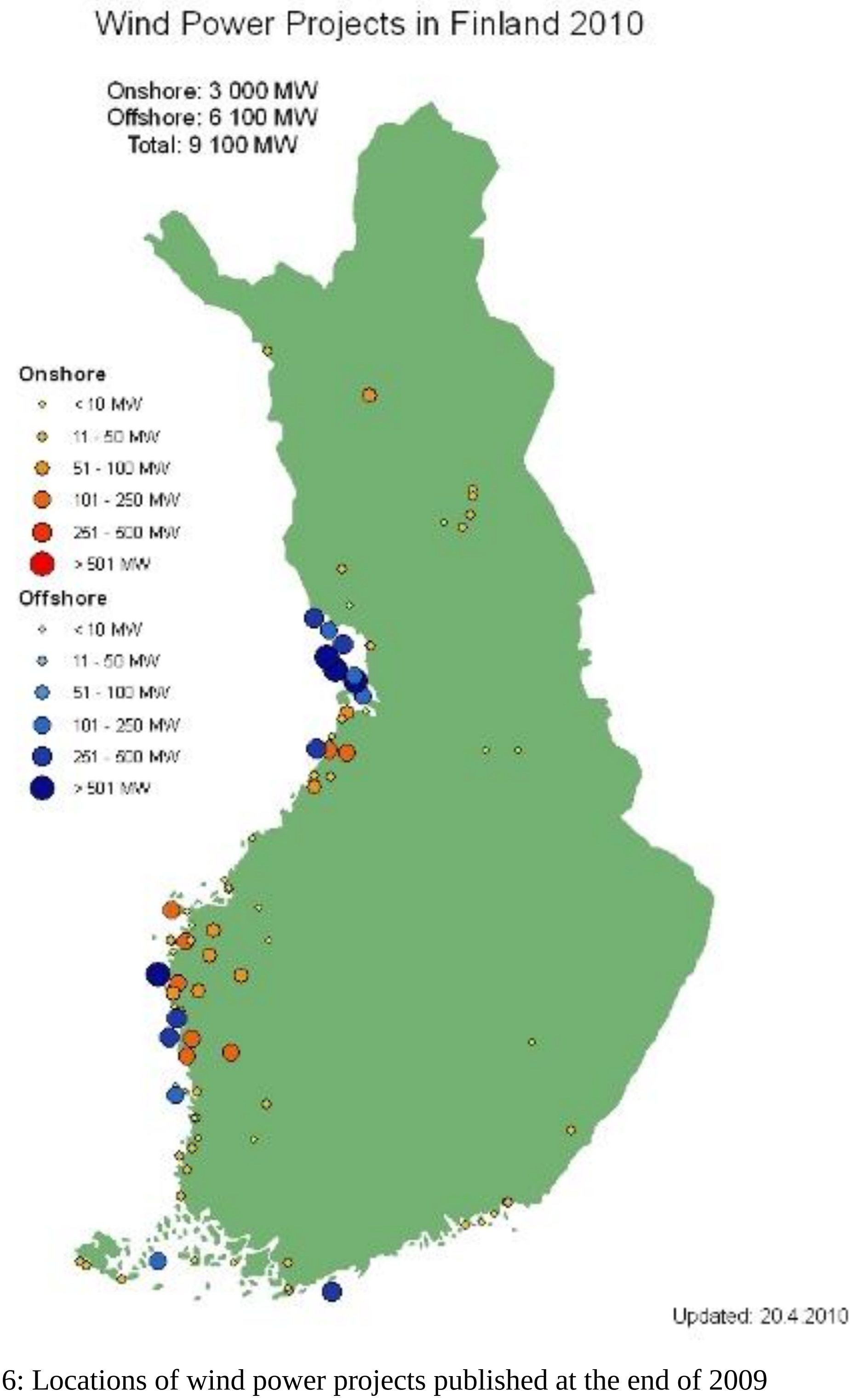
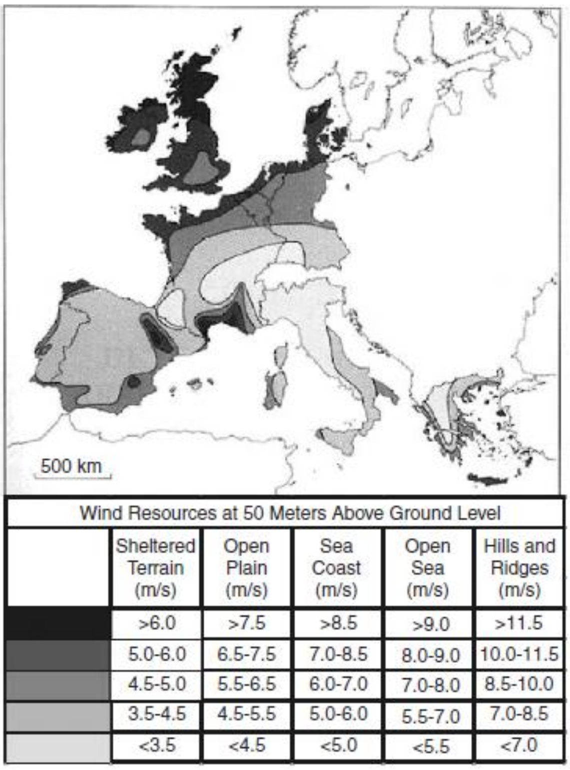


FIGURE 6: Locations of wind power projects published at the end of 2009 (VTT 2010)

## 2.5 Wind power in Europe



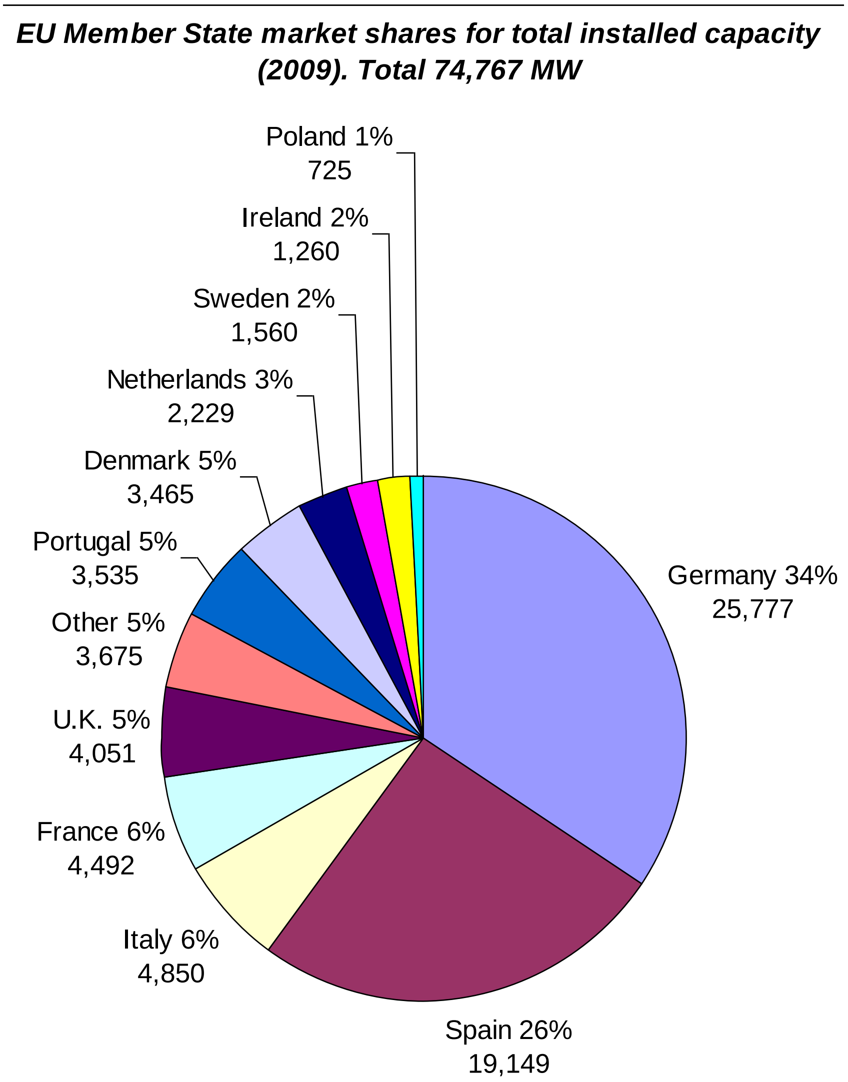
Wind Resources at 50 Meters Above Ground Level

| | Sheltered Terrain (m/s) | Open Plain (m/s) | Sea Coast (m/s) | Open Sea (m/s) | Hills and Ridges (m/s) |
|---|---|---|---|---|---|
| ■ | >6.0 | >7.5 | >8.5 | >9.0 | >11.5 |
| ▩ | 5.0-6.0 | 6.5-7.5 | 7.0-8.5 | 8.0-9.0 | 10.0-11.5 |
| ▨ | 4.5-5.0 | 5.5-6.5 | 6.0-7.0 | 7.0-8.0 | 8.5-10.0 |
| ▧ | 3.5-4.5 | 4.5-5.5 | 5.0-6.0 | 5.5-7.0 | 7.0-8.5 |
| □ | <3.5 | <4.5 | <5.0 | <5.5 | <7.0 |

FIGURE 4: Wind resources in Western Europe (according to RISOE, for the European Commission)

The EU has decided to produce 20% of its electricity by renewable energy, clean and safe in 2020. This can’t be done without offshore wind turbines, and then without establishing an interconnected power system which can deliver electricity with irregularity in the Baltic or North Sea to the rest of Europe, those are ones of the priorities announced by European Commissioner for Energy Andris Peibalgs late November 2007. It has entrusted the task of coordinating to the German Georg Wilhmelm Adamowitsh.

The production capacity of wind power deployment in Europe has been multiplied by 5 between 2000 and late 2007. An increase of 23% has been registered in 2009 compared to 2008, with a wind power capacity installed of 10,163MW, what cost 13 billion Euros.



The total wind power's installed capacity in Europe has augmented from 2% to 9% in these last nine years. *(EWEA 2006 Annual report, Powering change, European Wind Energy Association)*

# 3 WIND TURBINE TECHNOLOGY

## 3.1 The operation principle of a wind turbine

A wind turbine is a machine that produces electricity from the wind. In other words, it converts the kinetic energy of wind stream into electricity. A wind stream turns the aerodynamic rotor blades which, for one, spins the shafts inside the nacelle at the top of the tower. The gear box increases the rotational speed of the shaft which is connected to the generator. The generator converts the mechanical power of the shaft into electricity, which is led into the network either directly or via a transformer.

FIGURE 7: The parts of the wind turbine (World Wind Energy Association 2010)

*1. Foundation*
*2. Tower*
*3. Nacelle*
*4. Rotor blade*
*5. Hub*
*6. Transformer (this is not a part of the Wind Turbine)*

The components of a modern wind turbine:

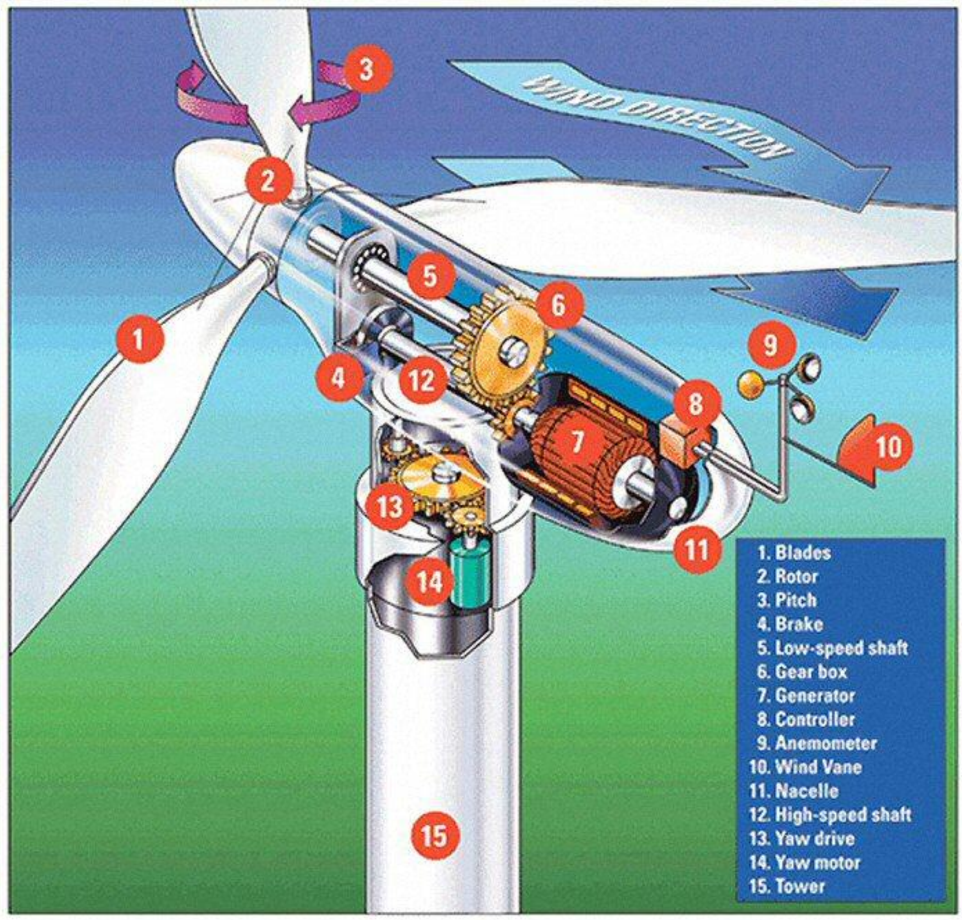


FIGURE 8: The components of a wind turbine (World Wind Energy Association 2010)

### 3.1.1 Rotor and rotor blades

The components of the rotor are the blades, the hub, the shaft, the bearings and the other internals.
The rotor and the blades are important parts of the wind turbine. Many demands are placed upon them due to the great loads they are must withstand.

The rotor blades are designed to capture the energy of a wind stream. The blades make the kinetic energy of a wind stream to rotate the rotor. In order to do this, the profile of the blades is carefully designed to be aerodynamic. The profile of the blade resembles the wing of an aeroplane, and the operating principle is similar as well: the blade uses the lift-principle in which the wind stream hits below the wing

causing overpressure there, while suction is composed above the wing. This forces the rotor to spin.
The majority of the present-day rotors are three-bladed and horizontal, but there are two-bladed rotors as well. In the past, even one-bladed rotors were made, but the manufacturing of those has been finished. The effectiveness of three-bladed, horizontal axis rotor when producing energy with large wind turbines has influenced its popularity. In addition, its three blades divide the mass more evenly, when also the rotation itself is more stable. They also give a calmer impression and are more silent than two- or one-bladed rotors. However, some smaller wind turbines (for example those used for battery charging) can be four, five or even six-bladed because they are designed to start even at low wind speeds. In horizontal axis of wind turbine (HAWT), the axis of rotation is parallel to the ground. The other option is a vertical axis, which is not so common but can benefit turbulent winds where the top of horizontal axis wind turbine spins around its tower in order to locate the wind direction.

Nearly every manufacturer has its own concepts for the rotor blades as well as ongoing researches for new innovative designs. Despite this, almost all rotor blades are constructed similar to an aeroplane’s wings. (Sathyajith 2006, World Wind Energy Association 2010)

The most commonly used material in the rotor blades is synthetics reinforced with fibreglass and carbon fibers. The majority of the commercial large scale energy generation systems use multi-layered fibreglass blades. These layers are usually glued together with an epoxy resin. When the size of the rotor has increased, some manufacturers have experimented with carbon-glass hydrid blades because they are supposed to have better fatigue charasteristics under severe and repetitive loading.

> *Because of the high stiffness charasteristic of carbon reduces the possibility of blade bending in high winds and hence, they can be positioned close to the tower. Carbon also improves the edgewise fatigue resistance of the blades which is an advantage for bigger rotors. (Sathyajith, M. 2006, 99)*

Also the weight of the blades is supposed to decrease 20% due to carbon, and when the blade is lighter, also the tower and other supporting structures can be lighter. This affects the economy of the whole system. It also means that we can twist couple the blades; twist coupling improves the turbine performance by better power regulation and quick response to wind gusts. However using carbon in the structure is more expensive option than the others.

More rarely is wood, wood-epoxy and wood-fiber-epoxy compounds used in wind turbines but that the other option. However the benefit of wood is good recycling ability. In small scale wind turbines can be also used aluminium and steel alloys. There have been many attempts to improve the blade behaviour by varying the matrix of materials, reinforcement structures, ply terminations and manufacturing methods. The traditional manufacturing method of the blades is open mold, wet lay-up. Some manufacturers use vacuum assisted resin transfer molding (VARTM). (Sathyajith 2006, Manwell, J.F., McGowan, J.G and Rogers, A.L. 2006)

### The hub

The hub is the center where the blades are attached to. Through the hub, the energy of wind is directed from the blades into the generator. However, between the generator and the hub, there is always the gear box and a slowly (at the speed of the blades) rotating gearbox shaft.

Normally, there are two ways for the attachment: fixed position with articulation or pendulum. Pendulum is used in two-bladed wind turbines where the pendulum is anchored to the hub. According to the World Wind Energy Association, most of today’s manufacturers use a fixed hub which is rugged and decreases the number of moving parts and the possibility of their fail. It is also easy to build. The materials for the hub are usually cast iron and cast steel. (World Wind Energy Association 2010)

## Power control: stall and pitch control

Power control is a way to restrain the rotation of the blades. It protects the wind turbine from breaking up in the moments of too intense wind.

In stall control (regulation by flow separation) the blades are attached to the hub at a fixed angle at which time the profile of the blade creates turbulence behind the blade at certain wind speeds. Also asynchronous generator restrains the power generation automatically restricting the systems speed at the frequency of the grid. Thus the rotor can not rotate faster even during high wind speed.

> *“In this concept the rotor blades are designed to cause flow separation at a certain wind velocity (stall), the power input is reduced even though the blades are not themselves pitched(World Wind Energy Association: Rotor and Rotor Blades 2010).*

Mostly in large (over 1 MW) wind turbines active stall control is used. In this concept, the pitch of the rotor blades can also be changed when at high wind velocities the rotor blades are turned into the wind which increase the turbulence even more. In this case, the power can be controlled and regulated more accurately than in passive stall control. (World Wind Energy Association 2010)

## Pitch control

Each rotor blade can be individually turn into or out of the wind. The pitch adjustment happens either mechanically (when the system output is less than 100 kW), hydraulicly (output over 300kW), or electronically which is the most common way (especially big scale turbines with output over 500kW).

> *A controller constantly monitors the turbine's power output. If the wind is too strong, the rotor blades are turned out of the wind along their axis, generally only by a fraction of the degree. This reduces the lift, so that the rotor continues to generate power at rated capacity even at high wind speeds (World Wind Energy Association: Rotor and Rotor Blades 2010).*

### 3.1.2 Nacelle

Nacelle is located behind the rotor and the blades on the top of the tower. It holds all the machinery of the wind turbine inside. Nacelle is attached to the tower via bearings, because it has to be able to rotate and follow the wind direction.

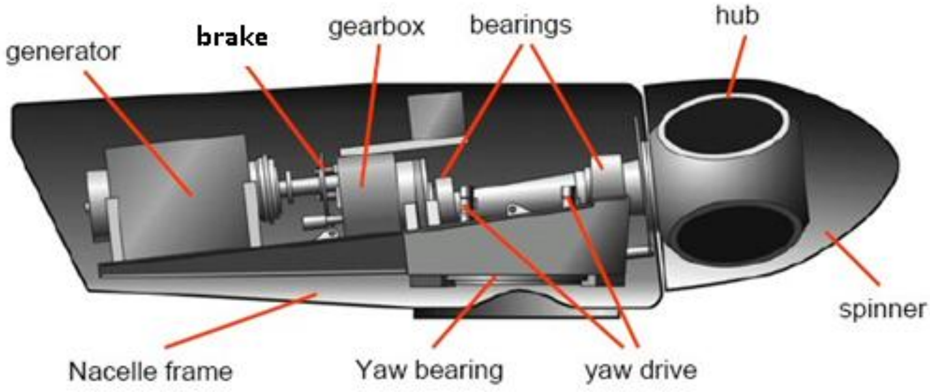


FIGURE 9: Drive Train with Gearbox (World Wind Energy Association 2010)

Nacelle contains the drive-train of which parts are:

- Rotor shaft (low-speed shaft) with bedding
- Gear box /when direct drive system is used, the turbine does not need one)
- Brakes and coupling
- Generator

#### High speed and low speed shafts

The low speed shaft, which is also known as the rotor shaft and the slow drive shaft, is situated between the rotor and the gear box, connecting the rotor with the gear box. It rotates at the same speed as the rotor (slowly) and therefore is connected to the gear box which increases its speed suitable for the generator. Thus between the gear box and the generator there is high speed shaft. This is why a gear box is essential when obtaining the rotational energy of the rotor more effectively at use. (BONUS Energy A/S 1998)

Gear box

Gear box increases the rotating energy of the rotor suitable and fast enough for the generator. It converts the rotation energy of the rotor (approximately 18-50rpm/min) to around 1500 rpm/min rotating generator shaft. The achieved rotational speed depends of a gear ratio that is used in a gear train. Due to massive torque, there is a rugged coupling between the main shaft and gear box. Gear trains manipulate the speed according to the requirement of the generator. An ideally working gear system would be both light and quiet and smoothly working. However, the gear box usually makes noise.

Gear ratio is the relationship between the numbers of teeth on two gears that are meshed. The gear ratio for example in a 150 kW turbine (smaller turbine) is 1:25 because the rotational speed of the rotor is around 40 r/min whereas the generator is designed to operate at 1000 r/min. In order to achieve this ratio, a two or three-staged gearing system is used. It includes low-speed shaft, intermediate shaft and generator shaft.

> *Low speed shaft from the rotor carries a bigger gear which drives a smaller gear on the intermediate shaft. Teeth ratio between the bigger and smaller gear is 1:5 and thus the intermediate shaft rotates 5 times faster than the low speed shaft. The speed is further enhanced by introducing the next set of gear combination with bigger gear on the intermediate shaft driving a smaller gear on the generator shaft. Finally the desired 1:25 gear ratio is achieved (Sathyajith, M 2006.)*

In order to get higher gear ratios, a further set of gears on another intermediate shaft can be harnessed in the system. Normally, in bigger turbines, integrated gear boxes with a combination of planetary gears and normal gears are used. In a typical gear box, there can be primary stage planetary gears combined with secondary two-staged spur gears to raise the speed to a desired level. When harnessing the planet gears, the size of the gear box can be significantly reduced. Furthermore, planet gears can reliably transfer heavy loads.

There are two types of gear boxes: helical and planetary gear boxes. After comparing the informative labels of several wind turbine manufacturers, I discovered that planetary gearboxes are the most popular at the moment. Their benefits, as mentioned above, is their compact size, but they also entail a problem with the heat, when being unable to misplace the heat generated during the power transmission in planetary gears.

### Bearings in gear box

The nature of loads that are transmitted is the basis for the selection of bearings for different points of the gear box. For example, the planet carrier handles medium-sized loads at lower speeds. The cylindrical roller bearings are recommended for this reason.

### Direct Drive System

If a specially developed multi-pole ring generator and a sufficient diameter are used in the wind turbine, it does not need a separate gear box at all. This concept is called Direct Drive System, and it is an intriguing new subject because the gear box is usually the weakest point of the wind turbine demanding lots of maintenance and causing noise.

### Safety brakes

For the safety of wind turbine it should be completely stopped during the periods of extremely high winds. There is also a risk of rapid acceleration and run-away condition (34 r/min shoots up to 90 r/min) of wind turbine if the power line fails, or the generator is disconnected due to some reason. In order to prevent a run-away situation, safety brakes are designed to react and response rapidly to acceleration.

There are generally two types of brakes: aerodynamic and mechanical brake systems. The recommendation (according to the certification guidelines of Germanic

Lloyd specify) is that two brake systems is used in a wind turbine: primary brakes are aerodynamic where “the tips of the blade can be adjusted or the entire rotor blade can be pitched, and, in addition, secondary (usually) mechanic brakes in case of the failing of primary brakes and during the time when the turbine is under reparation.

The type of mechanical brakes depends how power is controlled. When using stall control, the brakes have to be able to withstand the kinetic energy of both the rotor and the generator, and therefore be very high-performant and larger, while in pitch control, the brakes can be smaller. (Sathyajith, M 2006)

### Generator

In generator the mechanic energy is converted into electricity. Unlike the other generators that are used in energy production, the generator of a wind turbine is expected to work under fluctuating power levels. There are two types of generators: induction (aka. asynchronous generator) and synchronous generators. The majority of wind turbines that are installed to grid connected applications use induction generators. The benefits of induction generators are that they are rugged, inexpensive and easy to connect to an electrical network. They are also effective under varying operation conditions.

There are also generators with various output. Small scale turbines (capacity from few Watts to 1 kW) use DC generators, when in bigger scale turbines one to three phased AC generators are more common. The wind turbines that are integrated with the grid, a 3-phase AC generator is used.

### Synchronous and asynchronous generators

In large scale wind turbines the doubly-fed asynchronous generator is most commonly used. One of its benefits is that the operating rotation speed can vary unlike in conventional asynchronous generators. Other benefits are that "they allow for synchronization with the grid and are very robust and low-maintenance." Despite this, the synchronous generators are also used due to their bigger effectivity. They can also be connected directly to the grid, or an inverter can be used. But synchronous generators also need accessories in order to synchronise the electricity with the frequency of the grid. (World Wind Energy Association 2010)

Induction machines can operate both in motor and generator modes.
In a generator in general there are two main parts: the stator and the rotor. The stator is a stationary part and the rotor is the part that moves or in this case rotates inside the stator. It produces electricity by using electromagnetic induction where voltage is induced to the conductor that is in a changing magnetic field. (Wikipedia 2010)

This can also work vice versa as is shown in the following picture.
The number of windings inside stator slots represents the stationary magnetic field, and conductor bars in the spinning rotor represent the conductor.

The stator windings are connected to the power supply. The rotor of the machine has a cylindrical laminated core with slots for housing rotor conductors. The conductors, which are aluminum or copper bars, are individually placed in the slots. The bars are electrically connected with thick aluminum end rings, thus making them permanently short circuited. There are also induction motors with wound rotors available. (Sathyajith, M 2006)

In a synchronous generator, the rotor and magnetic field rotates, at same speed whereas in an induction generator the speed of the rotor lags behind the synchronous speed.

### Cooling system

The gear box and the generator produce waste heat, and thus the temperatures inside the nacelle can be quite high. This is why a cooling system is needed, and therefore special ventilators are installed in the nacelle. For the individual components of a wind turbine, such as the gearbox, there are usually also special cooling units.

### Heating

Heaters are often used to warm up the oil in the gearbox because where wind turbines are set up, the temperature can fall below the freezing point during the winter and freeze the oil. It would be hard to get the system running again if it had been motionless for some time.The rotor blades are also heated to prevent them from icing over, or being damaged by condensed water. (World Wind Energy Association 2010)

### Yaw system and sensors

The purpose of a yaw system is that it turns the nacelle and the wind turbine rotor towards the wind. In a horizontal axis wind turbine, the yaw system can be either passive or active. In an active yaw system, the torque producing device rotates the nacelle against the stationary tower based on automatic signals from wind direction sensors or manual actuation (control system overrive). The components of an active yaw system vary depending on the design but all of them include a means of rotatable connection between nacelle and tower (yaw bearing).

> *A means of active variation of the rotor orientation (i.e. yaw drive), a means of restricting the rotation of the nacelle (yaw brake) and a control system which processes the signals from wind direction sensors (e.g. wind vanes) and gives the proper commands to the actuating mechanisms (Wikipedia 2010).*

A common technical yaw bearing is the roller yaw bearing that is used by many wind turbine manufacturers because it offers low turning friction and smooth rotation of the nacelle. Gliding yaw bearing is another option.

When using roller yaw bearing, electric yaw drive and brake (which is a system used in most of the wind turbines), the nacelle is on the top of a roller bearing and the azimuth rotation is achieved via a plurality of powerful electric drives. (Sathyajith, M. 2006, Wikipedia 2010,) The yaw drive is used to keep the rotor facing the wind as wind direction changes and thus to ensure that the wind turbine is producing the maximal amount of electric energy at all times. This is only suited for wind turbines with a horizontal axis rotor. A yaw error in the wind turbine becomes apparent if the rotor is not aligned to the wind.

> *The main categories of yaw drives are the Electric Yaw Drives which are commonly used in almost all modern turbines, and the HydraulicYawDrive which are hardly ever used anymore on modern wind turbines. (Wikipedia 2010).*

In an electric yaw drive, the electric motors of the yaw system (usually very powerful AC motors) are equipped with electronic drives and connected to the main control system of the wind turbine. *They usually operate in fixed-speed mode and when they are not operational their rotors are "locked" via magnetic or mechanical brakes.*

Yaw drives (aka azimuth motors) are nowadays most commonly used, either alone or as multiple motors at a time. A weather vane on the nacelle provides information to the azimuth drive and the motors slide the nacelle into its optimal position on the azimuth ring.

FIGURE 10: Azimut drive. © Bundesverband WindEnergie e.V (World Wind Energy Association 2010)

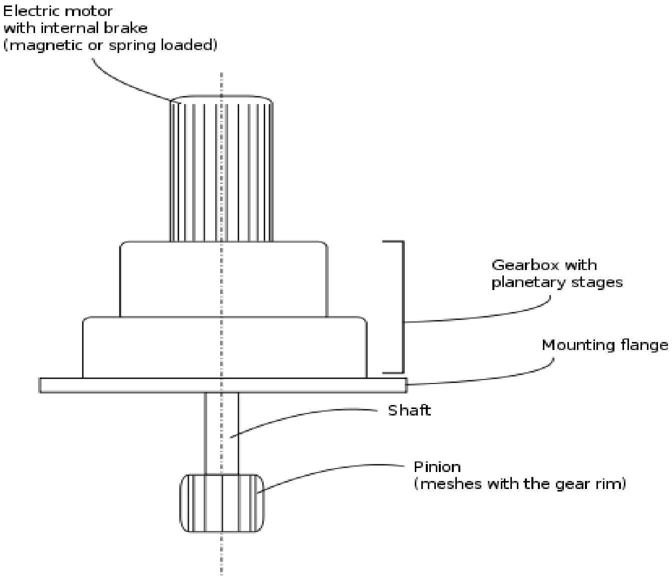


FIGURE 11: Schematic representation of a typical yaw drive (Wikipedia 2010)

Passive yaw systems do not need electric yaw drives. They use the wind force in order to adjust the orientation of the wind turbine rotor into the wind. In its simplest form this system “*comprises a simple roller bearing connection between the tower and the nacelle and a tail fin mounted on the nacelle and designed in such a way that it turns the wind turbine rotor into the wind by exerting a "corrective" torque to the nacelle. Therefore the power of the wind is responsible for the rotor rotation and the nacelle orientation.” (Wikipedia 2010)*
The tail (aka. Wind vane) is mostly used in small wind turbines.

### 3.1.3 Tower and foundation

A wind turbine is fixed into the ground by a foundation. The foundation gives the wind turbine a guarantee of stability. It is also a plinth for the massive weight of a wind turbine generator, nacelle (often several hundred tonnes) and the tower construction. Depending on the consistency of the ground the wind turbine is standing on, and the stability of the subsoil, either pile or flat foundation is used. Flat foundation is one of the most commonly used foundations. The footing of the generator is a large reinforced concrete plate under the ground. A pile foundation is especially essential in soft subsoil. In Figure 12, the foundation plates (plate foundations) are fixed with piles into the earth.

FIGURE 12: Foundation of the wind turbine is completed in Uetersen wind farm, Germany© Bundesverband WindEnergie e.V. (World Wind Energy Association 2010)

### Tower construction

The tower construction carries the weight of the nacelle (which often weigh several hundred tonnes) and rotor blades. Varying power of the wind also causes vast static loads, and the rotor blades induce stress which the tower construction must absorb. A tubular construction of the tower is most generally used. Concrete or steel is mostly used as the material.
The height of the tower and the diameter of the rotor depend on the power rating as represented in the following table:

TABLE 3: The relation between power and the size of tower and rotor

| **Power rating (approx)** | **600 rated** | **1,5 to 2 rated** | **4,5 to 6 rated** |
|---|---|---|---|
| **Hub height** | 40-65m | 65-114m | 120-130m |
| **Rotor diameter (approx)** | 40-65m | 70m | 112-126m |

Constituting creates 15-20 % of the costs but higher towers also increase the payoffs. This is because the height of the tower or hub height is a vital factor in the energy yield. In order to facilitate the rise, higher towers over 80m usually have a car or a lift inside the tower. Steel towers consists usually of two to four segments. The alternatives of a tubular form of tower are a lattice tower form, which is very commonly used in India and also in other countries such as the USA (western mills) and in Germany.

Other different tower types are:

- Concrete towers (in-situ concrete) with climbing formwork. They are constructed on site which makes transport and fitting easier.
- In pre-cast concrete towers the segments are placed on top of one another on site and braced with steel cables in the wall.
- If the tower consists of components of many of the above-mentioned types of towers, they are called hybrid towers.
- In small wind generators guyed poles are very commonly used due to their lightness and the possibility of setting them up without a crane.

Offshore foundations

There are different types of offshore foundations:

- Gravity foundations**:** Very heavy and stable concrete weights are placed on the sea floor. They do not need any more fixation to the seabed due to their own weight.
- Tripod foundations**:** The wind generator is put on a tripod when piles below the tower are connected with a steel frame distributing the tower's forces over three steel piles. Each of these steel piles is fixed approximately 10 - 20 metres deep on the sea bed.
- Bucket foundation: A steel cylinder which is open towards the bottom is placed on the sea bed. After that it is then pumped out and the foundation is pressed into the ground by the negative pressure generated inside the foundation. The material at the bottom of the inside of the cylinder supports the foundation and fixes it to the sea bed.
- Monopile: Into the sea bed is sunk a single mast, a steel pile with approximately diameter of 4 metres. The monopile is driven approximately 10 – 20 metres deep into the sea floor depending on the sea bed.

At the moment a lot of research is still being done and tried out here. (World Wind Energy Association, 2010)

### Lightening protection

Lightening often strikes the tips of rotor blades. For absorbing the lightening, the following solutions are used:

- Round metal discs called "receptors" at the tip of the rotor blade,
- Multiple receptors along the blade,
- Aluminum blade tips

The current is directed to the ground anchor through the rotor blade metal conductors, over the nacelle and down the tower. Thus the sensitive areas of the wind turbine are avoided.

### Cranes and elevators

A swinging crane and gantry cranes are used inside the nacelle because of the fact that most wind turbines contain winches to haul small spare parts.

### Fire extinguishers

Fire extinguishers are in the wind turbine in case of fire in the hardware or electronics. They are often manual tanks but automatic fire detection and extinguishing systems are also used. (World Wind Energy Association, 2010)

### Transformer

Electrical equipment of the wind turbine can be divided into the generator and the system for feeding electricity into the grid and the sensors for controlling and monitoring the generator. Let us first examine the transformer and the other devices that are needed for feeding electricity into the grid.

> *Wind turbines are connected to some electrical network. These networks include battery charging circuits, residential scale power systems, isolated or island networks, and large utility grids. (Manwell, J.F., McGowan, J.G and Rogers, A.L. 2006)*

FIGURE 13: Foundation and transformer for a wind turbine. ©Bundesverband WindEnergie e.V. (World Wind Energy Association 2010)

The system for feeding electricity into the grid depends of the generator that is used. The major part of larger (MW scale) modern wind turbines use grid-connected asynchronous induction generators running at almost constant speed and direct connection to the grid. This means that it does not need rectifiers or inverters unlike s Synchronous generator.

If a synchronous generator is used, it needs a rectifier and inverter so that the produced electricity (which is alternating current that fluctuates constantly in frequency and quantity) can be guided to the network.
In the rectifier, the electricity is converted into direct current (DC). Then it goes to the inverter where it is filtered and then converted back into alternating current. After this, in both generator types (asynchronous and synchronous generators), the transformer is used to convert the voltage for connection to the level of the grid.

### 3.1.4 Monitoring

Sensors for controlling and monitoring the generator

With monitoring, the generator can be controlled (put into operation or switched off) by using the data information that is collected by the sensors. There are sensors or measurement devices in the nacelle recording constantly the following parameters: wind speed and wind direction, speed of the rotors and the generator, the ambient temperature and individual components, oil pressure, pitch and azimuth angle (yaw mechanism based on the wind direction) and electrical values, as well as vibrations or vibrations in the nacelle.

## 3.2 Wind farms

### 3.2.1 Onshore wind farms

Onshore turbines are often installed in mountainous regions, sometimes on ridgelines, generally more than three kilometres from the nearest coast. This is in order to exploit topographic acceleration of the over a ridge. The exact positioning of wind turbines is very important; 30m away can occasionally make a double output.

In Spain, Denmark, Sweden or German, onshore can represent more than 10% of the electricity consumed. Its increase over the last ten years has been impressive.

Wind turbines on land are often a target to limitations and objections based on their noise, negative visual aspect, interference of radio waves or biodiversity threat... These restrictions significantly reduce areas susceptible to accommodate a wind farm.

Some of these drawbacks may justify the increasing of offshore wind farms which are far away from population. However, onshore wind farms may also have some financial advantages over offshore wind farms:

- Foundations;
- Integration with the electrical-grid network;
- Installation and access during the construction phase;
- Access for operation and maintenance…

FIGURE 14: The largest wind farm in the world: Horse Hollow in Texas, USA. A wind farm equipped with 421 wind turbines that generate a total capacity of 735 MW (Wikipedia; House Energy 2010)

### 3.2.2 Offshore wind farms

The offshore wind industry is very promising. Its potential is huge, with strong and very regular sea breezes. It is still relatively undeveloped because it requires the use of advanced technologies, benefiting from significant research and developments. This sector is now growing very rapidly and could represent 10% of the electricity generated in the European Union in 2020.

Europe is one of the most suitable areas in the world for offshore wind development, because it has a shallow sea area, particularly in northern Europe and especially in the northern seas and Baltic. These areas also have strong potential in wind. In addition, these waters are located near the "European metropolis", the area most populated and largest consumer of energy in the continent. In France, the most favourable sites are located on the shores of the Channel and North Sea, and on the Atlantic coast between La Bretagne and Aquitaine. However, the relatively important depth of the seabed makes more difficult the implementation of offshore wind farms in the Mediterranean Sea.

FIGURE 15: Offshore wind farm

In 2008, 25 offshore wind farms are operational in five countries (Denmark, United Kingdom, Sweden, Holland and Ireland), totalling an installed capacity of approximately 1,100 MW. They currently account for only 1.8% of installed wind capacity worldwide, but produce 3.3% of world wind energy, due to winds much stronger than on land. The most important offshore wind farms are parks Horns Rev and Nysted in Denmark, with 80 and 72 wind turbines totalling respectively 160 and 165.5 MW, approximately half the power of a thermal power plant. According to the Association for European Wind Energy Association (EWEA), the installed capacity in 2020 in Europe could reach 40,000 MW, equivalent to the entire French domestic consumption.

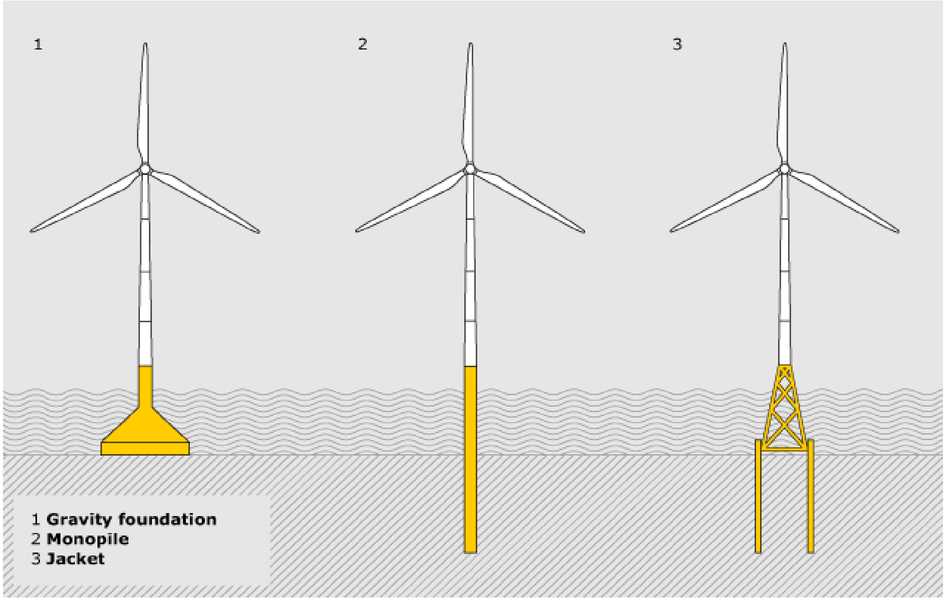


FIGURE 16: Three types of foundations

Offshore wind turbines operate on the same principle as onshore wind turbines, and the main components remain close to those used on land. However, something is very different compared to onshore turbines: their foundations. These are made according to the depth and characteristics of the seabed. They can be made by concrete or metal. The metal foundation is achieved either by a stake driven deep into the seabed, either a tripod or put down lightly into the soil, may be close to the technologies used by the offshore oil industry. The current offshore wind farms can be installed only at depths below 30 meters.

Offshore wind turbines are much more powerful than those used on Earth: their power up to 5 MW, three cons for onshore wind. The connection is made through the submarine direct current (DC) cables, a specific technology commonly used for interconnections underwater.

The floating wind turbine prototypes are currently being studied to allow the installation of deeper layers, then multiplying the exploitable potential. *(France Energie Eolienne 2010)*

FIGURE 17: Setting up a wind turbine in an offshore wind farm

### 3.2.3 Acoustic, biodiversity, airwaves and radar disruption

At the foot of a wind turbine, the noise level is 55 decibels, equivalent to the noise inside a house. When the wind blows hard, we can have, at the foot of a wind turbine, a normal conversation. The volume of a wind turbine operating at 500 meters away is 35 decibels, the equivalent of a whispered conversation. To eliminate any risk of noise disturbance to local residents, developers of wind farms projects respect a minimum distance of 500 meters between the turbines and the first houses.

Protecting biodiversity is a priority of the European Union, which adopted several guidelines since 1992 for the protection of species and their habitats, especially birds. When building a wind farm, work related to the site can disrupt wildlife particulary the game (animal) by changing its habitat. But apart of this very short phase of 6 to 9 months of bulding works, wind turbines do not have impacts on the local wildlife, which adapts its behavior to the presence of wind turbines.

> *"Most species of birds are not disturbed by the presence of wind turbines and adjust their flight path to avoid them."*
> *British study published October 15, 2008 in the Journal of Applied Ecology.*

Because of their height, materials used in their manufacture and movement of their blades, wind turbines can cause disruption of radio waves and radar. Solutions were found for the airwaves, studies are underway for the radar. About 95% of cases are settled amicably with the installation of a transmitter by the wind developers. Radars are sensitive to the presence of tall structures in their area of supervision. In the case of wind turbines, it can be a masking effect, a reflection of radar signals from fixed surfaces (tower), or false echoes by reflection from the moving parts (blades).

*Acoustic, biodiversity, airwaves and radar disruption, and wind turbines from France Energie Eolienne website*

# 4 LIFE-CYCLE ANALYSIS IN GENERAL

The purpose of the Life cycle analysis (LCA) is to investigate the general view of the environmental impacts of the product, package, material and operation in detail from “cradle to crave”. This includes the usage of the raw materials and energy consumption, the emissions to air, water and ground and the production of solid wastes during the whole life cycle and their potential environmental impacts. The environmental points of view and the potential environmental impacts are examined during the whole life cycle of the product from the manufacturing and acquisition of the raw materials to usage and finally to final processing.
In Life cycle analysis, all the beginning assumptions and data have to be clearly perceptible.

Usually it takes lot of time and money the carry out a wide and in-depth life cycle analysis due to the large amount of departure information required. This is why more concise and simple life cycle assessment is carried out more practically. It is usually made for some particular purpose. The more profound LCA is usually worthwhile to be made for products that have significant environmental effects or large sale volume.

For executing LCA, Finnish Standards Association SFS has given SFS-EN ISO 14040 standard as “the principles and outlines of LCA and environmental management”. In addition there are specifying standards SFS-EN ISO 14041, 14042 and 14043 as instructions for the following four phases of the LCA.
(SFS-EN ISO 14040 2008)

## 4.1 Goal and scope definition

In this phase as the significant limitings of the work are made, it is time for the planning phase of the LCA. The goals and appliance field have to be determined clearly and they have to be consistent with the target of appliance. In goal definition it has to be clear why the LCA is done and what is the target of appliance and to whom will the results be informed. The functions of the product are defined in quantitative form by using a so called functional unit.

The scope, the depth and how detailed the LCA is, have to respond to the goals. In this phase it is decided which unit processes are investigated in the process, which environmental emissions are estimated and how detailed an LCA in carried out. All the decisions concerning the phases of the life cycle, the processes or the outputs/inputs that are left out have to be documented clearly and explained. In order to represent the system, a process flowchart is often helpful. It depicts the proportions between the different unit processes. (SFS-EN ISO 14040, SFS-EN ISO 14041 2008)

## 4.2 Inventory analysis

Collecting information and calculation are main parts of the inventory analysis. In this phase collected data from different sources is used to define the environmental impacts, in other words all inputs and outputs (products, emissions, other environmental points of view).

After this, material and energy balances of each unit process is calculated as well as the material and energy balances of the entire product system.

Allocation is sometimes used in this phase to divide material and energy flows as well as their environment changing or straining factors into different products. Usually this is done in larger industrial processes which produce several products. However, allocation should normally be avoided if possible. (SFS-EN ISO 14041 2008)

## 4.3 Impact assessment (LCIA)

The purpose of this phase is to produce a better view of the environmental impacts with the help of the results of an inventory analysis. According to ISO 14044

(2006), the impact assessment proceeds through two mandatory and two optional steps.

### 4.3.1 Selection of impact categories and classification (mandatory)

In this phase:

> “*the categories of environmental impacts, which are of the relevance to the study, are defined by their impact pathway and impact indicator, and the elementary flows from the inventory are assigned to the impact categories according to the substances‘ ability to contribute to different environmental problems.*
> *(ILCD handbook2010)*

The mostly used impact categories are among other things; energy consumption, consumption of natural resources, climate change, ozone depletion, acidification, ecotoxicology impacts, toxicology impacts and eutrophication.

### 4.3.2 Characterisation (mandatory)

In this phase:

> *the impact from each emission is modelled quantitatively according to the underlying environmental mechanism. The impact is expressed as an impact score in a unit common to all contributions within the impact category (e.g. kg $CO_2$-equivalents for greenhouse gases contributing to the impact category climate change) by applying characterisation factors. A characterisation factor is a substance-specific factor calculated with a characterisation model for expressing the impact from the particular elementary flow in terms of the common unit of the category indicator. (ILCD handbook2010).*

### 4.3.3 Normalisation (optional)

A perception in which impact category the examined options cause relatively the biggest effect is formed in this phase.

### 4.3.4 Weighting (optional)

In this phase the indicator results between the different impact categories are estimated.

> *"Ranking and/or weighting is performed of the different environmental impact categories reflecting the relative importance of the impacts considered in the study."*
> *(SFS-EN ISO 14042 2008)*

## 4.4 Interpretation

This phase is a systematic process in which the results of the inventory analysis and the impact assessment are recognised and measured and finally reported according to goals of the application field. The purpose of interpretation aims at recommendations and conclusions which support decision-making. In addition, the possible uncertainty factors in different phases of the evaluation process, are considered. (SFS-EN ISO 14043 2008)

# 5 CASE STUDY: ENERGY AND ENVIRONMENTAL ANALYSIS OF A SPANISH WIND FARM

## 5.1 General Framework

The case study wind farm is called Montargull after its location. It is situated in Llorac, Talavera, approximately 80 kilometres from Barcelona in Catalunya, eastern Spain. It was founded on the 25th of November in 2008. This area consists of mainly forest and rural field areas. In the edge of this area also a small residential area (Santa Coloma de Queralt) is situated. This has been analysed roughly by using Google Earth satellite pictures of the area. Near the wind farm in Montargull is another, smaller wind farm (Ampl.Montargull) but in this case study it has been left outside the analysis.

The plant includes 15 turbines. The nominal power of wind turbines have been estimated 2 MW of each. Thus the total power of the wind farm is 30 MW. The steel tubular tower height is 100m (5 sections) and the rotor diameter is 87m. Start-up wind speed is 3m/s and the cut-out wind speed is 21m/s. The wind conditions of the area have been estimated medium level (between high and low wind speeds), thus all the wind turbines of the wind farm are designed to give “maximum output at minimum cost per kWh for medium wind sites”.

The rotors are typical three bladed rotors. The gearbox includes 1 planetary stage and 2 paraller stages. The generator is a doubly-fed machine with rated power of 2.0MW. Its speed and power is controlled through IGBT converters and a PWM (Pulse Width Modulation) electronic control. The generator uses the "total lightning protection" system according to standard IEC 61024-1. It protects the sensitive electrical components of wind turbine. Oil pump with oil cooler is used for cooling system.

Pitch and variable speed technology is used to maximize energy production. For creating lighter blades, fibreglass, carbon fiber and prepreg method are used in the manufacturing phase.

Gamesa has developed an SCADA System (a wind farm control system) that allows realtime operation and remote control of the wind turbines, the meteorological mast and the electrical substation. A predictive Maintenance System is used to notice potential malfunctions in the wind turbine’s main components beforehand. Aerodynamic design and Gamesa NRS® control system is used for the noise control. This system permits programming the noise emissions according to criteria such as date, time or wind direction.

The following life cycle steps are investigated in this chapter:
manufacturing of wind turbines, building works and maintenance cycles, transports and finally the decommissioning phase.

## 5.2 Manufacturing of wind turbines

The specific information about the GAMESA G87 2.0MW wind turbine, used in Montargull wind farm in Catalonia, has been selected from provider's technical report. The manufacturing of transformer, which is generally located at tower's foot, isn't mentioned.

The main components of wind turbines are:

- Tubular tower: depending on the number of sections: 3, 4 or 5. Height and weight are then variable from 67m to 100m and from 153T to 242T. It's constituted by plated sheets of steel alloy protected against corrosion by a special paint. 36% of GAMESA's requirements in towers come from Spain (see table). And here's the principal steps to manufacture a tower:
    - Shaping: transforming steel sheets into rings.
    - Welding: rings are arc-welded between them, they have different diameters.
    - Shot peening, painting and drying: the structure is provided by a C5 protection level.
    - Assembly of the auxiliary equipment: service elements are mounted on the tower, such as platforms and ladders.

TABLE 4: Gamesa's Tower Manufacturing Plants

| **Gamesa's Tower Manufacturing Plants** | | **Total area ($m^2$)** |
|---|---|---:|
| Olazagutía | Navarra (Spain) | 13,832 |
| Cadrete | Zaragoza (Spain) | 14,520 |
| Linares | Jaén (Spain) | 49,463 |
| Avilés | Asturias (Spain) | 70,000 |
| Tajonar | Navarra (Spain) | Equipment |

Nacelle: it's a hollow shell that contains the generator's components of the wind turbine. Made of fiberglass to be more resistant and lighter, the nacelle contains the main inner workings. It also contains electronic controls calculating wind's speed and direction. This G87 2.0MW's nacelle weighs approximately 9,980Kg and is mostly composed of steel and copper. Altogether, these plants (see table) produce annually a capacity of 4,000MW.

TABLE 5: Gamesa’s Nacelle Assembly Plants

| **Gamesa's Nacelle Assembly Plants** | | **Total area ($m^2$)** |
|---|---|---:|
| Sigüeiro | La Coruña (Spain) | 15,235 |
| Tauste | Zaragoza (Spain) | 17,000 |
| Ágreda | Soria (Spain) | 44,100 |
| Medina del Campo | Valladolid (Spain) | 83,622 |
| Fairless Hills | PA – US | 31,150 |
| Tianjin | China | 41,640 |
| Chennai | India | 12,950 |

Rotor: it is the mobile part of wind turbines and is composed of 3 blades linked by a hub. Main steps in blade’s manufacturing are:

- Beam manufacture: a mixture of glass and carbon fiber is molded and hardened.
- Shells manufacture: they are also molded and painted with a protective paint.
- Assembly: the beam is assembled between the two shells.
- Curing: a kiln is used to form a compact unit.
- Trimming and polishing: the blade’s edges are finished and checked.

TABLE 6: Details of the rotor and the blades

| **Rotor** | | **Blades** | |
|---|---|---|---:|
| *Diameter* | 87 m | *Number of blades* | 3 |
| *Swept area* | 5,945 $m^2$ | *Length* | 42.5m |
| *Rotational speed* | 9.0 - 19.0 rpm | *Airfoils* | DU (Delft University) + FFA-W3 |
| *Rotational direction* | Clock Wise (front view) | *Material* | Preimpregnated epoxy glass fiber + carbon fiber |
| *Weight (incl. Hub)* | Approx. 37 T | | |
| *Top head mass* | Approx. 107 T | *Total blade weight* | 6,150kg |

Various tasks must be accomplished before the installation of the wind turbine; the platform should be flat and support around $4Kg/cm^2$. The assembly is done using construction vehicles, machines and tools such as cranes.

### 5.3 Building works

According to the estimations of Gamesa, the development phase, which includes site streaming, wind measurement and permissions, takes 3 to 4 years and the installation phase 6 to 9 months. The generation phase when the wind turbine is working lasts for 20 years minimum. According to Gamesa, “the wind farm runs without further investment, maintenance contract signed with Gamesa’s WTG Business Unit”.

Gamesa uses the means of transport that allow for access to any kind of terrain, including the most difficult. The tasks as concrete work and constructing the assembly platform are performed to prepare the land before transporting and assembling the wind turbine on it.  The assembly platform requires compaction that is able to support weights of around 4 kg/cm2.
The tower is assembled in sections one on the top of the other using lattice cranes (either caterpillar or hydraulic jack types). Considering the surroundings of the wind farm, the variability of ground level and the nearby forests, it is estimated that hydraulic jack type cranes are used due to their narrow width and suitability for working in difficult terrain.

In situ, the sections of the tower are first installed. The number of sections depends on the estimated high of the finished tower (that would produce maximum power). In this case the towers include all five sections (total height 100m). Then the nacelle is installed to the top of the tower. The blades can be installed to the hub in the ground and then lifted to the tower but this requires more space for maneuvering. The other option, which is used in this case is to raise and install the hub and cone first and then lift the blades horizontally one by one. This requires less space and makes the assembly process quicker.

## 5.4 Operation and maintenance cycles

The productive life of this wind farm is supposed to be 20 years in minimum. The wind turbines are controlled by Gamesa’s own wind farm control systems, Gamesa Windnet. Most of the major wind energy manufacturers use their own computer control systems during this operational phase in the life-cycle of a wind turbine. During the maintenance cycle, mainly lubrication, painting and substitution of spare parts are done.

## 5.5 Transports

The analysis of the transporting step starts from calculating vehicles emissions. Conveyance by train is the least polluting and Spanish government encourages wind turbine’s industries to use it. GAMESA has its own means of transport, especially trucks and trains, to carry the wind turbines to their wind farm place. This means allow for access to unreachable areas with a minimal environmental impact.

## 5.6 Decommissioning phase

Take down a wind farm is straight simple and forward, comparing to problems encountered while decommissioning a nuclear power station or a coal/gas fired plant. A wind turbine lasts about 20-25 years, but meanwhile some parts inside the nacelle may need changing. Unfortunately, not the entire wind turbine is recyclable. Recent studies show that it is possible to reduce or eliminate the negative impact of the dismantling of a wind farm. These teams of researchers hope that industry will adopt their approach. Actually, they suppose that establishing and decommissioning phases have the same environmental impacts while using the same machines and tools.

Regarding wind turbines, the dismantling phase must include:

- The dismantling of the turbine
- Removal of ancillary equipment,

- The foundation leveling,
- The future of the network or local network between wind turbines (the network is the property of Network Transmission of Electricity and thus usable for any purpose other than the wind farm).

The foundation is leveled at least 1.5m deep, leaving the possibility of resuming agricultural activity on the site. In some cases it is possible to remove the entire foundation. The positions of these supplies on site are also removed from their foundations and completely removed. Each site is then covered with soil and restored to natural vegetation or a farm. This last step does not leave any significant mark on the site of the existence of the wind farm.

The cost of decommissioning of a wind turbine and recycling facilities is easy to estimate as opposed to other means of production where it remains impossible or partially secret. This relatively low cost is borne by the building owner thanks to the sale of "junk" towers and other components.

# 6 ENVIRONMENT AND ENERGY ANALYSIS OF THE WIND FARM

## 6.1 Goal and scope definition

The goal of this life-cycle assessment is to investigate the environmental impacts in the life-cycle of the case study wind farm. The aim is to focus especially on the manufacturing phase of the life-cycle, because in the earlier researches it has been pointed that it is the most energy intensive phase. The main environmental emissions and impacts appear in the beginning of the life-cycle, in the manufacturing and acquiring of raw materials.

The purpose of this study was to do a similar study of energy performances to a Spanish wind farm that the earlier research of “Energy performances and life cycle assessment of an Italian wind farm”. In addition, this study also includes the life-cycle approach of a wind farm. The functional unit in this study is 15 wind turbines, which is the size of the farm.

TABLE 7: The used materials of the parts

| **Parts** | **Materials** |
|---|---|
| Rotor and rotor blades | Preimpregnated epoxy glass fiber + carbon fiber |
| High speed and low speed shaft | Steel |
| Gear box | Steel |
| Safety brakes | Steel |
| Generator | Steel, copper |
| Cooling and heating system | Steel |
| Yaw system | Steel |
| Sensors and electronic equipment | Copper |
| Transformer | Steel (supposed) |
| Tower | Steel alloy + anticorrosion paint |
| Foundation | Steel reinforced concrete |
| Nacelle cover | Composites (estimated epoxy glass fiber + carbon fiber) |
| Lubrication | Oil |

In this study, it has been compulsory to make several assumptions due to lack of actual data of this specific wind farm and wind turbines. This has an effect on the results which are thus assumptions as well.

The investigated emission is CO2 because of its nature of greenhouse gas and it is estimated the major air-emission in the whole life-cycle (including the maintenance phase). Because of the manufacturing and incquiring of raw materials phase being so significant and major phases, is the environmental impacts of the raw-materials investigated. Only the main raw-materials (that are mostly used) are included in this study. According to “Wind energy explained” (Manwell, J.F., McGowan, J.G and Rogers, A.L. 2006) the mainly used raw materials are steel, concrete, copper and composites (preimpregnated epoxy glass fiber and carbon fiber). Energy consumption is monitored especially in the most energy consuming phases. The following process flowchart is presenting the system:

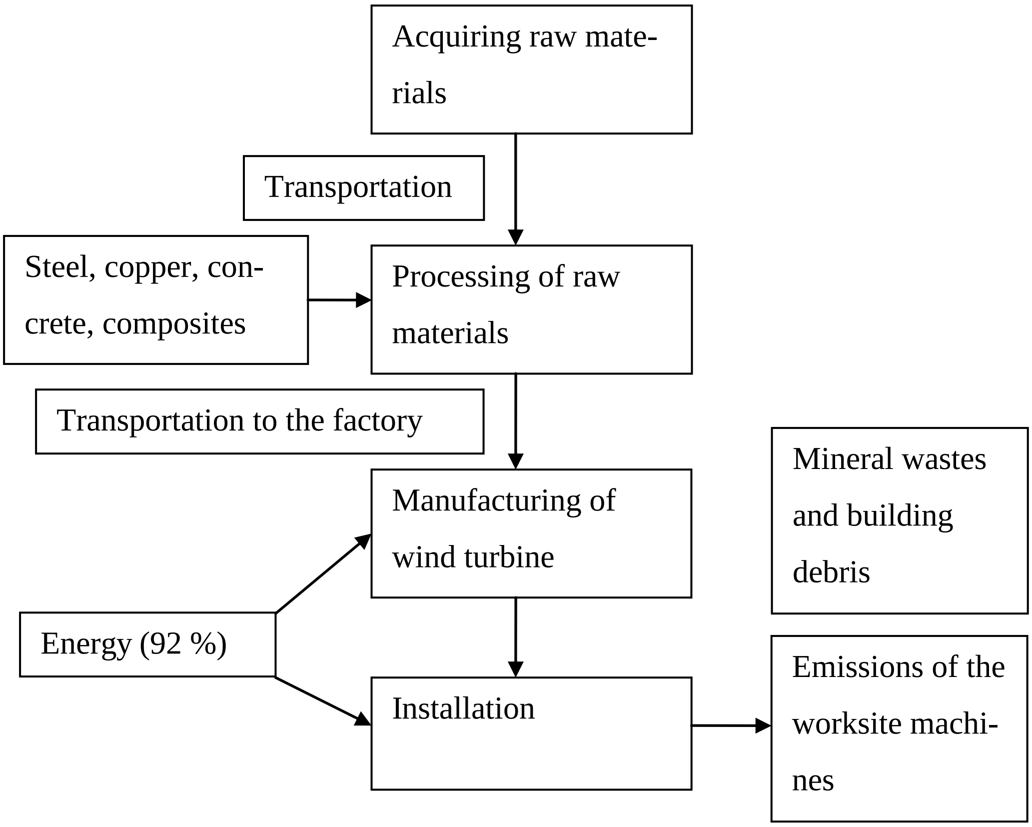


CHART 2: The process flow chart

Composites comprise at least two dissimilar materials, in this case glass and carbon fibers. Fibers are most commonly held in place by a binder matrix, in this case epoxy. Binders include polyester, epoxy and vinyl ester. The most common composite is fibreglass reinforced plastic (GRP). Glass fibers are manufactured by spinning glass into long threads and then usually combined into other forms (aka. performs). After this, fibers can be used in several forms, but when high strength is required, unidirectional bundles of fibers known as “tows” are used.

The resin (epoxy) is used in the liquid form during the lay up of the composite, but as cured form they are solid. In this case epoxy is used as resin. Other choices would have been polyesters or vinyl esters. The choice of resins affects the overall properties of the composite.

Copper is used in nearly all electrical equipment of a wind turbine, including the power conductors. (Manwell, J.F., McGowan, J.G and Rogers, A.L. 2006/ p.260)

As mentioned before, the manufacturing and installation phases are the most energy- consuming phases in wind farm’s life-cycle, and thus are focused in this study. According to earlier study, in manufacturing and installation phases, the transportation has only a minor energy consumption, when compared to manufacturing wind turbines and and building works.

Focusing in these two main energy-consuming actions, in the energy consumption of manufacturing wind turbines, the most significant parts are towers (49,4%), components manufacture (29,3%) and blades (15,7%).
(Energy performances and life cycle assessment of Italian wind farm, 2006)

The most energy-consuming part in building works are foundations (49,8%) and cables and transformer room (19,1%). The energy consumption of roads and paths, cable trenches and lay-bays are approximately the same.

## 6.2 Energy consumption of raw-materials

Let us first examine the energy consumption and environmental impacts of manufacturing of wind turbines. Because the tower and the manufacturing of the components have the most energy consumption and because of the fact that their mainly raw-material is steel, it can be estimated that steel has the most energy consumption in manufacturing phase. The ”components manufacture” is assumed to consist generator, gear box, sensors and the other components that mainly consists of steel.Also the major role of foundations in the energy consumption of building works and the fact that steel reinforved concrete is used as raw-material in foundations refers to steel’s major part in the energy consumption.

On the other hand, the usage of recycled steel may reduce the environmental affects of manufacturing phase (compered the mined raw-materials) decommissioning phase, because it is totally recyclable material. The towers are also painted with anticorrosion paint, whose environmental effects are thus also investigated here. The other energy consuming material in this phase is the material of blades, epoxy glass fiber and carbon fiber.

As mentioned before, in the energy consumption of building works, the foundation (which consists of steel and concrete) has the major part,. Cables and transformer room are the second energy-consuming parts, and, as cables consists of metal and transformer room consist steel and concrete it can be concluded that the main energy consumption of both manufacturing and building works are due to usage of steel. However, since, according to earlier study of an Italian wind farm (Energy performances and life cycle assessment of Italian wind farm, 2006) the construction materials (including concrete) have the second greatest (14,1%) incidence of embodied energy of raw materials into the GER (Global Energy Requirement), the concrete is also included in the examination.

In order to calculate the environmental impacts of different materials, the mass details of a wind generator of the earlier study have been used as material. Bronze is left out due to its negligible mass.

TABLE 8: Mass detail of a wind generator (ScienceDirect, 2006)

| **Material** | **Mass (kg)** |
|---|---:|
| Steel | 66,434 |
| Cast iron | 6,001 |
| Glass reinforced plastic | 4,950 |
| Copper | 924 |
| Paints | 389 |
| Lubricant oils | 111 |
| Aluminium | 85 |
| PVC | 65 |

TABLE 9: Building works-mass details (ScienceDirect, 2006)

| **Material** | **Total (kg)** |
|---|---:|
| Aggregate quarrying | 21,708,000 |
| Local soils and stones | 10,333,494 |
| Concrete | 4,097,280 |
| Sand | 2,802,279 |
| Steel | 122,527 |
| PVC | 18,932 |
| HDPE | 11,383 |
| Aluminium | 8,289 |
| Polybutadiene | 5,141 |
| Copper | 2,893 |
| Polypropylene | 115 |

Steel, sand, concrete, (local soils and stones), High-density polyethylene (HDPE) and PVC form the group of mainly used materials in the building works phase. Thus the following scrutinies focus on the environmental impacts of these materials.

To estimate the environmental impacts of required raw-materials, Material Input per Service Unit (MIPS) calculation was used as a working tool. According to The Finnish Association for Nature Conservation (FANC), the MIPS-calculations have been used as help in increasing the eco-efficiency of products. MIPS is an indicator that is based on material flows and it indicates how much material is used in relation to the service performed. Thus it is easy to compare, to each other, service solutions, which provide the same benefit but are produced differently. The factors of different materials used in the wind turbine manufacturing and installation are in the following table.

Abiotic resources are unrenewable natural resources (for example ores and gravel and  the fossil energy and electricity, including the ecological rucksacks for them).

The amount of water consumption during the product chains is usually high. In water comsumption, all human interfering with the natural course of water (including also the regulation of water systems for electricity production) and have been taken into account.

> *Air consumption in the production and use phases means the physical and chemical transformation and combustion of air and its components, such as oxygen. The output of carbon dioxide is thus often in indirect relation to the air consumption (The Finnish Association for Nature Conservation 2010).*

The categories of Biotic raw materials and Soil movements in agriculture and forestry has been left out, because according to Wuppertal instutut's ”Material intensity of materials, fuels, transport services” table, the examined raw-materials don't have impacts (or have not estimated) in these categories.

It is also notified that:

> *This information forms the basis for further investigations. In general, materials, fuels, transport services, etc., can only be properly assessed under concrete framework conditions, e.g. in products. Data in per kg of a material are not suitable for making a recommendation for or against a specific material, fuel, etc (Wuppertal Institute for Climate, Environment and Energy 2010).*

However, because a lot of estimations have been done along with this study, the material intensities have been calculated to above-mentioned main materials. The following figures show how much producing one kilogram of e.g. steel demand other natural resources. If some material has more than one figure, the average figure has been used.

TABLE 10: Material intensities of used raw-materials (Wuppertal Institute for Climate, Environment and Energy, 2010)

| **Material** | **Material intensity [t/t]** | | | |
|---|---|---|---|---|
| | **Abiotic material** | **Water** | **Air** | **Area** |
| ***Metals*** | | | | |
| engineering steel;blast furnace route | 8.14 | 63.7 | 0.444 | World |
| ***Plastics*** | | | | |
| epoxy resin | 13.73 | 289.9 | 3.751 | Europe |
| polyvinyl chloride | 3.47 | 305.3 | 1.703 | Europe |
| ***Construction materials*** | | | | |
| Concrete | 1.33 | 3.4 | 0.044 | Germany |
| sand (quartz sand) | 1.42 | 1.4 | 0.030 | Germany |
| ***Others*** | | | | |
| carbon fibre (PAN) | 58.09 | 1794.9 | 38.000 | Europe |
| fibre glass (E-glass) | 6.22 | 94.5 | 2.088 | Europe |

For some materials used, such as cast iron, figures were not available, and are thus not included in the calculations. For sand, the figure has been taken from quartz sand.

The aim of the calculations is to offer directional analysis of the sizes of environmental impacts, which materials are the most crusial, and where in these categories the largest impacts are placed. When the figures of the tables 8 and 9 are multiplied with the mass details of used raw-materials (combining the results of the tables 8, 9 and 10) following estimated directional results can be gained:

TABLE 11: The usage of natural resources

| **Material** | **Total mass inc.manufacturing & building works (kg)** | **Usage of abiotic materials (kg)** | **Usage of water (kg)** | **Usage of air (kg)** |
|---|---|---|---|---|
| Steel | 188,961 | 1,538 143 | 12,038,705 | 83,899 |
| Concrete | 4,097,280 | 5,449 382 | 13,930,752 | 180,280 |
| Sand | 2,802,279 | 3,979 236 | 3,923,191 | 84,068 |
| Polyvinyl chloride | 18,997 | 65,920 | 5,799,784 | 32,352 |
| Carbon fibre | 1,881 | 109,267 | 3,376,207 | 71,478 |
| Fibre glass | 1,881 | 11,700 | 177,755 | 3,928 |
| Epoxy resin | 1,188 | 16,311 | 344,520 | 4,456 |

As it was estimated in earlier study (Energy performances and life cycle assessment of Italian wind farm, 2006), also in this research the glass reinforced plastic is supposed to be a mixture composed by 76 % of glass fibres and 24 % of epoxy resin. In additional, because glass reinforced plastic is a mixture of carbon and glass fibres, it is estimated that ratio is 50/50.

From the calculated results of the Table 11, it can be concluded what raw-materials have the major usage of water, air and abiotic materials compared to the production of required amount of these materials. Although steel has several times larger usage of abiotic material and water when compared to produced steel mass, it is the production of carbon fibre and epoxy resin that has even larger usage of all the categories (abiotic, water and air) when compared to produced mass of raw-material

.

Thus, according to this study, epoxy resin and carbon fibre have the major impacts when using natural resources (abiotic, air and water). However, in this case, due to their smaller mass in the production of wind turbine, their impact is smaller than steel, concrete and sand. Only carbon fibre’s usage of water comes close to that of sand.

Thus largery due to their notable mass amount in the process, the environmental impacts of steel, concrete and sand, are in this case the most notably of the raw-materials used in the wind turbine production and installation, when considering the usage of these three categories of natural resources.

# 7 ECOPROFILE OF ELECTRICITY

An impact study is an initial study to assess the environmental consequences of a project to reduce or mitigate or compensate for adverse impacts. By extension, an impact study is a case that examines the consequences of a project.

The average estimation of electricity production is 53,690 MWh/year, according to the data on the Red Eléctrica de España website (www.ree.es). The calculated energy payback time for wind farms is about 3-7 months (www.windpower.org). The plant’s output is very determining for the ecoprofile calculation. By dividing the total plant’s impacts by the total electrical energy production during the functional life, we obtain 1kWh ecoprofile.

The Spanish electricity production system is mixed: hydropower (10%), gas (29%), oil (8%), coal (23%), nuclear power (20%) and wind (8%), giving an environmental impact of 5.73E−01 kg $CO_2$-Eq per 1 kWh in 2006.

The climate declaration, based on LCA results performed for an Environmental Product Declaration (EPD - www.klimatdeklaration.se), shows the emissions of greenhouse gases, expressed as CO2-equivalents.

TABLE 12: Ecoprofile of 1 kWh of electricity (ScienceDirect, 2006)

| | | |
|---|---:|---|
| Global warming potential | 14.8 | $[\mathrm{g}_{CO2}\text{-eq/kWh}]$ |
| Ozone depletion potential | $6.59\times10^{-7}$ | $[\mathrm{g}_{CFC11eq}/\mathrm{kWh}]$ |
| Acidification | $3.62\times10^{-3}$ | $[\mathrm{mol}_{H^{\pm}eq}/\mathrm{kWh}]$ |
| Photochemical ozone creation potential | $1.61\times10^{-2}$ | $[\mathrm{g}_{C2H4eq}/\mathrm{kWh}]$ |
| Eutrophication | 0.35 | $[\mathrm{g}_{O2eq}/\mathrm{kWh}]$ |
| Inert wastes | 154.2 | [mg/kWh] |
| Special wastes | 1.2 | [mg/kWh] |

## 8 CONCLUSIONS

The aim of this study was to create a similar but extended research as the earlier study of energy performances of an Italian wind farm is. In order to avoid repetition, some methods used (e.g. MIPS-calculation) differ from the earlier study. It is also important to take into account that a full and detailed life-cycle analysis of this wind farm would have demanded more in-debt data of the used materials and energy, in order to create an accurate life-cycle analysis for this particular wind farm. This is why many of the life cycle steps were left out of the study, and, in order to estimate the environmental impacts, the study focused on MIPS-calculations for its simplicity. Also because of the several estimations and e.g. the material data that is based on the data of the Italian wind farm, the research and the results are more directional and can be applied to more wind farms than this particular one.

This study only focused on the most significant materials (measured by the used mass and environmental impacts of that mass) of the most significant life cycle phases (measured by the energy consumption and emissions).

The research focused on the first two phases of the life cycle of the wind farm; manufacturing phase and the building works, and the environmental impacts such as consumption of natural resources (abiotic, water and air) and energy were calculated.

As results of the MIPS calculations, it is shown that, from the raw-materials, steel, concrete and sand are the most consuming of natural resources. Moreover, when examining the tables considering the energy consumption of wind farm (and especially the most energy consuming phases; wind turbine manufacture and the building works) of the earlier study, it was found out that the most energy consuming raw materials where steel and concrete, when used as parts, either together or separately.

The waste scenario of the wind turbine is also an important period of the life cycle. The recycling of the materials significantly reduces the negative environmental effects; otherwise wind turbines would not be ecological at all.

The manufacturing phase has the most important environmental impact during the life cycle, so it is a very decisive phase. The source of the electricity used while manufacturing is the primary reason. The system must be improved because, despite the recycling materials and reusing minerals, there are still fossil fuels that substantially affect this energy resource. The foundation is also the element which considerably influences the environment, mainly because of the cement. This fact ushers to the need to improve the preparing cement methods in other to reduce its footprint.

In building works, most steel and concrete is used in the foundations. Sand is only used in cable trenches (Energy performances and life cycle assessment of Italian wind farm 2006).At the same time, almost half (49,8%) of the building works' energy consumption is in the foundations. Also in the wind turbine manufacture, where the 49,4% of the energy consumption is in manufacturing the tower and 29,3% of that is in manufacturing the components (e.g. gear box, generator) and considering the fact that these parts mostly consist of steel, refers to steel's major role in energy consumption. It can be mentioned that the MI-factors for sand are close to those of concrete, but concrete is considered to be more significant in this case due to its almost double used mass in the process when compared to sand. Concrete also contains steel.

Thus it can be concluded that as raw-materials, steel and concrete have the most environmental effects. When considering to improve the energy efficiency of these early (and the most significant regarding the environment) life-cycle phases, and decreasing the environmental effects of the used raw-materials, this study gives the direction to focus on in terms of material management of future wind farm design, and shows that there is absolutely an environmental gain in setting up wind farms. But this does not mean that improving this renewable technology should stop, because future wind turbines will be bigger, which would increase their environmental impacts.

The aim was to prove if wind energy is truly 'green'. It came out to be incredibly competitive as far as environmental effects are concerned, exceeding the coal and oil energy expressively.

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SFS-EN ISO 14042 Ympäristöasioiden hallinta. Elinkaariarviointi. Vaikutusarviointi. Suomen Standardisoimisliitto SFS.

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TABLE 2 Installed windpower capacities (MW) in Spain (Wikipedia 2010). Available: http://en.wikipedia.org/wiki/Wind_power_in_Spain

TABLE 4: Gamesa’s Tower Manufacturing Plants
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TABLE 5: Gamesa’s Nacelle Assembly Plants
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TABLE 6: Details of the rotor and the blades. Available:
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