WHITEPAPER

WIND GENERATOR TECHNOLOGY

Eclareon

November 2012

ECI Publication No Cu0180

Available from www.leonardo-energy.org/node/156615

Document Issue Control Sheet

Document Title:	Whitepaper Wind Generator Technology
Publication No:	Cu0180
Issue:	01
Release:	November 2012
Author(s):	Eclareon
Reviewer(s):	Fernando Nuño, Bruno De Wachter

Document History

Issue	Date	Purpose
1	November 2012	Initial publication
2		
3		

Disclaimer

While this publication has been prepared with care, European Copper Institute and other contributors provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information or the data contained.

CONTENTS

SUMMARY

This Application Note starts with an overview of the expected evolutions in the wind market. The initial boom in the global onshore wind market lies behind us, with a growth rate of 31% between 2005 and 2010. That said, the market is expected to continue its growth in the subsequent three years, with a projected growth rate of 12%. The strongest growth for onshore wind power is predicted for countries outside of Europe. The size of the turbines will continue to grow steadily, with 95% of all new wind turbines having a power of 1.5 MW or more in the following three years. The market of the offshore wind power tells a different story. The boom in this market in the forthcoming years will be less significant than originally expected, with growth rates that have recently been adjusted downward from 49% to 37%. This market will continue to be largely dominated by Europe. After 2015, the growth is predicted to moderate significantly to a figure around 10%. The average size of new offshore wind turbines has been following an upward trend in recent years and has surpassed 3.5 MW. Turbines of above 5 MW have already been installed.

The main sections of this Application Note are dedicated to an analysis of the overall trends in wind turbine technology and the related market projections. A key influencing factor are the increasingly stringent grid code requirements imposed by the Transmission System Operators (TSO). Those requirements follow the rapidly growing penetration of renewables connected to the public grid and the related concerns of the TSOs regarding the management of this type of energy. This factor speaks in favour of the Permanent Magnet Synchronous Generator (PMSG), whose power output is controllable and through which even the most stringent grid codes can be met. This is in contrast to the Doubly-Fed Asynchronous Generator (DFAG), which may need external reactive power compensation. Despite this fact, DFAGs continue to dominate the market and give up market share in favour of the PMSG only at a relatively slow speed. The growth of PMSG is mainly hampered by the fact that the price of permanent magnets remains high and its production volumes are therefore lower than those of the DFAG.

The choice of a particular wind turbine technology has to be studied on a case-by-case basis. For instance, locations with high wind speeds and significant turbulence speak in favour of the PMSG, since their full-scale power converter can offer greater availability and thus a greater energy yield in such conditions. In general, the main driver for the technology choice for onshore applications will be the levelized cost of energy that can be achieved. Wear is more significant, and the cost of maintenance and repair is much higher, for offshore applications. This explains why reliability is usually the principal factor in selecting a given technology for offshore projects, and the reputation of the wind turbine manufacturer will be fundamental.

A new type of wind turbine technology currently under development is the High Temperature Super-Conductor (HTSG) turbine. This type of turbine is not expected to reach the market before 2016. It will enable the attainment of higher power than with any other type and will be particularly well suited for the niche market of very large offshore wind turbines.

Wind Market Overview

Expected Evolution of the Onshore Wind Market

The size of the market for Wind Turbine Generators (WTGs) is determined by the capacity of new wind power installations[1]. Annual installations of wind power worldwide have consistently increased over the past several decades. It is estimated that the onshore market will continue to grow by more than 10% per year until 2015. From 2015 onwards though, it is expected that market growth will moderate significantly.

Figure 1 shows the estimated evolution of CAGR (Compounded Annual Growth Rate) for the two five-year periods from 2010 to 2020 and the subsequent ten-year period running up to 2030.

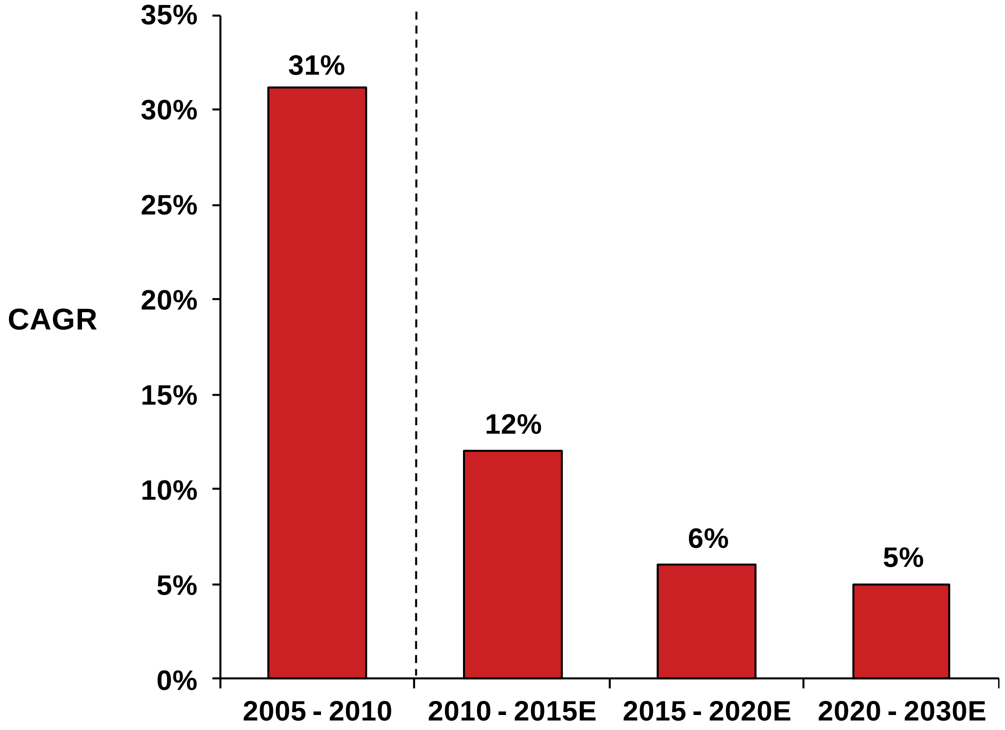


Figure 1 – Compounded Annual Growth Rates for Onshore Wind Installed Capacity[1]

As depicted above, annual onshore wind power installations are forecast to slow down, growing at a rate of ~5% on the longer term.

In 2011 the cumulative global onshore wind energy market reached a total of 240 GW, with just over 40 GW of that total being newly installed capacity.

It is expected that worldwide cumulative onshore installed capacity will almost double from 2011 to 2015, as illustrated in the following graph:

[1] Throughout the report, annual wind energy installations are expressed as net capacity: megawatts (MW) or gigawatts (GW) of wind capacity added, minus that decommissioned, for a given year.

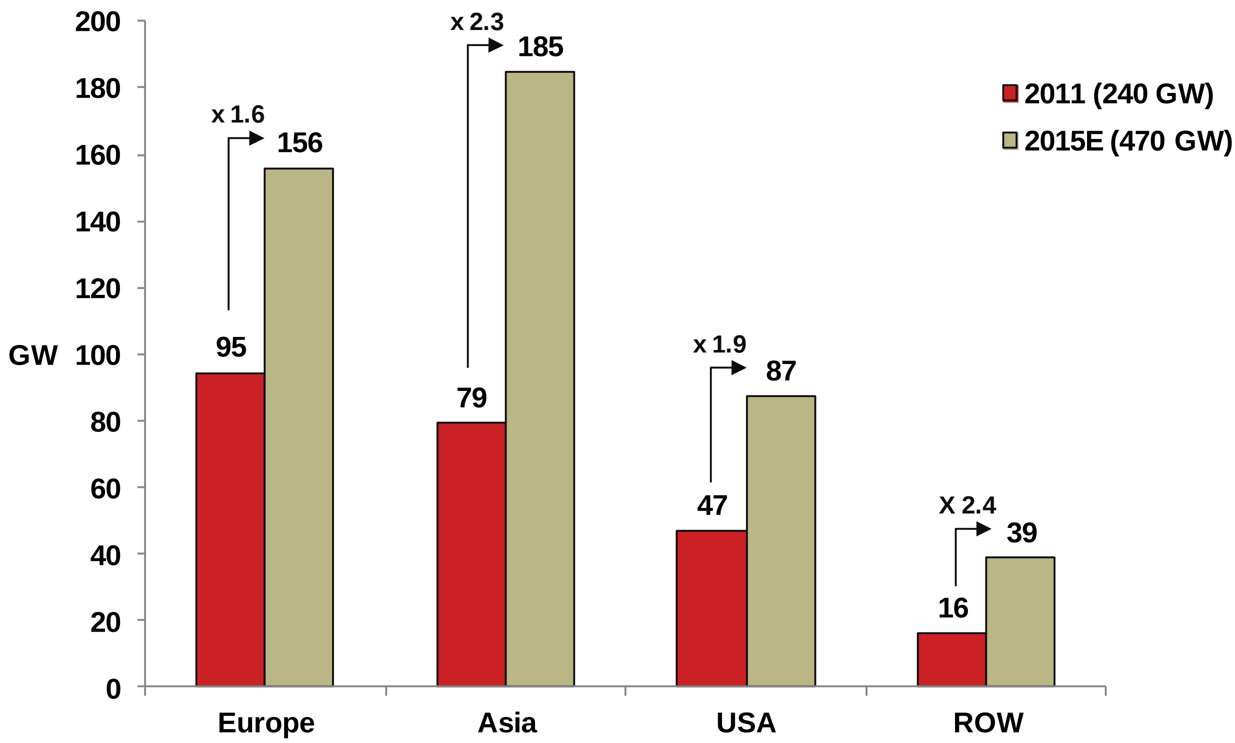


Figure 2: Cumulative onshore capacity (GW) in 2011 and 2015 Forecast (ROW=Rest of the World)[2]

In absolute terms, Asia is the region expected to exhibit the most growth, ousting Europe from its leading role. High economic growth in India and China, and the subsequent increase in electricity demand will be the main market drivers.

As for Europe and the USA, the strongest market driver in the past has been governmental regulation. Currently, however, there are some uncertainties about the future of public support.

When we examine the geographical distribution of installed capacity by individual country, we see that European countries trail China, USA, and India in annual onshore wind energy installations. China and the USA account for a combined ~60% of annual global installations. This figure that will remain more or less unchanged in the forecast period.

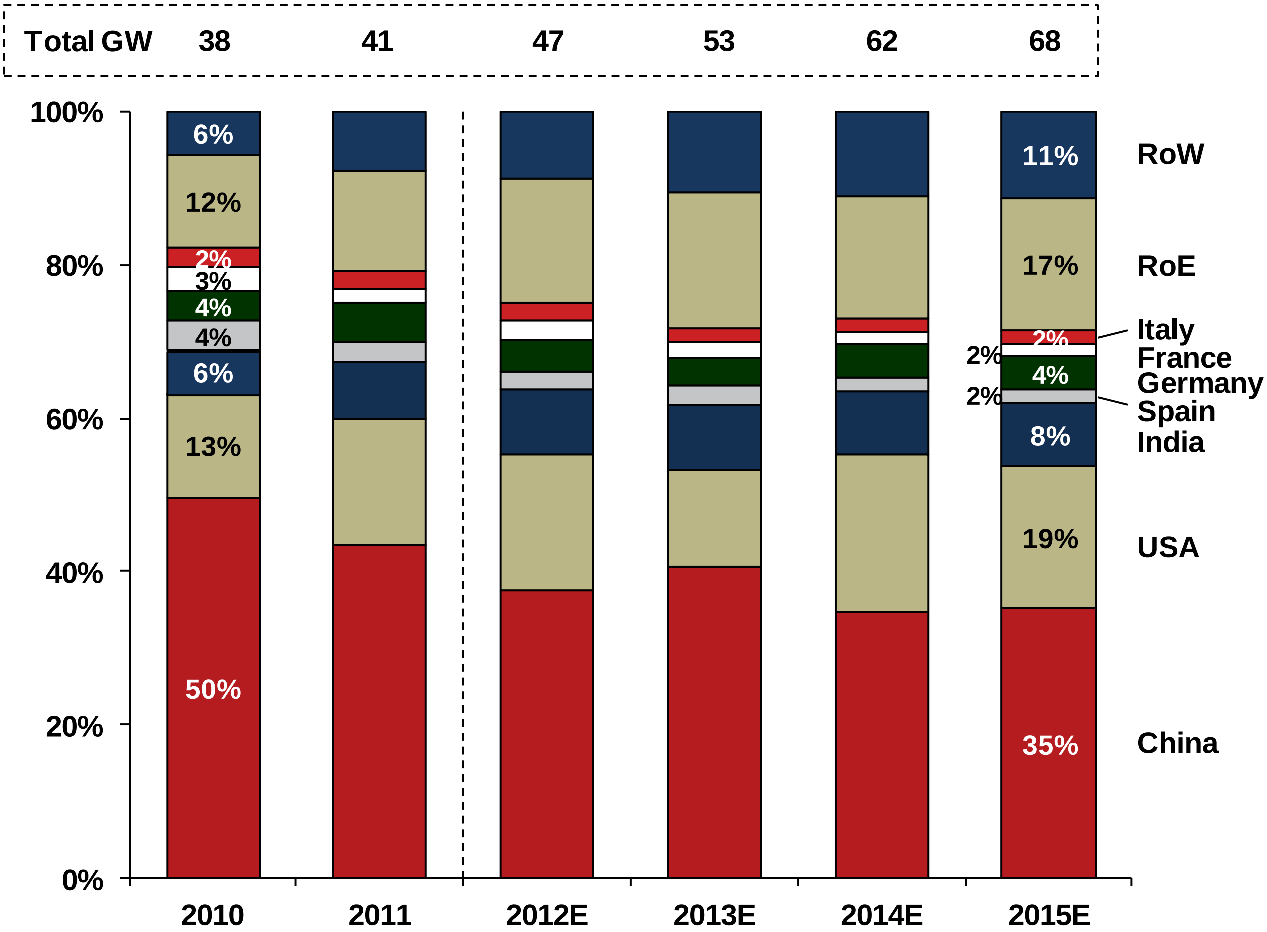


Figure 3 – Geographical Distribution of Annual Onshore Wind Installed Capacity[3]

As Figure 3 illustrates, it is expected that the global onshore wind energy market will be less concentrated in the near future.

On the one hand, China´s share of the market will decrease substantially to a more economically sustainable rate of growth. In addition, the contribution of some of the leading European markets will also decrease in the forecast period due in part to financing constraints. In this sense, the Spanish case stands out given its recent suspension of support schemes for renewable energy. This has had an immediate impact on the market.[2]

On the other hand, the onshore wind market will grow in emerging economies such as Brazil and Mexico in Latin America and Romania and Bulgaria in Europe. The increased demand in these markets will more than offset the diminishing demand in developed countries.

After 2015, the onshore wind market will continue to be driven by high economic growth in Asia. It is expected that China and India will account for nearly 42% of cumulative demand over the 2015-2020 period.

Wind power's market expansion will slow down in the mid- and long-term. While not experiencing outstanding growth, it will still exhibit attractive annual growth rates. As wind power capacity continues to increase, the

[2] Some WTG manufacturers claim that the feed-in tariff moratorium in Spain opened up many new opportunities for them, since the situation crowded out less competitive manufacturers.

availability of the most desirable locations will drop. But, at the same time, WTGs will become more efficient. This may result in the repowering of older wind farms with new, more efficient WTGs. Some countries will eventually find that wind power electricity will be cheaper than other sources of energy.

Expected Evolution of Onshore Wind Turbine Capacity

The WTG market is shifting toward larger WTGs: those over 1.5 MW nameplate capacity presently dominate the market and it is expected that the share of WTGs over 2.5 MW will increase steadily, though at a very slow pace.

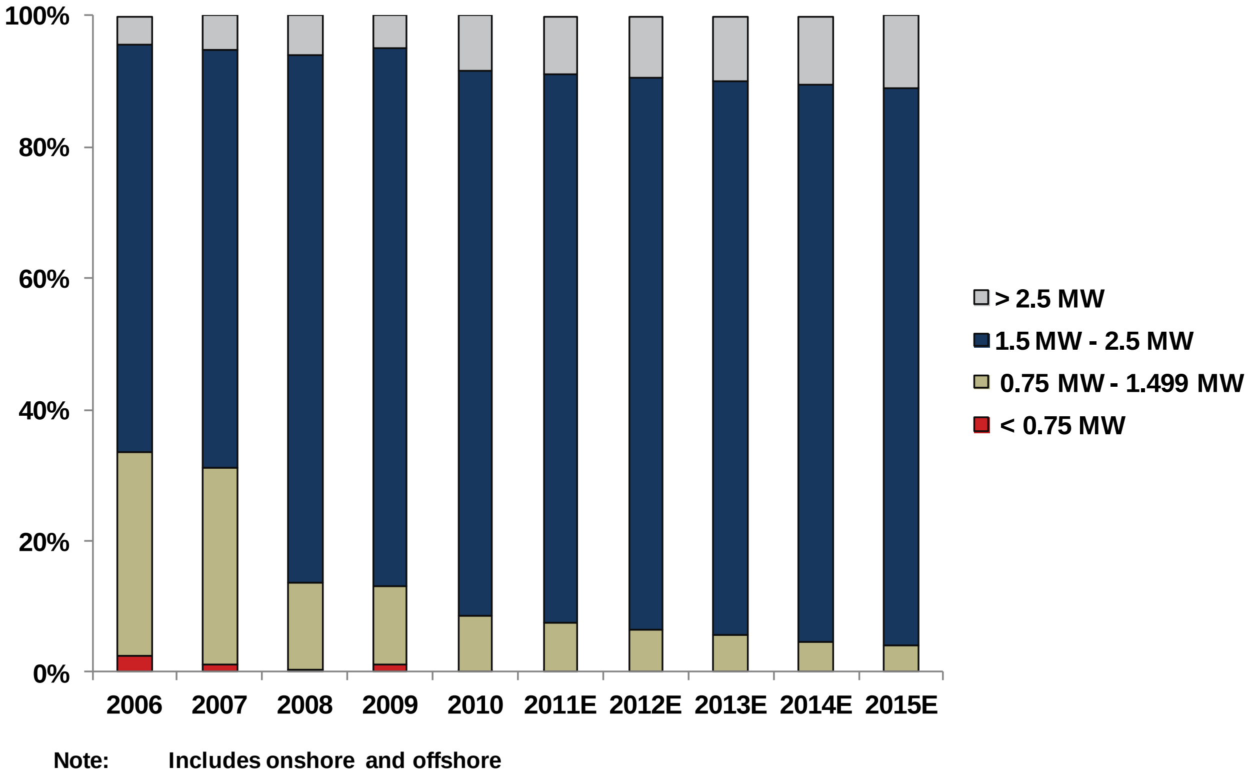


Figure 4 – Expected Share of WTG Sizes in GW Supplied[4]

In contrast with the Asian market where smaller turbines are the norm, 2-3 MW models are popular in Europe[3]. Many of the larger WTG models which were initially designed for offshore wind farms are being installed onshore.[4]

Logistics is an important factor which could limit further growth of turbine size. Many locations which are not easily accessible are not feasible target markets for larger size WTGs.

---

[3] Chinese WTG manufacturers entering the market mostly supply turbines in the 1.5 MW range.

[4] Explained in Section 0

Note that larger WTGs (in terms or power and rotor diameter) could compensate for the increasing lack of locations with higher wind speeds and be employed for repowering older sites.

WTG manufacturers have begun to launch next generation WGTs, larger machines which are now being commercialized. Enercon offers a WTG with a 7.5 MW nameplate capacity, the world's largest commercially available onshore WTG.[5]

According to industry experts, even 20 MW WTGs will eventually be developed. What cannot be predicted is whether larger WTGs will reach mass production, because '*it is simply a question of cost of energy*,' asserts Henning Kruse, director of governmental affairs at Siemens Wind. The size of the WTGs will be determined by the cost per MWh produced.

Some recently introduced new designs are illustrated in the following Table:

	Announcements of new WTGs (2010 onwards)
Vestas	• **V112-3.0 MW geared PMSG** for onshore low and medium wind speed sites and for offshore, with a rotor diameter of 112 metres. • **V164-7.0 MW hybrid PMSG,** offshore WTG with a rotor diameter of 164 metres (construction of prototypes in Q4 2012)
GE	• **GE's 2.75-100 PMSG**, (2.75 MW and 100 metre diameter) a 2.5-100 upgrade with minor alterations to the electrical system • **GE´s 2.75-103 PMSG**, the 2.75-100 with a slightly larger rotor
Siemens	• **SWT-6.0 direct drive PMSG**, a 6 MW machine with rotor diameters of 120 and 154 meters, designed for offshore (first prototype already installed in Denmark)
Enercon	• **E-82/3 MW (full converter CSG)** for strong wind sites and **E-101/3 MW (full converter CSG)** for inland sites and with the choice between two hub heights: 99 or 135 metres • Installed **E-126/7.5 MW (full converter CSG)**, an upgrade of the existing 6.0 MW design and currently the most powerful WTG in the world
Suzlon	• **S88 Mark II 2.25 MW DFAG,** developed exclusively for the Chinese market • **S9X DFAG** for low and moderate wind speed sites
REpower	• **REpower 3.2M114 DFAG**, with a rated output of 3.2 MW and a hub height of 123 metres • **MM100 DFAG** for the North American wind market, with a 80 metre hub height and a rated power of 1.8 MW (series production since mid-2012)
Gamesa	• **G11X-5.0 MW hybrid PMSG,** with a 128 metre rotor diameter, expected market launch in 2013 • **G14X- 6/7 MW hybrid PMSG**, with a pre-series scheduled for 2015

[5] >3 MW WTGs also include Repower's 5 MW and 6 MW, Siemens´ 3.6 MW and 3 MW, Areva Multibrid's 5 MW, and Bard's 5 MW, among others.

	Announcements of new WTGs (2010 onwards)
Nordex	• **N117/2400 DFAG**, with a 117 metre rotor diameter and a 91 metre hub height (series production started in 2012) • **6 MW PMSG direct drive** prototype for offshore (first installation in 2012 and series production set for 2014)
Sinovel	• **6 MW** WTG in production since the first half of 2011
Goldwind	• **6 MW PMSG direct drive** offshore turbine, in service since the end of June 2012
Alstom	• **3 MW ECO110 DFAG** WTG with a 110 m rotor diameter • **6 MW direct drive PMSG** offshore turbine (prototypes installed in 2011/2012, pre-series in 2013 and series production in 2014)

Table 1 – New WTG Designs

Expected Evolution of the Offshore Wind Market

Currently, the global wind energy market is almost entirely focused on onshore installations. However, it is estimated that the global offshore market will more than triple between 2010 and 2015, experiencing annual growth rates of over 30% and adding up to nearly 10% of total worldwide demand by 2015.

From 2015 to 2020, it is expected that growth will moderate significantly with a compounded annual growth rate of 10%, as indicated in the Figure 5 below:

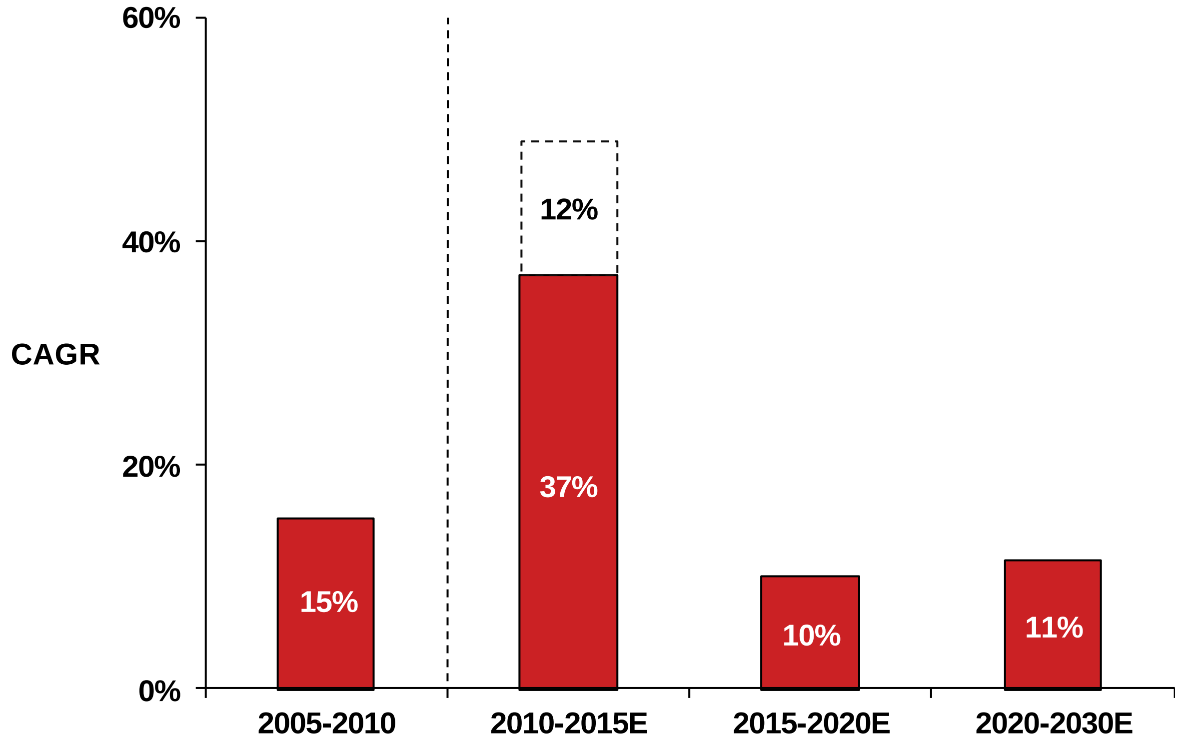


Figure 5 – Compounded Annual Growth Rates for Offshore Wind Installed Capacity [5]

For the near-term, it has been estimated that the offshore wind market would experience annual growth rates approaching 50% until 2015. However, the most recent figures show that this might have been too optimistic.

Given the current market outlook, annual growth rate until 2015 is estimated at no more than 40%.

In 2011, global offshore wind demand amounted to just under 1 GW, a similar level to that reached in the previous year. In 2012 it is expected that the market will reach at least 1.5 GW.[6]

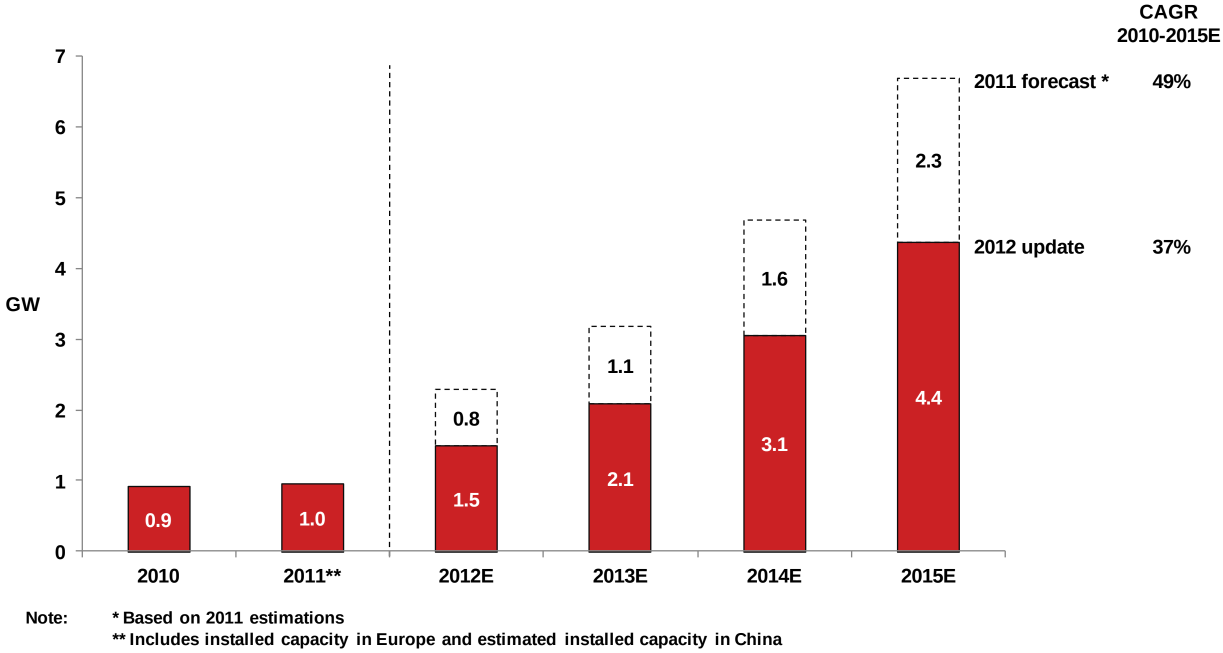


Figure 6 – Worldwide Offshore Annual Installations [6]

The offshore wind market development will be mostly driven by European markets in the forecast period. It is also expected that China´s share in overall demand will increase considerably from 4% in 2010 to 18% in 2015. Both China and South Korea are regarded as emerging markets.

[6] This forecast could prove conservative as that there are projects under construction with a cumulative capacity of over 5 GW. It all depends on when these WTGs will be installed and connected to the grid.

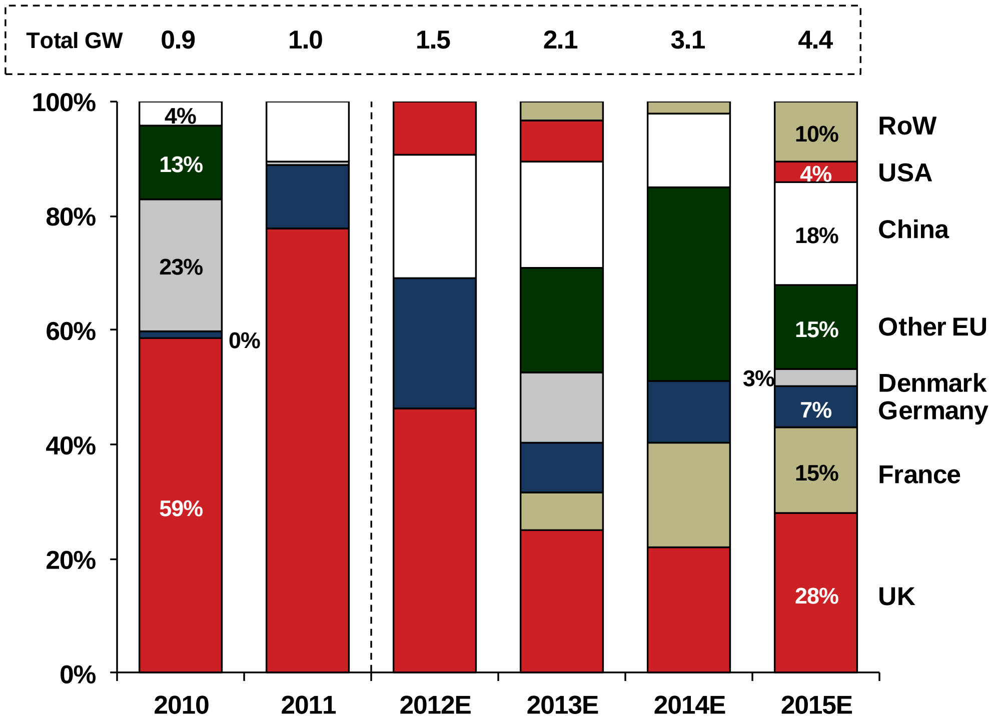


Figure 7 – Yearly Installed Capacity Forecast by Country[7]

Figure 7 indicates that in the short-term, the offshore sector will be mainly driven by the UK. This is because the great majority of projects in the pipeline over the next couple of years belong to this market. Currently, the UK represents over half of the worldwide installed offshore capacity with more than 2 GW installed. The UK also accommodates the largest offshore wind farm, a 300 MW project. Germany and France follow the UK in offshore installed capacity potential, and it is estimated that other European countries such as Sweden and the Netherlands will gain significant weight in 2013-2014.

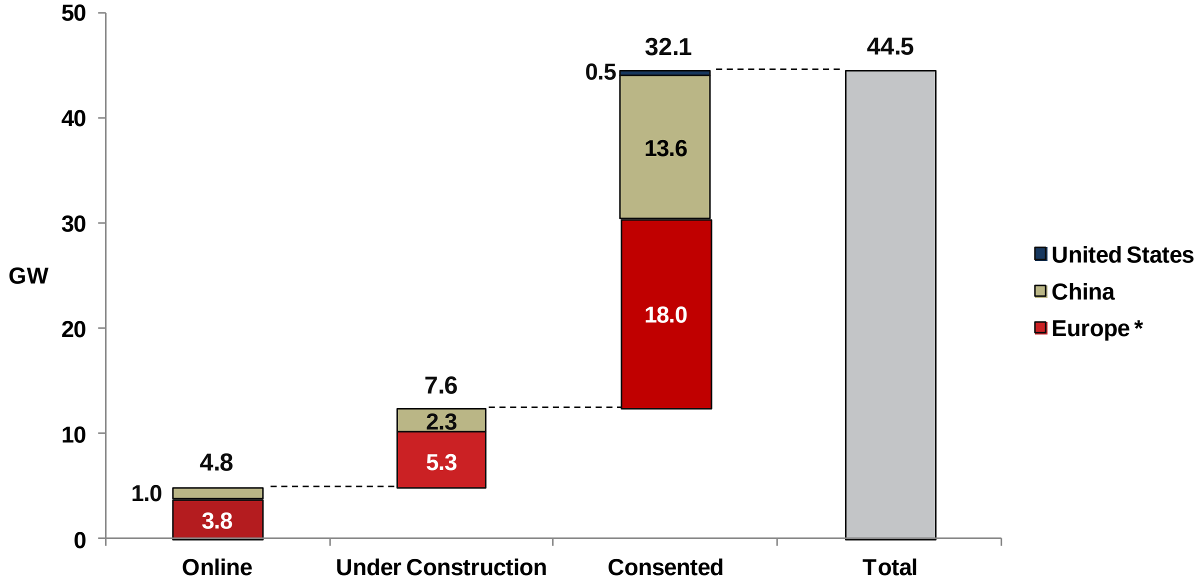
There are nearly 1,400 turbines installed and connected to the grid in Europe, the total sum of which is just over 3.8 GW of cumulative offshore wind capacity. Moreover, there are around 20 projects either under construction or whose preliminary work has been initiated. When all projects under construction or already approved are completed and connected to the grid, the offshore wind installed capacity could total more than 20 GW.

China's offshore wind potential is estimated at more than 750 GW[7]. Prior to 2010, it had only installed research and pilot offshore projects. Its first operational offshore WPP was installed in June 2010 and amounted to 102 MW (34 x 3 MW Sinovel WTGs). A public tender for a 1 GW offshore project was announced in October 2010.

The US trails Europe and China in this respect. As indicated in Figure 8, there are currently neither offshore WPPs online nor under construction. Projects with approved permits amount to 500 MW of overall capacity.

[7] China Meteorological Administration estimate.

2011[8]



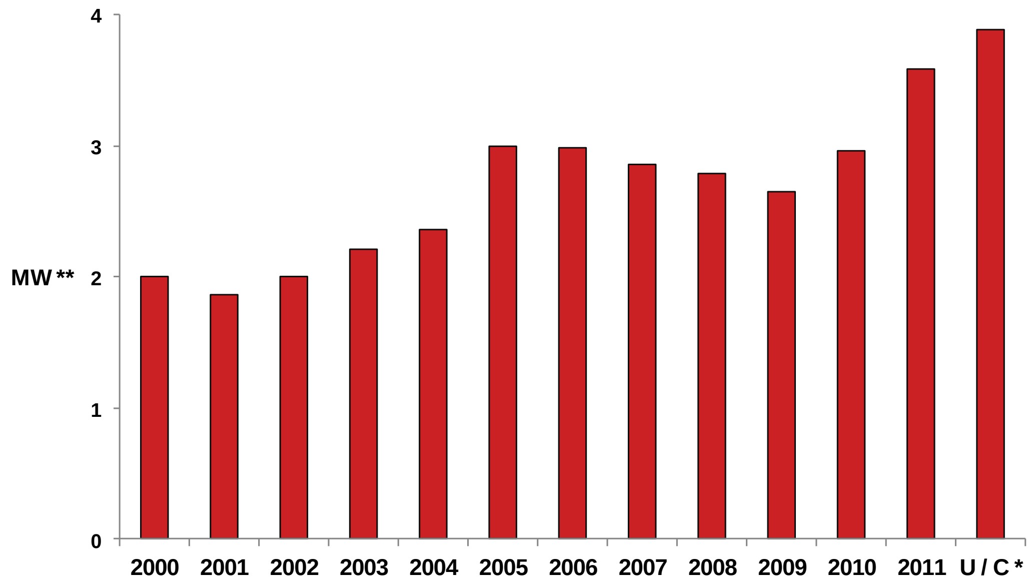
Note: * Belgium, Denmark, Finland, Germany, Ireland, Norway, Portugal, Sweden, the Netherlands, and the UK

Figure 8 – Offshore Wind Capacity: Projects Online, Under Construction, or Approved

However, there are still some obstacles to the development of offshore wind which need to be solved in order for the market to take off. Among them, are the needs to upgrade grid connections and build new transmission lines, as well as resolve financial and administrative bottlenecks.

Expected Evolution of Offshore Wind Turbine Capacity

The average size of offshore WTGs has been following an upward trend. The average nameplate capacity has increased from 2 MW in 2000 to more than 3.5 MW in 2011. The first WTGs with a rated capacity above 5 MW have been installed.



Note: ***Under construction offshore wind farm pipeline**

****Power based on installed and under construction WTG in Europe, exclusively**

Figure 9 – Average Annual Size of Offshore WTGs

Although 5 MW WTGs are being mass-produced, 3.6 MW[8] WTGs will continue to dominate the offshore market. Bigger turbines in the range of 5-6 MW that can offer a lower cost of energy because of their lower infrastructure cost, will also be used in offshore WPPs currently under construction. Consequently, the average size of offshore WTGs will soon approach 4 MW.

Market experts claim that the offshore market for very large WTGs is still immature. *'WTGs over 5 MW are not yet bankable. They are now being tested onshore to prove their feasibility. The offshore market will grow significantly five years from now,'* asserts the Head of Innovation of a renowned WTG manufacturer.

Some manufacturers, instead of launching larger capacity models, have lengthened the rotor diameter of their existing WTG models[9] in order to achieve a higher number of annual full-load hours.

However, average offshore WTG size will continue its slow rising trend. By 2015 it is expected that WTGs over 5 MW will have more than half of the overall offshore market. By 2020, a majority of all grid connected WTGs could have a nameplate capacity higher than 5 MW.

[8] Siemens´ model

[9] Rotor diameter of Siemens´ SWT-3.6 went from 107 to 120 metres and Areva´s M5000 from 116 to 135 metres.

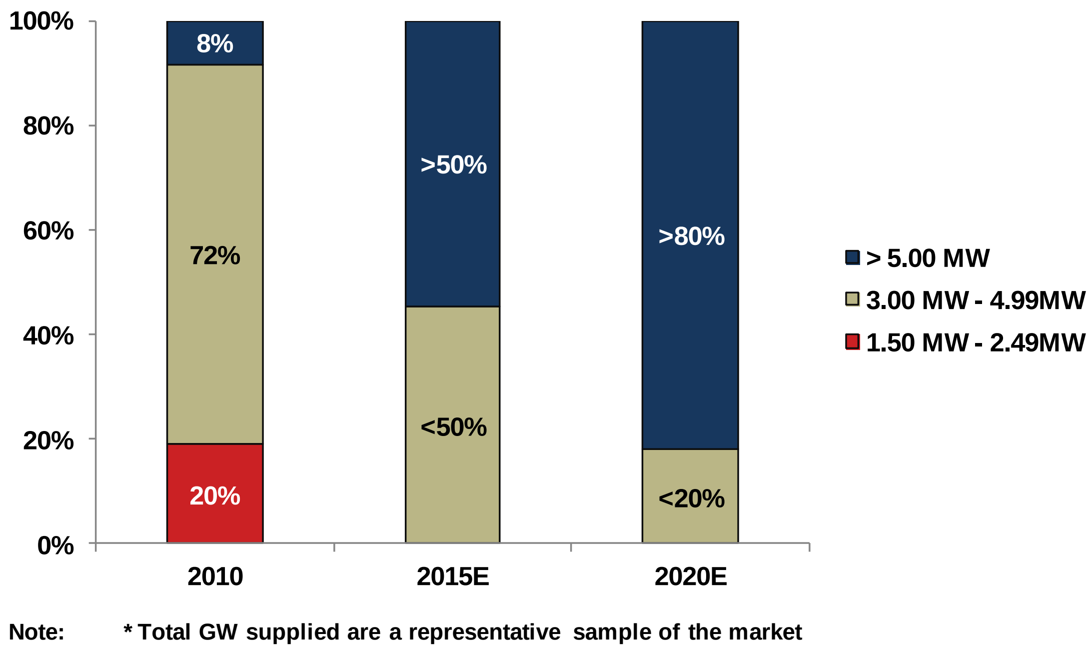


Figure 10 – Expected Share of WTG sizes in MW supplied[9]

At the moment, the largest commercial WTG for offshore projects is the REpower 6M 6.15 MW. Vestas is developing a 7 MW offshore turbine, whose serial production could begin in 2015. Moreover, a 10 MW offshore turbine is under development by OEMs[10] such as Clipper, SWAY, AMSC, and Sinovel. In the EU the Azimuth Offshore Wind Energy 2020 project is even planning a 15 MW offshore WTG.

Manufacturers from both inside and outside Europe have expressed an increased interest in launching offshore-dedicated WTG models. Over 50 new models were announced worldwide in the two year span between 2010 and 2011.

The trend towards larger turbines is apparent: the great majority of the new offshore WTG models (~70%) are larger than 5 MW. Almost half of these announcements are being made by WTG manufacturers based in Europe, followed by companies in China, USA, South Korea, and Japan.

[10] Original Equipment Manufacturers (OEMs) design WTGs and sell the turbines under their brand name

Comparative Wind Generator Analysis

Technical Analysis

This section provides a detailed description of WTG technologies[11]:

- First, a description of drivetrain types and their evolution over the years is presented. This is essential in order to identify the relative advantages and disadvantages of each technology and future market trends.
- Second, a definition of the different WTG technologies from an electrical standpoint is provided. Given that every country has a binding grid code, those technologies which do not comply with minimum standards will most likely not be able to develop in the future. The higher the RES penetration, the more stringent is the grid code. Thus, an analysis of WTG characteristics is critical in order to project the future evolution of each technology.

Introduction to Drivetrain Technology

Drivetrain gearboxes within a WTG increase the rotational speed of the shaft which feeds into the generator. WTGs which use direct drive generators produce electricity at lower revolutions per minute (rpm).

Input from the blades ranges between 15 and 25 rpm. Rpm after the gearbox range between 1,200 and 1,800. Such speeds are required by the rotor shaft.

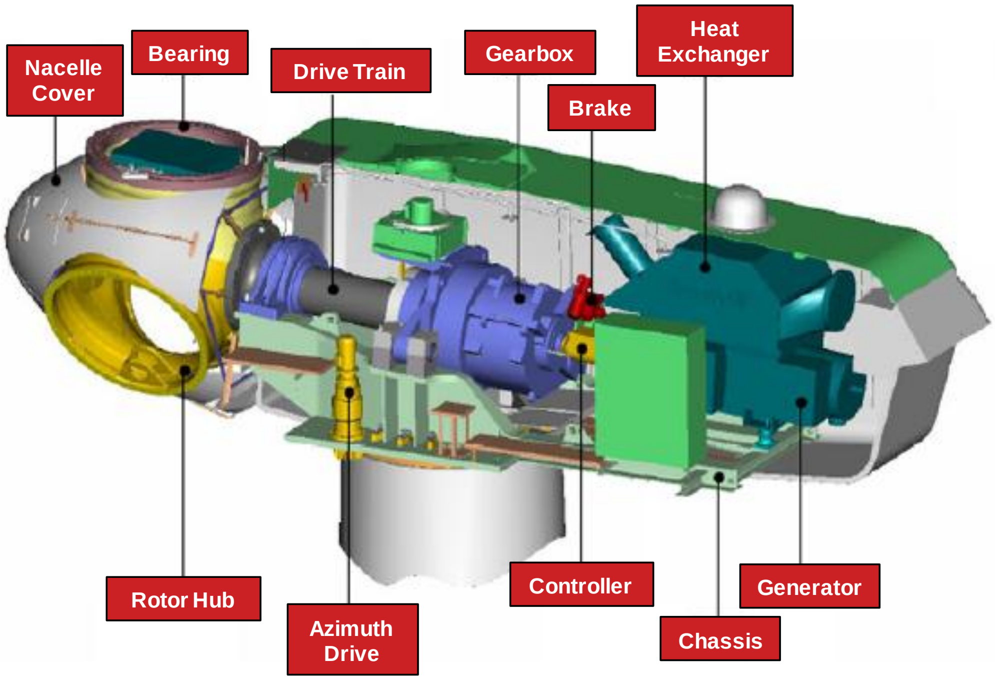


Figure 11 – Nacelle, Drivetrain, and Other Components[10]

[11] Namely CAG, CSG, DFAG, PMSG, and HTSG

Figure 11 shows the components of a WTG with conventional drivetrain (with gearbox). Other drivetrain types include direct drive (gearless) and hybrid (usually with a single-stage or 2-stage gearbox).

Synchronous generators (CSG, PMSG, and HTSG) are compatible with all three drivetrain types.

Fixed-speed CSGs were originally commercialized with a gearbox since this option was generally more economical than direct drive CSGs. In addition, the concept of a direct drive CSG with a full-scale power electronic converter has been developed and commercialized mainly by Enercon[12]. Full converter CSGs are similar to PMSGs but do not require the use of permanent magnets.

PMSG systems are commercialized without a gearbox, or with a single-stage or 2-stage gearbox. Some manufacturers such as Clipper, Multibrid, and Siemens produce hybrid WTGs.

CAG and DFAG always rely on a multi-stage gearbox for their asynchronous generators.

WTG technologies and their components will be explained in greater detail later in this paper (chapter 'Description of WTG Technologies').

The choice between drivetrain technologies is relevant because, among other factors, it defines the extent of efficiency losses.

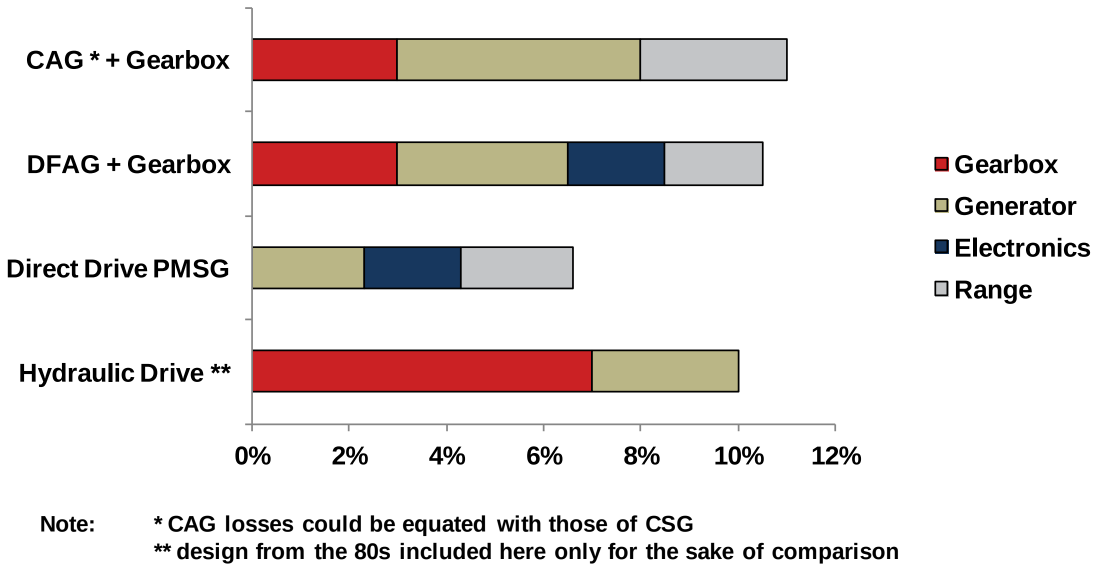


Figure 12 – WTG Efficiency Loss[11]

Figure 12 illustrates that gearbox losses represent a considerable portion (3% to 7% on average) of global efficiency losses. The fact that direct drive technologies are exempt from gearbox losses is a significant advantage of these machines over conventional WTGs.

For conventional WTGs, the average mechanical losses are as follows:

---

[12] Throughout this report, this WTG concept will be referred as 'full converter CSG.'

	Wind turbine losses (%)
Bearings	1.5
Gearbox	3-7
Other mechanical losses	0.9

Table 2 – Average WTG Mechanical Losses[12]

Direct Drive (Gearless)

Direct drive WTGs are synchronous generators that usually employ either PMSG or wound rotor technology. Also known as low-speed generators, this machines use a large diameter rotor to compensate for the lack of a gearbox. Enercon is the largest manufacturer of this type of turbine.

Direct drive machines with respect to conventional ones have the following advantages:

- The machine is full converter, making it more compliant with grid codes since it can easily withstand voltage sags and can control active and reactive power, as well as frequency
- Lower level of harmonics and flicker
- No need to incur in costs related to the gear such as maintenance, repair, or waste oil treatment. Lower maintenance costs are a significant competitive advantage[13] particularly for offshore WPPs
- Furthermore, the mechanical system of a direct drive WTG is simple and its efficiency is higher than that of a conventional system since it eliminates mechanical losses. Gearbox mechanical losses are estimated at an average of 5% for conventional WTGs.

Direct drive machines with respect to conventional ones have the following disadvantages:

- As
- Table *3* indicates, a direct drive WTG generally weighs more than its conventional counterpart. It also has larger dimensions, making transportation more expensive

	Enercon E-112	Vestas V120
Power (MW)	4.5	4.5
Nacelle + Rotor Weight (Tons)	440	214
Drivetrain	Direct drive	3-stage gearbox
Technology	PMSG	DFAG

Table 3 – Comparison of Enercon´s Direct Drive and Vestas' Conventional WTG [13]

- Its weight is more poorly distributed, since it is split between the rotor winding and multiple poles. This can generate mechanical stress
- Although WTG manufacturers such as Enercon and MTorres have always developed direct drive machines, in general, the technology is not particularly mature[14]

[13] See Section 4.2 for an economic analysis.

- Siemens launched prototypes relatively recently (2008) and currently sells and installs both direct drive wind turbines and WTGs with a gearbox. In 2011, Siemens launched SWT-2.3-113, a new WTG model for low to moderate wind speed regimes with direct drive PMSG. The company is now developing a similar design but with a 6 MW output.
- Other major WTG manufacturers are still launching new geared WTGs. This is the case with Vestas, whose most recent addition is a conventional machine.

Conventional Drivetrain (with Gearbox)

As previously explained, the rationale behind WTGs with gearbox is to adapt the rotation speed of the blades to the speed of the rotor in the generator. Usually, this design comes hand in hand with asynchronous generators[15] and is currently the model most widely used.

Conventional machines with respect to direct drive ones have the following advantages:

- It is a very mature technology
- The nacelle is more compact and lightweight and weight distribution is better. Easier transportation can be a decisive factor in some areas with limited access

Conventional machines with respect to direct drive ones have the following disadvantages:

- Conventional drivetrain configurations have a higher number of mechanical components
    - These lead to higher mechanical losses
    - For powers above 1 MW, failures in high-speed mechanical components (especially the gearbox) could prove problematic
- In some cases, WTGs may need reactive power compensation devices
- Higher (and regular) maintenance costs
- Higher level of harmonics and flicker

Hybrid Drivetrain

In the search for a solution that lies between conventional and direct drive drivetrain, the following characteristics are sought:

- Compact drivetrain
- Simple, reliable gearbox with less stages than conventional ones
- Lighter nacelle than that of direct drive WTG, which means cheaper foundation costs

Hybrid turbines can be combined with PMSG and can have a gearbox with less than three stages and a generator with two or four poles.

Clipper, for example, introduced a PMSG with a single-stage gearbox. They are currently working on a 10 MW machine for the *Brittannia Project*, an offshore project currently under development. It is expected that larger offshore turbines will enable lower operating and maintenance costs, as well as lower installation and foundation costs per electric power generating unit.

---

[14] Except for Enercon´s 1992 gearless machines

[15] Geared synchronous generators are a less attractive alternative because of their technical characteristics

There are industry experts who maintain that Siemens WTGs are hybrids because the number of stages in the gearbox has been considerably reduced, to decrease the number of components and, consequently, reduce maintenance costs too.

Hybrid machines have the following advantages with respect to direct drive and conventional ones:

- Combined advantages of both conventional and direct drive
- Simpler logistics

Hybrid machines with respect to direct drive or conventional ones have the following disadvantages:

- Technology is still immature
- Currently more expensive

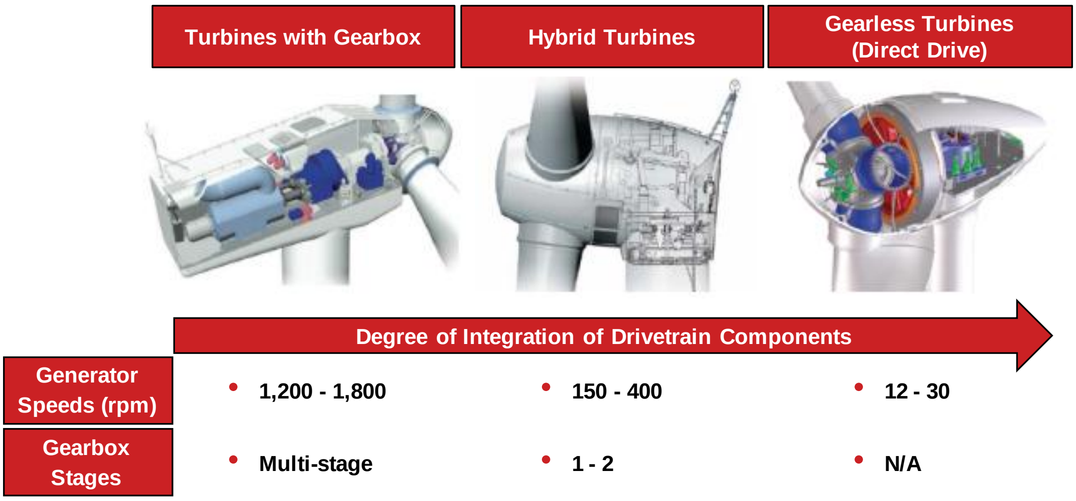


Figure 13 – Drivetrain Types and Components[14]

Figure 13 illustrates that the lower the number of stages in the gearbox, the lower the rotor speeds. Fewer high-speed resistant materials are needed for lower speeds and there are lower maintenance costs.

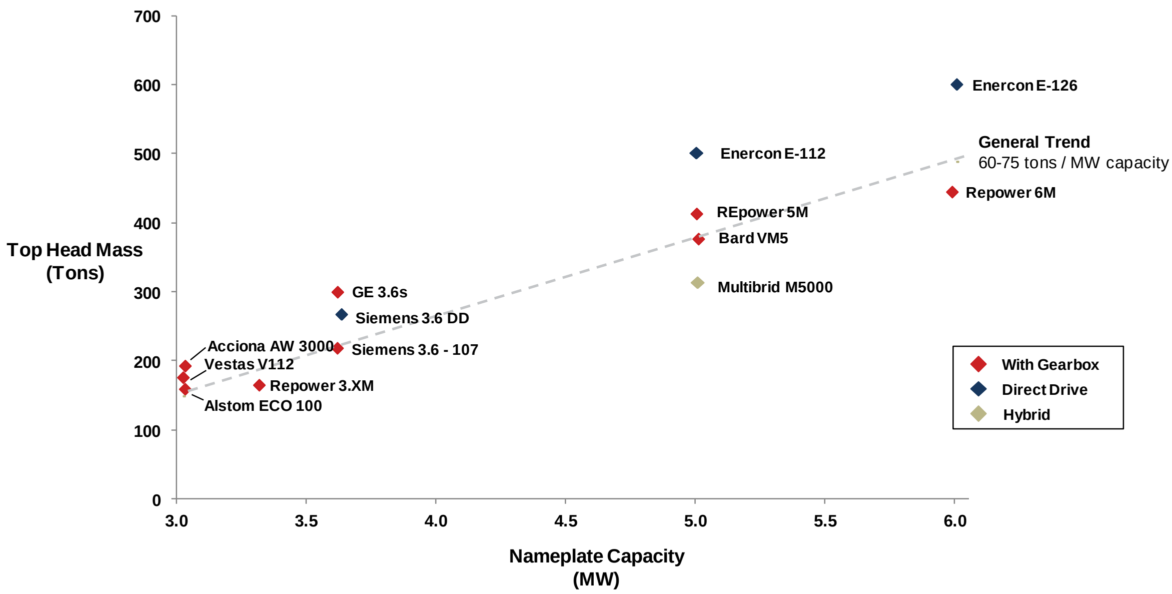


Figure 14 – Turbine Top Head Mass vs. Turbine Size[15]

Figure 14 shows the relation between turbine size and nacelle weight. The general trend displays a relation of 60 to 75 tons per MW. However, relevant differences between drivetrain technologies exist, which are highlighted as follows:

- High-power direct drive machines are generally heavier than conventional ones
- Hybrid turbines optimize weight

Wind Turbine Evolution

Control and Drivetrain

The evolution of WTG technologies in terms of control and drivetrain is illustrated in the following table:

Technology Spectrum	Old Days	1980´s	1990´s	2000´s	Present Days
• **Fixed speed / Stall regulated / Gearbox**	✓				
• **Fixed speed / Active stall / Gearbox**		✓			
• **Limited variable speed / Gearbox**		✓	✓	✓	
• **Pitch regulated / Variable speed / Gearbox**			✓	✓	✓
• **Pitch regulated / Variable speed / Direct drive**			✓ *	✓	✓

Note: *** Mainly Enercon´s WTG**

Table 4 – WTG Technology Trend [16]

The previous table reveals the following facts:

- WTG technology could be evolving towards direct drive
- Technologies that allow for fixed speed regimes are disappearing (or limited to small WTG [16])
- The stall control system has been discarded in favour of pitch control

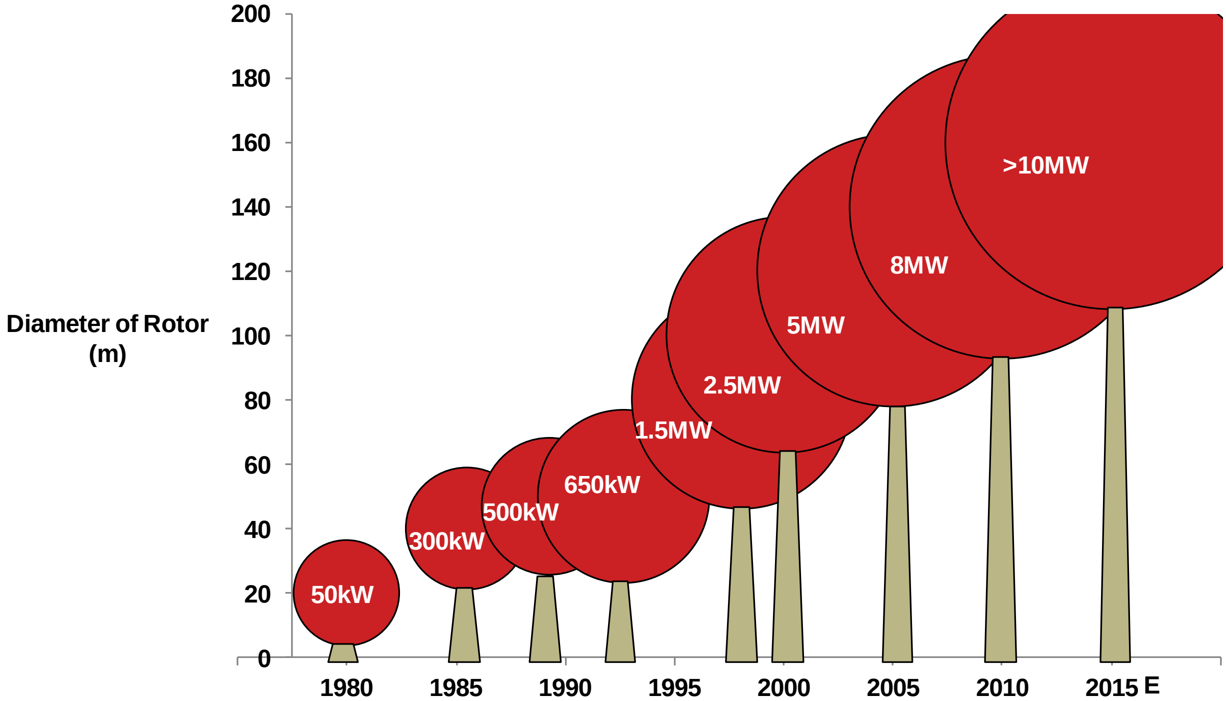
Although wind technology is evolving towards direct drive, major WTG manufacturers have chosen not to do away with gearboxes entirely. For example, Vestas decided to keep the geared drive system in their new 7 MW turbine, for the following reasons:

- Direct drive is not fully proven while geared ones are a proven technology
- Geared drive WTGs offer a lower cost of energy in many locations

Siemens on the other hand, recently decided to launch a new 2.3 MW hybrid turbine. They justified the choice of a hybrid drive by stating that it would enable high efficiency and reduced maintenance costs.

[16] As previously remarked, the present report relates only to multi-megawatt Wind Power Plants

WTG Size Evolution



Drivetrain	CAG	DFAG	DFAG	DFAG	PMSG	PMSG	HTSG
Tower Height	60 m	70 m	75 m	80 m	100 m	120 m	140 m
Torque (k ft/lb) *	19	124	218	754	353	2,932	5,118
Top Weight (metric tons)	50	100	-	200	-	400	450

Note: * Torque measures the degree that a force acting on an object causes it to rotate

Figure 15 – Size and Power Evolution of Wind Turbines[17]

Figure 15 illustrates the extent to which turbine size (in terms of rated power and hub height[17]) has increased over time and is expected to continue to increase until 2015. As the table beneath the graph shows, permanent magnet technologies allow for a considerable power increase with a relatively lower increase in rotor diameter.

In order to get more power, the area swept by the turbine blades must be greater. However, the length of the blade is limited by the following variables:

- Blades have upper limits to the wind speed they can handle; if the wind speed is too high, they can disintegrate due to the excess kinetic energy at the tip of the blade.
- For mono-block wind turbines, blade length is limited by transportation requirements

As the following figure shows, blade length has stagnated around 130 metres since 2005:

[17] Currently, the highest WTG turns at a height of 160 metres on top of a lattice tower in Eastern Germany

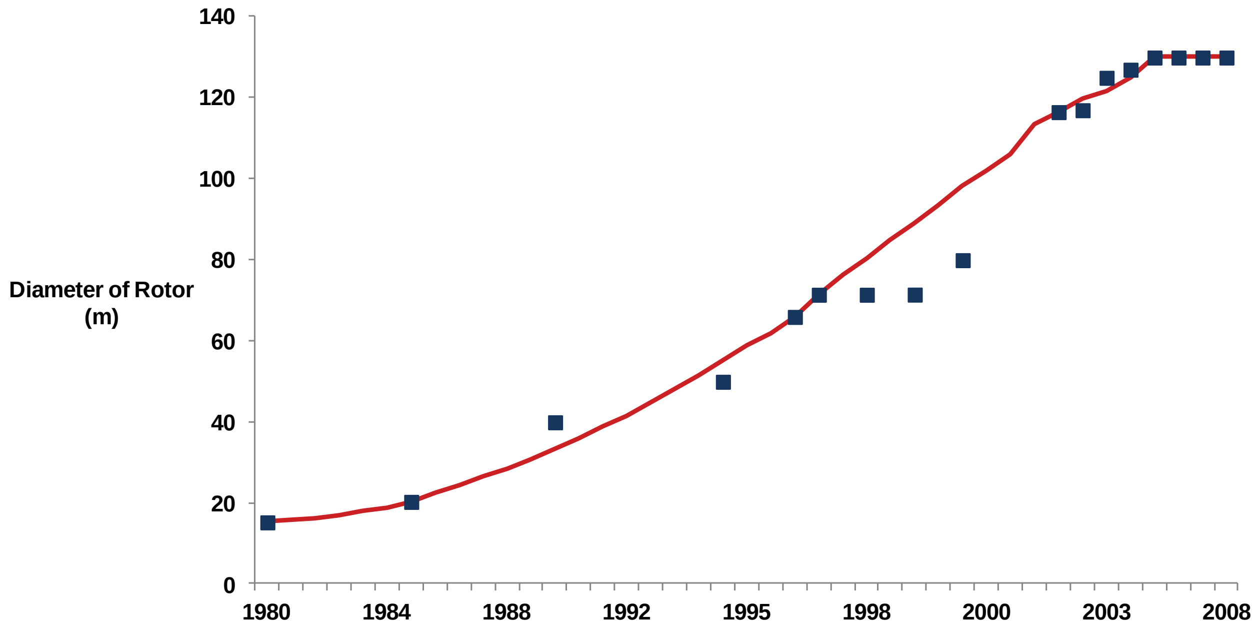


Figure 16 – Turbine Diameter Growth with Time[18]

Description of WTG Technologies

Basic configurations of WTG technologies, which are schematically segmented in *Figure 17*, are explained in detail in this section. The description will be made according to the sequence given in the following graph, in which technologies are classified by drivetrain components and rotation speed.

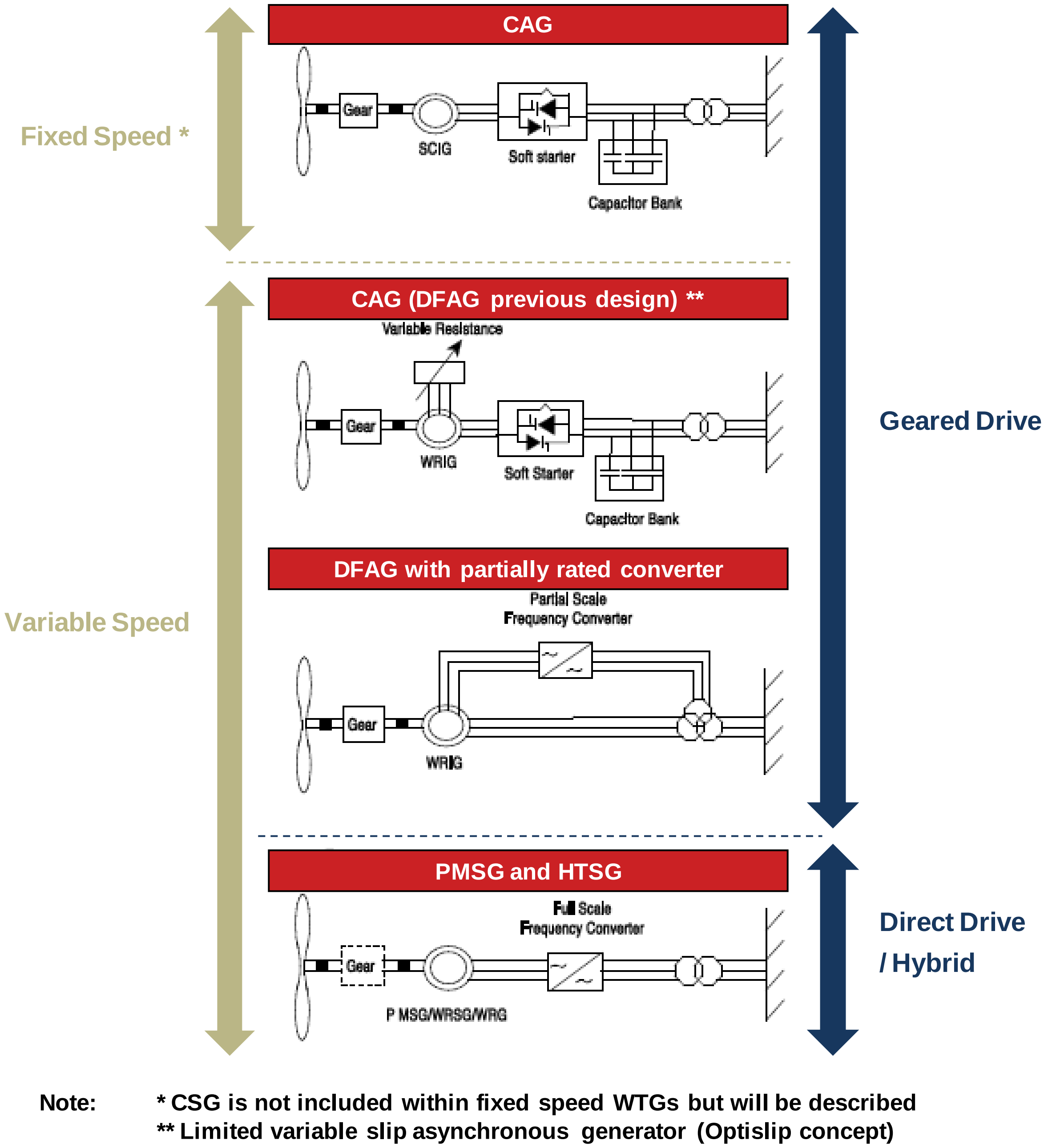


Figure 17 – Summary WTG Drivetrain and Rotation Speed [19]

We will first explain fixed speed wind technologies, including Conventional Asynchronous Generators (CAGs) and Conventional Synchronous Generators (CSGs). Following that, we will describe variable speed wind technologies, including the Double-Feed Asynchronous Generator (DFAG), the Permanent Magnet Synchronous Generator (PMSG), and High Temperature Synchronous Generator (HTSG).

Constant wind speed regime generators CAG and CSG are currently obsolete technologies for powers over 100 kW. Our main focus will therefore be on analysing DFAG, PMSG, and HTSG and their different types of drivetrain.

Other types of WTGs are sometimes mentioned in the literature. These include the limited variable speed concept with a multi-stage gearbox (OptiSlip™ is a registered trademark of Vestas Wind Systems A/S) and are not included in our classification since we only intend to provide an indicative orientation of WTG technologies.

There is more power capacity installed employing DFAG than of any other technology. It was in fact the DFAG technology that facilitated wind sector expansion. The world's largest manufacturers are, in order of installed capacity, Vestas (Denmark), Sinovel (China), GE Wind (US), Goldwind (China), and Enercon (Germany).

Figure 18 shows the evolution of newly installed capacity by WTG technology up to 2010 and the capacity that is expected to be installed annually per technology from 2011 to 2015. It is worth highlighting the expected increase of PMSG installations at the expense of DFAG.

HTSG machines are not expected to be installed before 2015.

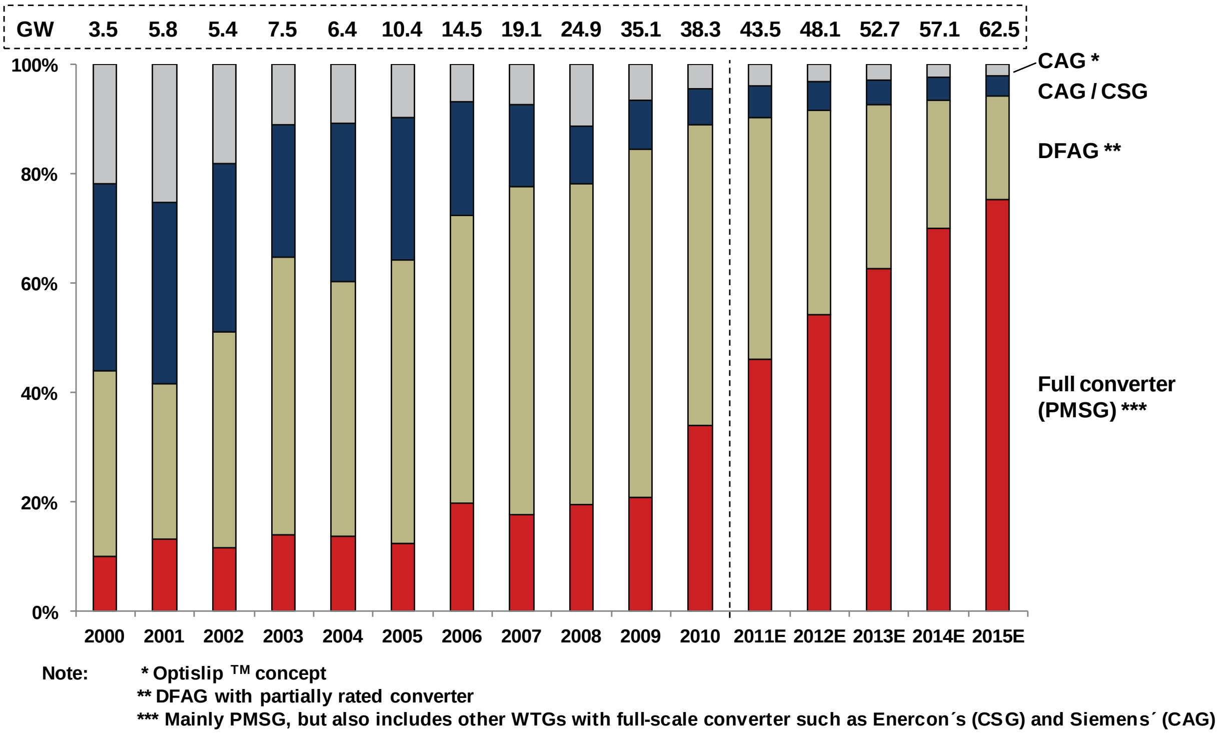


Figure 18 – Yearly Installed Capacity per Technology[20]

Grid codes will have to become more stringent and mandatory in order to further increase wind power capacity in countries that already have a high RES penetration. This speaks in favour of WTGs with a full converter (PMSG).

Because of the current financial crisis however, the expected growth of PMSG in the near future as shown in Figure 18 could be over-estimated. The crisis could hamper the development of new designs and force WTG manufacturers to opt for proven models with a low investement cost.

In the longer term, however, the evolution towards full converter WTGs will continue, since this is the only technology that enables a smooth integration of WTGs into a grid system with a high penetration of renewables.

Constant-Speed Wind Turbines

In contrast with the design of variable-speed wind turbines, the design of constant-speed turbines limits the rotor power that can be captured from the wind. In constant (or fixed) speed wind turbines, the angular velocity of the generator is constant and determined by grid frequency, regardless of wind speed.

To achieve the maximum potential energy yield, rotor speed must reflect wind speed. Wind turbines with a constant rotor speed only achieve this maximum power efficiency at one particular wind speed, namely the one for which it was designed.

Wind speed variations generate flicker on the grid. In order to avoid generating electrical fluctuations and optimize the energy yield, the blade position is adapted with increasing speed (they are turned to the side). Apart from that, wind speed peaks are also absorbed by the mechanical parts, causing mechanical stress. [18]

There are two types of technologies that work in this way:

- Conventional Asynchronous/Induction Generator (CAG/CIG), also known as Squirrel-Cage Induction Generator
- Conventional Synchronous Generator (CSG), also known as Wound-Rotor Synchronous Generator

These turbines are currently being used for small WPPs.

In contrast, variable-speed wind turbines (explained in detail in the next section) can achieve optimum rotor power at every wind speed.

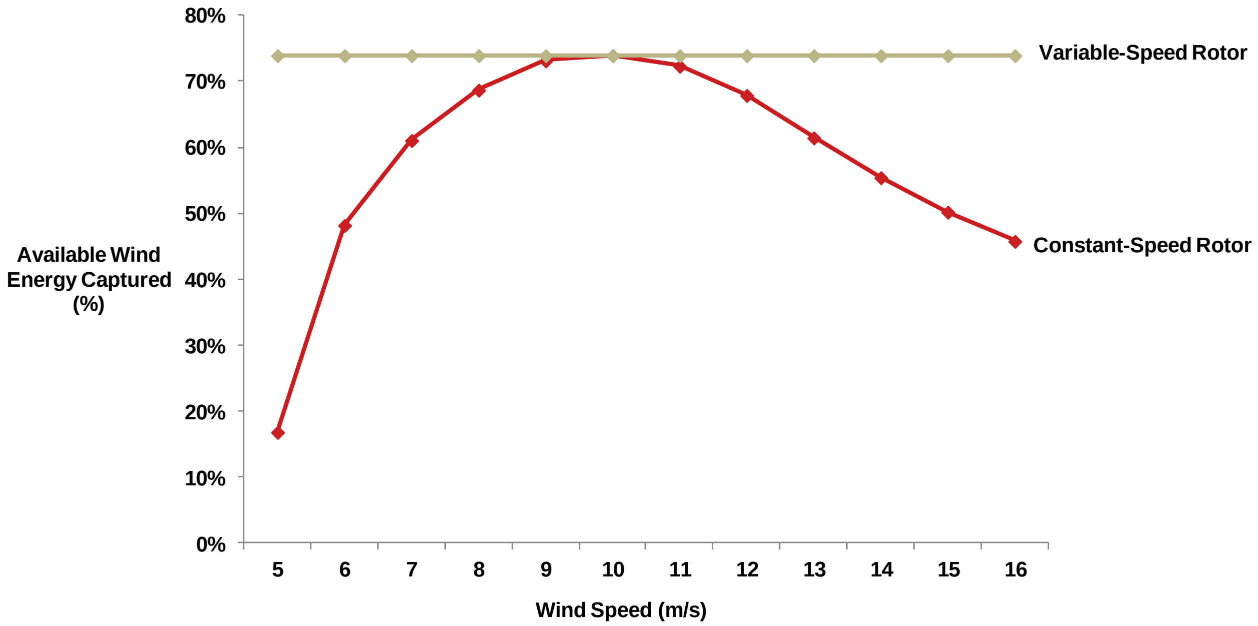


Figure 19 – Available Wind Energy Captured[21]

Figure 19 demonstrates that constant-speed rotors can extract the maximum percentage of available wind power only at a specific wind speed. In contrast, variable-speed rotors can capture the optimum percentage of available wind energy at every wind speed.

CAG (Conventional Asynchronous Generator)

The CAG was the most widely used constant-speed technology until it evolved into the DFAG.

[18] This characteristic is more relevant for CSG than for CAG, which buffers the impact better than the former.

With respect to other turbine technologies, CAGs have the following advantages:

- Relatively simple design and construction
- Lower manufacturing and maintenance costs

On the other hand, CAGs have the following disadvantages:

- Low efficiency
- Consumes reactive power during operation. Capacitor banks should be installed to avoid penalization by the grid operator.
- Consumes a significant amount of reactive power during start. A soft-start is required to compensate for this.
- Wind regime variations cause electrical disturbances (usually flicker) in the network.
- Current WTGs do not meet the grid codes established by Power System Operators (PSOs)[19] in many countries. Installation is allowed if – and only if – additional devices such as FACTS are added, making the Wind Power Plant less economically viable.

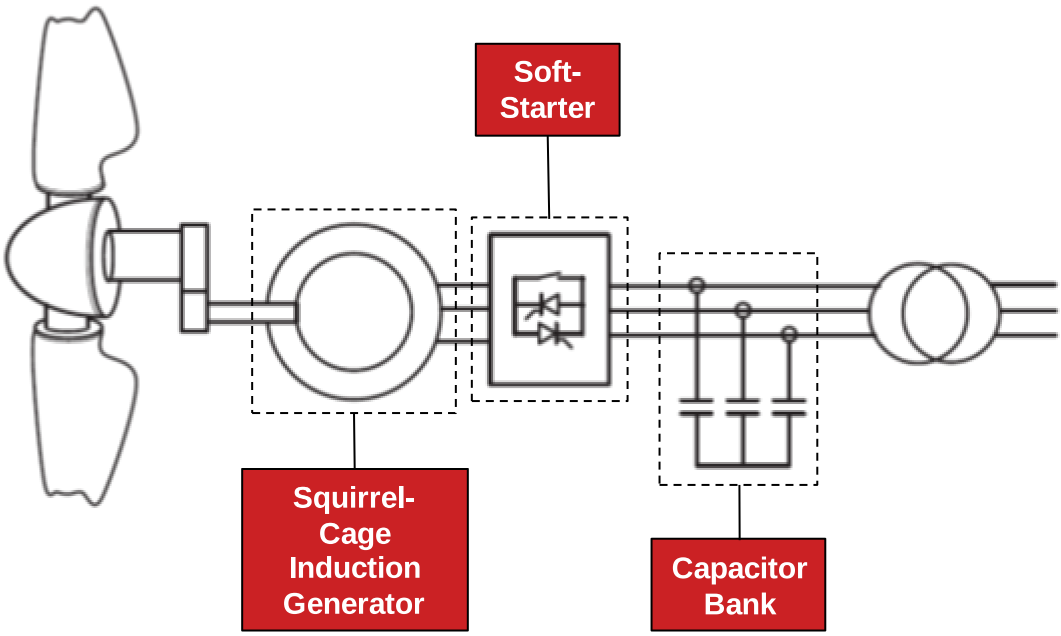


Figure 20 – Conventional Asynchronous Generator

The figure above illustrates the standard topology of a CAG, with a capacitor bank in parallel for reactive power compensation and a soft-starter to achieve a smoother connection to the electricity grid.

Rated Power CAG	3 MW
Variable Speed	No
Gearbox	Yes

[19] The PSOs´ main role is to keep the power system in a secure and appropriate state of operation.

Slip Rings	No
Reactive Power Control (%)	No
Reactive Power Consumption	Yes, compensated by capacitor bank or FACTS
Energy Quality: Compliance with Current Standards	No
Power Quality: Compliance with Grid Codes	No
% of auto consumption [20]	< 5%
% of generated power that goes through power electronics	N/A
Power Losses: Copper, Iron, and Converter (% of generated power)	6%
Gearbox Losses (% of generated power)	3%
Total Losses (% of generated power)	9%
Energy Yield (MWh)	7,760
Cost (k€)	1,837
Annual Energy Yield/Total Cost (kWh/Euro)	4.22
Components with Highest Maintenance Cost	Gearbox

Table 5 – CAG Technical Overview

Technical data in *Table 5* have been extrapolated from small-size WTG to a 3 MW installation to make the data comparable with the other technologies. A 3 MW CAG is not presently available on the market.

CSG (Conventional Synchronous Generator)

CSGs are directly connected to the grid and the angular speed is fixed by grid frequency.

CSGs have the following advantages with respect to other turbine technologies:

- Reactive power consumption can be controlled to a certain extent
- Depending on the design and the number of poles, direct coupling between the hub and the generator shaft could be achieved, thereby eliminating the gearbox

However, CSGs have the following disadvantages:

- Small wind speed variations generate transients
    - Quality of generated power can be very poor

[20] <5% of generated power is auto-consumed, instead of extracted from the grid, in order to feed WTG components.

- WTG components experience mechanical stress
  - These turbines do not meet the grid codes established by PSOs in many countries
- The exciter is fed through slip rings. These must be replaced from time to time, increasing maintenance costs.

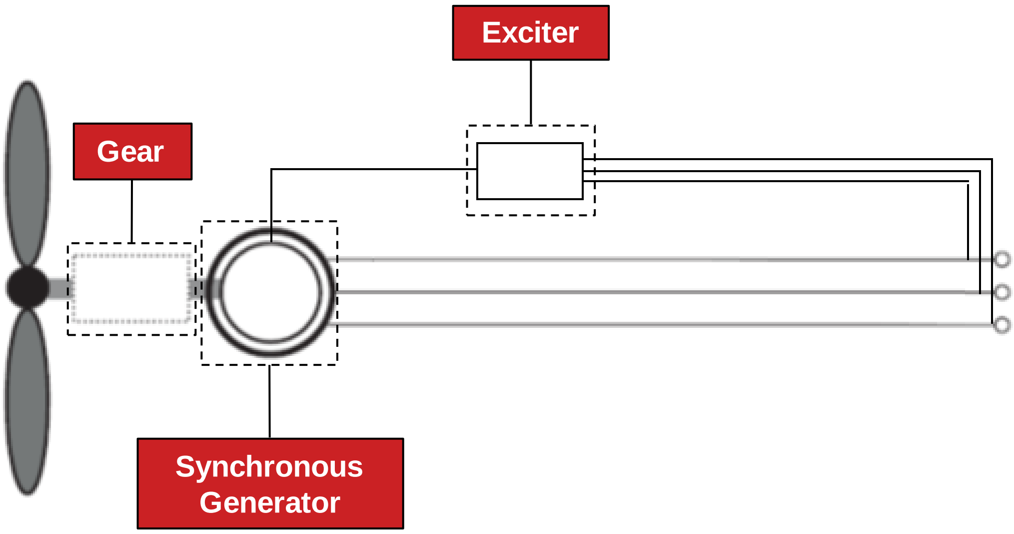


Figure 21 – Conventional Synchronous Generator

The stator winding is directly connected to the grid and the rotation speed is set by grid frequency. In the rotor, the poles are fed with direct current, which is varied to match grid frequency.

Rated Power CSG	3 MW
Variable Speed	No
Gearbox	Yes
Slip Rings	Yes
Reactive Power Control (%)	20%
Reactive Power Consumption	No
Energy Quality: Compliance with Current Standards	No
Power Quality: Compliance with Grid Codes	No
% of auto consumption [21]	< 5%
% of generated power that goes through power electronics	N/A
Power Losses: Copper, Iron and Converter (% of generated	7%

[21] < 5% of generated power is auto consumed, instead of extracted from the grid, in order to feed WTG components.

power)	
Gearbox Losses (% of generated power)	3%
Total Losses (% of generated power)	10%
Energy Yield (MWh)	7,700
Cost (k€)	1,883
Annual Energy Yield / Total Cost (kWh/Euro)	4.09
Components with Highest Maintenance Cost	Gearbox (if present), slip rings

Table 6 – CSG Technical Overview

As with the case for CAG, technical data have been extrapolated from a small wind turbine data to reflect that of 3MW turbine, a turbine size which doesn´t currently exist for this technology.

Variable-Speed Wind Turbines

This technology was developed jointly with power electronics, which enables blade rotation frequency and grid frequency to be different at all times. Add to this the fact that it allows turbines to operate at peak rotor power at every wind speed (proper tip speed ratio), thus maximizing rotor efficiency.[22]

Flicker problems caused by wind speed variations can be minimized with this technology.

DFAG (Doubly-Fed Asynchronous Generator)

Unlike in the CAG system, the DFAG rotor winding is not shorted. The rotor is electrically accessible and, apart from being used to magnetize the poles, it may also be used to extract power and to control the rotation speed.

A DFAG is connected to the grid through a bidirectional electronic power converter, converting between 30% and 40% of rated power. This results in economic savings.

However, the DFAG system has some disadvantages; principally, its configuration always includes a gearbox in the drivetrain and a slip ring, both of which require constant maintenance.

A crowbar is used for protection.

[22] This quality was illustrated in *Figure 19*.

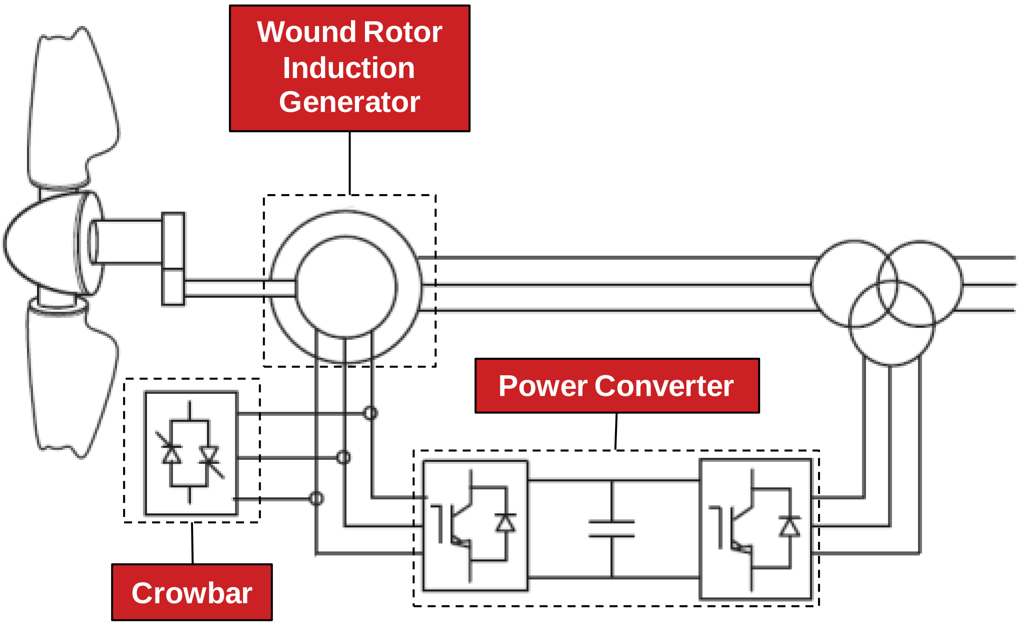


Figure 22 – Doubly-Fed Asynchronous Generator

Rated Power DFAG	3 MW
Variable Speed	Yes
Gearbox	Yes
Slip Rings	Yes
Reactive Power Control (%)	60%
Reactive Power Consumption	Yes
Energy Quality: Compliance with Current Standards	Yes
Power Quality: Compliance with Grid Codes	It depends on the country and its wind energy penetration.[23]
% of auto consumption [24]	N/A
% of generated power that goes through power electronics	40%
Power Losses: Copper, Iron, and Converter (% of generated power)	3%

[23] In emerging markets with low wind energy penetration, grid codes are not as strict as in countries with high RES penetration such as Germany and Spain

[24] There is no auto consumption of power to feed WTG components

Gearbox Losses (% of generated power)	7%
Total Losses (% of generated power)	10%
Energy Yield (MWh)	7,690
Cost (k€)	1,870
Annual Energy Yield/Total Cost (kWh/Euro)	4.11
Components with Highest Maintenance Cost	Gearbox, slip rings, encoder

Table 7 – DFAG Technical Overview

PMSG (Permanent Magnet Synchronous Generator)

In PMSG the generator rotor is not connected with the grid. The rotor contains powerful magnets that generate the electromagnetic field without an electric current.

This technology requires that all the generated power passes through a full converter before it is transmitted to the grid.

Using a full converter has the following advantages associated to power electronics:

- The WTG can operate in wide wind ranges, since the rotation speed of the blades is decoupled from grid frequency
- No reactive power is consumed to start or excite the rotor
- It complies with grid code requirements
- It can operate both as direct drive and as geared drive
- It can operate as reactive power compensator even when the blades are still. This is highly valued by PSOs as it contributes to a stabilization of the electrical system
- The use of slip rings – and related maintenance costs – is avoided

These attributes are increasingly becoming an obligation for new WPPs as wind energy penetration increases and TSOs[25] face greater challenges integrating renewable energy while maintaining security of supply. The ability to control the quality of generated power is even deducted from the electricity tariffs.

- Permanent magnet prices are going down and the technology is becoming more efficient. A PMSG can be smaller and lighter compared to a DFAG of equal power.
- WTG manufacturers such as Multibrid (M5000-135), GE Energy (4.1-113), Vestas (V164-7.0 MW), and Gamesa (G128-4, 5 MW) design PMSG. These turbines have higher power than any other turbine in their product offering

A drawback of this technology is that alloys of rare earth elements[26] are sometimes used to produce the permanent magnet. One example is high-strength neodymium, a mineral whose supply is controlled by a select group of exporting countries (mainly China) and whose extraction process is regarded as a highly polluting practice.

---

[25] TSOs main focus is the transportation of energy

[26] Elements listed in the rare-earth section of the periodic table

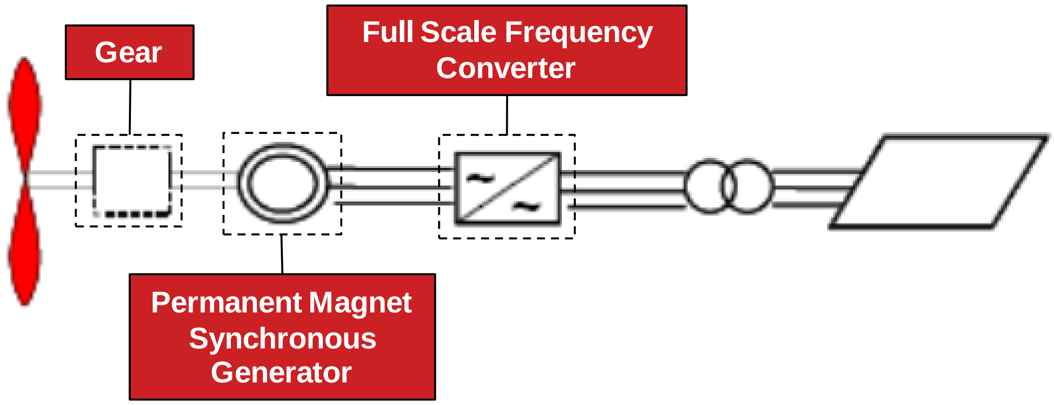


Figure 23 – Permanent Magnet Synchronous Generator

Figure 23 depicts the scheme of a geared PMSG system, with a three-phase cable connection made through power electronics that transforms the AC produced by the generator to a DC bus and from there to the grid.

As opposed to direct drive PMSG, other types of gearless WTGs exist that do not require the use of permanent magnets. Enercon, the main manufacturer of these direct drive WTGs, produces a direct drive WTG with the same design as a PMSG but employing a full converter synchronous generator with a rotor consisting of electrical windings instead of a permanent magnet. This type of direct drive WTG can be categorized as a full converter CSG, in which voltage is completely controlled by power electronics.

Rated Power PMSG	3 MW
Variable Speed	Yes
Gearbox	No[27]
Slip Rings	No
Reactive Power Control (%)	Full 100%
Reactive Power Consumption	No
Energy Quality: Compliance with Current Standards	Yes
Power Quality: Compliance with Grid Codes	Yes
% of auto consumption [28]	N/A
% of generated power that goes through power electronics	100%
Power Losses: Copper, Iron, and Converter (% of generated power)	8%

[27] In addition, there are also hybrid and geared versions, with a single-stage gearbox (Multibrid concept) or a multiple-stage gearbox (GE multi-megawatt series), such as the one illustrated in Figure 23

[28] There is no auto consumption of power to feed WTG components

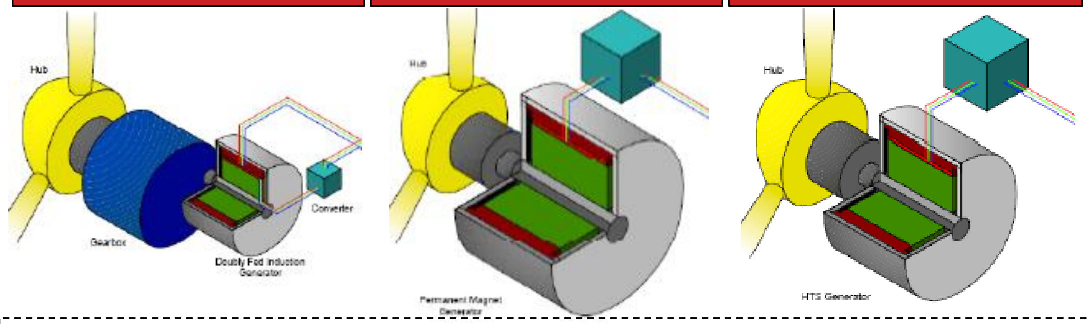
Gearbox Losses (% of generated power)	N/A
Total Losses (% of generated power)	8%
Energy Yield (MWh)	7,890
Cost (k€)	1,982
Annual Energy Yield/Total Cost (kWh/Euro)	3.98
Components with Highest Maintenance Cost	Encoder

Table 8 – PMSG Technical Overview

HTSG (High Temperature Superconductor)

HTSGs use high-temperature superconducting wire and ceramics and are currently being developed in order to solve one of the main drawbacks present in other technologies, e.g. heavy weight. American Superconductor (AMSC) is planning to launch a 10-MW direct drive turbine with HTS in the rotor winding instead of copper wire.

The following comparative table[29] summarizes the benefits and drawbacks of HTSG as opposed to DFAG and PMSG and shows the relative cost of energy of these generators, a cost which is 20% lower for HTSG than for DFAG.



	DFAG	PMSG (Direct drive or geared)	HTSG (Direct Drive)
History	~ 1990	~ 2005	~ 2020
Power	1.5 to 3 MW	2 to 4 MW	5 to 10 MW
Benefits	• Low cost • Mature technology	• Good power quality • Possibility of no gear	• Great power quality • Efficient at all loads • Small, light, no gear
Drawbacks	• Poor power quality • Gear failures	• Large / Heavy (difficult to transport)	• In development
Cost of Energy *	1.0	0.9	0.8

Note: * relative; onshore about 5¢/kWh, offshore about 10¢/kWh

Table 9 – Drivetrain Evolution [22]

[29] Note that hybrid drivetrain systems are not included

HTSG advantages over other technologies are as follows:

- Superconductors can carry 100 times more power than conventional wires, without electrical resistance or loosing heat. Materials with semiconducting properties are cooled at very low temperatures until electrons move nearly freely through the material. In order to achieve this effect, the coils are placed in vacuum containers which are constantly cooled by special gases (similar effect to that used in heat pumps).
- This turbine can extract more wind energy than other types of machines with the same nominal efficiency
- They are smaller and lighter than conventional WTGs. Size can be reduced to half that of a conventional turbine with the same nominal power and weight can be reduced to one third.
- No other machine reaches >10 MW. Their low weight per MW makes them particularly suitable for off-shore applications
- This design is associated with direct drive and full converter

HTSG disadvantages over other technologies are the following:

- Technology still in development phase. Superconducting direct drive technology still has to prove that it has superior reliability compared to more established technologies.
- The cooling process could become problematic
- HTSGs are not expected to reach commercial development before 2014-2016 and validation of designs will still then be needed, a process which could take a further two or more years, taking us to 2016 as the earliest date by which HTSGs may feasibly reach the market

Rated Power HTSG	3 MW
Variable Speed	Yes
Gearbox	No
Slip Rings	No
Reactive Power Control (%)	Full 100%
Reactive Power Consumption	No
Energy Quality: Compliance with Current Standards	Yes
Power Quality: Compliance with Grid Codes	Yes
% of auto consumption [30]	N/A
% of generated power that goes through power electronics	100%
Power Losses: Cryogenic, Iron, and Converter (% of generated power)	11% [31]
Gearbox Losses (% of generated power)	N/A

[30] There is no auto consumption of power to feed WTG components

Total Losses (% of generated power)	11%
Energy Yield (MWh)	7,740[31]
Cost (k€)	2,117[31]
Annual Energy Yield/Total Cost (kWh/Euro)	3.67[31]
Components with Highest Maintenance Cost	Cryogenic system, encoder

Table 10 – HTSG Technical Overview

Economic Analysis

Context

In this section, an analysis of the current economic value – expressed as project IRR – of different wind energy projects with different WTG technologies is performed.

The type of WTG technology is generally decided before the development phase. The main IRR influencing factors of the WTG technology include investment costs (CAPEX), WTG performance, reliability, after-sales service, and O&M costs (OPEX).

Consequently, a comprehensive economic analysis should provide a detailed breakdown of WPP development costs and returns.[32] The results presented hereafter are only indicative, intended to provide an overall perspective of the impact of different WTG technologies on the profitability of a project.

The WTG alternatives which will be analysed are the following:

- Geared DFAG
- Direct Drive PMSG
- Geared PMSG

Methodology

Sources

The overall lifecycle costs and returns of two onshore wind energy projects are examined taking into account different parameters. Data is based on the following sources:

- Consultation with WTG manufacturers, EPC companies, wind power project developers, and wind energy technicians
- Specialized market reports by engineering institutes, research centres, wind power associations, and other groups

[31] Estimated figures; there are no published figures

[32] In addition to an economic analysis, it would be worth considering qualitative criteria such as wind power quality, especially now as RES penetration increases and grid codes become more stringent.

Project Scenarios

Inputs will vary depending on the location of the chosen site (Location 1 vs. Location 2) and the project outlook (Aggressive Scenario vs. Conservative Scenario), as follows:

- Two different onshore locations[33] have been chosen to compare the selected technologies
  - Location 1 is a site with **low** risk of excessive wind speeds and **low** risk of wind turbulences
  - Location 2 is a site with **high** risk of excessive wind speeds which could lead to shuts down in the WTG and **high** risk of wind turbulences which could lead to mechanical stress and thus premature aging of mechanical parts
- Secondly, two scenarios are set
  - An aggressive scenario: the CAPEX for each WTG technology corresponds to its lower range value and number of full load hours to its upper range value
  - A conservative scenario: the CAPEX for each WTG technology corresponds to its upper range value and the number of full load hours to its lower range value

Within this framework, the cash flows for each project scenario and for each WTG technology are calculated and the project IRR is computed, applying the input described on the following subsection.

Input

As can be expected, elements such as OPEX and the performance of the WTG (full load hours) will vary depending on the WTG technology in conjunction with the chosen location.

Choosing the right WTG technology is important, as it affects costs and revenues, which affect project economics through the parameters depicted in *Figure 24*:

	Description of WTG Parameters	Implications for the Analysis
CAPEX	• **Major construction costs, including procurement of all the generating plant and infrastructure** - WTG supply and installation is the main component (~ 70%)	• **Varies significantly between WTG technologies** - Direct drive technologies require higher investment costs than geared ones • **Does not depend on the chosen site, although the larger the project size, the lower the CAPEX**
OPEX	• **Ongoing expenditure: management, O&M (scheduled service and unscheduled repair), insurances and other business overheads** - 50% to 70% of total OPEX corresponds to O&M costs, of which WTG can sum up to 90% *	• **Varies significantly between WTG technologies** - The more reliable, the less corrective O&M costs • **Different locations will require different cost levels** - Corrosive environments can damage mechanical components
Number of Full Load Hours	• **WTG average annual production divided by its rated power** • **Function of the wind regime at the chosen site** - Highly dependent on wind conditions, selecting the adequate location is key	• **Varies significantly between WTG technologies** - The more efficient the WTG, the more production • **Each site has different wind characteristics** - In some sites, installing a more efficient WTG is critical for wind power economics

Note: * The rest of O&M costs mainly corresponds to substation costs

Figure 24 – Main Variables in WPP Project IRR

Of the above drivers, CAPEX and WTG electricity production (full load hours) have the greatest impact on the economic value of the project; that is, they are the main drivers of a wind energy project´s profitability. This is illustrated in the following graph:

[33] Balance of plant charges was assumed to remain unchanged in both locations.

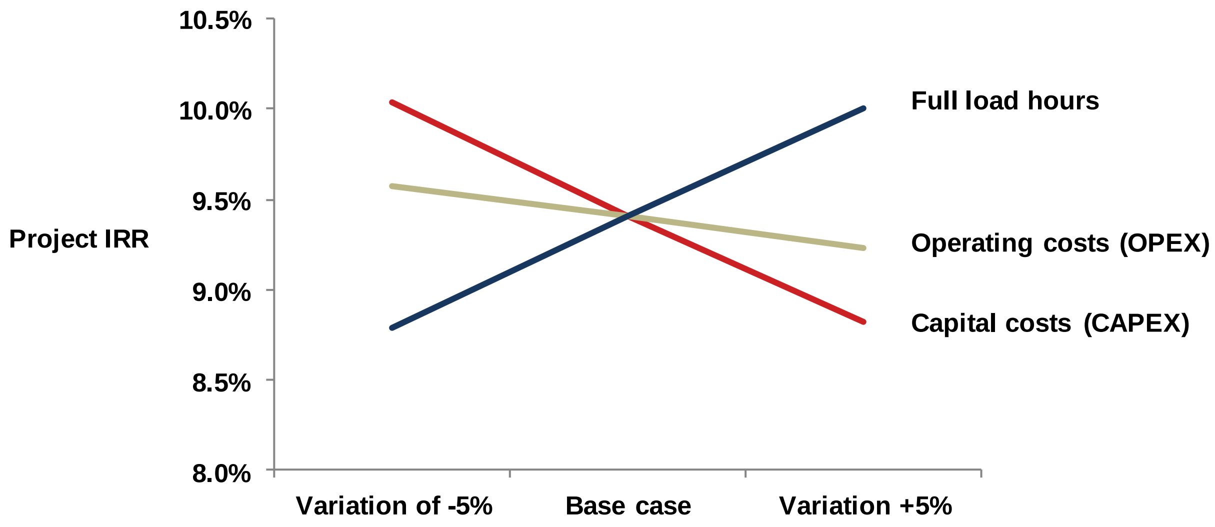


Figure 25 – One-way Sensitivity Analysis of WPP Parameters

Variations on the above parameters exist between different WTG technologies, as mentioned in Figure 24. This fact is relevant because of the impact that a seemingly small change in electricity production efficiency, CAPEX and, to a lesser extent, OPEX has on a project´s return.

The price of the WTG represents a significant share of CAPEX and there is considerable price variation between different WTG technologies[34]. PMSG is the most expensive technology, as explained in the previous Technical Analysis.

Though comparatively not as important as CAPEX and energy production, O&M costs could add a significant ammount to the Levelized Cost of Electricity (LCOE) over the service life of a WTG, particularly in violent environments.

A dominant component of O&M costs includes replacement and maintenance of mechanical parts such as the gearbox. Although maintenance and replacement of spare parts are hard to predict, these will clearly differ between WTG alternatives (most notably, between direct drive and geared WTGs).

Variance in wind project economics can also be explained in part by project financing costs, as well as tax credits and other incentives. As changes in these variables do not (generally) depend on the WTG technology installed, they will not be included in the present economic analysis (or set at the same value for all technologies).

Assumptions

The projection of wind power project lifetime return is based on a specific set of assumptions, which are as follows:

[34] Other cost components such as foundation costs, electrical installation, and land rental remain unchanged between WTG technologies for the sake of simplification.

Assumptions	
WPP Size	20 MW
WTG size [35]	Medium (< 3 MW)
Construction date	31/12/2011
Investment accounting life	15 years
WTG service life	20 years
Weighted Average Cost of Capital	7.2%
Inflation [36]	2.0%
Feed-in tariff	85 Eu/MWh in 2012 (1.5% increase p.a.)
Tax rate (over EBIT)	30%
Indicative CAPEX [37]	~ 1.2 M Eu/MW
Indicative OPEX [38]	~ 23 cEu/MWh in 2014
Working Capital Requirements (WCR)	0 Eu [39]

Table 11 – WPP Characteristics and Project Assumptions

The following table highlights the negative and positive impacts that changing site conditions have on the performance and cost structure of each technology.

[35] Hub height, swept rotor area, and WTG rated power are considered similar between technologies.

[36] OPEX costs increase by the estimated annual inflation rate of 2%.

[37] Based on 2010 figures, includes not only the WTGs itself, but also site work, foundation, grid connection costs, et cetera.

[38] Based on 2010 figures, O&M costs for the first two years of WTG life (2012 and 2013) are covered by the manufacturer´s warranty

[39] Average collection period and average payment period are considered both equal to 45 days

	Location 1	Location 2
Geared DFAG		
Electricity Production	• Constant wind regime poses no negative impact on full load hours	• WTG can shut down to prevent damage when speeds reach 25 m/s • Maintenance and replacement of mechanical parts causes downtime
OPEX	• Gearbox has to be replaced every 6-7 years • Slip rings have to be maintained, as well as other mechanical components	• Harsh wind regimes (wind speeds that reach 25 m/s) can cause mechanical stress, gearbox failure, et cetera
Direct Drive PMSG		
Electricity Production	• High efficiency, energy yield, reliability, and availability	• Can access higher wind speeds to generated more full load hours • Can handle higher wind speeds before shutting down
OPEX	• Simplified drivetrain (does not include gearbox or slip rings)	• Not as negatively affected by cyclonic wind regimes as other technologies (fewer mechanical components)
Geared PMSG		
Electricity Production	• Constant wind regime poses no negative impact on full load hours	• WTG can shut down to prevent damage • Maintenance and replacement of mechanical parts cause downtime
OPEX	• Gearbox has to be replaced • Less mechanical components than a DFAG	• Corrective costs are higher than in Location 1 due to possible damage of mechanical parts

Table 12 – Impact of Location on Production and OPEX

Results

The following figure depicts the range of IRRs that can be achieved with each of the three different WTG technologies in the two different locations—returns which were estimated according to the methodology and assumptions indicated in the previous sections.

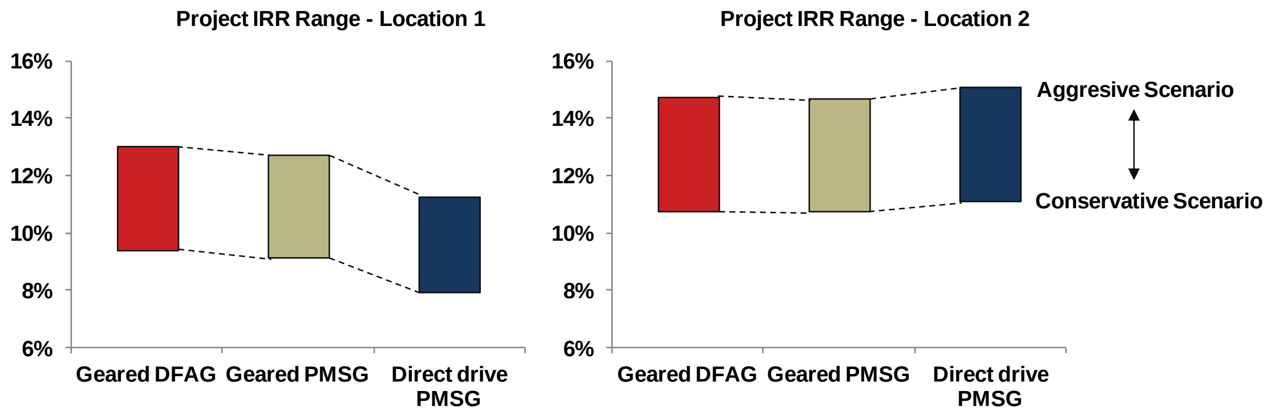


Figure 26 – Project IRR for Three Different WTG Technologies

It is worth highlighting the following:

- It could be equally profitable to install any of the three WTG technologies in both locations
- On average, Location 2 project IRR is superior to that of Location 1
    - Increased electricity production resulting from higher wind speeds compensates for higher O&M costs within a harsher environment (this finding could be expected, given that the IRR is more sensitive to changes on full load hours than on OPEX, as illustrated in Figure 25)
- In Location 1, geared DFAG offers on average the highest profitability, followed by geared PMSG; project return could be negatively affected if direct drive PMSG machines are installed
    - In such a location, the higher efficiency of the PMSG does not make up for a relatively higher capital expenditure
- In Location 2, the maximum IRR that could be attained is with direct drive PMSG. As opposed to Location 1, the superior number of full load hours that can be achieved in such high wind speed location counterbalances higher cost of the technology

Finally, it should be noted that these results are not representative of all wind energy projects, as each wind power project has a different set of conditions, so care must be taken in interpreting them.

In addition, PMSG is a technology which is neither fully proven nor being massively produced, so available data are limited.

Illustrative Case Studies

Onshore vs. Offshore

Onshore wind power plants were developed on the 80s, reaching significant technological advances in the following decade. The first offshore wind farm, with 5 MW power WTGs, was installed in Denmark in 1991. Since then, approximately ten other countries have installed offshore WPP. Despite this fact, the global market for WTGs is still almost exclusively for onshore wind farms, since onshore WTGs are easier to install and maintain.

The relative advantages of each location are summarized in *Table 13*:

	Onshore	Offshore
Relative Advantages	• Cheaper foundations Easier grid integration Cheaper installation and access during installation or maintenance and not as dependant on weather conditions	• Suitable for larger projects, as larger areas are available • No noise pollution, eventually no visual pollution • Higher wind speeds, which increase farther from the coast • Less turbulence, which increases efficiency and reduces mechanical stress • No obstacles, thus the layer of wind that touches the surface is thinner, allowing the towers to be smaller

Table 13 – Onshore vs. Offshore Wind Power Parks

The main disadvantage of offshore WPPs is their higher cost. Offshore WTGs are more expensive than onshore, mainly due to their size and complicated logistics during the installation and maintenance process. Foundation, construction, installation, and connection costs are all much higher for offshore than onshore. The price of an offshore wind farm depends on many factors such as wave conditions, water depth, and distance from the coast.

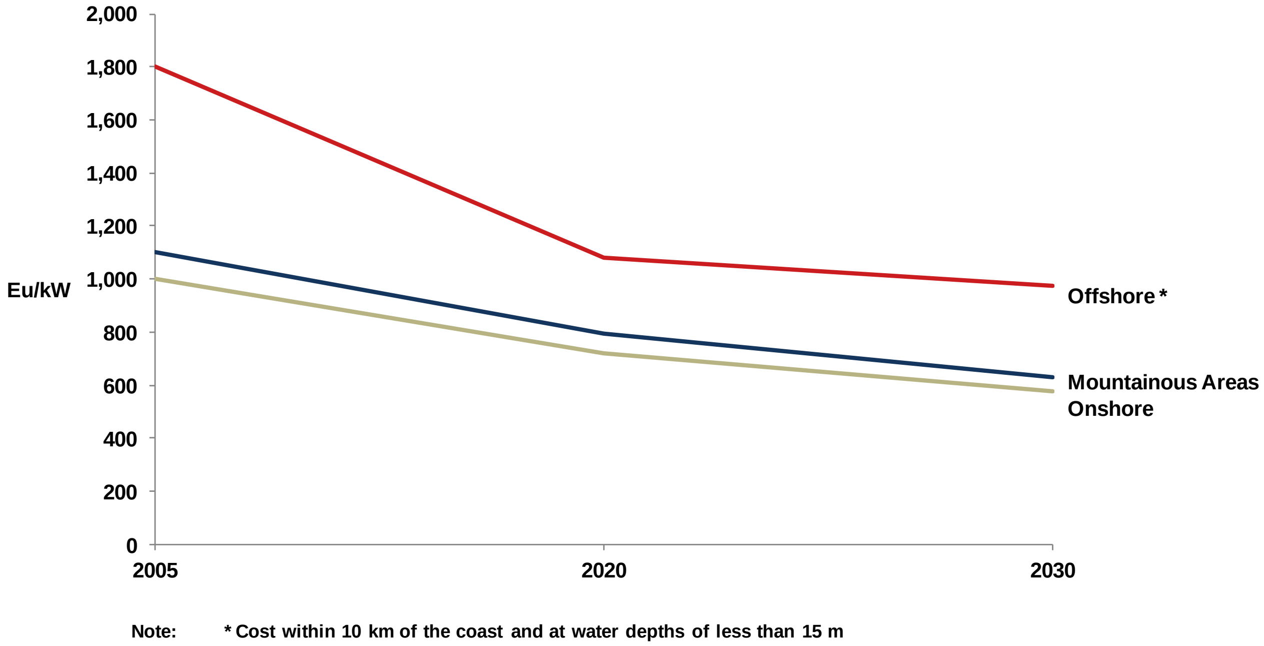


Figure 27 – Indicative Turnkey Cost Expected Evolution[23]

WIND FARM DESIGN

The design process of a wind farm always follows the same path:

1. Location

   Identifying a suitable location is based on historical wind records by year and installation, environmental, and social considerations.

   There is no direct relationship between location and technology in terms of performance. Specialized engineering companies can suggest installing different technologies for a given location. For example, for one particular location, the following technologies were compared:

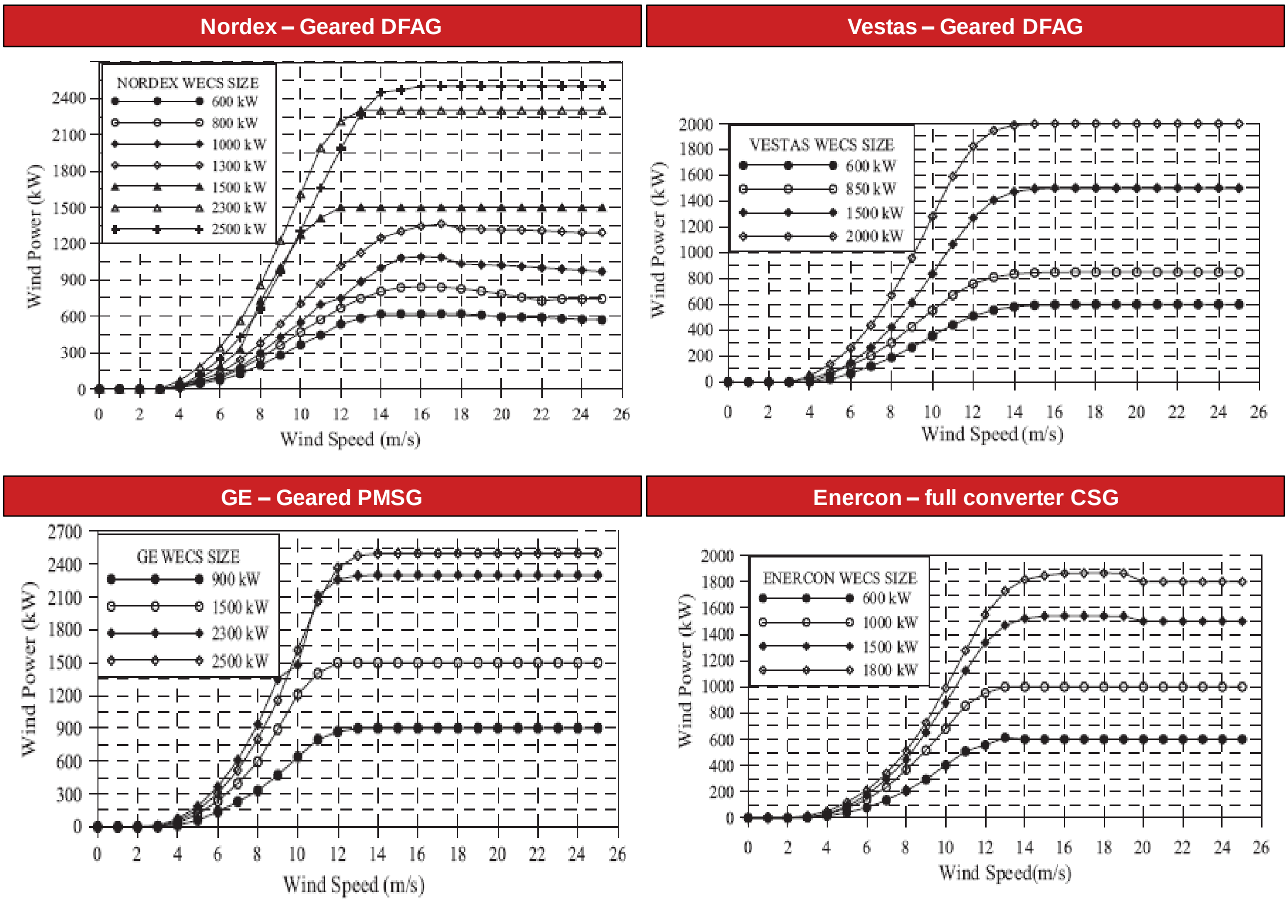


Figure 28 – Wind power curves for WECS of different sizes from Nordex, Vestas, GE, and Enercon[24]

2. Number of WTGs

   The number of turbines and their technology is limited by the extension of the land. A critical parameter is the minimum distance between wind turbines. This is calculated by computer software using genetic algorithms, Monte Carlo simulation, and combinatorial optimization, among other methods.

   The size of a group of wind turbines depends on:

   - Location
   - Wind direction and speed

- Turbine size, power, and performance

3. Type of WTG

   The type of turbine or technology is directly related to its power and price, as well as to its reliability and maintenance costs. The rotor size will determine the distance from other turbines as well as determine the maximum number of turbines to install.

4. Hub height

   The height of the WTG tower will be defined by wind conditions such as speed and turbulence. Computer programs are used to calculate the optimum height in order to maximize wind energy yield realization.

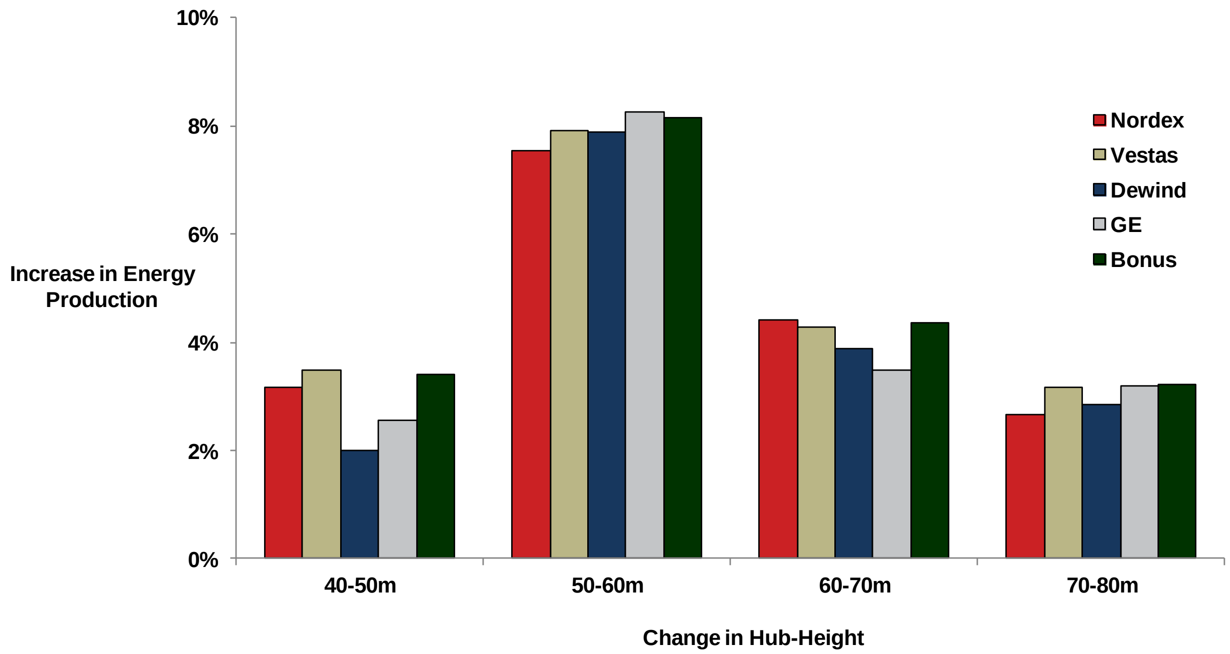


Figure 29 – Comparison of % Increase in Energy Yield with Increase in Hub Height[25]

Figure 29 illustrates the extent to which the height of the tower affects the amount of generated power of these turbines[40], for one particular location. Hub height is limited by transportation limitations, as well as the visual and environmental impact of the wind turbine.

WTG manufacturers such as Siemens have technical solutions suitable for every condition, as illustrated in the following graph:

[40] 600-2,500 kW sized wind turbines

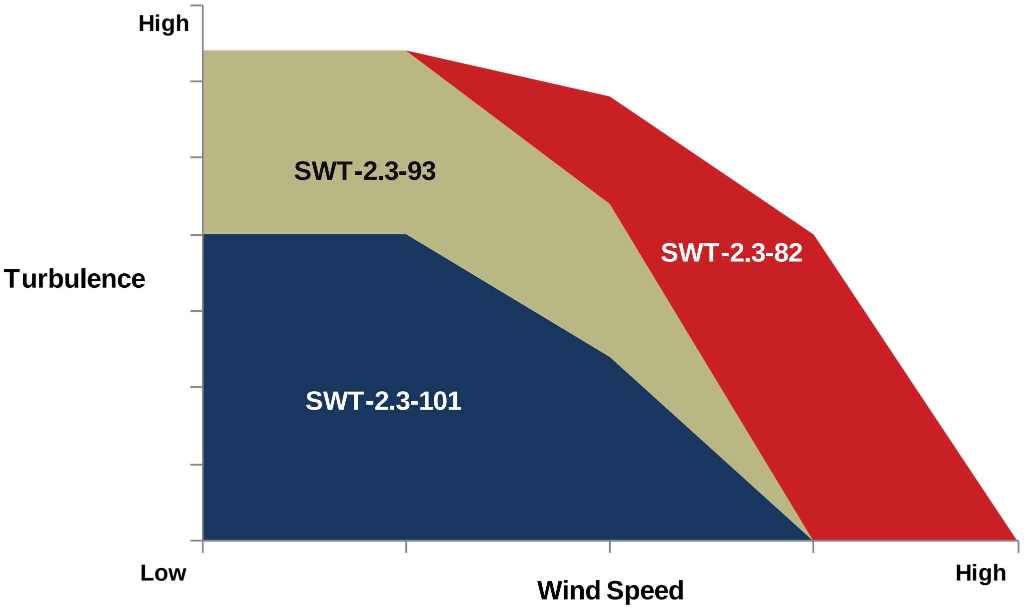


Figure 30 – Siemens WTG for Different Wind Regimes[26]

Siemens offers the same WTG technology, but with different tower height, control elements, and blade design in terms of varying wind characteristics.

Case Studies

To illustrate different types of WPP design depending on location and WTG technology, the following different cases have been collected:

- Coastal wind farms: full converter CSG vs. DFAG
- Inland wind farms: geared DFAG vs. full converter CSG
- Offshore wind farms: hybrid PMSG and geared DFAG

The data used in the following case studies are limited and represent specific wind energy projects. Therefore, the presented results cannot be extrapolated to other projects in different locations, with different site conditions, requirements, configurations, et cetera.

Coastal wind farms: full converter CSG vs. DFAG

Figure 31 illustrates two WTG options for a coastal WPP: full converter CSG vs. geared DFAG.

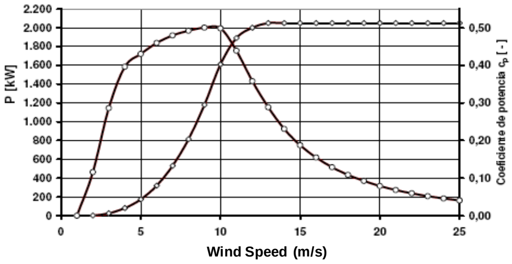
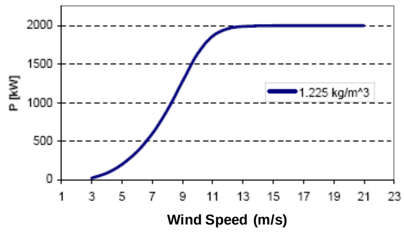
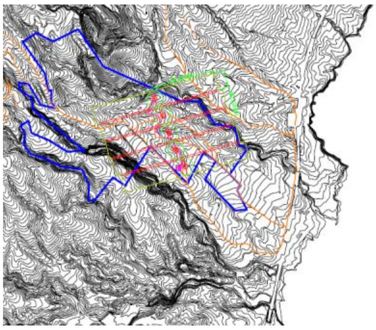
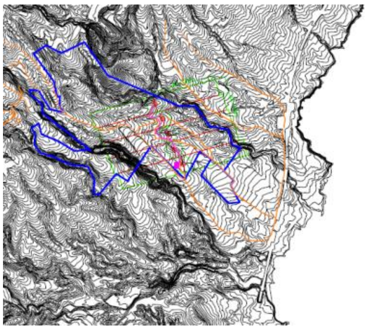
	CASE 1: Coastal Wind Farm – Full Converter CSG	CASE 2: Coastal Wind Farm – Geared DFAG
Total Power	10,000 kW	10,000 kW
Energy	32,276,637 kWh	32,233,595 kWh
Equivalent Hours	3,228 equivalent hours per year	3,223 equivalent hours per year
Capacity Factor	36.8 %	36.8 %
Wind Turbine Model	Enercon E82; Drive train: Direct: Synchronous	Gamesa G90; Drive train: Geared: DFAG
Turbine Curve		
Number of Units	5	5
Turbine Cost	2,530,000 € / turbine	2,299,000 € / turbine
Project Total Cost	14,893,565 €	13,738,565 €
MW Cost	1,489,356 € / MW	1,373,856 € / MW
Maps		

Figure 31 – Coastal WTG Options

In this case, installing a geared DFAG (option 2) is cheaper than installing a full converter CSG (option 1). In addition, both options have a similar capacity factor[41].

INLAND WIND FARMS: GEARED DFAG VS. FULL CONVERTER CSG

Figure 32 shows two options for an Inland WPP: a geared DFAG vs. full converter CSG.

[41] The capacity factor of a WPP is the relation between the total amount of energy generated during a period of time and the potential amount of energy the WPP would produce if it continuously operated at full nameplate capacity.

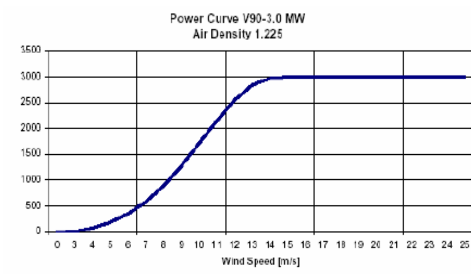
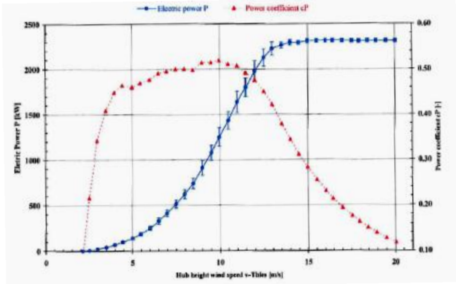
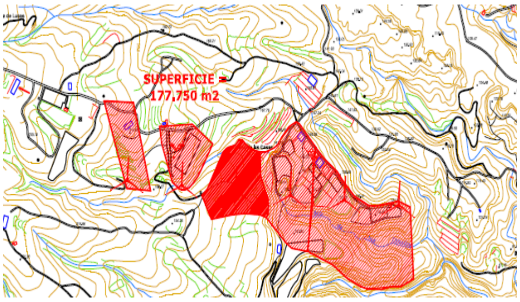
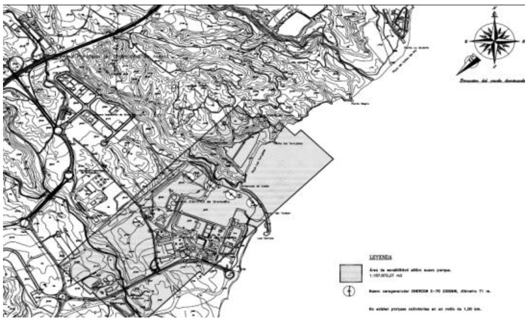
	CASE 3: Inland Wind Farm – Geared DFAG	CASE 4: Urban Wind Farm – Full Converter CSG
Total Power	18,000 kW	16,100 kW
Energy	55,744,011 kWh per year	50,380,500 kWh per year
Equivalent Hours	3,097 equivalent hours per year	3,129 equivalent hours per year
Capacity Factor	35.4 %	35.7 %
Wind Turbine Model	Vestas V90-3MW Drive train: Geared: Asynchronous	ENERCON E70-2,3 MW Direct Drive: Synchronous
Turbine Curve		
Number of Units	6	7
Turbine Cost	2,789,636 € / turbine	1,976,900 € / turbine
Project Total Cost	20,052,497 €	14,884,629 €
MW Cost	1,114,027 € / MW	924,511 € / MW
Maps		

Figure 32 – Inland and Urban WTG Options

The full converter CSG illustrated above is the best project in terms of € per MW and shows a higher capacity factor.

As stated at the beginning of this section, there is no technology designed specifically for one type of location. That is, there are no absolute arguments in favour of one technology over another in terms of technical performance.

Figure 33 shows three other options for an inland wind power project: full converter CSG and two geared DFAG.

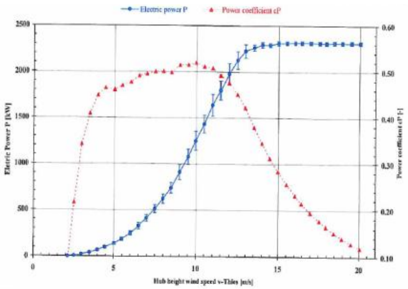
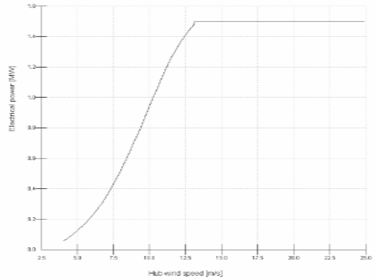
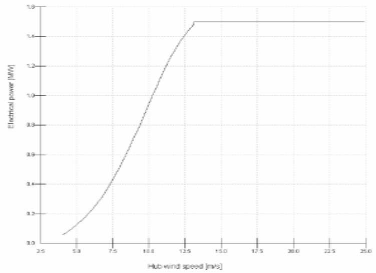
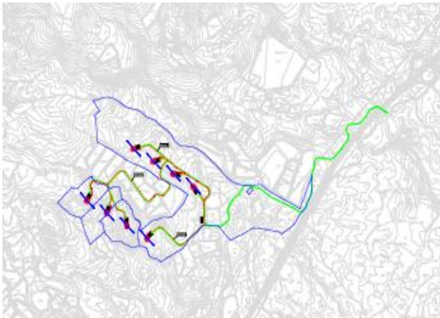
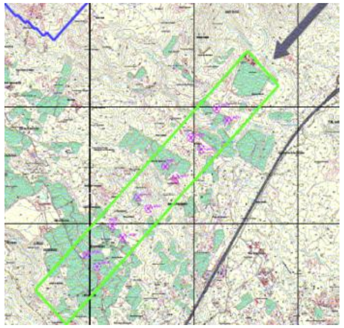
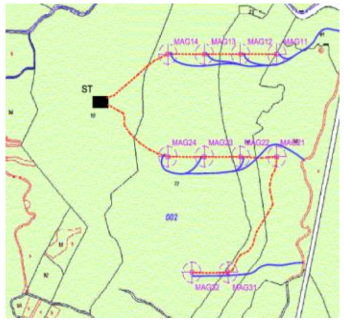
	CASE 5: Inland Wind Farm – Full Converter CSG	CASE 6: Inland Wind Farm – Geared DFAG	CASE 7: Inland Wind Farm – Geared DFAG
Total Power	18,400 kW	18,000 kW	15,000 kW
Energy	52,807,420 kWh per year	60,894,000 kW/h	51,615,000 kW/h
Equivalent Hours	2,870 equivalent hours per year	3,383 equivalent hours per year	3,441 equivalent hours per year
Capacity Factor	32.8 %	38.6 %	39.3 %
Wind Turbine Model	ENERCON E70/2.300 Direct Drive: Synchronous	AW70/1.500 IEC IA T80A Drive train: Geared: DFAG	AW70/1.500 IEC IA T80A Drive train: Geared: DFAG
Turbine Curve			
Number of Units	8	12	10
Turbine Cost	1,776,900€ / turbine	1,819,292€ / turbine	1,819,292 € / turbine
Project Total Cost	16,589,623.49 €	28,526,053 €	23,891,578 €
MW Cost	901,610 € / MW	1,584,780 € / MW	1,592,771 € / MW
Maps			

Figure 33 – Inland and Urban WTG Options

Enercon´s full converter CSG offers the lowest investment of the three options but, at the same time, the smallest capacity factor.

For the other two cases, it can be seen that in spite of installing the same technology and the same WTG model, different results can be obtained by varying location and the number of WTGs. However, these differences only account for a 0.5% difference in cost €/MW. With respect to Case 6, Case 7 has two WTGs less and offers a 0.7% higher capacity factor.

OFFSHORE WIND FARMS: HYBRID PMSG AND GEARED DFAG

Figure 34 illustrates the case of the first German offshore installation, Alpha Ventus, designed in 1999 and launched in 2010. The offshore installation was experimental and had six WTGs of PMSG model and other six of DFAG. It is worth highlighting that PMSG is not direct drive but a hybrid model with a few-step gearbox.

The comparison results and performance are currently under study, but the first results (year 2011) suggest that the project has been successful: power yield has been 15% higher than expected (267 GWh).

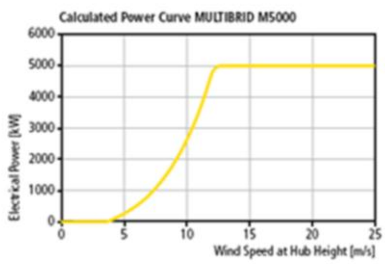
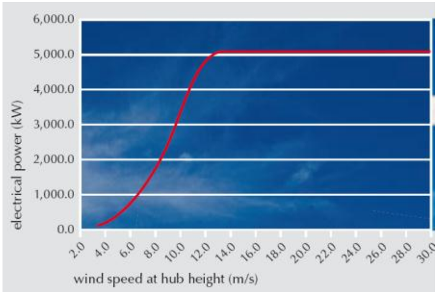
	CASE 8: Offshore Wind Farm – Hybrid PMSG and Geared DFAG	
Total Power	60,000 kW	
Energy	220,000,000 kWh per year	
Equivalent Hours	N/A	
Capacity Factor	42 %	
Wind Turbine Model	Multibrid M5000 (Areva) Hybrid, PMSG	REpower 5M Gearbox DFAG
Turbine Curve		
Number of Units	12 (6 Multibibrid M 5000)	12 (6 REpower 5M)
Turbine Cost	Unknown	2,789,636 € / turbine
Project Total Cost	250,000,000 €	
MW Cost	4,166,666 € / MW	
Maps		

Figure 34 – Offshore WTG Options

CONCLUSION

Wind power technology has evolved significantly during the boom in renewable energy over the past decade. This has spurred the development of numerous novel wind turbine generator technologies. Currently, the rather conventional Doubly-Fed Asynchronous Generator (DFAG) still dominates the market, but innovative concepts such as the Permanent Magnet Synchronous Generator (PMSG) are increasingly seen as attractive alternatives.

As long as the penetration of renewables onto the grid remained low, power quality fluctuations could be compensated for relatively easily by Transmission System Operators (TSOs). Compensating for transients, reactive power consumption, random connections, and harmonics, among other fluctuations, was not problematic. Now that renewable penetration has risen to record levels in many countries, managing the influence of the renewable input on the grid is a major concern for the TSO. Grid codes and operational procedures that were historically not designed for the integration of renewables must now be adapted and many countries are making the requirements for such adaptations mandatory. In order to satisfy those requirements, installations with DFAGs may require external reactive power compensation. In older wind power parks, installing power electronic devices such as STATCOMs, FACTs, and fixed compensators have been necessary to meet the evolving grid codes.

Due to the changing priorities, the market share of DFAGs is slowly declining in favour of full converter wind turbine generators such as PMSGs, which have controllable power output and can therefore more easily meet the increasingly stringent requirements. However, this shift in technology is happening at slow pace, primarily because the cost of permanent magnets is still high. DFAGs on the other hand can offer relevant cost savings because their power converter only has to cover 30 to 40% of the generated power.

Each wind project has different circumstances, so the decision regarding which wind turbine generator technology to use must be taken on a case by case basis. Comparison of the technologies that are commercially available today reveals that each has a particular niche in which they have the biggest advantage. Locations with high speed and turbulent winds, for example, are better suited for variable speed wind turbine generators with full-scale power converters, since they offer a higher availability under such conditions. This means that PMSGs will generally be preferred over DFAGs at such locations. In conditions with low wind speed and little turbulence, this technology preference could be reversed.

In general, PMSGs not only deal with grid related faults better, they also offer higher efficiency, reliability, and availability compared to their geared counterparts. This is obviously due to the fact that they contain fewer mechanical components. Nevertheless, geared models have been more thoroughly field-tested and are cheaper due to the greater volumes that are produced. The current trend is moving in the direction of PMSG hybrid solutions, i.e. with a single stage or two-stage gearbox. Vestas' most recent wind turbine generator is a geared drive, while the most recent model of Siemens is a hybrid. The cost of power electronics is expected to further decrease in the medium term and direct drive PMSGs will become more attractive.

The High Temperature Super-Conductor (HTSC) wind turbine generator is currently still in development phase and are not expected to be commercially available before 2016. It is expected to attain a higher power than any other wind turbine technology. If the offshore market continues its evolution towards ever larger machines, this could become an important niche market for the HTSC.

ANNEX 1: DEFINITIONS

Term	Definition/ Description
Nacelle Components	
Low/High Speed Shaft	Transmits rotational work from the rotor hub to the gearbox and from the gearbox to the generator.
Gearbox	Converts low-speed rotation from the input shaft of the rotor to high-speed rotation.
Coupling	Attaches the gearbox to the generator.
Mechanical Brakes	Stops the WTG blades during maintenance and overhaul.
Electrical Generator	Converts shaft work into AC electricity.
Power Electronics	Application of electronics for the control and conversion of electric power.
Cooling Unit	Drives air to cool the generator and gearbox and exhausts waste heat from the nacelle assembly. Helps prevent rust and corrosion.
Yaw Mechanism	Rotates the WTG directly into the wind in order to generate maximum power.
Rotor Components	
Rotor Blades	Blades utilize the principles of lift to convert the energy of the wind into mechanical energy. Stall-regulated blades limit lift when wind speeds are too great to avoid damaging the machine. Variable-pitch blades rotate to minimize their surface area and regulate rotational speed.
Pitch Drive	This system controls the pitch of the blades to achieve the optimum angle for the wind speed and desired rotation speed.
Extenders	Support the rotor blades and secure them to the hub.
Hub	Base for the rotor blades and extenders, and means of housing the control systems for the pitch drive. It rotates freely and attaches to the nacelle using a shaft and bearing assembly.
Balance of System Components	
Electrical Collection System	Transformers step up voltage transmission in the collector line; underground cables connect the power lines until a standard 25kV overhead collector line may be used; recloses and risers act as circuit breakers; power substations raise the voltage for standard long-distance transmission.
Communications System	The communications subsystem allows the wind WTGs to monitor themselves and report performance to a control station. A control station consolidates data and routes information to the local utility.
Other definitions	
Full converter	Allows separation between the WTG and the grid, i.e., while the grid operates at a given frequency, the stator winding of the generator may operate at variable frequencies.
Torque	Measure of the turning force on an object.
Reactive Power	Difference between active power measured and total power consumed. Some machines require an amount of reactive power in addition to active power. The Power Factor measures the relationship between active and reactive power.
Soft Starter	Used for reactive power compensation, it temporarily reduces the load and torque in the power train of the generator during start-up.
Crowbar	Electrical circuit used to prevent overvoltage.

Table 14 – Term Definitions[27]

ANNEX 2: ACRONYMS

Acronym	Meaning
WTG	Wind Turbine Generator
CAGR	Compounded Annual Growth Rate
CAG (CIG)	Conventional Asynchronous/ Induction Generator (or Squirrel-Cage Asynchronous Generator)
CSG	Conventional Synchronous Generator (or Wound-Rotor Synchronous Generator)
DFAG (DFIG)	Double Feed Asynchronous Generator (or Double Feed Induction Generator)
PMSG	Permanent Magnet Synchronous Generator
HTSG	High Temperature Synchronous Generator
IRR	Internal Rate of Return
DC	Direct Current
AC	Alternating Current
RES	Renewable Energy Sources
TSO	Transmission System Operator
NdFeB	Neodymium-Iron-Boron
WECS	Wind Energy Conversion System
AMSC	American Superconductor
WPP	Wind Power Plant
OEM	Original Equipment Manufacturer
PSO	Power System Operator
Rpm	Revolutions per minute
IPP	Independent Power Producer
PPA	Power Purchase Agreement
LCOE	Levelized Cost of Electricity/Energy

Table 15 – Acronym Glossary

[1] BTM, GWEC, EWEA

[2] BTM Consult, GWEC

[3] BTM, GWEC

[4] BTM Consult; GWEC; EWEA

[5] Iberdrola Renovables; BTM

[6] Iberdrola Renovables; BTM

[7] BTM; Wind Energy; EWEA; GWEC

[8] EWEA; 'China to boost offshore wind power generation', China Daily; Centre for American Progress; Eclareon Analysis

[9] IHS Emerging Energy Research; Eclareon Analysis

[10] AMSC; Eclareon Analysis

[11] Wind energy: a technology that is still evolving. D. J. Milborrow; Eclareon Analysis

[12] Wind energy: a technology that is still evolving. D. J. Milborrow; Eclareon Analysis

[13] Enercon and Vestas data; Eclareon Analysis

[14] SKF Group; Eclareon Analysis

[15] SKF Group; Emerging Energy Research; Eclareon Analysis

[16] P. J. Tavner, Introduction to Present Day Wind Energy Technology, The Wind Power Station (2010); Eclareon Analysis

[17] AMSC; Eclareon Analysis

[18] Garrad Hassan; Eclareon Analysis

[19] P. J. Tavner, Introduction to Present Day Wind Energy Technology, The Wind Power Station (2010); Eclareon Analysis

[20] Llorente Iglesias R, et al. Power electronics evolution in wind turbines—A market-based analysis. Renew Sustain Energy Rev (2011) and GWEC Annual Market Update 2010—2nd edition April 2011; Eclareon Analysis

[21] IQwind; Eclareon Analysis

[22] AMSC; Eclareon Analysis

[23] European Environment Agency (EEA). Europe's onshore and offshore wind energy potential. 2009; Eclareon Analysis

[24] Review of 600-2500 kW sized wind turbines and optimization of hub height for maximum wind energy yield realization Md. Mahbub Alama, Shafiqur Rehman, Josua P. Meyera, Luai M. Al-Hadhramib; Eclareon Analysis

[25] Review of 600–2500 kW sized wind turbines and optimization of hub height for maximum wind energy yield realization Md. Mahbub Alama, Shafiqur Rehman, Josua P. Meyera, Luai M. Al-Hadhramib; Eclareon Analysis

[26] Siemens data; Eclareon Analysis

Other references:

http://www.gobiernodecanarias.org/

http://www.alpha-ventus.de/index.php?id=80.

[27] Renewable Energy Policy Project; EDF Energy