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Chapter 6

# Wind energy technology developments

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This chapter describes the present mainstream development of the wind turbine technology at present. The turbine technology development trend is characterized by up-scaling to turbines with larger capacity for both onshore and offshore applications, larger rotors and new drivetrain solution, including the direct-drive solution without gearbox. The technology solutions are strongly influenced by the development of the international industry with a global market for components and a trend towards a "shared" development effort in collaboration between the OEM's and component sub-suppliers. Wind turbine blades and towers are very large series-produced components, which costs and quality are strongly dependent on the manufacturing methods. The industrial wind energy sector is well developed in Denmark, and the competitive advantage of the Danish sector and the potential for job creation will be discussed. Finally, the ongoing development of standards and certification of technology and wind turbine plants will be described.

### Global development

In spite of the slow-down of the global market development recent years have seen a renewed effort in the technological development of wind turbine technology. This effort is driven by a stronger global competition within the wind energy sector as well as the competing energy technologies. This competition provides a pull for lower cost-of-energy, the need for larger and more reliable wind turbines for offshore applications and an increased interest in development of sites with low or moderate wind regimes. Thus the main-stream turbine technology development trend is characterized by up-scaling to turbines with larger rated capacity for both onshore and offshore applications, larger rotors for higher capacity factors and new drivetrain solution, including the direct-drive solution without a gearbox.

While the global annual new installed capacity was slightly reduced in 2013 to 36 GW (comparable to the installation rates in 2008–2009) reaching a total of 321 GW [1], the trend towards larger wind turbines continued with the average rated capacity of wind turbines reaching 1.926 MW in 2013. The slow-down of the installation world-wide was due to very large declines in new installations in 2013 in USA and Spain, while Europe showed a minor decline. The Asian market picked up, led by China, which again in 2013 became the world's largest market. The offshore market has continued to grow with 1.7 GW installed in 2013 reaching a total of 6.8 GW. The offshore market is primarily in Northern Europe, only 5 % of the installed capacity is installed outside Europe (in Asia).

However, in spite of the industry becoming more and more international, the market diversification grows with turbines designed for different markets and applications, e.g. for low wind areas, cold climate, high altitudes or offshore. Hence, the average size of wind turbines installed in Denmark in 2013 was 3.326 MW, while turbines in India were in average 1.336 MW. The average size of turbines in USA and China was 1.719 MW and 1.841 MW, respectively, while the average size of installed wind turbines in Europe exceeded 2 MW.

Most of the installation in Denmark was offshore, which favours large wind turbines. The average rated capacity of wind turbines installed offshore in 2013 was 3.612 MW. At present there are 9 suppliers of wind turbines larger than 3 MW (6 European and 3 Chinese).

Even larger wind turbines are available or will become available in 2014, the largest of which is the 8 MW Vestas V164 with the prototype installed in Denmark early 2014.

In terms of market share, the trend towards larger wind turbines is very clear with the 2MW size range being the dominant for onshore application and a strong development of the multi-MW size range. The market share for various size ranges is shown in *Table 2*.

Other technology trends in addition to the up-scaling are the appearance of wind turbine versions with taller towers and longer blades for better performance in low wind regimes, e.g. for IEC classes II and III sites with annual average wind speeds of 8.5 m/s and 7.5 m/s in hub height, and increased use of direct drivetrain solutions, which in 2013 accounted for 28.1 % of the installed capacity. These technology trends will be further discussed in the following section.

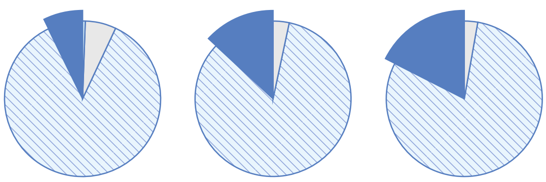
## Technology Trends

The reduction of the cost-of-energy is the primary driver in the development for making wind energy commercially competitive to other energy sources. Innovative technical solutions for wind turbine design such as new rotor design philosophies and drivetrain concepts have been developed to bring down the turbine cost. Large volume manufacturing and installation costs are reduced by specialized tools such as robot assisted blade layup and vessels for fast and robust offshore installation. The operation costs are reduced by optimized maintenance programs based on new health monitoring systems. The shares of turbine costs, installation costs, infrastructure costs, and operation costs in the levelized cost-of-energy depend on the project type: the turbine cost is typically more than half for onshore but less than half for offshore projects. The high installation and infrastructure costs offshore explain the favouring of larger offshore turbines.

Table 2 - Wind turbine size classes by market share 2011–2013.

World Market Update 2013, March 2014, Navigant Research [1].

| | Year | 2011 | 2012 | 2013 |
|---|---|---|---|---|
| | Total MW supplied | 40,495 | 43,134 | 37,478 |
| | Size range | % of total MW supplied | | |
| | <750 kW | 0.6 % | 0.1 % | 0.1 % |
| | 750-1499 kW | 6.6 % | 3.5 % | 2.8 % |
| | 1500-2500 | 85.7 % | 83.5 % | 79.6 % |
| | >2500 kW | 7.2 % | 12.8 % | 17.5 % |



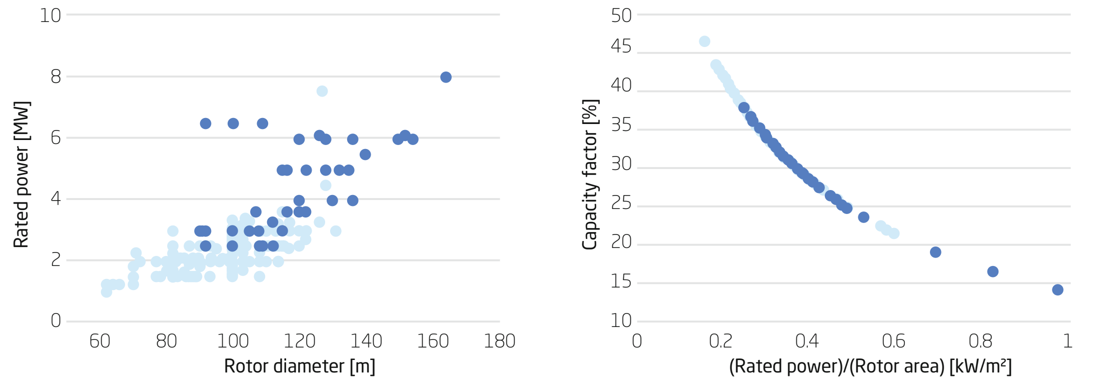

A secondary driver in the development of competitive wind energy is the increased security of wind energy production to enable a higher penetration on the grid. Increased capacity factors[2] of wind turbines and higher controllability of wind farms are some of the current trends that focus on this objective.

*Figure 7* shows rated power plotted versus rotor diameter of existing onshore and offshore wind turbines in the left plot and their capacity factors plotted versus rated power per rotor area in the right plot. Turbines with low rated power and large rotor diameters will have high capacity factors, while turbines with high rated power and relatively small rotor diameter will have low capacity factors. The three offshore 6.5 MW turbines with rotor diameters of 92 m, 100 m, and 109 m have the lowest capacity factors of about 14%, 16%, and 19%. The turbine with the highest capacity factor of about 47% is an onshore turbine with rated power of 1.5 MW and rotor diameter of 108 m. Note that the capacity factors are here computed assuming an optimal power coefficient of 45%, a Rayleigh wind distribution with 7 m/s as average speed, and cut-in at 5 m/s and cut-out at 25 m/s. These assumptions are of course not representative for all turbines and sites; however, the site-dependent average speed has the largest influence on the capacity factors, thus *Figure 7* can be used to compare the effect of changing rated power and rotor diameter on this competition parameter.

Hence, turbines with low rated power and large rotor diameters have high capacity factors, but they may not be more cost-efficient unless they are based on new advanced technologies. With conventional rotor design based on up-scaling, the blade mass and therefore the material and manufacturing costs for the rotor will increase with the power of three with the blade length, while the energy production will increase with the power of two. *Figure 8* shows blade mass versus length for existing glass and carbon fiber blades. The purple curve shows the conventional cubic up-scaling of a 40 m glass fiber blade, whereas the red and blue curves show power law trend lines for the glass and carbon fiber blades, respectively. The exponent for the glass fiber blades is significantly lower than three, whereas the trend for the carbon fiber blades is less clear due to the low number of data points. The blade mass

2. **The capacity factor** is the expected energy production over a given period normalized by the energy that could be produced when operating constantly at rated power over the same period. For a wind turbine, this factor is highly dependent on the wind speed distribution used for calculating the expected energy production.

Figure 7 - Rated power versus rotor diameter.




Rated power versus rotor diameter of existing onshore and offshore wind turbines (**left plot**) and their capacity factor versus rated power per rotor area (**right plot**).

onshore turbines

offshore turbines

Capacity factors are computed assuming an optimal power coefficient of 45%, a Rayleigh wind distribution with 7 m/s as average speed, and cut-in at 5 m/s and cut-out at 25 m/s.

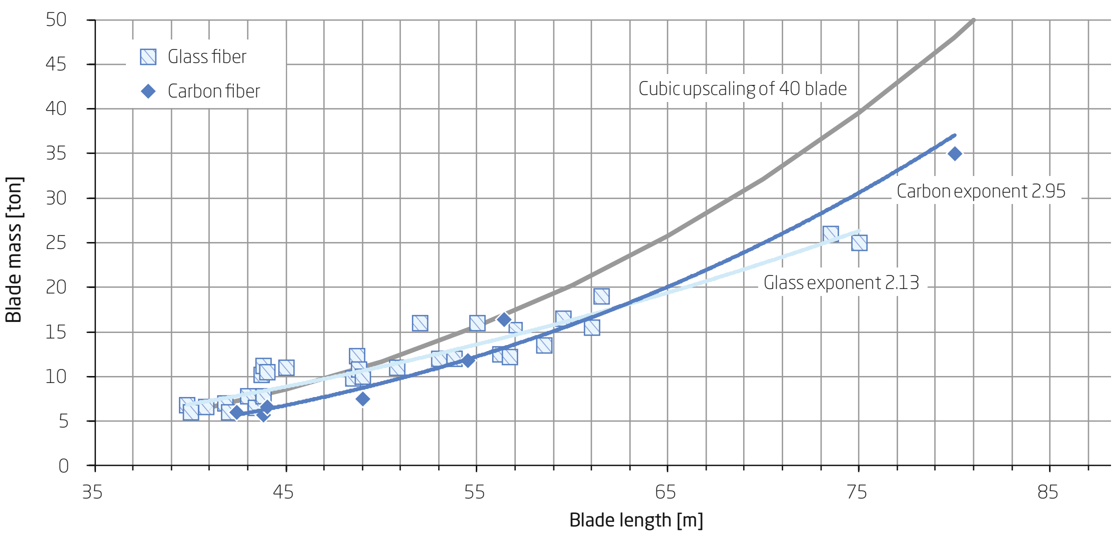
Data based on WMU 2013 [1].

trends for modern glass fiber blades have only been possible through the development of new rotor design philosophies.

A key element in the new rotor design philosophy is the use of new high lift and relative thicker airfoils that allows for the design of more slender rotor blades, as illustrated in *Figure 9*. The power producing lift force is proportional to the blade width, also called the chord length of the airfoils, and the lift coefficient. If the lift coefficient is increased by design new airfoils or adding vortex generators to existing airfoils for delayed flow separation (stall), then the chord length can reduced by the same fraction without compromising the total lift force. The absolute thickness of the blade must however remain the same to be able to carry the same lift force, thus these new airfoils must have a higher relative thickness.

Blade masses can be further reduced if new load reduction technologies are built into the blade itself by a sweep of the blade shape and/or by advanced layups of the fiber laminates in the blade. These

Figure 8 - Wind turbine blade mass versus blade length.




Wind turbine blade mass versus blade length of existing glass and carbon fiber blades. Based on data from [2] extended with the Siemens 75 m blade at 25 ton.

Figure 9 - llustration of a key element in the new rotor design philosophy.

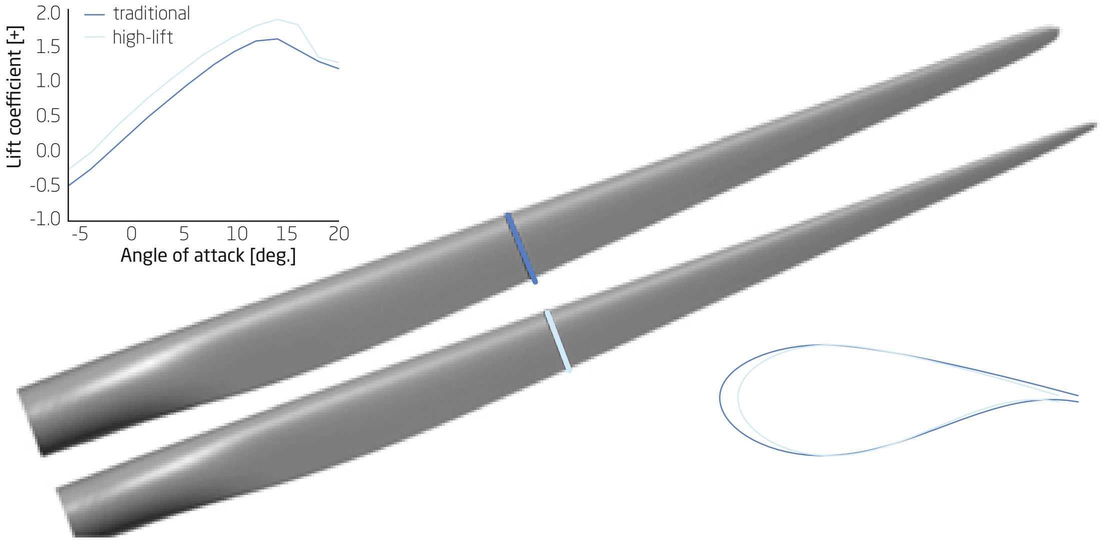



Illustration of a key element in the new rotor design philosophy: the design and use of new high lift and relatively thicker airfoils allow for the design of more slender rotor blades because the shorter airfoil chords along the blade (reduced blade width) can be compensated by the higher lift coefficient.

advanced design concepts can create a passive structural coupling between bending and twisting of the blade such that sudden increases in lift forces on the blade during a wind gust will be alleviated by the reduced angle of attack resulting from the twisting when the blade is bend under the increased loading.

*Figure 10* illustrates the final result of the last thirty years of research and development in rotor design; the top blade is the Siemens B55 blade which includes load reducing bend-twist couplings and high lift airfoils, whereas the bottom blade is an equally scaled version of a 30 year old blade designed with a linearly chord variation and old airfoils designed for glider aircrafts. Note that the Siemens 75 m blade with the mass of 25 ton which lays more than 5% below the state-of-the-art blade mass trend in *Figure 8* is designed after the same principles as the B55 blade. This further decrease in blade mass is mainly due to the load reduction obtained by the advanced bend-twist couplings in these cutting-edge blades.

The trend of higher capacity factors of commercial turbines is also related to these new rotor design philosophies because lighter rotors with built-in load alleviating properties allow for replacing smaller and heavier rotors on existing turbine platforms with a larger rotor of equivalent weight and load contributions. Assuming that the manufacturing costs of the blades and the loads transferred from the rotor to the remaining structure are similar for the new rotor of similar mass, the cost-of-energy based only on the turbine cost is reduced proportionally to the rotor area increase.

New drivetrain concepts represent another significant trend in the turbine technology development that aims towards lowering the turbine costs. New drivetrain concepts represent another significant trend in the turbine technology development that aims towards lowering the turbine costs. The predominant drivetrain design has for some years been with a three-stage gearbox and a double-fed induction generator (DFIG). This concept provides variable speed operation and can with the latest developments meet grid requirements. In this concept only the rotor circuit is connected via a power converter and hence approximately one-third of the generator power passes through the converter with obvious cost advantages. The drawback compared to passing the full power output through a power converter is a more limited speed range and fewer options for regulation of the power output and provision of ancillary services from the turbine to the grid.

The primary competitor is the direct drive (DD) concept, which avoids the gearbox and transforms the main shaft torque directly to electric power by

Figure 10 – Thirty years of technology development.

**Thirty years** of technology development: State-of-the-art Siemens B55 blade (**top**) that includes load reducing bend-twist couplings and high lift airfoils versus a blade designed 30 years ago (**bottom**) up-scaled to the same length.

(with courtesy of Siemens Wind Power A/S)

a multi-pole generator with permanent magnets as is the case with the Siemens DD wind turbines or with wound magnets as used by Enercon. The main advantage of the DD concept is a mechanically much simpler drivetrain requiring less maintenance and with expected higher reliability. This reliability is advantageous especially for offshore wind turbine due to the high cost of access and repair. The DD concept is increasingly being used and present in 28.1% of all new capacity in 2013 [1].

Other drivetrain concept are being used, e.g. hybrid drivetrains combining one or two-stage gears with a multi-pole (permanent magnet) generator or hydraulic drives, where a hydraulic pumps, accumulators and motors replace the gearbox and the power converter. Mitsubishi Heavy Industry currently has a 6 MW prototype of this concept. A fairly recent summary of current drivetrain options can be found in e.g. [8] or [9].

### Manufacturing trends

With the up-scaling of the wind turbines there is an increased need for test facilities which for the largest wind turbines are rather large and also very expensive. This makes a push toward further developments in numerical simulation tools for the drivetrain that can facilitate a better understanding of the load situation of the involved components. For these numerical tools to give reliable results the loads on the structure are needed and specifically also their variation in time. Having reliable load data the numerical tools can be used to estimate the fatigue life of e.g. the bearings or the gear-box.

With the need for larger, lighter and stronger structures there is also an increase focus on the material design, keeping in mind that the wind turbine must be able to withstand the environment at the specific installation sight.

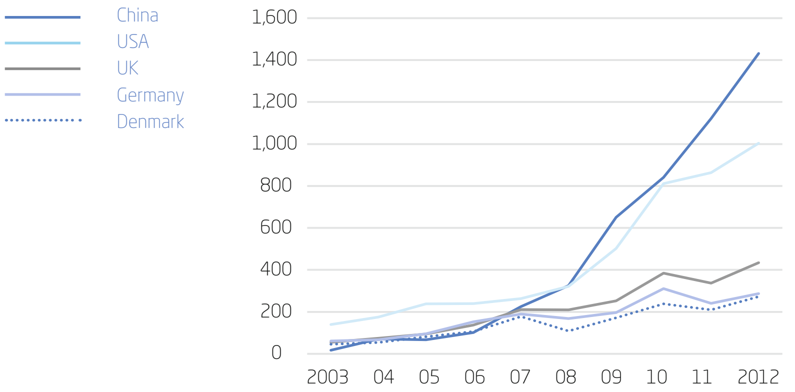
With the increase in size the number of sub-suppliers in the supply chain, capable of delivering the needed components, e.g. bearings, is also drastically reduced. It is highly important that steady and trusted supplies of high level components with competitive prices are available.

### Competitive advantage and job creation

According to World Market Update [1] the turbines installed in the world in 2013 were supplied by 62 OEM's, of which 42 companies were from Asia, 18 from Europe and two were from North America. The top ten suppliers of wind turbines are listed in *Table 3*.

Contrary to what was expected a few years ago, the market has not consolidated with a few large

Figure 11 – Number of scientific publications from the five most publishing countries 2003–2012 [5].




suppliers. The top-ten supplies 69.5 % of the market, and adding the delivery of turbines from the next five largest suppliers, all from China, provides an additional 13.4 % of the market.

Of any single country, China leads on the supply side. However, the Chinese manufacturers supply almost exclusively to the domestic market, and only Goldwind and Mingyang supply outside their home market, to one and four other countries, respectively [1]. This isolation is in contrast to the European companies and GE on the top-10 list, which typically are active on 15 markets with Vestas being in the lead on 27 markets. Being presence on many markets clearly creates robustness and is a strength.

One should be careful not to interpret the Chinese companies focus on the home market as lack of technology for the world market. Goldwind has manufactured direct-drive turbines for almost a decade, and a 6 MW turbine is under testing. United Power installed its 6 MW wind turbine in 2012 and Mingyang has a 2-bladed 6 MW turbine under testing. However, European and US industry has a stronger knowledge and experience basis. Much of the Chinese wind turbines are based on European technology, initially through licenses but now more through cooperation with European design companies, by acquisition, or by setting up R&D departments.

That China as a country intends to be in the lead, not only in manufacturing, but also in the design and the know-how and -why is illustrated by the immense development of the scientific effort in China on wind energy. *Figure 11* shows the development of scientific wind energy papers from the five most publishing countries in the world from a bibliometric analysis by Damvad in 2014 [5].

Most forecasts agree that the wind energy market will grow, both with respect to installed new capacity, repowering, and operation and maintenance. EWEA estimates in [6] that by 2020 there should be 520,000 jobs in the European wind energy sector and almost 800,000 jobs by 2030. The sector created 30% more jobs from 2007 to 2010 to reach nearly 240,000, while the EU unemployment simultaneously rose by 9.6%.

The trend is also that the manufacturing jobs follow the market and hence will grow the most in developing markets. For a country like Denmark, which hosts two suppliers on the top-ten list (Vestas and Siemens), job creation is closely tied to the development of the offshore wind market in Northern Europe and to technology development. The number of jobs has been fairly constant during the last five years at approximately 28,000. However, there

Table 3 – Top-10 wind turbine suppliers in 2013.

from World market Update 2013 [1].

| | Accu. MW 2012 | Supplied MW 2013 | Share 2013 | Accu. MW 2013 | Share accu. |
|---|---|---|---|---|---|
| Vestas (DK) | 56,780 | 4,893 | 13.1 % | 61,673 | 18.9 % |
| Goldwind (CN) | 15,452 | 4,112 | 11.0 % | 19,564 | 6.0 % |
| Enercon (DE) | 29,370 | 3,687 | 9.8 % | 33,057 | 10.1 % |
| Siemens (DK) | 20,192 | 2,776 | 7.4 % | 22,968 | 7.0 % |
| GE Wind (US) | 37,108 | 2,458 | 6.6 % | 39,566 | 12.1 % |
| Gamesa (ES) | 27,745 | 2,069 | 5.5 % | 29,814 | 9.1 % |
| Suzlon Group (IN) | 23,582 | 1,995 | 5.3 % | 25,577 | 7.8 % |
| United Power (CN) | 7,323 | 1,488 | 4.0 % | 8,811 | 2.7 % |
| Mingyang (CN) | 4,159 | 1,297 | 3.5 % | 5,456 | 1.7 % |
| Nordex (DE) | 8,884 | 1,254 | 3.3 % | 10,138 | 3.1 % |
| Others | 58,962 | 11,448 | 30.5 % | 70,410 | 21.5 % |
| **Total** | **289,557** | **37,478** | **100 %** | **327,034** | **100 %** |

Figure 12 – Relative impact of the ten most publishing countries 2003–2012 [5].

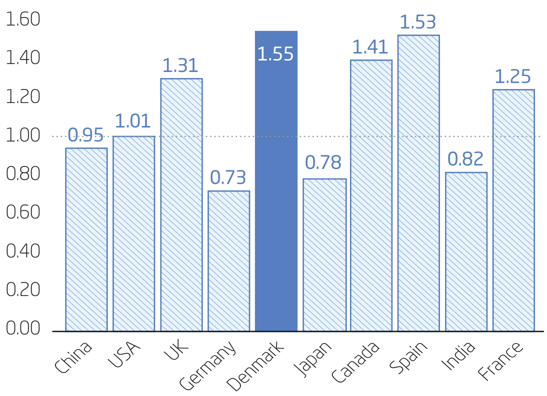
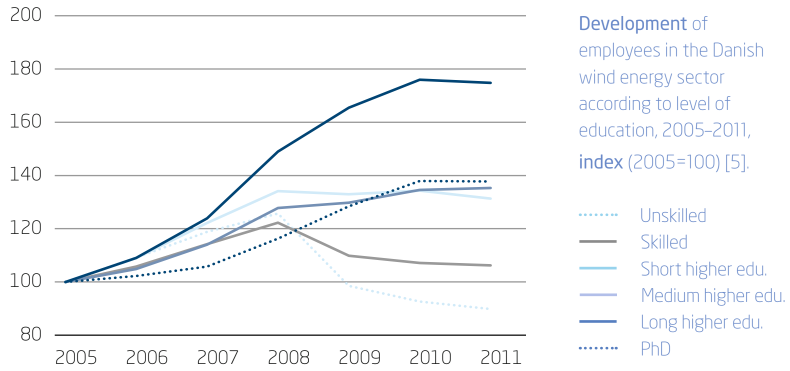



Figure 13 – Development of employees in the Danish wind energy sector.




has been a shift from jobs requiring unskilled manpower to highly skilled jobs as shown in *Figure 13* from [5].

Especially the jobs requiring master and PhD level have grown consistently, and only jobs for unskilled labor have fallen in the period. This development is fortunate in the sense that such jobs are associated with high value creation. However, highly trained staff is scarce, and require a strong effort on education and research to grow. In the EWEA study [7] the European industry already finds it difficult to hire suitably trained staff. EWEA estimates that there is currently a shortage of 7,000 qualified personnel required by the European wind energy sector each year, a figure that could increase to 15,000 by 2030 if the number of graduates taking courses relevant to the industry does not rise. However, the positive message is that nearly 50,000 additional trained staff will be needed by the industry by 2030. By that year, operations and maintenance will become the greatest source for new jobs and demand for trained staff.

Hence, maintaining and developing the competitive edge and jobs will require significant investments in education and research.

### Standards and Certification

Much of the technology development and the globalization of the wind energy industry have been immensely helped by the development of international standards. The responsible standards organization is IEC (International Electrotechnical Committee), which in 1988 formed the Technical committee TC88 with the task to prepare international wind energy standards. The scope for TC88 is

> *"To prepare international standards for wind turbines that convert wind energy into electrical energy. These standards address design requirements, engineering integrity, measurement techniques and test procedures. Their purpose is to provide a basis for design, quality assurance and certification. The standards are concerned with all subsystems of wind turbines, such as mechanical and internal electrical systems, support structures and control and protection systems. They are intended to be used together with appropriate IEC/ISO standards."*

The development of standards has followed the general development of wind turbines: 1) Initially preparation of standards giving essential safety and functional requirements to assure the general safety and function of a new technology. 2) Test standards by which the performance can be compared and validated. 3) Conformity testing and certification as a means to document and instill confidence of a complex product to the market and authorities. 4) Standards for interfaces and components when wind turbines are becoming a recognized and significant element in power systems and where components are acquired on the international market.

As of 2013 IEC has issued the following standards publications in the 61400 series [3]:

| Reference | Title |
|---|---|
| IEC 61400-1:2005 +AMD1:2010 | Wind turbines – Part 1: Design requirements |
| IEC 61400-2:2013 | Wind turbines – Part 2: Small wind turbines |
| IEC 61400-3:2009 | Wind turbines – Part 3: Design requirements for offshore wind turbines |
| IEC 61400-4:2012 | Wind turbines – Part 4: Design requirements for wind turbine gearboxes |
| IEC 61400-11:2012 | Wind turbines – Part 11: Acoustic noise measurement techniques |
| IEC 61400-12-1:2005 | Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines |
| IEC 61400-12-2:2013 | Wind turbines – Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry |
| IEC TS 61400-13:2001 | Wind turbine generator systems – Part 13: Measurement of mechanical loads |
| IEC TS 61400-14:2005 | Wind turbines – Part 14: Declaration of apparent sound power level and tonality values |
| IEC 61400-21:2008 | Wind turbines – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines |
| IEC 61400-22:2010 | Wind turbines – Part 22: Conformity testing and certification |
| IEC 61400-23:2014 | Wind turbines – Part 23: Full-scale structural testing of rotor blades |
| IEC 61400-24:2010 | Wind turbines – Part 24: Lightning protection |
| IEC 61400-25-1:2006 | Wind turbines – Part 25-1: Communications for monitoring and control of wind power plants – Overall description of principles and models |
| IEC 61400-25-2:2006 | Wind turbines – Part 25-2: Communications for monitoring and control of wind power plants – Information models |
| IEC 61400-25-3:2006 | Wind turbines – Part 25-3: Communications for monitoring and control of wind power plants – Information exchange models |
| IEC 61400-25-4:2008 | Wind turbines – Part 25-4: Communications for monitoring and control of wind power plants – Mapping to communication profile |
| IEC 61400-25-5:2006 | Wind turbines – Part 25-5: Communications for monitoring and control of wind power plants – Conformance testing |
| IEC 61400-25-6:2010 | Wind turbines – Part 25-6: Communications for monitoring and control of wind power plants – Logical node classes and data classes for condition monitoring |
| IEC TS 61400-26-1:2011 | Wind turbines – Part 26-1: Time-based availability for wind turbine generating systems |
| IEC TS 61400-26-2:2014 | Wind turbines – Part 26-2: Production-based availability for wind turbines |

In addition to the normal revision of standards the following new publications are underway:

| Reference | Title |
|---|---|
| IEC/TS 61400-3-2 Ed. 1.0 | Wind turbines – Part 3-2: Design requirements for floating offshore wind turbines |
| IEC/TS 61400-5 | Wind turbines – Part 5: Wind turbine rotor blades |
| IEC 61400-6 Ed. 1.0 | Wind Turbines: Tower and foundation design |
| IEC 61400-15 Ed. 1.0 | Wind turbines – Part 15: Assessment of site specific wind conditions for wind power stations |
| IEC/TS 61400-26-3 Ed. 1.0 | Wind turbines – Part 26-3: Availability for wind power stations |
| IEC 61400-27-1 Ed. 1.0 | Wind turbines – Part 27-1: Electrical simulation models for wind power generation |
| IEC 61400-27-2 Ed. 1.0 | Wind turbines – Part 27-2: Electrical simulation models for wind power generation – Wind power plants |
| PNW 88-477 Ed. 1.0 | Future IEC 61400-415 Ed.1: Wind turbines – Part 415: Terminology |

There are several critical issues for wind energy standardization. A wind turbine is a series-produced industrial product that later is being implemented under site-specific condition. Firstly, this means that in general a wind turbine is not designed to the specific conditions that it will meet, but rather to typical conditions, as specified in wind turbine classes. In the committee draft for the fourth edition of IEC 61400-1 Design Criteria [4], the possible general type classes are defined in terms of the basic parameters Vref, the 10 min average extreme wind speed with 50 years return period, $V_{ave}$, the annual average wind speed, and $I_{ref}$, which specifies the turbulence level, as listed here in *Table 4*.

Clearly, safety and function can only be ensured for a wind turbine designed to such general classes, when the conditions at the site of application have been analyzed and conformity with the assumed basic parameters or resulting loads has been assured.

Secondly, standards are being used as the normative requirements for certification by third parties. IEC standards have become the basis for many of the certifications with interpretations and supplementary requirements added from local national standards or private certification body guidelines. Almost all turbines are now certified. Certification of major components has become common. While certification by a qualified certification body means that the designer can enter into a dialogue on how to meet and document conformity with less stringent performance or functional requirements and hence not be limited in the development, the approach with a large number of certification bodies offering their services in several countries has led to harmonization issues.

Table 4 – Basic parameters for wind turbine classes.

| Wind turbine class | | I | II | III | S |
|---|---|---|---|---|---|
| $V_{ref}$ | (m/s) | 50 | 42.5 | 37.5 | Values specified by the designer |
| $V_{ave}$ | (m/s) | 10 | 8.5 | 7.5 | |
| $V_{ref,T}$ | (m/s) | | 57 | | |
| A+ | $I_{ref}$ (-) | | 0.18 | | |
| A | $I_{ref}$ (-) | | 0.16 | | |
| B | $I_{ref}$ (-) | | 0.14 | | |
| C | $I_{ref}$ (-) | | 0.12 | | |

Thirdly, a wind turbine plant is a complex system where random external conditions interact dynamically with the structural system with advanced control and interdependent components. Well-designed components do not necessarily add up to a safe and well-functioning system; a reality that standardization needs to take into account.

Finally, although the wind energy technology can be considered mature in the sense of the existence of a commercial market, the technology development is rapid, as can be seen from the previous discussion of what is considered the main-stream technology. While standards can be used to share new technical knowledge and best practices, create and maintain an international market without technical barriers and hence facilitate technical development, the development of more and more comprehensive technical standards may also be a barrier for technical development.

As most international markets base their technical requirements on IEC standards and require certification, standards and certification at this point has a good balance between ensuring safety and performance and instilling confidence in the technology, while also allowing and even facilitating further development. However, national regulations, limited understanding of the background of the standards and harmonization issues are serious challenges. Only by maintaining and developing standards, which are not overly descriptive and limiting, and by having very qualified certification bodies with mutual recognition, can international standards and certification be an effective tool to facilitate the technological development and the reduction of the cost of energy from wind energy.

## Conclusions

Recent years have seen a renewed effort in the technological development of wind turbine technology from competition within the wind energy sector as well as the competing energy technologies. The main-stream turbine technology development trend is characterized by up-scaling to turbines with larger rated capacity for both onshore and offshore applications, larger rotors for higher capacity factors and new drivetrain solution, including the direct-drive solution without gearbox.

The industry is international, and the old markets and suppliers from Europe and USA are challenged by Asia, in particular China. Maintaining and developing the competitive edge and jobs will require significant investments in education and research.

Standards and certification have been important instruments for facilitating technical development and create an international market without technical barriers; care should be taken in the future development to avoid limiting the technical development, which is necessary for reducing the cost of energy from wind.