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RESEARCH ARTICLE

Technological evolution of onshore wind turbines—a market-based analysis

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ABSTRACT

Wind energy technology is evolving towards larger machines (longer blades, taller towers and more powerful generators). Scaling up wind turbines is a challenging task, which requires innovative solutions as well as new configurations and designs. The size of wind turbines (in terms of rotor diameter, hub height and rated power) has increased extraordinary from 30 m rotor diameter, 30 m of hub height and 300 kW rated power, usual in the late 1980s, to 92.7 m rotor diameter, 87.7 m of height and 2.1 MW on average at the end of 2014. However, technological evolution has not only been focused on the scaling up process but also on developing innovative solutions that minimize costs at the same time as they deal with aspects of different nature, such as grid code requirements, reliability, quality of the wind resource or prices and availability of certain commodities, among others.

This paper analyses the evolution of wind technology from a market-based perspective by identifying trends in the most relevant technological indicators at the same time as stressing the key differentiating aspects between regions/markets. Evolution and trends in indicators such as rated power, rotor diameter, hub height, specific power, wind class, drive train configuration and power control systems are presented and analysed, showing an intense and fast technological development, which is enabling wind energy to reduce costs and becoming increasingly more competitive with conventional fuel-based generating technologies. © 2016 The Authors Wind Energy Published by John Wiley & Sons Ltd.

KEYWORDS
drive train; hub height; market penetration; power control; rated power; rotor diameter; wind class; wind turbine

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1. INTRODUCTION

Wind power is the renewable energy that has seen the largest and most successful deployment over the last two decades, achieving 370 GW of global cumulative capacity at the end of 2014.[1] Most installed capacity is concentrated in Asia with 142 GW (38% of worldwide capacity), Europe with 134 GW (36%) and North America with 78 GW (21%). Nevertheless, the role of emerging markets has increased considerably in recent years from 5.5 GW in 2010 (2.8% of total cumulative capacity installed at that year) to 15.5 GW at the end of 2014, and this trend is expected to continue in the following years.[2]

At the same time as installed capacity has increased, wind energy technology has evolved towards machines with longer blades and higher rated power. However, innovations have not only been focused on scaling up wind turbines, since as technology evolves, new market opportunities arise. Recent developments—such as those in blades, coatings or heating systems, just to name a few—enable wind energy to profitably expand to locations with limited wind resource, in cold climates or at higher altitudes (i.e. with lower air density). Innovation in offshore technology is pushing forward cost of energy reductions with more reliable wind turbine designs, new solutions in foundations as well as improvements in installation and maintenance. Innovation is not only aimed at maximising efficiency and reducing costs but also at providing additional services such as minimising environmental impacts (e.g. new blade designs and control strategies to minimize noise emission) or enhancing grid integration (e.g. developments in converters and controllers increasingly allow wind farms to provide grid support in a similar way to conventional generation plant). In summary, wind turbine manufacturers offer a product portfolio increasingly more tailored to the specific conditions or needs of each project. This fact, along with the concentration of local manufacturers in some markets, has led to differentiating technological aspects between regions[1].

Out of a wide variety of wind turbines, in the 1980s, the Danish three-bladed, fixed speed, stall-regulated turbine became the dominant model in the market at rated power levels of less than 200 kW. Since then, technology has evolved, and almost all modern utility-scale wind turbines are equipped with variable speed and pitch-regulated control systems at the same time as dimensions—both in terms of generator capacity and of rotor diameter—have grown steadily. Currently, wind turbines with 1.5–3 MW rated power, 90–110 m of hub height and 97–117 m rotor diameter are commonly installed in onshore projects. The main technological characteristics of current turbines can be summarized as follows:

- Steel, concrete or hybrid towers.
- An upwind rotor with three blades, active yaw system, preserving alignment with the wind direction. Rotor efficiency, acoustic noise, costs and visual impact are important design factors.
- High-wind-speed control. Pitch regulation, an active control where the blades are pitched along their axis (flapwise) to regulate the extracted power and reduce loads.
- Variable rotor speed, which allows optimising the energy capture at low-wind speeds (by operating at maximum power coefficient) as well as reducing mechanical loads on the drive train.
- The drive train converts the mechanical power captured by the rotor into electric power. A preliminary classification of wind turbines can be provided according to the steps (and hence the drive train components) involved in this conversion: (i) geared wind turbine with doubly fed induction generator (DFIG). Under this arrangement, the gearbox converts the slow rotating speed of the blades into the high rotational speed required by standard induction generators. A partial power converter allows the control of the electric generator speed so that it can be adapted to the rotational speed of the mechanical system. (ii) Gearless or direct drive configuration. A synchronous generator, either electrically excited or using permanent magnets, is directly coupled to the main shaft without gearbox (i.e. spinning at the same speed as the turbine rotor). The electric generator is connected to the grid through a full-power converter that adapts the variable frequency/voltage of the electricity generated to the grid frequency. (iii) Hybrid configuration. Slow rotating electric generators require a large number of poles that are translated into larger generator diameters (and hence heavier machines). This issue is even more pronounced in large wind turbines where the rotational speed of the blades is slower. Alternatively, in the case of geared wind turbines, higher speed conversion ratios imply more demanding operating conditions for the gearbox components and bearings. A compromise solution can be achieved by this hybrid configuration equipped with a gearbox—which converts the slow rotational speed of the blades to medium-/high-speed generator coupled with a full converter.

The existing literature describing technological aspects of wind turbines is vast, but because of the continuous technological evolution, a significant part of it is outdated. Therefore, this paper intends to complement and give continuity—by providing updated information as well as analysing trends on key technological features—to previous pieces of research analysing the state of wind energy technology. The main features of some of these studies are discussed in the following lines.

In 2000, Ackermann and Söder[3] published a thorough description of the then current wind turbine technology state of the art; this work was updated and extended in 2002.[4] In 2003, Carlin *et al.*[5] studied the capability of operating at variable speed different drive train configurations taking into account then–recent developments on power electronics. Along the same lines, in 2004, Hansen *et al.*[6] classified wind turbines in four configurations (introduced in the succeeding texts in Section 4) according to their speed control capability (i.e. drive train configuration). In 2007, Herbert *et al.*[7] presented latest technological developments on aspects such as aerodynamics, wind resource assessment or reliability. Also in 2007, Hansen and Hansen[8] presented a market-based study of wind technology by mainly analysing the worldwide evolution, from 1995 to 2004, of drive train configuration and power control system. In 2011, Kaldellis and Zafirakis[9] analysed the evolution of rated power and rotor diameter as well as the market share of stall-regulated versus pitch-regulated wind turbines. Finally also in 2011, Llorente *et al.*[10] analysed the evolution of wind turbine topologies with a specific focus on their power electronics content.

In a similar way to the work by Hansen and Hansen,[8] the present research analyses the evolution and market penetration of different technological solutions in the last 10 years (in this case, from 2005 to 2014). Nevertheless, in addition to the drive train configuration, other technological aspects (refer to description in Table I) have been analysed in this paper, at

[1]In this study, the global market has been divided in the following regions: Europe, Asia, North America and rest of the world. The countries considered in each region are detailed in the Appendix 2.

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Table I. Main wind turbine features analysed in this study.

Technological feature	Comments
Rated power (MW)	Regards to scaling up process
Rotor diameter (m)	Regards to scaling up process
Hub height (m)	Regards to scaling up process
Specific power (W m^{-2})	Represents the rated power per unitary area swept by the rotor; it is mainly related to the local wind resource conditions and/or desirable capacity factor
IEC wind class	Regards to local wind conditions
Drive train configuration	Selected according to several aspects (e.g. reliability requirements, grid codes or wind turbine size)
Power control	Enables to control the power output for high-wind speeds. It is selected according to power output requirements, complexity of the control system and requirements for loads reduction on blades

the same time that differences between regions are stressed. The scope of the present research is limited to onshore wind technology, since offshore wind has key technological characteristics—such as foundations, electrical system or installation and maintenance issues—that are perhaps more significant than the turbine itself. Therefore, providing a precise and up-dated picture of current offshore wind technology would require a considerably different approach than the proposed in the present research.

The present study is based on data collected by the Joint Research Centre (JRC) of the European Commission. This wind farm database contains information about more than 26 000 wind farms[2] worldwide with 336.4 GW of cumulative capacity. This is 97.9% (of the capacity declared by the Global Wind Energy Council (GWEC) at the end of 2014 excluding 2014 Asian installations[3]).[1]

Section 2 of the paper shows the evolution of the technological aspects of scaling up wind turbines (namely rated power, hub height and rotor diameter). Section 3 analyses the market penetration of different wind turbines according to IEC 61400-1 wind class standards. Section 4 examines the market evolution of the different drive train configurations currently employed by the manufacturers. Section 5 discusses about power control methods. Finally, conclusions and final remarks are included in Section 6. Additionally, as the information contained in the database about each technological feature is not entirely complete, the appendix will provide quality indicators of the data employed to perform the present analysis.

2. EVOLUTION OF RATED POWER, ROTOR DIAMETER AND HUB HEIGHT

Figure 1 shows a box plot representation[4] of the evolution of the rotor diameter of new wind turbines annually installed in the analysed markets during 2005–2014. The trend to longer blades is shown, a trend made possible thanks to materials technology being at the leading edge of technology development in wind energy. Blades are made (using moulds) of fibre-reinforced polymers (resins) in the form of laminates or sandwich substructures. Traditionally, blades were made of glass fibre and polyester resin. Current materials include as well epoxy resins reinforced mainly with glass fibres and to some extent with the lighter but more expensive carbon fibres. Carbon fibre was expected to be a key component to keep the blade light at the same time as stiff and slender. However, higher costs of carbon fibre and difficulties in the manufacturing process are preventing its generalized use.[11]

Almost all wind turbines installed during the analysed period use three blades, with the exception of 200.1 MW (0.06% of the installed capacity), mainly represented by the Vergnet GEV MP275, the Ming Yang MY 3.0 SCD and the Windflow 500 wind turbine models. Two-bladed wind turbine may have some room in the future for the offshore market (option currently explored by the Chinese manufacturers Ming Yang and Envision) because the potential cost reduction—in addition to lower noise requirements and visual impact offshore—of using two blades may overweigh the lower aerodynamic efficiency. However, the lower potential cost reduction for inland wind turbines makes this solution less attractive in case of onshore wind turbines.

[2]This number may differ from the actual number of wind farms installed in the world because different phases or wind turbines (officially belonging to the same farm) connected to the grid in different years are considered as independent entries to the database.

[3]At the moment of writing this paper, wind farms installed in China during 2014 (26 GW, according to the GWEC) were still not included in the JRC database.

[4]Bottom and top sides of each rectangle refers to the 25th and 75th percentiles. The horizontal line inside each rectangle represents the median, and the lower and upper horizontal lines outside the rectangles are, respectively, the 1th and 99th percentile. For the sake of clarity, wind turbines with less than 20 m rotor diameter, rated power under 0.2 MW and hub height below 30 m have been excluded from the analysis shown in this paper.

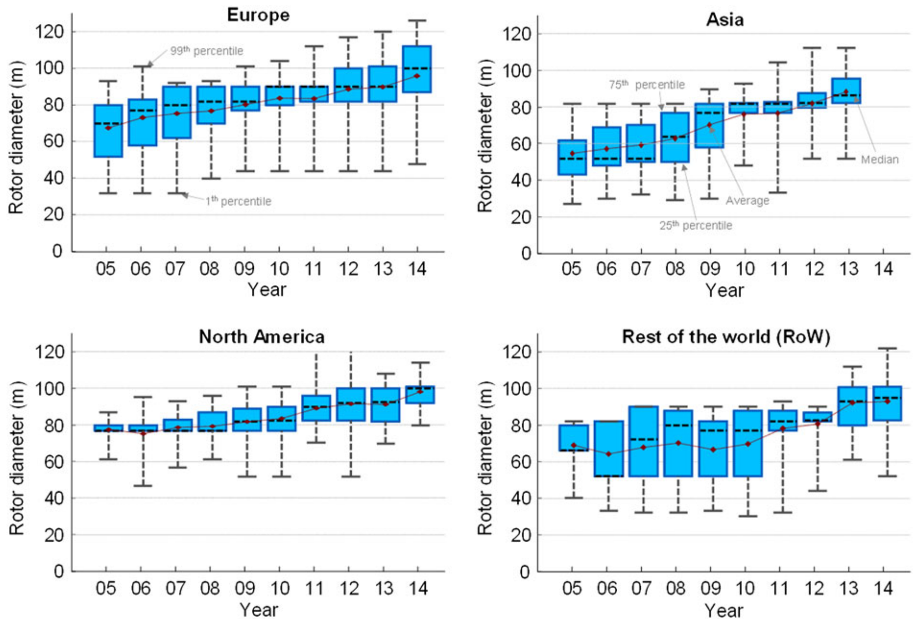

Figure 1. Box plot representation of rotor diameters of onshore wind turbines annually installed. Source: JRC database.

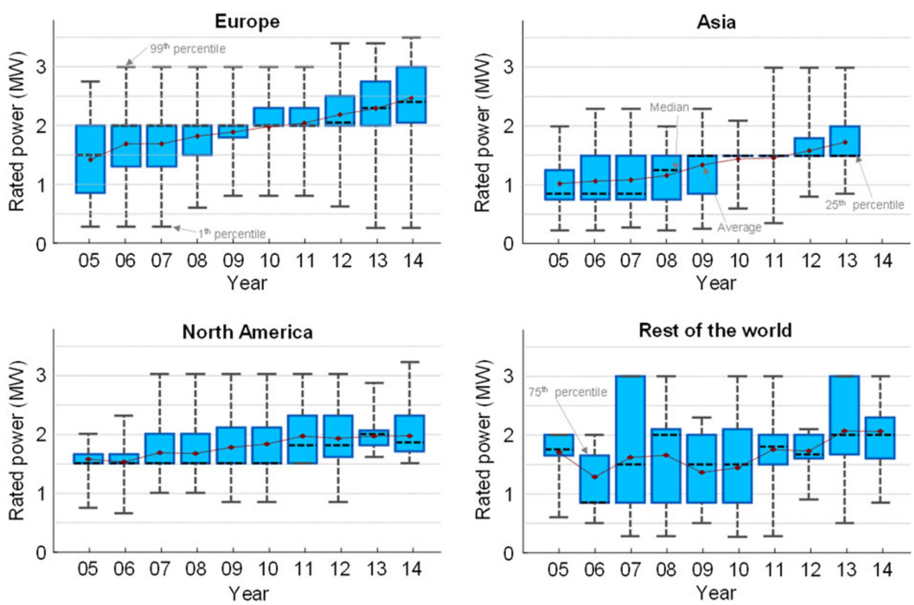

Figure 2. Box plot representation of rated power of onshore wind turbines annually installed. Source: JRC database.

The turbine rotor diameter of new installations in the world has grown steadily during 2005–2014, from an average 67.4 m in 2005 (equivalent to a swept area of 3568 m^2) to 95.9 m in 2014 (a swept area of 7223 m^2). This involves a 42.3% growth in rotor diameter, and more importantly from the point of view of energy capture, the swept area has doubled.

In 2014, the largest rotors were installed in North America (99.5 m average) followed by Europe (95.9 m) and by the rest of the world (93.1 m). Rotor diameters used in North America have historically been larger than in other markets mainly because it is a market dominated by medium wind speed characteristics. Rotor diameters in Asia (for which there is only data available until 2013) averaged 88.6 m, slightly smaller than in Europe that year (90.0 m). In this region, rotor diameters during the 2000s decade were significantly smaller than in Europe and North America; however, the increasing trend to low wind (as shown later in Figure 5) in the early 2010s prompted a sharp increase in rotor diameter in the following years.

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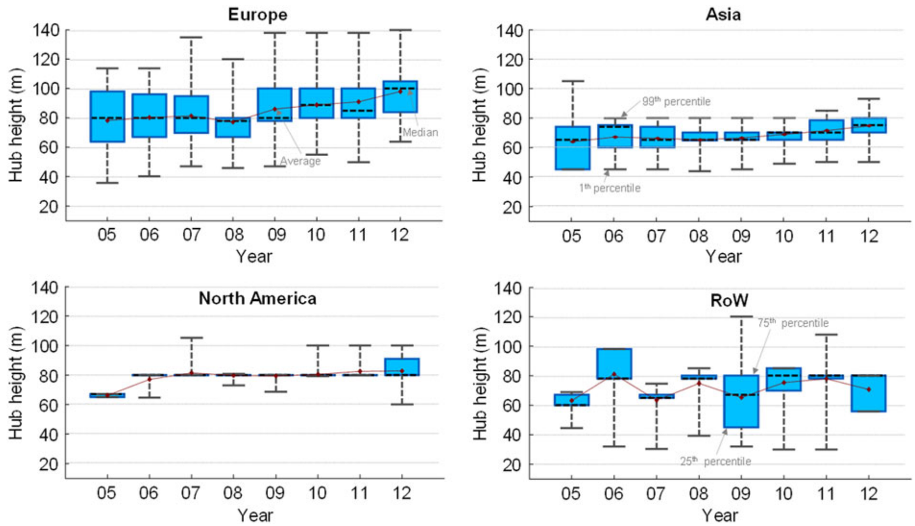

Figure 3. Box plot representation of hub heights of onshore wind turbines annually installed. Source: JRC database.

It is also interesting to notice that rotor diameters in Europe and the rest of the world (RoW) are more diverse than in Asia or North America, the underlying reason is the diverse quality of the wind resource across countries, which influences the type of wind turbine (i.e. aimed at low-, medium- or high-wind locations) and hence on the rotor diameter.

The evolution on rated power is shown in Figure 2. The average rated power of wind turbines installed in the world increased from 1.38 MW in 2005 to 2.20 MW in 2014. However, the increasing trend has been deeper in Europe, where average rated power has increased a 74.8% during the period analysed (from 1.42 to 2.47 MW), followed by Asia with a 68.6% of increase until 2013 (from 1.02 to 1.73 MW). In North America and the RoW, the increase of rated power has been much more moderated: a 27.4% (from 1.54 to 1.96 MW) and a 21.6% (from 1.69 to 2.06 MW), respectively.

In the same way as with rotor diameters, the rated power of wind turbines employed in Europe and the RoW is generally more diverse than in other regions. Contrariwise, Asian and North American markets are dominated by wind turbines with similar rated power (interesting is the case of Asia, where during 2010 and 2011 more than half of installed wind turbines had exactly 1.5 MW of rated power).

Figure 3 represents the hub heights of new wind turbines annually installed in Europe during 2005–2012.[5] The trend to taller towers is clear, and it is mainly motivated by the larger rotor diameters deployed in recent years (as shown before in Figure 1) and the emerging demand for low-wind turbines, since the increase of wind speed with height is generally more pronounced in low-wind locations (e.g. forested areas). As wind speed increases with height, it would be desirable to make the tower as taller as possible. However, the costs of the tower and foundations would also increase. Therefore, the tower height is optimized by taking into consideration both aspects: energy yield gained and tower costs.

Tubular steel towers have been the most widely spread solution, but the growing demand for taller towers is encouraging the development of alternative designs. The diameter of the towers increases with height, which may pose a transport problem for tall wind turbines (e.g. tower above 100 m height usually requires a base diameter above 4 m. The increase in hub heights is making that concrete increasingly emerge as an alternative to tubular steel towers supported by lower cost in particular for high heights and markets with high local content. Another solution, based on hybrid steel–concrete towers, is offered by manufacturers as Gamesa, Enercon, Nordex or Senvion. The base of the tower is made of concrete (either casted in site or composed by precast elements), and the upper part of the tower is compounded by tubular steel sections. Finally, lattice towers (used in first-generation wind turbines back in the 1980s and 1990s) require lower material in comparison with other types. However, their higher visual impact, maintenance requirements and aerodynamic interference limit their current usage to small wind turbines.

The trend towards bigger machines (especially in terms of hub height and rotor diameter) is expected to continue in the following years. However, increasing the blade length, hub height and/or rated power mean higher costs, more material and mass is required at the same time as nacelle, rotor, drive train, tower and foundation have to withstand additional structural loads. It is generally accepted that price of the turbine increases depending on the rotor diameter with a higher than

[5]Data on hub heights for the 2013–2014 is not still available in the JRC database. Additionally, the specific nature of this variable, depending on particular conditions of each wind farms, considerably affects to the availability of data. As shown in Appendix 1, the quality of the sample is limited, and results shown in the figure may differ from the real hub height evolution.

Table II. Wind classes according to IEC 61400-1.

Wind class turbine		I	II	III	S
Reference wind speed average (V_{ref}) over 10 min (m s^{-1})[a]		50	42.5	37.5	Values specified by the designer
Turbulence category	A:		0.16		
	B:		0.14		
	C:		0.12		

[a]The annual average wind speed (V_{ave}) is calculated as $V_{ave} = 0.2V_{ref}$.

quadratic trend.[12] Increasing the wind turbine size is also a challenge for land transportation. Blades longer than 50 m usually pose a transportation issue because of large turning radius. Nevertheless, it is the necessary increase to the base sections of the tower, in order to hold longer blades, the more restrictive constraint.[13] Another element that can also play a role in deploying longer blades is the limitation by law of maximum tip height currently in force in some countries, whether because of interference with aviation radars or for aesthetic reasons.

3. TECHNOLOGICAL FEATURES DEPENDING ON WIND RESOURCE

The design of wind turbines also depends on the quality of the local wind resource. Table II summarizes the four wind classes defined by the IEC 61400-1 standards.[14] In practice, *classes I* to *III* refer to high, medium and low-wind locations, respectively.

In addition to the particular design requirements associated with each wind class and aimed at ensuring wind turbine integrity, wind turbine low-wind locations are usually equipped with larger rotors, taller towers and moderately rated power as a compromise between equipment costs and energy output. Overall, wind turbines aimed at low-wind sites imply higher specific (per rated power) capital costs than turbine designs aimed at high-wind sites. Nevertheless, the higher costs of larger rotors and taller towers are partly compensated by smaller electric generators, power converters and gearboxes (if applicable) enabling turbines aimed at low-wind conditions to be competitive in locations with less favourable wind resources.

Figure 4 shows a comparison of rotor diameter versus wind turbine rated power for a selected sample of wind turbines currently available in the market. Figure 4 also shows the contour lines of equal specific power (200, 300, 400 and 500 W m^{-2}). These contour lines give an insight of the market (low or high wind) to which the wind turbine models are addressed (i.e. wind turbines with lower specific power are addressed to low-wind locations whereas higher specific powers refer to high wind).

As can be observed, there is a significant number of wind turbine models in the range 2–3 MW with the same rated power and diverse rotor diameter. More specifically, the achievement of such a wide range of specific power has been possible thanks to the recent growth of rotor diameters. As an example, for wind turbines with a rated power around 3 MW, the rotor diameters vary from a minimum 82 m (568 W m^{-2}) for the Enercon E-82 E3 to a maximum of 131 m (223 W m^{-2}) for the Nordex N131/3000.

Figure 5 shows the evolution of onshore installed capacity according to the different wind classes. As can be observed, *class I* wind turbines are progressively losing ground in the global market in favour of *class II* and *class III* wind turbines.

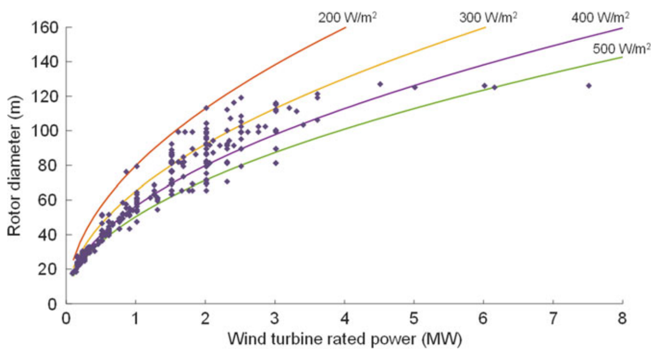

Figure 4. Comparison of rotor size with turbine rated capacity for onshore wind turbines currently being commercialized. Source: JRC database.

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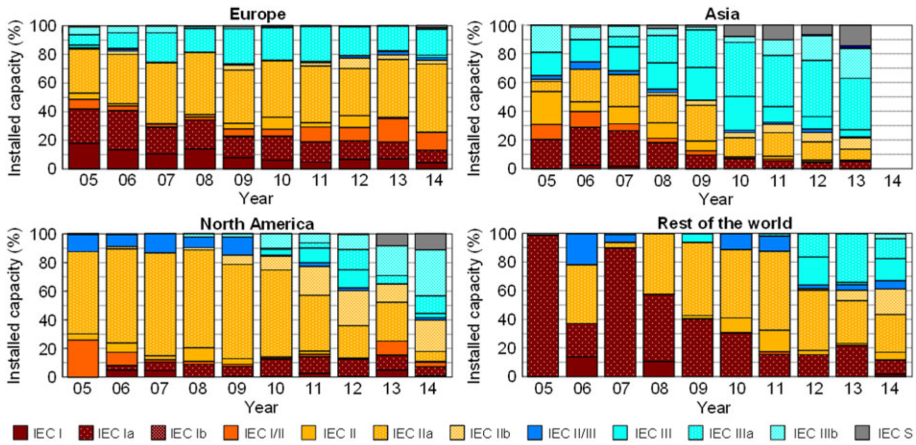

Figure 5. Evolution of the share of onshore installed capacity by IEC wind classes. Source: JRC database.

In Europe, the evolution is highly dependent on the country-specific wind conditions. In particular, Germany (which represented a 41% of the installed capacity in Europe during 2014) is increasingly a market dominated by low-wind turbines (*classes II* and *III* represented 77.4% of the market, whereas *class I* took a mere 2.2% and *Class I/II* took 18.7%) as a consequence of the reduced availability of high-wind locations and of a support scheme tailored to the quality of the local wind resources.

Class III wind turbines predominate in the Asian market mainly because the prevailing low-wind resource in large parts of China and India. The North American market was mainly dominated by *class II* turbines (medium wind); however, an increasing deployment of low-wind (*class III*) applications can be observed during the period 2010–2014. A similar scenario can be observed in the RoW where *class II* wind turbines prevail, with a declining role of *class I* that can be because of high-wind sites being taken first during the previous decade.

As previously introduced, wind turbines aimed at low-wind locations have smaller ratio rated power to swept area than wind turbines aimed at high-wind locations. This ratio can be represented by the so-called specific power, defined as the ratio rated power to swept area. The evolution of this parameter is shown in Figure 6, where it can be observed the trend towards lower specific power that is consistent with the increasing market penetration of *class II* and *III* wind turbines.

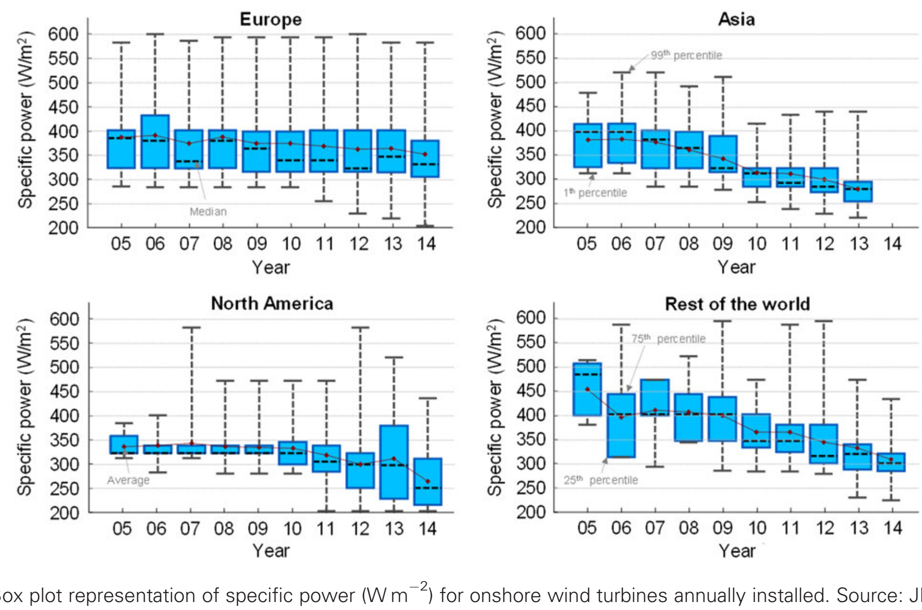

Figure 6. Box plot representation of specific power ($\mathrm{W\,m^{-2}}$) for onshore wind turbines annually installed. Source: JRC database.

North America averaged the lowest specific power in 2014 (264 W m^{-2}). However, the higher decreasing trend has been observed in the emerging markets in the RoW. The trend towards lower specific power is less pronounced in Europe; however, the wider diversity of the wind resource has led to higher differences between minimum and maximum values of specific power, as a consequence of more tailored turbines to wind resource availability.

4. DRIVE TRAIN CONFIGURATION

Drive train configuration is one of the criteria usually employed to classify wind turbine technology. The classification provided by Hansen *et al*. (2004) has been widely employed in the existing literature. For a more detailed description of each configuration and electric generator types, we would like to refer to[61516] and[17].

- *Type A*. Fixed-speed generator. The rotational speed of the electric (asynchronous) generator—squirrel cage induction generator (SCIG) is usually employed in this configuration because of its constructive simplicity and robustness—is constrained by the spinning speed of the blades with very limited range response to variations in wind speed. Neither power converter nor other speed regulation techniques are employed in this configuration. NEG Micon N48 and Vestas V27 are some examples of type A wind turbines.
- *Type B*. The speed of the asynchronous generator is controlled by a variable resistance that enables modifying the current circulating in the rotor. As a consequence, wounded rotor induction generators are employed in this configuration. This solution provides higher control flexibility than type A. However, the electrical losses are relatively high, and the response to grid requirements is very limited. Vestas V52 and Suzlon S82 are the main representatives of this configuration in the market.
- *Type C*. This configuration is known as DFIG. The current in the electric generator's rotor is controlled by a power converter. Thus, electrical losses are lower, and the response to grid requirements is enhanced. Since the power converter is only connected to the rotor of the generator, the converter only covers around 30% of the energy generated by the wind turbine. Vestas V90, Gamesa G80 and General Electric GE 1.5 are some representative models of this configuration.
- *Type D*. A full-power converter enables decoupling the generator from the grid frequency, so that the frequency (and hence the rotational speed) of the generator can be fully controlled and the use of a gearbox can be avoided. Additionally, the full converter provides enhanced grid services. Enercon is the dominant manufacturer in direct drive wind turbines based on electrically excited synchronous generators (EESGs); this configuration is referred hereafter as *type D-EE*, whereas Goldwin has manufactured most wind turbines in the market employing direct drive combined with permanent magnet synchronous generators (PMSG); this arrangement is referred hereafter as *type D-PM*.

Hansen's original definition of type D covers either direct drive or gearbox-equipped wind turbine. However, the market has changed, and recent years have seen the development of new turbine models with increasing variations (no direct drive-based) on the original type D definition. This market evolution limits the analysis of new wind turbines to configurations of types C and D, which greatly reduces the margin that technologists have for their analysis.

In order to solve this limitation, this paper suggests that the different configurations currently classified as type D should be redefined into several categories for market analysis purposes. Therefore, we propose that hereafter when referring to the *type D* configuration only full-converter, direct drive machines are included and that the following configurations including gearbox and full converter are defined as separate categories:

- *Type E*. Gearbox-equipped wind turbine with a full converter and medium-/high-speed synchronous generator (EESG or PMSG). In practice (with exception of the old model Made AE-52), all type E wind turbines use permanent magnets. Gamesa G128-4.5 MW and Vestas V112-3.0 are some examples of this configuration.
- *Type F*. Gearbox-equipped wind turbine with a full converter and high-speed asynchronous generator. Thanks to the use of the full converter, a simpler generator (SCIG) can be used, which is the case for the most popular turbines under this configuration, the Siemens SWT-2.3 and SWT-3.6 series.

In summary, types A, B and C are geared high-speed wind turbines, type D corresponds to direct drive configuration and types E and F are hybrid arrangements.

Figure 7 depicts the components and topology corresponding to each one of the previously defined wind turbine types. Table III (compiled and adapted from[18–20] and[21]) summarizes the main features of the configurations presented in the preceding texts. This table, when combined with the advantages and disadvantages of permanent magnet-based generators (to be taken into consideration just for types D and E), should identify an overall picture of the drive train configurations currently employed by wind turbine manufacturers.

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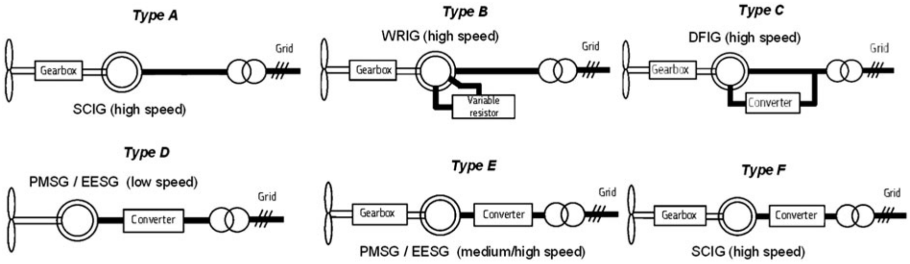

Figure 7. Wind turbine types according to drive train configuration.

Table III. Comparison of different drive train configurations.

	Advantages	Disadvantages
Type A	• Low upfront cost: no power converter and SCIG generator (cheaper than wounded induction generator).	• No speed control • Low aerodynamic efficiency (as speed control cannot be performed, power coefficient is maximum in just one operating point)
	• Robust electric generator (low maintenance)	• Low grid integration: no fault ride-through capability, no reactive control • Highly demanding for mechanical components and poor mechanical control • Gearbox required
Type B	• Low upfront cost (compared with types C, D, E and F)	• High electrical losses • Gearbox required
	• Enhanced speed control capability (compared with type A). Typically, −10% around the synchronous speed	• Wounded rotor: need slip rings, more expensive and higher maintenance than SCIG
Type C	• Variable speed (limited to ±30% around the synchronous speed)	• Limited grid integration (compared with full converter, i.e. types D, E and F)
	• Relatively inexpensive power converter	• Wounded rotor: need slip rings, it is more expensive and requires higher maintenance than SCIG • Gearbox required
	• Capability of reactive power control (enabling voltage control) • Power converter provides smooth grid connection	• Operating speed range still limited
Type D	• Full-speed range • No gearbox required • Complete control of reactive and active power • Full control of amplitude and frequency of the voltage	• Expensive full-scale power converter • Heavy electric generator required for bigger wind turbines
Type E	• Full-speed range • Complete control of reactive and active power • Full control of amplitude and frequency of the voltage • Reduced size and weight of electric generator (compared with type D) • Less amount of rare earths required (compared with type D-PM) • Reduced gearbox ratio and less weight (compared with types A, B, C and F)	• Expensive full-scale power converter • Gearbox required
Type F	• Full-speed range • Complete control of reactive and active power • Full control of amplitude and frequency of the voltage • Reduced size and weight of electric generator (compared with types D and E) • Robust and cheap electric generator	• Expensive full-scale power converter • Gearbox required • Higher gearbox ratio required, i.e. heavier and bigger (compared with type E)

Permanent magnet-based generators are more efficient than the traditional DFIG and EESG, especially operating at partial loads. Additionally, permanent magnet generators have fewer moving parts than EESGs and wound rotor induction generators, being more robust and requiring less maintenance.

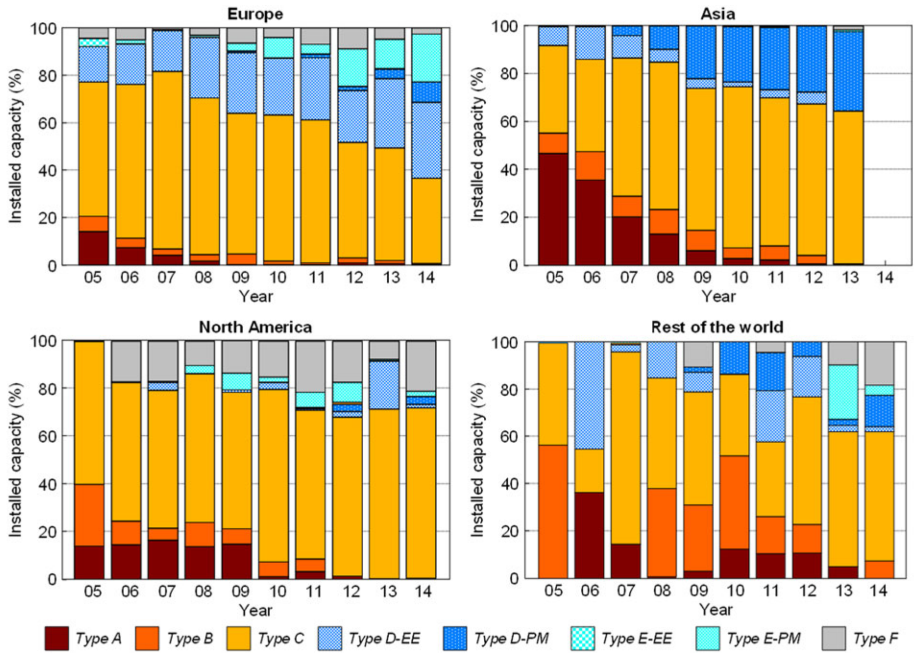

Figure 8. Evolution of the share of installed capacity by wind turbine configuration Source: JRC database.

The main problem faced by permanent magnet generators is the high variability in the price of its raw materials, namely the rare earths needed to manufacture permanent magnets, mostly neodymium and dysprosium.[22] The latter increased in 2011 to reach more than 20 times above their previous 5-year average (a more detailed analysis can be found in[23]). The effect of this spike in prices is reflected by the reduction on the share of installed wind turbines employing permanent magnets during the following years, mostly in the European and North American markets. Manufacturers such as General Electric decided to abandon permanent magnet generators[6]. Currently (mid-2015), the prices of rare earths are at pre-2010 levels, but there is no guarantee that they will remain at these levels. A further problem with rare earths is the double risk associated with the high geographical concentration of the supply of rare earth elements with about 90% of them extracted in China.

Figure 8 shows the market share depending on the drive train configuration. As it can be observed, types A and B have currently a marginal role, being the market dominated by type C and at a lesser extent by type D but with an increasing trend. Nevertheless, types E and F are gaining more market share (in particular type *E* in European countries and type F in the North American market). This trend is expected to continue in the following years as the grid codes are becoming more demanding. The share of PMSG installed has increased in the late years and, especially in the Asian market, where most of installed type D generators are based on permanent magnets.

Figure 9 shows the type of turbine configuration employed in onshore wind turbines installed during 2014 (2013 in case of Asia), classified according to wind turbine rated power. As it can be appreciated, turbine configuration are strongly related to rated power; DFIG (type C) is by far the preferred solution for wind turbines below 2 MW, with the exception of Asia because of the dominance of manufacturers of direct drive permanent magnet-based generators in China. Type C configuration loses ground for rated powers higher than 2 MW in favour of other alternative solutions:

- In the range of 2–3 MW, direct drive, EESGs were the most employed solution in the European market (Enercon covered the whole European market in this segment). Type D-PM, type E-PM and type F represented respectively 11, 20 and 3% of the European market. However, *type F* configuration had a more prominent role in the North American (1500 MW) and the RoW (948 MW) markets. It is also interesting to mention the market impact of type B configuration for this power range—used in some Suzlon turbines—in the RoW markets with 370 MW installed during 2014 (mainly in Brazil and South Africa).
- For wind turbines with rated power higher than 3 MW, geared configurations seem to be the preferred solution in Europe with type C—mainly supplied by Senvion and Nordex—and type E based on permanent magnets having similar market share, whilst type D-EE represented an 8% of the European installed capacity in this rated power range.

[6]GE's 2.5 MW turbines were originally sold with a permanent magnet generator and a full converter, according to the 2010 brochure 2.5 MW Wind Turbine Series, but the models currently being sold are DFIG.

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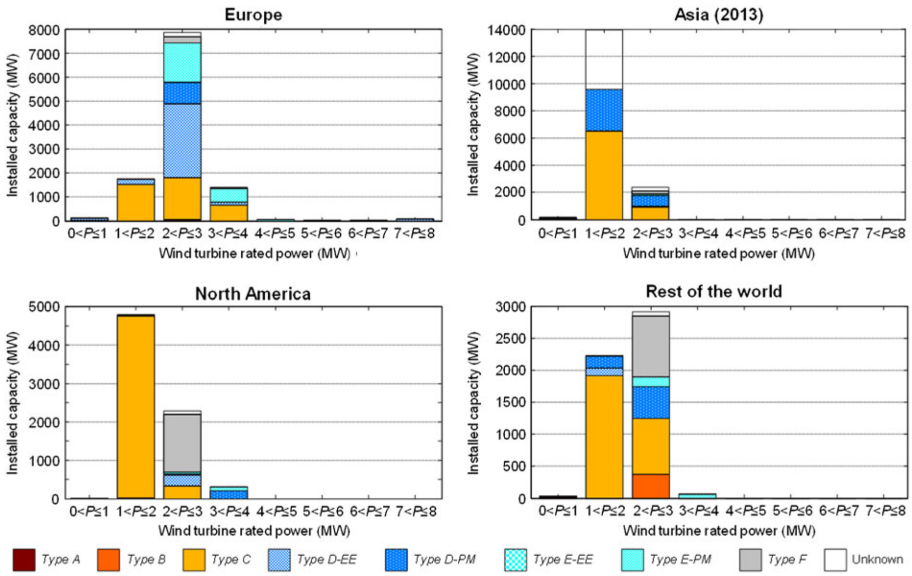

Figure 9. Turbine configuration according to rated power in onshore wind turbines installed during 2014 (during 2013 in Asia). Source: JRC database.

However, in North America, type D-PM dominated the market representing 205 MW compared with 99 MW corresponding to type E-PM.

The spread of the different configurations in the market depends on the manufacturers that support them with commercial machines. For this reason, we consider it important to look at the share of each manufacturer in the different wind turbine configurations, and this is shown in Figure 10 globally for the 2013 market[7].

The global market share of each wind turbine type is shown in parenthesis (letters in bold), and the indicated percentages per manufacturer refer to the particular share for each type. As it can be observed, there are clear technological differences for the top four manufacturers in 2013: Vestas, Goldwind, Enercon and Siemens.[24,25] The technology of Vestas is based on geared wind turbines, mainly type C (covering 70% of its total installed capacity) but also type E-PM (30%). Goldwind's wind turbines are characterized by permanent magnet-based generators: 97% of its installed capacity was direct drive (i.e. type D-PM), and 3% was geared (type E-PM). Enercon's technology is exclusively based on direct drive with EESGs (type D-EE), being the clear leader in this technology. Finally, Siemens' wind turbines are equipped with full-power converter: 74% of installed capacity by the company was type C—technology exclusively employed by Siemens—and the remainder 26% was type D-PM.

Overall, the analysis shows that there is no clear convergence towards a single best drive train configuration but that configurations are continuously evolving. Therefore, it is still a very active field of research and development, and new configurations may potentially achieve significant market shares in the future. Some of these alternative designs are

- Continuously variable transmission, which would allow assembling synchronous generators directly connected to the grid, avoiding the power converter.[26,27]
- Hydraulic transmission that is also continuously variable but lighter and cheaper than conventional gearboxes[28]; on the negative side, its performance is still low. Large diameter generators with hydraulic transmission would enable a reduction in generator structural materials[29,30]; however, protecting windings and magnets from environmental conditions may be an issue.
- Magnetic pseudo-direct drive train, the magnetic gear and the electric generator are integrated in the same machine. It is claimed that this device would be around 50% smaller in terms of mass and size than a conventional direct drive with permanent magnet generator.[28] Additionally, the absence of rolling and frictional elements would reduce losses and improve reliability. On the negative side, a significant amount of permanent magnets would be required.

[7]Because of lack of data for Asia in 2014, 2013 has been taking into account in order perform a fair analysis between manufacturers of different regions.

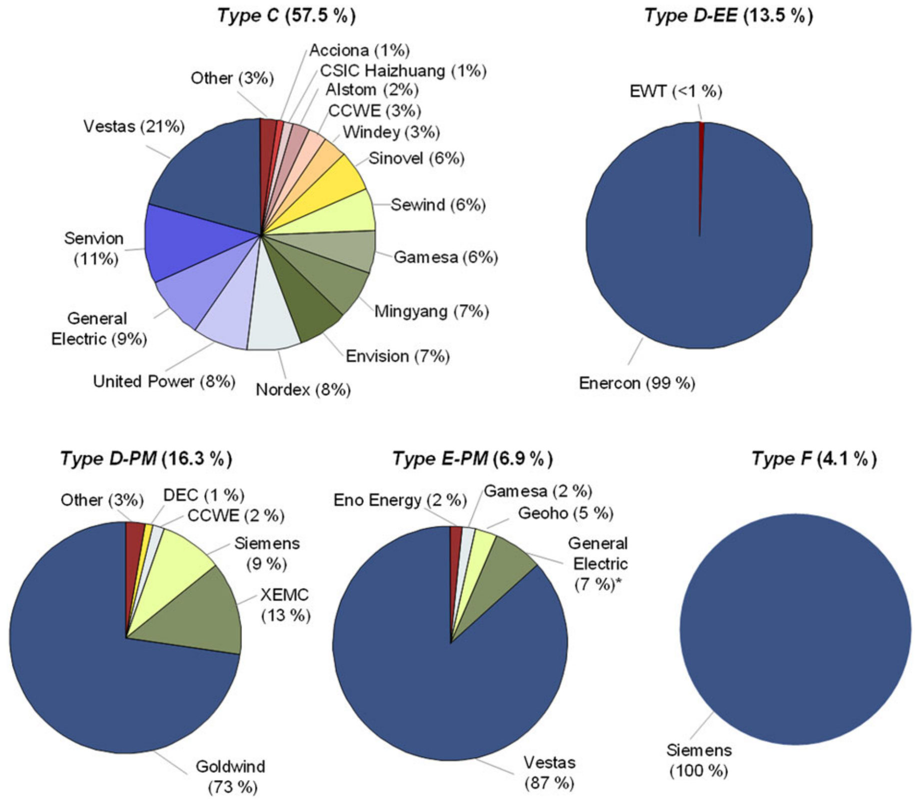

Figure 10. Manufacturers' global market share (capacity) per wind turbine type during 2013. Source: JRC database. In 2012, GE started to use DFIG instead of PMSG in the GE2.5 series. Therefore, as the share of wind turbines using DFIG or PMSG has not been disclosed, in this analysis, half of the capacity installed during 2013 of the GE2.5 series has been considered as *type E-PM* and the other half as *type C*.

- Superconducting generators may potentially be an alternative to permanent magnet generators, because superconductors exhibit virtually zero resistance that would allow to increase the circulating current in the windings and to achieve higher air-gap flux densities. In this case, the volume of the machine can be reduced by a factor of two to three compared with traditional machines.[31] Despite the attractive advantages offered by superconductors, there are also substantial uncertainties and challenges, mainly related to the necessary cooling systems and costs.

5. POWER CONTROL

The power extracted by a wind turbine depends on the tip speed ratio—the ratio between the linear speed of the tip blade and incoming wind speed—and especially on the pitch angle of the blades. In case of low-wind speeds, the turbine operates to maximize the conversion from aerodynamic energy to mechanical energy (i.e. operating at maximum power coefficient) by controlling the tip speed ratio. However, for higher wind speeds (higher than the rated wind speed), the energy extracted from the airflow is controlled/limited to avoid excessive loads on the rotor and prevent structural damages on the turbine. There are mainly four approaches to control the extracted power under these conditions:

(i) Passive stall control (PSC), which is the simplest approach consisting on firmly attaching the blades to the hub. Therefore, the angle of attack is fixed for all operational conditions. However, for high-wind speeds, the design of the blade makes the airflow to stall (loosing aerodynamic efficiency) and hence limiting the energy captured. Despite being cheaper—in terms of upfront costs—than other approaches, there are several drawbacks, as the energy production is not maximized (the rated power is achieved just for one operating point) and the blades are subject to high stress in case of wind gusts and extreme weather conditions. Gamesa G47-660, Goldwind 0.75/48 and Goldwind 0.75/50 are some examples of this configuration.

(ii) Active stall control (ASC). Under this control approach, when the wind speed is higher than the rated wind speed, the blades are pitched to increase the angle of attack in order to achieve stall conditions. Compared with PSC, the

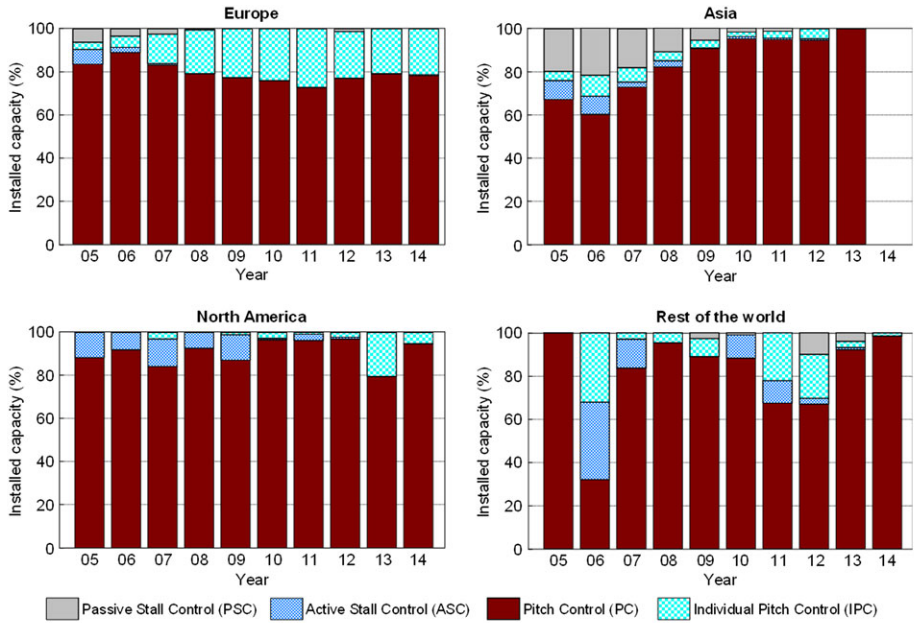

Figure 11. Evolution of power control approach of onshore wind turbines annually installed. Source: JRC database.

turbine is more complex, as it has to be equipped with pitching mechanism and controllers. However, it has several advantages such as smother power output and assisted start-up. Vestas V82-1.65 is the main representative of this approach in the market.

(iii) Pitch control (PC). This method consist on turning the blades into the opposite angle as they are turned by the ASC, i.e. reducing the angle of attack in order to limit the power captured by blade feathering (instead of stalling as in case of ASC). PC requires a more sophisticated and faster control system than active stall approach. However, the power output can be maintained at the rated power for a certain range of wind speeds above the rated wind speed. As shown in Figure 11, most modern wind turbines use PC as power regulation method. Some of the most representative examples are General Electric GE 1.5sle, Vestas V90-2.0, Siemens SWT 2.3-93 or Gamesa G90-2.0.

(iv) Individual pitch control (IPC). As the length of rotors increases, reducing the loads on blades is increasingly more important in order to improve the lifetime of wind turbines. IPC aims at reducing the asymmetric loads (mainly produced by wind shear effect, tower shadow, yaw errors and turbulence), by individually pitching each blade during the rotational movement of the rotor. In contrast, the control algorithms become more complex, and the continuous adjustments during rotation lead the pitch system (mainly, drives and bearings) to be operated under more demanding conditions. Enercon E-82/2000, E-82/2300 and General Electric GE 2.85-100, GE 2.85-103 are representatives of this technology.

As it can be observed in Figure 11, PC is the most widespread solution for power control in modern wind turbines. IPC also has some market impact, especially in Europe, where its market share progressively increased during the late 2000s. However, this trend slightly reversed by 2012 resulting in 21% of the European market in 2014. The impact of IPC in other markets is lower, with some market share (with an irregular trend) in the RoW and to a lower extent in North America. In Asia, IPC has progressively lost ground since 2006. Finally, both PSC and ASC have a marginal presence in the current market. PSC had some market share in the late 2000s in Asia, whilst ASC was occasionally used in North America and the RoW during last decade.

6. CONCLUSIONS

The analysis performed in this paper on current state of wind energy technology shows, despite being considered a mature technology, continuous development and active research aiming at improving the competitiveness of wind energy. Scaling up wind turbines is one of the main challenges faced by the industry given the pseudo-exponential growth of mass/weight with size in most components such as blades and towers.

The evolution to longer blades observed in recent years has also enabled an increasing trend to new wind turbine designs aimed at low-wind locations, with large rotors, tall towers and moderated rated power. As a result, there is increasing diversity in the ratio rotor diameter to rated power that encourages manufacturers to adopt a modular approach, enhancing flexibility, at the same time as production of components is standardized. This means that, as technology evolves, more tailored products to the local wind resource are offered by manufacturers.

The market shows that there are clear technological differences between geographical zones. Some of them are driven by the local quality of the wind resource that mainly affects the selection of the wind class (hence to the ratio between rated power and swept area). It can be expected that the technology of the dominant (local) supplier or suppliers is also a factor. However, other differences seem to be triggered by other technological aspects. Drive train configuration is evolving towards the use of full converters, whereas DFIGs are losing ground. In Europe, permanent magnets are mostly employed onshore in hybrid wind turbines—with full converter and gearbox—which enable reducing the size of the electric generator (hence reducing the amount of rare earths required) for wind turbines in the range of 2–3 MW. In other words, most direct drive wind turbines (employed in 1–3 MW range) installed in Europe are based on electrically excited generators. However, the trend is completely different in Asia where direct drive wind turbines in the 1–2 MW range with permanent magnets are becoming increasingly popular. There are several drivers that can justify this trend: First, the Asian market is predominately a low-wind market (i.e. moderate rated power, which favours the deployment of direct drive configuration); secondly, the use of permanent magnets is not an issue for Asian manufacturers, because of the availability of rare earths in China; third, the main world manufacturers of turbines with permanent magnet generators are Chinese (Goldwind and XEMC).

Finally, the analysis performed on power control systems shows a clear preference pitch-controlled wind turbines, followed by IPC (with uneven impact on the analysed markets) and a marginal role of passive and active stall-regulated wind turbines.

APPENDIX 1. Assessment of the database used

The quality of the technological analysis performed in this study is dependent on the quality of the data used. There are some pieces of information that are particularly critical in order to perform the present analysis. In a first step, a wind farm database with accurate information about wind turbine models and number of wind turbines installed in each wind farm is crucial. In this regard, as stated in the introduction, the JRC wind turbines database covers 97.9% of the capacity installed in the world excluding the Asian installations of 2014. However, information about wind turbine model and number of wind turbines is available for 96.3% of the overall installed capacity (also excluding new installations in Asia during 2014). In a second step, the technical specifications of some wind turbine models are not disclosed by manufacturers. Therefore, in order to give an insight of the accuracy of the presented study, Table IV shows the percentage of capacity identified in the JRC database—in each one of the aspects analysed—compared with the actual installed capacity in each region (shown in Table V).

As it can be appreciated, in most cases, the identified capacity is above 90% taking as a reference the annual installed onshore capacity compiled from GWEC annual reports. Rated power and rotor diameter (and consequently specific power) are the technological indicators that are easier to identify, since they are commonly provided by the manufacturers and, in most cases, also implicit in the wind turbine model name. Data about IEC wind class and drive train configuration is for some wind turbine models more difficult to obtain; hence, the identified capacity for these aspects is lower than in the case of rotor diameter and rated power. Nevertheless, with the exception of Asia, in most cases, the identified capacity is above 75%, being a reliable sample to assess the actual market share for these technological features. Finally, it is also worth mentioning the differences on the methodology employed to allocate new capacity to a certain year, depending on whether the wind farm are commissioned or actually connected to the grid, may lead to small mismatches between the installation year in the JRC database and the capacity stated by GWEC, resulting, in some cases, on an ratio of identified capacity slightly above 100%.

Table IV. Percentage of capacity in the JRC database, for each analysis and year, compared with capacity reported by GWEC.

		Year									
Technological indicator	Region	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Rotor diameter (Figure 1)	Europe	97.2	88.8	97.2	94.1	100.7	98.4	82.5	75.2	97.4	98.7
	Asia	42.4	63.6	81.6	90.8	97.3	90.3	87.4	97.4	75.5	—
	North America	77.0	104.4	87.4	85.7	99.9	104.6	96.4	94.5	97.7	99.9
	Rest of the world	71.9	80.6	102.8	95.1	95.2	71.1	113.4	107.8	91.9	99.4
Rated power (Figure 2)	Europe	101.6	98.0	101.9	98.5	107.9	100.0	85.7	76.9	99.6	99.9
	Asia	61.0	73.1	86.4	94.5	102.7	99.0	96.0	97.8	91.0	—
	North America	94.6	107.3	94.3	99.3	104.7	111.6	101.4	99.4	98.0	100.4
	Rest of the world	71.9	80.6	102.9	95.1	95.2	68.5	113.4	107.8	104.5	99.7
Hub height (Figure 3)	Europe	5.6	30.3	11.9	11.5	13.1	11.0	15.6	15.2	—	—
	Asia	8.0	11.5	18.3	40.2	39.3	43.3	37.3	35.3	—	—
	North America	5.6	30.3	11.9	11.5	13.1	11.0	15.6	15.2	—	—
	Rest of the world	40.0	30.3	54.3	51.9	37.0	26.9	54.9	8.7	—	—
IEC wind class (Figure 5)	Europe	76.0	75.7	88.8	91.4	99.2	95.9	81.9	73.6	94.7	97.0
	Asia	29.9	53.8	76.1	81.4	94.6	90.8	84.0	85.1	65.6	—
	North America	93.0	101.0	92.9	96.3	100.7	107.8	98.8	99.1	97.0	97.1
	Rest of the world	52.8	62.7	93.1	93.3	92.7	67.5	106.9	90.2	91.9	94.4
Specific power (Figure 6)	Europe	97.2	88.8	97.2	94.1	100.7	98.4	82.5	75.2	97.4	98.7
	Asia	42.4	63.6	81.6	90.8	97.3	90.3	87.4	97.4	75.5	—
	North America	77.0	104.4	87.4	85.7	99.9	104.6	96.4	94.5	97.7	99.9
	Rest of the world	71.9	80.6	102.9	95.1	95.2	71.1	113.4	107.8	91.9	99.4
Drive train configuration (Figure 8, Figure 9 and Figure 10)	Europe	94.4	86.4	95.5	93.0	100.0	96.7	82.7	74.8	96.9	97.5
	Asia	42.0	62.3	80.6	88.9	96.9	89.7	83.3	83.9	64.8	—
	North America	93.3	103.5	90.4	97.8	104.6	111.1	97.3	97.9	92.1	98.8
	Rest of the world	71.9	80.2	102.8	93.7	93.1	68.5	111.9	107.8	91.9	98.4
Power control (Figure 11)	Europe	93.3	85.9	94.4	87.9	95.8	91.1	76.8	68.0	86.8	87.9
	Asia	43.1	61.6	80.2	87.8	97.8	90.2	84.8	83.5	63.4	42.9
	North America	93.3	107.3	94.3	97.9	104.6	111.6	98.8	99.1	97.2	96.7
	Rest of the world	71.9	80.6	102.7	93.7	95.2	68.5	108.4	90.2	89.1	93.9

APPENDIX 2. List of countries in each analysed market

The countries considered in each one of the analysed markets are summarized in Table VI.

Table V. Annual onshore installed capacity (MW) per region.

	Year									
Region	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Europe	6226	7616	8343	8504	9941	9036	9415	11578	10464	11374
Asia	2352	3679	5225	8579	15371	21350	20830	15380	18153	25766
North America	2670	3230	5630	8884	10946	5805	8127	14860	3063	7359
Rest of the world	431	580	348	711	1429	1092	1226	1685	1980	5250

Source: GWEC.

Table VI. Countries considered in each analysed market.

Europe	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovenia, Slovakia, Spain, Sweden, the UK, Turkey, Faroe Island, Iceland, Norway, Russia, Switzerland, Ukraine and Macedonia
Asia	Bangladesh, China, Fiji, India, Iran, Israel, Japan, Jordan, South Korea, Sri Lanka, Taiwan, Thailand, Vietnam, Pakistan, Philippines and Mongolia
North America	Canada, the USA and Mexico
Rest of the world	Albania, Algeria, Argentina, Armenia, Australia, Azerbaijan, Bahamas, Belarus, Bolivia, Bosnia & Herzegovina, Brazil, Cape Verde, Chile, Colombia, Costa Rica, Crimea, Cuba, Dominican Republic, Ecuador, Egypt, Eritrea, Ethiopia, Honduras, Jamaica, Kenya, Maldives, Mauritius, Morocco, New Zealand, Nicaragua, Panama, Peru, Puerto Rico, Saint Kitts and Nevis, Seychelles, Somalia, South Africa, Tunisia, Uruguay, Vanuatu and Venezuela

REFERENCES

1. Global Wind Energy Council (GWEC). Gobal wind statistics 2014. [accessed 02.06.2015]. Available at: bhttp://www.gwec.net/wp-content/uploads/2015/02/GWEC_ GlobalWindStats2014 _FINAL_10.2.2015.pdf
2. Global Wind Energy Council (GWEC). Global wind report annual market update 2014. [accessed 02.06.2015]. Available at: bhttp://www.gwec.net/wp-content/uploads/2015/03/GWEC_Global_Wind_2014 _Report_LR.pdf
3. Ackermann T, Soder L. Wind energy technology and current status: a review. *Renewable and Sustainable Energy Reviews* 2000; **4**: 315–374. DOI: 10.1016/S1364-0321(00)00004-6.
4. Ackermann T, Söder L. An overview of wind energy-status 2002. *Renewable and Sustainable Energy Reviews* 2002; **6**: 67–128. DOI: 10.1016/S1364-0321(02)00008-4.
5. Carlin PW, Laxson AS, Muljadi EB. The history and state of the art of variable-speed wind turbine technology. *Wind Energy* 2003; **6**: 129–159. DOI: 10.1002/we.77.
6. Hansen AD, Iov F, Blaabjerg F, Hansen LH. Review of contemporary wind turbine concepts and their market penetration. *Wind Engineering* 2004; **3**: 247–263. DOI: 10.1260/0309524041590099.
7. Joselin Herbert GMM, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. *Renewable and Sustainable Energy Reviews* 2007; **11**: 1117–1145. DOI: 10.1016/j.rser.2005.08.004.
8. Hansen AD, Hansen LH. Wind turbine concept market penetration over 10 years (1995–2004). *Wind Energy* 2007; **10**: 81–97.
9. Kaldellis JK, Zafirakis D. The wind energy (r)evolution: a short review of a long history. *Renewable Energy* 2011; **36**: 1887–1901.
10. Llorente Iglesias R, Lacal Arantegui R, Aguado Alonso M. Power electronics evolution in wind turbines—a market-based analysis. *Renewable and Sustainable Energy Reviews* 2011; **15**: 4982–4993. DOI: 10.1016/j.rser.2011.07.056.
11. Zhou Y. Research Note-Wind. Wind Technology—Rotor Blades, Bloomberg New Energy Finance (BNEF), 2014.
12. Fingersh L, Hand M. Wind turbine design cost and scaling model. National Renerwable Energy Laboratory, 2014. [accessed 17.07.2015]. Available at: bhttp://www.nrel.gov/wind/pdfs/40566.pdf
13. Cotrell J, Stehly T, Johnson J, Roberts JO, Parker Z, Scott G, Heimiller D. Analysis of transportation and logistics challenges affecting the deployment of larger wind turbines: summary of results. National Renerwable Energy Laboratory, 2014. [accessed 17.07.2015]. Available at:http://www.nrel.gov/ docs/fy14osti /61063.pdf
14. International Electrotechnical Commission (IEC). IEC 61400-1 Wind Turbines - Part 1: Design requirements, 2005. Available at: https://webstore.iec.ch/preview/info _iec61400- 1%7Bed3.0%7Den.pdf
15. Bang D, Polinder H. Review of generator systems for direct-drive wind turbines. European Wind Energy Conference & Exhibition, Belgium. 2008. 1–11.
16. Chen Z, Guerrero JM, Blaabjerg F, Member S. A review of the state of the art of power electronics for wind turbines. *IEEE Transactions on Power Electronics* 2009; **24**: 1859–1875.
17. Baroudi JA, Dinavahi V, Knight AM. A review of power converter topologies for wind generators. *Renewable Energy* 2007; **32**: 2369–2385. DOI: 10.1016/j.renene.2006.12.002.
18. Li H, Chen Z. Overview of different wind generator systems and their comparisons. *IET Renewable Power Generation* 2008; **2**: 123. DOI: 10.1049/iet-rpg:20070044.
19. Amirat Y, Benbouzid M, Bensaker B, Wamkeue R. The state of the art of generators for wind energy conversion systems. *Electromotion* 2007; **14**: 163–172.

20. Wagner HJ, Mathur J. Introduction to wind energy systems: basics, technology and operation. Springer Science & Business Media: Berlin Heidelberg, 2012. DOI: 10.1007/978-3-642-32976-0
21. Stander JN, Venter G, Kamper MJ. Review of direct-drive radial flux wind turbine generator mechanical design. *Wind Energy* 2012; **15**: 459–472. DOI: 10.1002/we.484.
22. Lacal-Arántegui R. Materials use in electricity generators in wind turbines—state-of-the-art and future specifications. *Journal of Cleaner Production* 2014; **87**: 275–283. DOI: 10.1016/j.jclepro.2014.09.047.
23. Lacal-Arantegui R. 2013 JRC wind status report, 2014. DOI: 10.2790/97044. Available at: https://setis.ec.europa.eu/system/files/JRC_wind_status_report_0.pdf
24. Lacal-Arántegui R, Serrano-Gonzalez J. 2014 JRC wind status report, 2015. DOI: 10.2790/676580. Available at: https://setis.ec.europa.eu/system/files /2014JRCwindstatusreport_EN_N.pdf
25. World Market Update 2015. Navigant Research, BTM Consult, 2015. Available at: https://www.navigantresearch.com/research/world-wind-energy-market-update-2015
26. Hall JF, Mecklenborg CA, Chen D, Pratap SB. Wind energy conversion with a variable-ratio gearbox: design and analysis. *Renewable Energy* 2011; **36**: 1075–1080. DOI: 10.1016/j.renene.2010.08.037.
27. Polinder H, Ferreira JA, Jensen BB, Abrahamsen AB, Atallah K, McMahon RA. Trends in wind turbine generator systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics* 2013; **1**: 174–185. DOI: 10.1109/JESTPE.2013.2280428.
28. Ragheb A, Ragheb M. Wind turbine gearbox technologies. 2010 1st International Nuclear & Renewable Energy Conference (INREC), 2010, 1–8. DOI: 10.1109/INREC.2010.5462549
29. Bang DJ, Ferreira JA, Polinder H, Hong SS. Structural mass minimization of large direct-drive wind generators using a buoyant rotor structure. *2010 IEEE Energy Conversion Congress and Exposition (ECCE)* 2010: 3561–3568. DOI: 10.1109/ECCE.2010.5617705.
30. Mueller MA, McDonald AS. A lightweight low-speed permanent magnet electrical generator for direct-drive wind turbines. *Wind Energy* 2009; **12**: 768–780. DOI: 10.1002/we.333.
31. Lewis C, Müller J. A direct drive wind turbine HTS generator. *2007 IEEE Power Engineering Society General Meeting* 2007. DOI: 10.1109/PES.2007.386069.