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# Trends in the technological development of wind energy generation

## ABSTRACT

*This article presents a global overview of emerging trends of wind energy technology development. The research conducted: a bibliographic review of the methods of technological prospecting and wind energy; a patent analysis, presenting the current panorama of technologies in this sector; and mapping of the technological evolution of wind turbines and a proposal of the future trends. The patent analysis identified 25,644 patent registrations from 2003 to 2012, showing a growth trend primarily in the United States and China, with significant representation of companies such as General Electric and Mitsubishi. As defined by the World Intellectual Property Organization (WIPO), knowledge areas focused on patent application deposits cover mechanical engineering; lighting; heating; weapons; blasting; and electricity. The trends show that wind turbines of the future are likely to be vertical and synchronous with the height of the turbine greater than 194m and rotor diameter greater than 164m, and that the power of a wind*

## KEYWORDS

wind turbines  
wind technology  
technological  
forecasting  
technological  
development  
wind power  
patent analysis

*turbine will exceed 10 MW. The materials used in the blades will be nanomaterials with the characteristics of low density and high resistance such as graphene. Wind turbine towers will feature a hybrid material, combining steel and concrete.*

## **INTRODUCTION**

Wind energy is considered one of the most promising sources of renewable energy, as demonstrated by investment trends in its development, its increased use and the growing concern for environmental sustainability at national, regional and global levels. In recent years, wind energy has seen a rapid evolution in the development of installed capacity. Installed capacity for wind energy generation is currently concentrated in China, the United States (USA) and Germany. In 2017, China was the country with the largest installed capacity in the world, accounting for 37 per cent of new installed capacity, followed by the United States, which accounted for 13 per cent of the total (Santos and González 2019; GWEC 2014).

Wind energy generation is currently experiencing a moment of expansion in emerging countries whilst its significance in developed countries, in general, remains undiminished. The growing environmental concern across countries has increased its appeal over the years even in the face of unfavourable cost trends. For instance, large hydropower plants have the lowest energy cost when compared to the wind sector. However, because wind energy is clean and renewable, the general consensus is that investment in research and development (R&D) in the wind sector would improve the sector's cost profile and competitive advantage in relation to other sources of energy generation (Sampaio et al. 2020). According to the Organization for Economic Cooperation and Development (OECD), efficient management of the development of new technologies allows the generation and adequate selection of knowledge, transforming the technology regime in wind energy generation (OECD 2005).

Innovation can be realized as a radical rupture in mature technologies and as incremental changes to these technologies (Falani et al. 2014). Innovation, either incremental or radical, has the potential of impacting the economic and social life of communities (MDIC 2001). Success in the delivery of innovation largely depends on corporate aspects such as the structure of the workforce, corporate strategy, alliances with other companies or with universities and, above all, the internal organization companies themselves (González et al. 2013).

The technological change is one of the most important factors behind economic growth (Kaur and Singh 2016). There is a growing concern about the importance of wind energy and its technological development, and knowing trends in technological development to support decisions relating to investments in R&D. Considering the points mentioned above, this article aims to address the following question: how will technologies for wind energy generation evolve?

In an attempt to respond to this question, the article aims to identify technological trends in the development of wind turbines. This article has been organized in eight parts: Section 1 is its introduction; Sections 2 and 3 discuss the theory about wind power and technology prospecting, respectively; Section 4 describes the adopted research method; Sections 5 and 6,

respectively, present technological mapping by means of patent analysis of wind power generation and the technological evolution of wind power generation; Section 7 discusses technology trends studied through technological prospecting of wind power generation; and Section 8 presents the conclusions.

## TECHNOLOGICAL FORECASTING

Technological forecasting is a systematic attempt to identify emerging technologies as they relate to scenarios of future social and economic trends (OECD 2005). This information about trends in technology development helps business managers at the micro level to improve the quality of decisions regarding corporate strategic planning, R&D management, new product development, investment in new process technologies, production, marketing and acquisition of new technologies (Porter 1998). At the macro level, technology forecasting derives its significance as a basis for policies and strategies for investment in research and workforce development (R&D) and skill development for emerging technologies.

The processes for analysing the characteristics of emerging technologies, development paths and potential impacts in the future are currently embedded in the 'technology future analysis' (TFA) concept presented by Porter (2004). This concept incorporates a variety of technological forecasting methods. The methods of technological forecasting can be classified according to the types of technique (Alencar 2008), the approach (Wright and Giovinazzo 2000) and grouping by family of methods (Porter 2004). The types of technique can be presented as qualitative, offering meanings to events and perceptions involving subjective views; quantitative, which involves identifying and measuring variables and applying statistical analyses by using or generating verifiable data; and semi-qualitative, which combines both the qualitative and the quantitative.

As for the approach to forecasting, there are three different types: the extrapolatory, the exploratory and the normative (Porter 1991; Wright and Giovinazzo 2000). While the extrapolation approach focuses on what *is going* to happen, the exploratory approach is focused on what *can* happen, and the motivation for doing normative analysis is to determine what *should* happen (Wright and Giovinazzo 2000).

The selection of methods to be used in a prospective study depends on several factors: the scope of the study, the area of knowledge in question, the political conjuncture, the application of technology in the regional or local context, the governmental or business context, the availability of time and money, etc. In general, more than one technique is used in a prospective study.

Forty studies that foresee the trends were analysed to observe the characteristics and methods most commonly used between 2010 and 2014. Among the technological surveys carried out, the most contemplated sectors were energy (Alberth 2008; Shibata et al. 2010; Bronstein 2011; Daim et al. 2012; Huang et al. 2012; Zimmermann et al. 2012; Jeffrey et al. 2013; Winskel et al. 2014); telecommunications (Christodoulos et al. 2010; Lee et al. 2010; Kivi et al. 2012; Kwakkel et al. 2014); and electronics (Tseng et al. 2009; Gao et al. 2013; Choi and Hwang 2014).

Systematization of the information collected shows that most studies (80 per cent) analyse the future in the form of forecasting, focusing on new or emerging technologies from the perspective of corporate business. Among these, the most used prospecting models are the 'patent analysis model' and

the 'diffusion model', which involve the quantitative approach, and the 'Delphi model', which involves a qualitative approach.

The foresight analysis, which analyses future trends of technological development and the political, social, cultural and economic underpinnings, was approached in eight articles, representing 20 per cent of all studies. Among these, the most used method is 'technological road-mapping' (TRM).

When analysing the articles studied in terms of the families of the methods, thirteen articles applied prospective studies with the purpose of modelling and simulating the future, and eight focused on the objective of monitoring.

Some authors of the surveyed articles were observed applying more than one method to forecast future trends (Alberth 2008; Tseng et al. 2009; Lee et al. 2010; Shibata et al. 2010; Järvenpää et al. 2011; Wu et al. 2011; Behkami and Daim 2012; Zimmermann et al. 2012; Karvonen and Kässi 2013; Choi and Hwang 2014; Winskel et al. 2014). In some cases, more than one grouping per family of methods was verified (Tseng et al. 2009). The use of more than one grouping per family of methods is justified by the need to increase the reliability of the forecast (Alencar 2008).

In this article, the patent analysis method, which falls into the 'Trend Analysis' family, is used. This choice is based on the work of Fye et al. (2013), which evaluated the robustness of 300 prospective studies and concluded that most commonly, quantitative methods produce more robust forecasts. Patent analysis involves the use of statistical methods to convert patent information into useful knowledge and can be applied at different levels – such as at country, industry and company levels and across technology families (Wu et al. 2011). According to Karvonen and Kässi (2013), patent analysis can be used to evaluate both the effects of technology spillover between industries and the importance of transforming the technology base.

Analysing patent data enables the identification of a variety of technological activities, leading to the process of invention and innovation and enabling the collection of information and knowledge about technologies and technological changes (Archibugi et al. 2009). Trends in technological change, technology levels and commercial values can be understood through the analysis of patent components (Choi and Hwang 2014).

The set of data used for technological mapping has magazines, patents, catalogues, scientific articles, etc. as its main technical sources (Canongia et al. 2004). A patent is an industrial title of invention or utility model, a prize granted by the state as a reward to the inventor (Amadei and Torkomian 2009). Patent registration guarantees the inventor certain security when the innovation is applied in an industrial sector.

In patent registration, the inventor/innovator is obliged to disclose in detail all the technical contents of the invention, making it possible for any technician to reproduce it in the laboratory. It is estimated that 70 per cent of the information contained in patent documents is not available from any other source of information (WIPO 2013). For legal reasons, patents are systematically registered by government agencies. The documents are properly processed, classified and organized, providing a source of information on possible industrial innovations. The classification of patent data was established in 1971 by the WIPO and signatory countries of intellectual property agreements. Hence the International Patent Classification (IPC) is used in all countries to facilitate the retrieval of documents.

According to WIPO (2018), the IPC is a hierarchical classification system comprising sections, classes, subclasses, groups and subgroups. The last

revised edition of the classification consists of eight main sections, 131 classes, 642 subclasses, 7461 main groups and 66,454 subgroups. In the IPC divisions, sections (indicated by capital letters) comprise the following fields of technology: A – human necessities; B – performing operations; transporting; C – chemistry and metallurgy; D – textiles and paper; E – fixed constructions; F – mechanical engineering; lighting; heating; weapons; blasting; G – physics; and H – electricity. The other divisions (subsections, classes, subclasses, groups and subgroups) constitute more specific areas, which is necessary for the framing of the technology.

There are a number of global regional and national organizational bodies responsible for the protection of intellectual property, also generically referred to as patent offices. The more important ones are WIPO, the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO). The office responsible for granting the patent in Brazil is the National Institute of Industrial Property (INPI).

Studies on patents have been conducted in two levels, using advanced data mining tools (Alencar 2008). The first level of study relates to the results that are sought in a prospective analysis, answering the *when*, *where* and *who* questions. The ‘when’ question refers to the specific time the technology is patented; the ‘how’ question relates to the historical trend, or the behaviour of the patented technology over time; the ‘where’ question refers to the patent filing countries; and the ‘who’ question identifies the persons or companies holding the patents.

The second level of study is based on the results found in the first level study, combined with other parameters, and is aimed to deepen understanding of the technological development of objects of the study. For this study, two distinct types of information organization are proposed to group and analyse patent applications: (1) the IPC system and (2) classification of the studied technological systems. After the discussion about the categorization of patents by IPC, the classification of the technological system in wind energy presents the second category of patents used. This enables a quantitative analysis of the patents from a taxonomy based on the technological subsystems of wind power generation.

## WIND ENERGY

Until 2008, growth of the wind energy technology market was led by Europe. However, since 2008, installed power generation capacity became more intensive in the United States and China. China has been the largest overall market for wind power since 2009 (GWEC 2013, 2018). According to GWEC (2018), the world market for wind energy in 2017 showed a cumulative growth of 10 per cent, installing approximately 52GW of new wind power. The total global capacity at the end of 2017 was 539,123GW, as shown in Figure 1.

Figure 2 shows the top ten countries with the highest cumulative capacity of wind power up to December 2017, accounting for approximately 85 per cent of installed capacity worldwide. Nine countries have more than 10,000 MW of installed capacity: China (188,392 MW); United States (89,077 MW); Germany (56,132 MW); India (32,848 MW); Spain (23,170 MW); United Kingdom (18,872 MW); France (13,759 MW); Brazil (12,763 MW); and Canada (12,239 MW) (GWEC 2018).

Most wind turbine manufacturing takes place in China, the European Union (EU), India and the United States. In 2016, the top five turbine

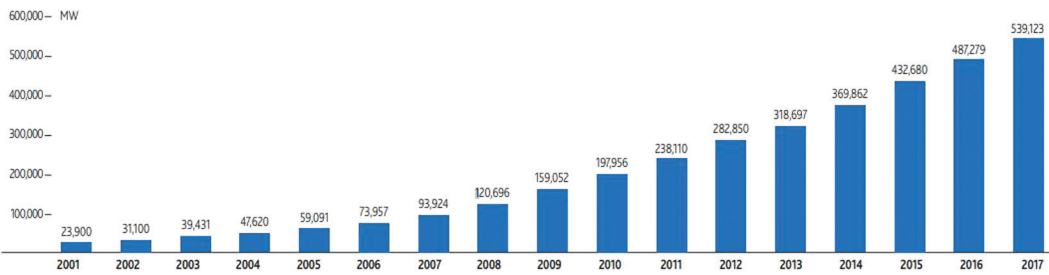


Figure 1: Global cumulative installed wind capacity 2001–17 (GWEC 2018).

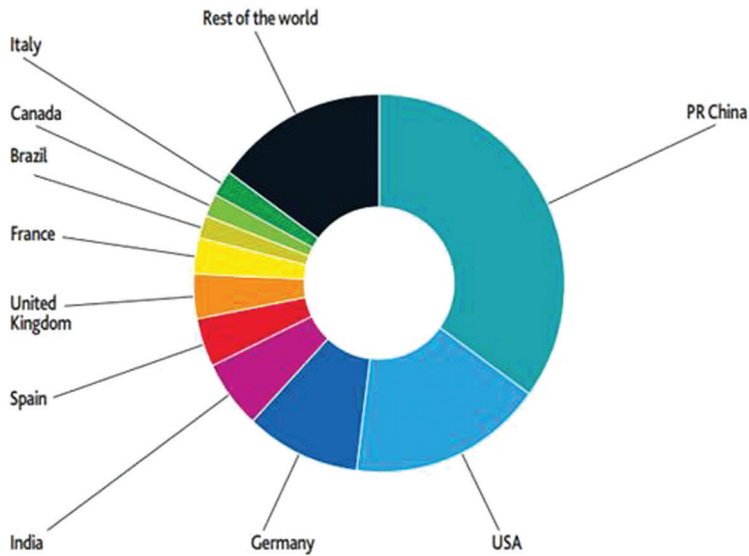


Figure 2: Top ten countries with the highest cumulative capacity of wind power up to December 2017 (GWEC 2018).

manufacturers were Vestas (Denmark); General Electric (United States); Goldwind (China); Gamesa (Spain); and Enercon (Germany). The world’s top 10 turbine manufacturers captured 75 per cent of the 2016 market. However, components are supplied from many countries. Blade manufacturing, for example, has shifted from Europe to North America, South and East Asia, and, more recently, to Latin America and North Africa (REN21 2017).

The basic physical principle underlying the functioning of modern wind power generation equipment is aerodynamic support. This allows the movement of the blades through the differential pressure between the upper and lower surfaces of the blade, thus generating a force that sets the system in motion (Castro 2008; Cresesb 2008).

Wind generation equipment can be divided into three systems: wind energy capture system, transmission system and electrical generation and control systems. Given the characteristics and configurations of the components of the wind turbines, the need for technological organization arises

<b>Systems</b>	<b>Classification of wind turbines adopted for research</b>	<b>Possibilities</b>	<b>Authors</b>
Wind energy capture system	Axis type	Horizontal	Remage 2003; Dismukes et al. 2007; IEA 2013
		Vertical	
	Number of blades	1 blade	IEA 2013
		2 blades	
		3 blades	
		Multiblades	
	The size of the rotor blade radius	Varied	IEA 2013
Location	Onshore	Eriksson et al. 2008; Del Río and Tarancón 2012; IEA 2013	
	Offshore		
Capacity		Industrial	Remage 2003; Eriksson et al. 2008; Silva 2009
		Small	
		Medium	
		Mini generator	
		Micro generator	
	Height of the nacelle	Varied	National Renewable Energy Laboratory [NREL] 2012; IEA 2013
Transmission and electrical generation system	Generator type	Synchronous Asynchronous	Dutra 2007; Castro 2008; Cresesb 2008; Silva 2009; NREL 2013
	Height of the nacelle	Varied	IEA 2013; NREL 2013
Control system	Control type	Blade pitch control	Cresesb 2008; NREL 2013
		Stall	Cresesb 2008; NREL 2013

Table 1: Classification of wind turbines in the literature.

through its classification. Table 1 presents a summary of possible classifications used in the sector's literature.

## RESEARCH METHOD

The research method of this article involves three stages, defined here.

### Stage 1: The bibliographic review

The bibliographic review stage covers the construction of knowledge in two strands.

- *Technological forecasting*: A systematic review of the studies of the future was carried out by 40 articles (González and Toledo 2012). These articles were collected from the portfolio of research on the Portal of Periodicals of the Coordination of Improvement of Higher Level Personnel (CAPES) using the keywords: 'technological forecasting', 'road-mapping technological'

or 'road-mapping technology' and 'technology planning'. This systematization contributed to the organization of the knowledge about the techniques, methods and approaches of technology prospection, enabling the choice of the technique adopted in the research.

- *Wind energy*: Published articles dedicated to this theme were surveyed from research covered in the CAPES periodicals portal through the following keywords: wind energy; wind power; wind power technology; and wind turbines. This search allowed the construction of technical and technological concepts related to wind turbines. In addition, technical sector reports issued by the following international organizations helped in the elaboration of the salient features of the wind sector: the Global Wind Energy Council (GWEC); the International Energy Agency (IEA); the International Renewable Energy Agency (IRENA); and the Brazilian Wind Energy Association (ABEEÓLICA).

### **Stage 2: Technological mapping**

Technological mapping is the stage of constructing the knowledge about technologies and their development. The first step for technological prospecting is to know the evolution of the technology under analysis (Alencar 2008). Accordingly, this article describes the technological information from published patents of wind energy technologies. For the patent analysis, the WIPO database was consulted. WIPO gathers data on the main patent offices around the world and data deposited via the Patent Cooperation Treaty (PCT). The survey covered 25,644 patent registrations deposited in the WIPO database between 2003 and 2012.

The search for data is a process based on strategies that seek to recover a set of patents representative of the area of interest of the research for the desired period. The following steps were undertaken to carry out the search:

- *Definition of search terms*: Keywords were defined as 'wind power' or 'wind energy'. The nomenclatures used in the search were selected from step 1 during the construction of the technical knowledge of the technology studied. The IPC system was also considered to align with the overall strategy.
- *Data processing*: This study required transformation of the raw data set into a format that is as uniform and cohesive as possible, representing the universe of desired documents (Alencar 2008). Excel software and its PivotTable tool were used for data organization and subsequent analysis.
- *First-level analysis*: The prospective analysis seeks to answer three main questions: when, where and who (Alencar 2008). The 'when' question refers to the analysis of the historical trend of development of the technology. The 'where' question refers to the geographic context of technology analysis. The 'who' question seeks to identify the holders of the technology.
- *Second-level analysis*: This involves discussion of the results of the first analysis in relation to other parameters to deepen understanding of technological development. In this analysis, the IPC classification of patents was used, in accordance with the classification of the technological components normalized in the IPC and that carried out in stage 1.

### Stage 3: Mapping technology evolution

We searched the literature on the technological configuration of wind energy over time. The articles surveyed were the same as in stage 1, but with the analytical focus and search for information that enabled the mapping of technology evolution. After that, wind energy news surveys were conducted regarding the dissemination of new technologies in the industry and their respective patent registrations in the WIPO database.

It was possible to construct a chronological map of the evolution of wind turbines to the present day by synthesizing this information. The map in timeline format presents the evolution of the main technology parameters found, namely: (1) axis type; (2) height of the nacelle; (3) rotor blade diameter; (4) capacity; (5) tower material; (6) material of blades; (7) number of blades; and (8) generator type. The information presented in the timeline served as a means to analyse the current configuration of the studied technology and the construction of possible future trends in the evolution of each of the specified technology parameters.

### PATENT ANALYSIS OF WIND ENERGY

The data set included 25,644 patents deposited in the WIPO database between 2003 and 2012.

#### First-level analysis

The number of patents deposited during the period 2003–12 under the rubric of wind technology shows exponential growth, as observed in Figure 3.

The data cover eleven countries that have patents for wind technology, excluding patents deposited via the PCT. Overall, the United States leads with 8686 patents filed during the study period, followed by China with 4990 patents; the Republic of Korea with 2107 patents; Japan with 1420 patents; and Canada with 1118 patents, as shown in Figure 4.

Evolution of the major patent depositors in wind power technology can be seen in Figure 5, which also shows China's large increase and Japan's large decrease in patent deposits since 2007. By comparison, the Republic of Korea has increased its patent filings by nearly four times, while the United States and Canada approximately doubled patent volumes from 2008 to 2012.

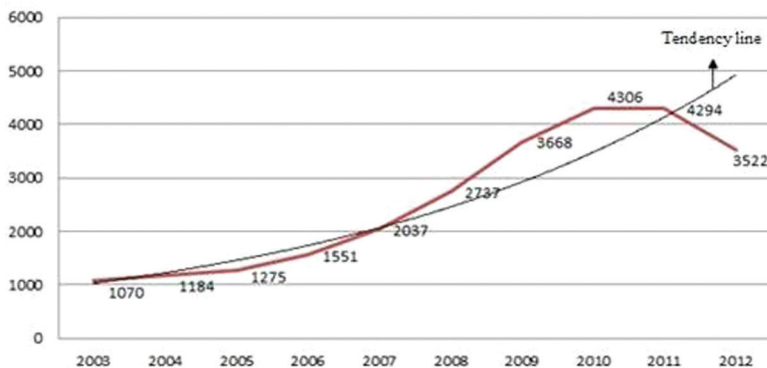


Figure 3: Number of patents deposited per year.

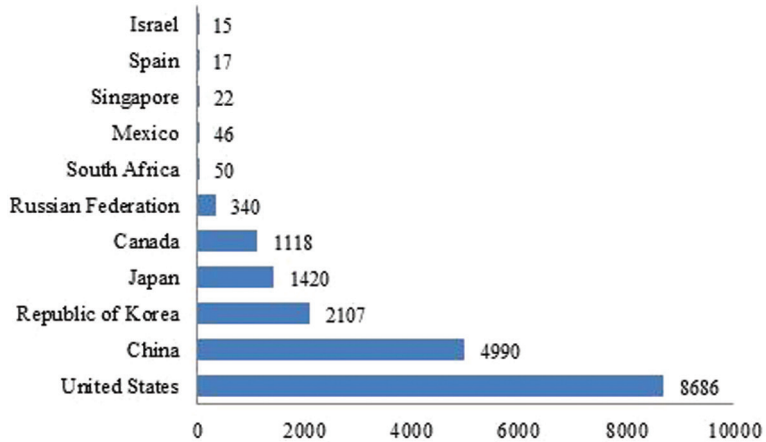


Figure 4: Number of patents in wind energy per depositor country.

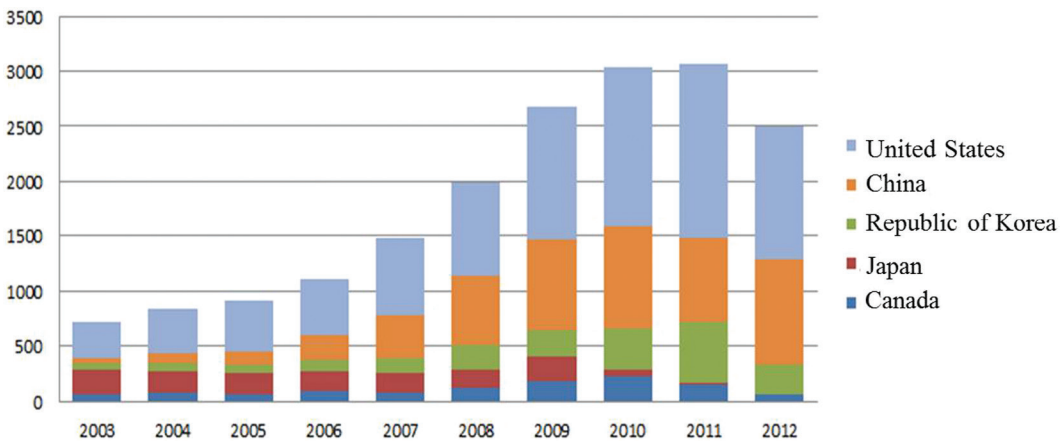


Figure 5: Historical evolution of the main patent depositors in wind energy technology.

Figure 6 presents the names of the ten patent depositors and the number of patents of the most innovative companies in wind energy technology.

Table 2 presents the ten depositors with the highest number of patents for wind power during the period from 2003 to 2012.

The US company General Electric (GE) and Japan’s Mitsubishi have the largest number of patents for wind energy technologies, but fail to lead when compared to other companies in terms of the proportion of patents related to wind energy technology and the number of all patents deposited. In terms of this issue, the German companies, Wobben Aloys and Repower Systems, and the Danish company, Vestas Wind Systems, have a high representation of patents related to wind technology within their portfolio of patents when compared to the other companies.

When the geographical origin of the leading depositors is observed, Asian countries are in a leading position, with three Japanese depositors and two South Korean depositors. Germany also stands out as the origin of major depositors. The other major depositors originate in the United States and

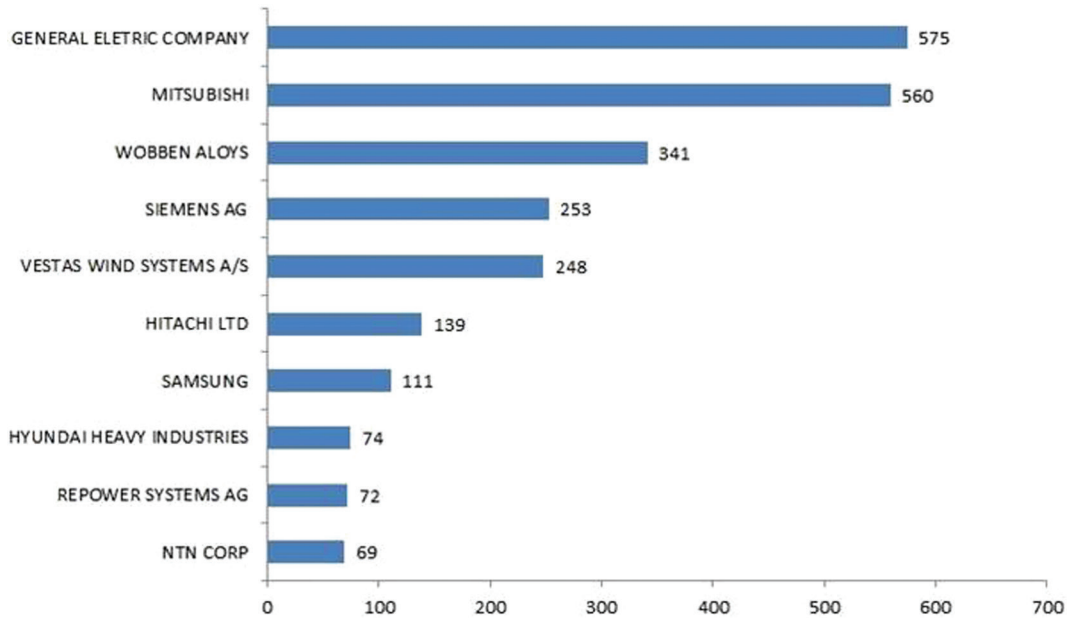


Figure 6: Top patent depositors in wind energy technology.

Primary applicant	No. of patents	Representativeness in the company portfolio (per cent)	Country
General Electric Company	575	1.29	United States
Mitsubishi	560	0.43	Japan
Wobben Aloys	341	27.19	Germany
Siemens AG	253	0.31	Germany
Vestas Wind Systems A/S	248	11.16	Denmark
Hitachi LTD	139	0.09	Japan
Samsung	111	0.04	Republic of Korea
Hyundai Heavy Industries	74	0.15	Republic of Korea
Repower Systems AG	72	12.44	Germany
NTN Corp	69	0.54	Japan

Table 2: Leading wind energy technology depositors.

Denmark. In terms of the main depositors of wind energy technology during the ten years of the study, it is observed (see Figure 7) that some companies, such as GE and Mitsubishi, filed patents for wind energy technology throughout the period. Meanwhile, other companies, such as Vestas Wind Systems and Siemens, were active in patenting wind energy technologies during the last five years of the study. It is interesting to note that although the German

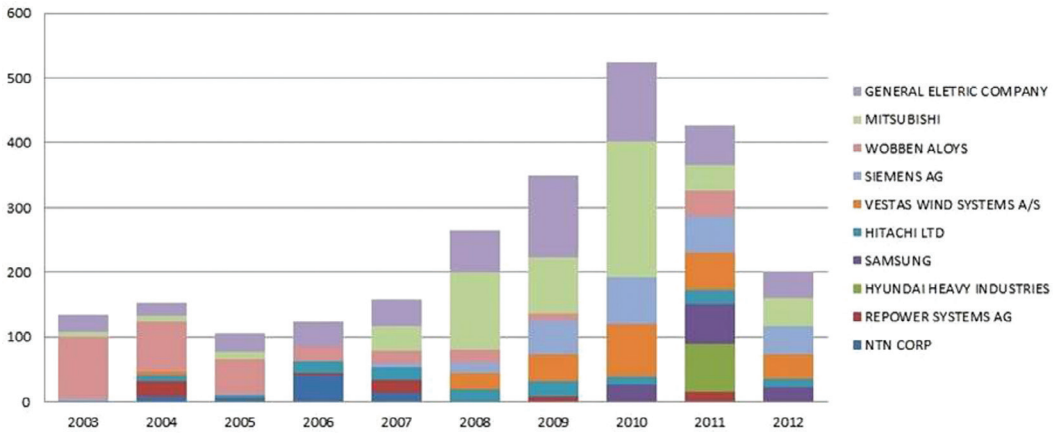


Figure 7: Historical evolution of the main patent depositors in wind energy technology.

IPC		No. of patents	Percentage of total wind power patents (%)
F	Mechanical engineering; Lighting; Heating; Weapons; Blasting	13,838	54
H	Electricity	8097	31.6
G	Physics	1554	6.1
E	Fixed constructions	536	2.1
B	Performing operations; Transporting	1451	5.6
C	Chemistry; Metallurgy	168	0.6
A	Human necessities	0	0.0
	Total	25,644	100

Table 3: Distribution of technology patents by IPC sections.

company, Wobben Aloys, had 27 per cent of its patent applications focused on wind technologies; it did not deposit such patents in 2010.

### Second-level analysis

To obtain a holistic view of patents related to wind power technology, analyses were conducted to identify the main areas of knowledge and the use of patents in the classification of technology. These results were used to further look into countries and companies that lead in patent deposits. To identify trends in specific areas of knowledge, sections of the IPC are used. When evaluating wind technology patents, it is observed that approximately 86 per cent of patents are concentrated in sections F and H, which refer to ‘mechanical engineering’; ‘lighting’; ‘heating’; ‘weapons’; ‘blasting’; and ‘electricity’, respectively, as demonstrated in Table 3.

Table 3 describes the distribution of wind energy technology patents across IPC subsections from over 100 patent sites. By deepening the analysis in the sections of the IPC, a highly asymmetric distribution is observed in its subsections. The classification with the highest frequency is F03D (wind engines),

IPC	Description	Technology classification	No. of patents	Percentage
F03D	Wind motors	Transmission and electrical generation	11,262	43.92
H02J	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy	Transmission and electrical generation	2548	9.94
H02P	Control or regulation of electric motors, electric generators or dynamo-electric converters; controlling transformers, reactors or choke coils	Transmission and electrical generation	1667	6.50
H02K	Dynamo-electric machines	Transmission and electrical generation	1609	6.27
F03B	Machines or engines for liquids	Transmission and electrical generation	1149	4.48
H01M	Processes or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	Transmission and electrical generation	862	3.36
G06F	Electric digital data processing	Control	783	3.05
H02M	Apparatus for conversion between ac and ac, between ac and dc, or between dc and dc, and for use with mains or similar power supply systems; conversion of dc or ac input power into surge output power; control or regulation thereof	Transmission and electrical generation	606	2.36
H01L	Semiconductor devices; electric solid-state devices not otherwise provided for	Transmission and electrical generation	569	2.22
F16H	Gearing	Transmission and electrical generation	473	1.84
F03G	Spring, weight, inertia or like motors; mechanical-power-producing devices or mechanisms, not otherwise provided for or using energy sources not otherwise provided for	Transmission and electrical generation	444	1.73
B60L	Propulsion of electrically propelled vehicles; supplying electric power for auxiliary equipment of electrically propelled vehicles; electrodynamic brake systems for vehicles in general; magnetic suspension or levitation for vehicles; monitoring operating variables of electrically propelled vehicles; electric safety devices for electrically propelled vehicles	Transmission and electrical generation	402	1.57
E04H	Buildings or like structures for particular purposes; swimming or splash baths or pools; masts; fencing; tents or canopies, in general	Wind energy capture	397	1.55

(Continued)

IPC	Description	Technology classification	No. of patents	Percentage
<b>F16C</b>	Shafts; flexible shafts; mechanical means for transmitting movement in a flexible sheathing; elements of crankshaft mechanisms; pivots; pivotal connections; rotary engineering elements other than gearing, coupling, clutch or brake elements; bearings	Transmission and electrical generation	349	1.36
<b>G06Q</b>	Data processing systems or methods, especially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes; systems or methods especially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes, not otherwise provided for	Management	297	1.16
<b>B63B</b>	Ships or other waterborne vessels; equipment for shipping	Wind energy capture	294	1.15
<b>B63H</b>	Marine propulsion or steering	Wind energy capture	269	1.05
<b>H02N</b>	Electric machines not otherwise provided for	Transmission and electrical generation	246	0.96
<b>G01R</b>	Measuring electric variables; measuring magnetic variables	Control	232	0.90
<b>B01D</b>	Separation	-	186	0.73
<b>C02F</b>	Treatment of water, waste water, sewage or sludge	-	178	0.69
<b>F01D</b>	Non-positive-displacement machines or engines, e.g. steam turbines	Transmission and electrical generation	171	0.67
<b>B64C</b>	Aeroplanes; helicopters	Wind energy capture	165	0.64
<b>E02D</b>	Foundations; excavations; embankments; underground; or underwater structures	Wind energy capture	149	0.58
<b>B29C</b>	Shaping or joining of plastics; shaping of material in a plastic state, not otherwise provided for; after-treatment of the shaped products, e.g. repairing	Wind energy capture	145	0.57
<b>G05B</b>	Control or regulating systems in general; functional elements of such systems; monitoring or testing arrangements for such systems or elements	Control	131	0.51
<b>G05D</b>	Systems for controlling or regulating non-electric variables	Control	121	0.47

Table 4: Main classifications and their uses.

which totals approximately 54 per cent of the patents for wind energy technology, as presented in Table 3.

The data are related to scientific knowledge about wind energy technology and to the classification systems of wind technology presented in Section 3.1

IPC	Associated company	Inventor	No. of patents
F03D	Wobben	Wobben Aloys	321
F03D	Mitsubishi	Numajiri Tomohiro	64
F03D	-	Litvinenko A.M. (Ru)	49
F03D	AMSC Windtec GMBH	Hehenberger Gerald	36
F16C	NTN Corp	Omoto Tatsuya	35
H02P	Suzhou Nanji Wind Energy Equipment CO	Zhu Yiren	31
F03D	Wuxi Tongchun	Miao Tongchun	28
F03D	Genedics, LLC	Fein Gene S.	26
F28D	-	Yang Tai-Her	26
G06F	Endurance International Group, INC	Ravichandran Hari	25

Table 5: Main inventors with the companies and the patent subclasses.

of this article. The number of patents is concentrated in the sub-classification of wind motors (F03D); circuit arrangements, or systems for supplying or distributing electric power; and systems for storing electric energy (H02J). Together, they total more than 50 per cent of the patent deposits.

We also analysed the IPC classification of patents by verifying where the patented technology is located in the system structure proposed in Table 1. The technological system of wind energy generation consists of three parts classified according to their functions – namely, energy capture wind, transmission and generation of electric power and control mechanisms.

The methodology for positioning wind energy technology patents in their system categories consists of intersecting the IPC subclasses with the indicated uses of the patent. It was done in two steps: (1) segregating the most frequent terms in a selected IPC subclass and (2) positioning these terms in the technological system. Table 4 shows that patented technologies are more concentrated in the second wind power system – i.e. the transmission and generation system.

By cross-referencing the information of the top ten inventors with the companies and the patent subclasses (presented in Table 5), it is found that most inventors are associated with some companies and that their patents are concentrated in the subclasses of wind motors (F03D), covering the following: shafts; flexible shafts; mechanical means for transmitting movement in a flexible sheathing; elements of crankshaft mechanisms; pivots; pivotal connections; rotary engineering elements other than gearing, coupling, clutch or brake elements; bearings (F16C), control or regulation of electric motors, electric generators or dynamo-electric converters; controlling transformers, reactors or choke coils (H02P); and electric digital data processing (G06F).

It is important to note, however, that the high occurrence of deposited patents in F03D by inventor Wobben Aloys (321) is only 1.25 per cent of the total deposited patents (25,644) during the period covered by this study.

## TECHNOLOGICAL EVOLUTION OF WIND ENERGY

Research based on scientific publications and news reports relating to wind energy was used for the construction of timeline showing the evolution of technologies for wind power generation worldwide. This involved thirteen news reports on technological advances in the wind sector. The news reports served as a guide in the search to provide precise information about patents. To reach the current configuration of wind power technologies, many innovations have occurred, and it is important to know the historical path of technological innovations that have enabled the generation of wind energy in its current form.

The forerunner of wind turbines for electric power generation was the horizontal axis windmill for mechanical power generation, which has been used since about 900 AD in Persia, Tibet and China (Dubarić et al. 2011). The diffusion of mechanical mill technology from the Middle East to Europe occurred between 1100 and 1300 AD. This was followed by the development of the technology across Europe. In the Netherlands, the use of large-scale windmills between the seventeenth and nineteenth centuries was primarily related to the reclamation of land covered by water. During the nineteenth century, thousands of mechanical windmills with rotors 25 metres in diameter were operated in France, Germany and Holland. These countries had 90 per cent of the mechanical energy used in the wind energy industry (Dismukes et al. 2007).

The first windmill used to generate electricity was a system built by Charles F. Brush in Cleveland, Ohio, in 1888 (Dismukes et al. 2007; Dutra 2007). The machine had a rotor with 144 blades, making it 17 metres in diameter with a large tail hinged to rotate the wind rotor. This was on a tower that was 18m high, which provided 12 kW in direct current for battery charging. Despite its success for twenty years, the windmill demonstrated the limitations of low speed for electricity production applications.

The advent of power plants in 1882 in New York and 1884 in Germany, followed by the introduction of the electric power production phase in 1890, provided a technological basis for the construction of wind turbines for electric power generation in lieu of mechanical energy (Dismukes et al. 2007). Danish scientist and engineer, Poul La Cour, was an entrepreneur in the field of electricity generation using wind power in 1891 in Askov, Denmark. He introduced a rotor model generating around 10 kW of electrical energy (Kaldellis and Zafirakis 2011). La Cour's efforts unleashed the research, development and commercialization of wind-based electricity in Denmark and Germany in the twentieth century, which stimulated Europe's initial leading role in wind power for electricity generation.

In 1891, La Cour developed the first outgoing electric wind machine that incorporated the principles of aerodynamic design used in the European power plants, making the wind turbines very practical for the generation of electricity (Dutra 2007). By the end of the First World War, the use of 25 kW electric output wind machines had already spread throughout Denmark.

In 1920 in the United States, the development of electric power generation systems relying on wind energy was inspired by the design of airplane propellers and monoplane wings. These small-sized wind turbines were widely used in rural areas, but they disappeared from the market, as they could not cope with the increasing energy demand during the 1930s and the 1940s.

In 1922, Georges Darrieus patented his invention of a wind turbine with a vertical axis, which could have straight or curved blades. The Darrieus Wind Turbine has two main advantages: the equipment, including the gearbox and the generator, can be placed close to the ground, and it does not require a new mechanism to position the rotor against the wind. The large-scale energy development per unit of wind energy conversion systems was carried out in Russia in 1931 with the 100 kW Balaclava wind generator. Subsequently, experimental wind power plants appeared in the United States, Denmark, France, Germany and Great Britain during the period 1935–70, but they did not yield a large wind turbine practice because the leap of scale required was too large for the materials available at the time (Kaldellis and Zafirakis 2011).

Second World War contributed to the development of medium- and large-sized wind turbines as countries generally made massive efforts to save fossil fuels. The United States set out to build the largest wind turbine ever designed. It was the Smith–Putnam wind turbine, whose model was 53.3 m in diameter, a 33.5 m high tower and two sixteen-tonne steel blades. In its system of generation and electric transmission, a synchronous generator, which acted in alternating currents, was used and connected directly to the local power grid. This wind turbine began operating on 10 October 1941, on a Vermont hill called Grandpa's Knob. In March 1945, after four years of intermittent operation, one of its metallic blades broke due to fatigue (Thresher and Laxson 2006; EWEA 2012).

In 1945, F. L. Smidth was a pioneer in the development of small wind turbines, which had only two blades and generated about 45 kW power. The success of the F.L.S. small-scale wind turbines, which still operated in direct current, enabled a project even more audacious than the Smith–Putnam wind turbine. The temporary shortage of fossil fuel in 1958 led Europe to continue R&D in wind power generation. In Denmark, a 200 kW Johannesburg-designed three-pitch stationary wind turbine, which used windmill technology augmented with a concrete support structure, successfully operated until early 1967, supplying current alternating to an electric company.

In Germany in 1958, Professor Ulrich Hutter developed a number of advanced functions, such as horizontal axis design, fibreglass type airfoil and variable-pitch plastic blades, for lightness and high efficiency. One of the most innovative features of the design was the use of a bearing on the rotor hub, which allowed the rotor to 'rock' in response to gusts of wind (Kaldellis and Zafirakis 2011).

Post-war activities in Denmark and Germany dictated two major horizontal-axis design approaches that emerged when attention returned to the development of wind turbines in the early 1970s. In 1980, Canada and the United States built several Darrieus turbine prototypes. The prototype was proven to be quite effective and feasible, according to reports from the US National Laboratory (Möllerström et al. 2019). In 1987, the company Éole built a vertical shaft turbine with a height of 110m and power-generating capacity of 3800 kW (Möllerström et al. 2019).

Between 1973 and 1986, the turbines were used in wind farms with applications connected to computers, generating between 50 and 600 kW. In 1987, Sandia developed a Darrieus turbine, which had symmetrical profiles, was 34m high and generated 625 kW of power (Dismukes et al. 2007). These machines had inefficiency at startup, requiring a starter to begin the operation.

In the United Kingdom (UK), a vertical-axis turbine called the H-rotor was developed by a team led by Peter Musgrove. The largest H-rotor turbine

built was a 500 kW machine, which was designed in 1989 (Dismukes et al. 2007). In the 1990s, the German company Heidelberg Motor GmbH worked on the development of H-rotors and built several prototypes that generated around 300 kW (Eriksson et al. 2008). In 1999, Canada's Sustainable Energy Technologies Company sold a Darrieus turbine called the 2000 Chinook, which generated 250 kW (Dismukes et al. 2007). In the same year, new turbine designs were installed worldwide and followed mainly the horizontal axis model.

In 2007, an engine was developed that takes advantage of the circular movement of a column of gases – the well-known swirl. The turbine consists of a vertical cylinder with a heater at the base and the upper end open, producing approximately 200 MW (Garcia et al. 2006). This invention was patented in 2007 under the title 'Vortex engine'. Also in 2007, the MagLev turbine was developed, which uses magnetic levitation to offer superior performance over traditional turbines. Vertical wind turbine blades are suspended in the air above the base of the equipment. Instead of supporting themselves and turning on bearings, these blades are suspended and do not have contact with other mechanical parts, and therefore can rotate without friction, which exponentially increases their yield and generates about 1 GW of electrical power. This innovation was patented under the title 'System and methodology for wind compression' (Mendonça 2009).

In 2008, Magenn in Canada designed the wind turbine based on inflatable balloons equipped with a system that rotates them along its horizontal axis, and generates 10 kW, depending on its size. The rotation allows it to gain lift and stability, and can remain positioned in a restricted and fully controlled area. The MARS concept (Magenn Power Air Rotor System) for the generation of electricity from wind is an adaptation of the 'Magnus Aircraft', an airship invented in the 1970s by the founder of the company, Fred Ferguson. This innovation was patented under the title 'Systems and methods for tethered wind turbines' (Mendonça 2009).

Later in 2009, the Italian company Kitgen developed kites that fly between an altitude of 800 and 1000m, generating 3 MW. The movements of the kites are controlled automatically by a computer and are anchored through cables to a structure that rotates and generates electricity every moment that the force of the winds pulls and retracts the cable. This structure is similar to the high-altitude turbine, except that the turbine blades are replaced by the kites. The company has patented the invention under the title 'System for converting wind energy into electrical energy through the flight of power wing profiles tethered to the ground by cables of a fixed length, without passive phases, and with automatic adaptation to wind conditions' published in 2012 and patent register in WIPO: PCT/IB2012/051378.

In 2011, the German company Siemens developed the offshore turbine of 6.0 MW of power and a rotor diameter of 154m. The turbine has 50 per cent fewer moving parts in comparison to gearboxes and a mass of less than 350 tonnes. It constantly manages its own operating load, helping to keep its design criteria in place irrespective of the conditions (Siemens 2012). Also, in the same year, the Danish company Vestas marketed the Turbine V164-7.0 MW, capable of generating 7 MW with a 164m rotor diameter and synchronous generator (Vestas 2012). The wind farm operating company determines the height of the wind turbine during the planning.

In 2012, the German company Repower System marketed the 5M Turbine that is capable of generating 5 MW of power by means of a rotor

with a diameter of 126m and a height between 90 and 120m. The generator is asynchronous and its tower is made of steel. Also in the same year, the German company NTS GmbH, in partnership with the Institute of Industrial Engineering and Automation (in Stuttgart, Germany), developed a system using unmanned sport kites, which produce 100 kW of power, usually enough to meet the demands of several homes with an average energy consumption. The principle of operation consists of connecting kites to a train using 700-metre cables of support. The movement of the kites, which are connected to a generator, pulls the vehicle. The company has patented the invention entitled 'Wind-operated power generator' published in 2009 and patent register in WIPO: 20090285681.

The largest commercial wind turbine available was developed by Wobben Aloys in 2012. It generates 7.5 MW, with a rotor diameter of 126 metres, reaching up to 198m in height with a synchronous generator, the steel and concrete tower. The Robotic Pipe was developed in 2013 in Switzerland and is an ultralight inflatable structure known as Tensairity, which uses pneumatic plastic materials to achieve great resistance with low weight. The high-tech kite is attached to a reel in the ground station. When the kite rises to an altitude of approximately 300m, strong winds create a tension in the line, putting the spool in motion. This movement is converted into electrical energy by means of electromagnetic induction. This invention is patented under the name 'Pneumatic structural element' published in 2006 and patent register in WIPO: WO/2007/071101.

In 2013, Japan's Mitsubishi announced in its portfolio the turbine Sea Angel 7/165 (offshore), capable of generating 7 MW of power and with 165m of rotor diameter. In the same year, GE introduced in its portfolio the Turbine 4.1-113 (offshore), capable of generating approximately 4 MW of power by means of capture of wind in a rotor 113m in diameter. Both innovations are focused on offshore generation (Mitsubishi 2012).

When compared with the horizontal axis model, the evolution of the vertical axis turbines came into focus later, featuring in the study of Georges Darrieus in 1922. Wind turbine technology with this type of axis has been under development, such as those from the American laboratory Sandia (Möllerström et al. 2019). On the other hand, the horizontal axis model has been produced on an industrial scale since 1986.

The height of the nacelle has been growing steadily since the first windmill, rising from 18m in 1888 to 198m in 2012, which is an elevenfold increase. The rotor diameter of the wind turbines also shows significant growth: from 17m in 1888 to 165m in 2013.

In terms of the challenge posed by strong wind performance at higher altitudes, new wind generation models capable of capturing wind strength up to 1000m high have been developed. An example is the wind turbine developed and marketed by the Italian company, Magenn, in 2009. Power generation models, such as those with a kite shape or magnetic levitation, present different characteristics from traditional models.

Observing the trajectory of wind turbines for traditional power generation, an increase in power from 12 kW to 10 MW is identified, representing an increase of approximately 625 times. However, it was only from 2000 that the power of 6 MW was achieved. Offshore turbines have received increased attention in recent years, as reflected in the average turbine installed power that grew from 3 MW in 2008 to 4 MW in 2012 (IEA 2013).

In 2011, Siemens stood out for its investments in this type of generation, when it presented this new technology in its portfolio. The wind turbine rotors are made of composite materials, such as glass fibre and carbon fibre, and meet the requirements of weight, rigidity and aerodynamics. On the other hand, the material used in wind towers requires characteristics that can sustain all the equipment, besides sustaining vibrations caused by the inconstant wind. In addition to the presence of steel, some companies are currently adhering to the use of concrete in part of the tower to improve performance (Mitsubishi 2012; Siemens 2012; Vestas 2012).

Most large grid-connected turbines have three blades in a horizontal rotor. The blades can be moved to control the power output. The size of the blades continues to increase the average nominal capacity of new turbines connected to the grid (Navigant 2013). The first invention of wind power generation had 144 blades. This high number of blades facilitated the onset of fatigue. The number of blades became similar to the current configurations from 1957 with the wind turbine designed by Johannes Juul.

Since 2008, the share of wind turbines installed without the gearbox has increased from 12 per cent to 20 per cent (Navigant 2013). This confirms the growth in the use of synchronous generators. The synchronous generator provides reduction of energy loss between the rotor and the generator and mechanical wear, mainly reducing operating and maintenance costs because it has fewer components.

## **TECHNOLOGICAL FORECASTING OF WIND ENERGY**

The overall trend in turbine design has been to increase tower height, blade length (which influences the rotor diameter) and load capacity (IEA 2013). However, turbines have grown in height and rotor diameter faster than their electrical capabilities. This decrease in the specific power in relation to the height of the tower and the length of the blades increased capacity factor (wind energy transformation index in electric energy) at the same wind speed.

This trend has also led and will continue to lead to the emergence of rotors designed for low speed winds. The high towers and long blades in relation to generator size and higher capacity factors allow the installation of wind turbines in low-speed wind areas, which often occur closer to consumption centres than the best 'wind spots' (Chabot et al. 2002).

Advances in blade design, often with new materials and also advanced control strategies, will contribute to increase turbine efficiency compared to its installed capacity (IEA 2013). In the technological evolution, we observe influences from studies of other areas of knowledge, aiding the application of new concepts to the aerodynamics of the blades. An example is the case of fin studies of humpback whales and dolphins, studied by Dr Frank Fish, a professor of biology at West Chester University of Pennsylvania (Kwon and Kareem 2013).

The search for lightweight materials and with greater resistance encourages the use of new composite materials. Thus, studies in the areas of nanomaterials are considered possible applications to achieve the requirements, as presented by Zarbin and Oliveira (2013), who identified the application of the graphene material in turbines of capture of wind energy by the companies Amroy, Hexcel and Eagle Windpower.

In the literature of development of new products, the application of Design for Manufacturing and Assembling (DFMA) aims to reduce manufacturing

costs (by the search of alternative materials, reduction of number of components and use of standard devices) and assembly costs (through reduction of assembly time and diminution of number of operations and facilities for assembly).

Offshore wind turbines are evolving from previous versions based on onshore models for larger sea turbines, exploring different sub-structures. It is expected that this type of turbine will be installed mainly in places with territorial limitation. Wind turbines generate electricity from winds ranging from 3 or 4m/s, up to 25m/s or 34m/s (Hassan 2010). It is believed that in the future, innovation efforts will be in the generation of energy from low wind speeds, encouraging the generation of wind energy in regions that are considered to have with low wind potential.

## CONCLUSIONS

This research integrated technological forecasting and wind energy technology, which contribute strategically to the development of new technologies in an expanding sector. In companies that develop equipment or solutions in general, the R&D sector is involved in decisions about the technological possibilities that aim to reduce costs and increase the efficiency of the systems developed.

The amount of effort that a company puts in to use technological forecasting practices is a measure of its commitment as an organization to develop new products by exploring the world technology landscape and identifying which technologies other companies are developing. Systematic bibliographic review allows broad contact with the state-of-the-art technology prospecting, insofar as it gives access to the techniques and methods used by research communities worldwide.

In its aim to explore issues in the evolution of technologies for wind energy generation and look into future development trends, this study has sought to address the question about the research gap on the use of technological prospecting techniques for the wind energy sector by recognizing that patent analysis combined with scientific article and news analysis provides critical knowledge on the sector. Bridging the knowledge gap is crucial for the sector as it has implications for the quality of investment decisions in R&D and, consequently, influences the efficiency and effectiveness of wind energy generation through the emergence of technological innovations in the sector.

The application of technological prospecting tools, like the ones discussed in this article, can also be replicated by the benefit of other sectors, including renewable energy as a whole. Based on the available evidence, it can be argued, however suggestively, that companies that use such tools would stand to gain from decisions made to invest in the development of new technologies and new products by reducing the risk of project failures.

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