The wind energy (r)evolution: A short review of a long history

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1. Introduction

It was centuries ago when the technology of wind energy made its first actual steps—although simpler wind devices date back thousands of years ago—with the vertical axis windmills found at the Persian-Afghan borders around 200 BC and the horizontal-axis windmills of the Netherlands and the Mediterranean following much later (1300–1875 AD) [1–3]. Further evolution [4] and perfection of these systems (Fig. 1) was performed in the USA during the 19th century, i.e. when over 6 million of small machines were used for water pumping between 1850 and 1970. On the other hand, the first large wind machine to generate electricity (a low speed and high-solidity wind turbine (WT) of 12 kW) was installed in Cleveland, Ohio, in 1888, while during the late stages of World War I, use of 25 kW machines throughout Denmark was widespread. Further development of wind generators in the USA was inspired by the design of airplane propellers and monoplane wings, while subsequent efforts in Denmark, France, Germany, and the UK (during the period between 1935 and 1970) showed that large-scale WT's could work. European developments continued after World War II. In Denmark, the Gedser mill 200 kW three-bladed upwind rotor WT operated successfully until the early 1960s [5], while in Germany, a series of advanced horizontal-axis designs were developed, with both of the aforementioned concepts dictating the future horizontal-axis design approaches later emerging in the 70s.

One of the most important milestones of the wind energy history coincides with the USA government involvement in the wind energy research and development (R&D) after the oil crisis of 1973 [6–8]. Following, in the years between 1973 and 1986, the commercial WT market evolved from domestic and agricultural (1–25 kW) to utility interconnected wind farm applications (50–600 kW). In this context, the first large-scale wind energy penetration outbreak was encountered in California [9], where over 16,000 machines, ranging from 20 to 350 kW (a total of 1.7 GW), were installed between 1981 and 1990, as a result of the incentives (such as the federal investment and energy credits) given by the USA government. In northern Europe on the other hand, wind farm installations increased steadily through the 80s and the 90s, with the higher cost of electricity and the excellent wind resources leading to the creation of a small but stable market. After 1990 most market activity shifted to Europe [10], with the last twenty years bringing wind energy at the front line of the global scene with major players from all world regions.

In this context, in the current work, a short review of the developments noted in the field of wind energy at the global level is undertaken, with special emphasis given on the major fields of global market facts, technology issues, economics, environmental performance, wind energy prospects and R&D. Highlights and some insight for each of the fields are currently presented, while special attention is given to the European achievements. More specifically, in the global market facts’ section, the time evolution of the global wind power capacity and energy generation are presented along with the leading markets of today and the most important EU and
Fig. 1. From the early stages of wind energy exploitation to the outbreak of California (Source: [4]).

Time Evolution of Global and European Wind Power Capacity

![Graph of Time Evolution of Global and European Wind Power Capacity](image)

Fig. 2. Time evolution of global and European wind power capacity and wind energy generation (based on data from [11–14]).
world wind power facts. Following, in the technology issues section, discussion concerning the upscale of machines, the main technological characteristics of contemporary WTs and issues such as grid integration, efficiency of the machines and expansion of the small scale machines’ industry is undertaken.

In the economics section, issues such as the time evolution of investment costs, the costs of both onshore and offshore applications, the effect of financial support mechanisms, the employment opportunities appearing due to the expansion of the wind energy industry as well as a comparison with other power generation technologies are all presented. Next, in the environmental performance section, a short notice on the impacts of wind energy is provided while attention is given to the externalities avoided and the social acceptance levels of wind power. Finally, in the wind energy prospects and R&D part, a summary of future targets is provided at both the market and the technological level.

2. Global market facts

According to the latest official data [11–14], the global wind power capacity was increased during 2009 by 37.4 GW (Fig. 2a), thus reaching a total of almost 158 GW on the basis of remarkable development rates exhibited for the past twenty years. Europe is at the moment approaching, if not yet exceeded, 80 GW and is now heading to offshore applications [15]. In fact, it is since the mid-90s that the EU market corresponds to over 50% of the global installed capacity, that is nowadays said to yield an overall of 260TWh/year. In this context, although the EU held only 20% of the world wind energy generation in the early 90s (Fig. 2b), production of European wind parks managed to even reach 70% in the years after 2000, with a production of 100TWh/year already achieved by the end of 2007.

![Fig. 3. The gradual shift of wind energy generation between world regions (based on data from [14]).](image1)

![Fig. 4. Country and regional distribution of wind power capacity installed in 2009 (based on data from [13]).](image2)
However, restart of the USA market [16] and development of the wind energy industry in China [17] have considerably reduced the aforementioned numbers during the recent years to a current 60%. As a result, the aggregate share of North America and Asia & Oceania in 2007 corresponded to an approximate 38% of the world wind energy production (Fig. 3). In the meantime, 80% of wind energy production attributed to North America in the early 90’s shrank to 20% within a decade’s time, while for the region of Asia & Oceania considerable contribution may be encountered since 1995. Concerning the present status of wind power capacity (Fig. 4a), the USA managed during 2009 to add a new 40% over its cumulative capacity. At the same time the Chinese achieved to install...
almost 14 GW, i.e. 20% and 40% of the EU and the USA cumulative capacity respectively, which leads to an aggregate (USA and China) of 62% of the 2009 capacity. As a result, China has reached the second place of the world ranking table together with the long-term leader of the EU, i.e. Germany. Besides, at the regional level (Fig. 4b), Asia has managed to marginally exceed the North Americans in terms of cumulative capacity, while the EU is still the world leader with almost 50%.

At the same time, at the European level (Fig. 5) Germany (25.8 GW) and Spain (19.1 GW) are now followed by Italy (4850 MW), France (4492 MW), UK (4051 MW), Portugal (3535 MW) and Denmark (3465), with the latter presenting a long-term stagnation that calls for the improvement of the local legislation [18] although considerable exploitation of the local wind potential has already been achieved. On the other hand, France and Portugal present remarkable developing rates since 2000, while for Italy and Netherlands the local wind energy market encountered an earlier start (i.e. since 1990) with analogous results only for the case of Italy.

Further, what is also interesting to see is the time evolution of generating capacity of all technologies in the EU during the time from 1995 to 2009. As one may see in Fig. 6a, during the last two years, new wind power capacity exceeds any other technology with more than 10 GW of wind power installed in 2009. Additionally, in terms of cumulative installations (Fig. 6b), European wind farms exceed oil-based generation by 20 GW and are down by 50 GW when compared to nuclear power. In fact, the developing rate of wind energy capacity is only comparable to the respective of natural gas installations, with the remarkable growth of photovoltaic plants also designating the shift attempted in the EU to clean power generation technologies.

In this context, contribution shares of wind energy production to the gross electricity generation of certain EU countries already exceed 10% (e.g. Denmark, Portugal and Spain) [19], while for the Danish approximately 20% should be considered, with the respective EU average kept at 4.1% (Fig. 7). Nevertheless, shift to offshore attempted by many European countries [20,21] (1.5 GW already in operation in Denmark and the UK), with short-term plans of 33 GW by 2015 mainly supported by Germany and UK (Fig. 8), shall further increase the contribution shares of EU wind farms.

Summarizing, according to the latest official data, the EU still remains the world leader, although the USA made a considerable come-back with over 10 GW installed in 2009. Meanwhile, China persists on its outstanding growth rates, each year doubling its cumulative capacity, and seems ready to overtake the first place in the world ranking table. On top of these, India following a steady growth rate [22] is the China’s most important ally, adding more than 10 GW
for the Asian region. Besides, after a long stagnating period Australia managed to install almost 1 GW during 2008–09 [23], thus increasing the Pacific capacity at more than 2 GW. On the other hand, in the Latin America, noteworthy is only the development encountered in Brazil, Chile, Mexico and Costa Rica, summing up however to a total of only 1 GW [24]. Finally, Egypt, Morocco and Tunisia [25] are the only active African countries (more than 0.7 GW), with Iran being the only Middle East country found to considerably exploit its local wind potential (~100 MW) [26].

3. Technology issues

The development of contemporary WTs in the course of time [27–29] may be reflected by the gradual upscale of machines, based on the rationale for better land exploitation, presence of scale economies, reduced maintenance and operation (M&O) requirements and past funding development programs [1] pushing towards the development of big-scale machines. On the other hand, a stabilizing trend is noted during the recent years that has put an end to the exponential increase of the rotor diameter met in the first two decades (Fig. 9a) [30]. As a result, WTs of nowadays are mainly in the order of 2–3 MW, although larger scale machines that are already commercial do exist (Fig. 9b). Contrariwise, the shift to offshore applications calls for multi-MW solutions—already offered by some of the manufacturers (even at the levels of 7 MW) —, while designs of machines that will exceed the nominal power of 10 MW are already underway.

Meanwhile, during the evolution of technology, multi-bladed turbines are found to be constrained to water pumping applications. On the other hand, among the types of electricity generation, the three-bladed WTs prevailed over the respective single- and
two-bladed machines that appeared to be both less efficient and less accepted concerning their visual impact. Similarly, the inherent lower efficiency and the cost-ineffectiveness were the main reasons for the vertical axis WTs (VAWTs) actually never becoming mainstream, although a new market seems to emerge for the smallest scale VAWTs in building applications [31,32].

Concerning power regulation, pitch control found itself to be gradually more adaptable to new machines, with the ratio of pitch to stall machines increasing from 1:1 (1997) to 4:1 in 2006 (Fig. 10). Following, introduction of the variable speed concept, although inducing extra costs and additional losses in the variable speed drive, allowed for increased energy capture below the rated power area and relief of loads, enhancement of the pitch and smooth power output above the rated power area.

In this context, a long term increase of the mean annual capacity factor (CF) met at both the EU and the global level (Fig. 11a), exceeding 20% in 2007, reflects the effect of technological improvements, this also including the gradual establishment of pitch control machines.

More specifically, although good wind potential areas are now harder to find, exploitation of wind energy per kW has increased due to improved efficiency of contemporary turbines, sophisticated assessment of the local wind potential, considerable reduction of downtime periods, upgrade of networks and operation of offshore applications. In this context, of special interest are countries such as Germany and Denmark where although local wind potential keeps CFs at moderate values, diffusion of wind parks is remarkable, and countries such as Ireland, Spain and Turkey where the long-term CF is found to exceed 25% (Fig. 11b).

![Graph showing Time Evolution of the Mean Annual CF on the EU & the Global Level](image1)

**Fig. 11.** Time evolution of the mean annual CF for the world and the EU wind energy applications (based on data from [14]).

![Graph showing Long-Term Capacity Factor of Wind Power Installations in European Countries (1990-2008)](image2)

**Fig. 12.** Range of applications for small scale wind turbines (based on data from [45]).
Another important technology issue is grid integration, with large-scale penetration of onshore and offshore wind parks challenging all parties involved and with system issues including power quality, voltage management, grid stability, grid adequacy, control of emissions and efficiency reduction of other generating plants [33–35]. As a result, in order to confront future wind power grid integration, the main directions include design and operation of the power system with the introduction of demand side management techniques and energy storage [36–38], grid infrastructure issues meaning reinforcement and upgrade of networks, grid connection of wind power with grid codes issued, market operation with the introduction of more flexible mechanisms and other issues such as institutional [39].

Finally, of special interest is as already implied, the industry of small scale WTs [40–42], satisfying a range of applications [43–45] (Fig. 12). Such applications may concern both on-grid and off-grid concepts like building integration, mini wind farms and single turbine installations for the first category, and wind–battery along with wind–based hybrid systems for the second [46]. Besides, the interest lately exhibited may also be illustrated by the recent developments in the specific field, these including active pitch controls for high wind speeds, vibration isolators to dampen sound, advanced blade design, self-protection mechanisms for extreme winds, dual mode models (both on- and off-grid), software development, inverters fitted into the nacelle, attempts to make small WTs more aesthetically attractive and integration of small WTs into several structures.

4. Economics of wind energy

Among the main trends dominating the market of wind energy during the years, one may note the size increase of contemporary WTs, the efficiency improvement and the long-term reduction of the specific investment cost per kW (turnkey cost) of installed wind power capacity [47]. Concerning the latter, although starting from a remarkable 3500€/kW during the mid-eighties, it has during the last years stabilized in the order of 1200€/kW, i.e. between 1000€/kW and 1400€/kW [48], depending also on the area of study (Fig. 13a and b).

In this context, some rough numbers may also be given in terms of investment cost breakdown, noting also the difference between onshore and offshore applications. More specifically, the turbine component being critical in onshore projects (~930€/kW) (Fig. 14a) drops to a typical 48% in offshore plants (Fig. 15a) while on the other hand, foundation requirements increase by more than four times and grid connection in offshore is increased by more than 150€/kW. Overall, the total specific investment cost of offshore applications is found to be higher by more than 40% for most of the plants in operation and may increase to even exceed 3000€/kW for installations that are under construction [49,50]. Besides, based on
the experience of in operation offshore parks employment of more turbines implies relatively lower turnkey costs (Fig. 15b). Any case given, M&O costs (Fig. 14b) including insurance, regular maintenance, repairs, spare parts, administration, land rent and others [51–53], are also considerable for wind power installations, although the introduction of more efficient machines and the reduction of downtime hours constantly decrease the M&O requirements which are now in the order of 1.2–1.5€/kWh.

On the other hand however, the wind energy production cost is found to be comparable with the respective of conventional fossil-fueled generation methods [54], even without internalizing the externalities. As a result, clear advantage of wind power in the economic field as well becomes evident (Fig. 16), with estimations concerning the near future electricity generation cost of onshore and offshore wind parks supporting values between 50€/MWh and 80€/MWh and between 75€/MWh and 120€/MWh respectively [55–57].

Following, State support, as already seen in the introduction section, led to the outbreak of California. In this context, of analogous importance for the remarkable growth of the wind energy market has been the implementation of various support mechanisms [58] including price- and quantity-driven instruments such as feed-in-tariffs, investment and production tax incentives for the first and quota along with tradable green certificates and tendering systems for the second. At this point, one should underline the effectiveness of most of these measures and especially the feed-in-tariff mechanism [59], which since being adopted by the majority of leading countries worldwide (Germany, USA, China, Denmark, Spain, India, etc.) [60] led to the remarkable growth of wind energy generation (see also Fig. 17a–c).

Finally, one should also emphasize on the employment opportunities [61] offered by the expansion of the wind energy market at a global level. Somewhat 100,000 plus 50,000 is the number of people employed directly and indirectly in the wind energy field of Europe, while another 85,000 correspond to the 100 manufacturing plants operating in the USA. These include employment posts in manufacturing companies, in promotion, utilities, engineering and R&D (direct employment) or employment in companies providing services or producing components for WTs (indirect relation). Note that according to rough estimations [62], among the leader countries on the basis of the people employed per MW installed ratio (Fig. 18), Denmark, Belgium and Finland employ more than 7 persons while in terms of absolute numbers Germany currently employs 38,000 people [63].

5. Environmental performance of wind energy

Although suggesting an a-priori clean energy source, wind power also comes with certain environmental impacts [64] such as the visual [65] and the noise impact [66], the land use, the bird fatalities [67], the electromagnetic interference, the impacts on fish and marine mammals and the embodied energy plus LC emissions common in every power generation technology. Many of these impacts are nowadays perceived by many as “myths” [68,69] (see also Fig. 19a), while others still lie on the subjectivity of oneself. What is documented however [70–74] is that WTs require primary
LC embodied energy amounts in the order of only 1–3 MWh/kW (that usually implies energy payback periods of months), with the stage of manufacturing being the most demanding (Fig. 19b).

Furthermore, if also considering externalities [75–77], a clear advantage may be recorded for wind power installations in comparison with conventional power plants (Fig. 20a). In fact, according to estimations [78], realization of the high expectations set by the EU for 2020 implies avoidance of externalities in the amount of almost 40 billion €/year, with the distribution of cost savings per country given in Fig. 20b.
Besides that, environmental performance of wind energy perceived by the majority of people (over 70% in favor) [79,80] and transformed into widespread social support (only solar energy seems to be more socially accepted) further boosts wind energy developments (Fig. 21). On the other hand, one of the challenges that wind energy is faced with during the recent years is the paradox of increased social support being obscured by real-life NIMBY attitudes [81–83], especially since availability of good sites is becoming increasingly rare.

6. Wind energy prospects and R&D

Up till now, the policy framework of the EU was of critical importance for the promotion of RES and wind energy in particular.
In this context, new targets set call for 20% coverage of the final energy consumption by RES by 2020, while in terms of electricity consumption, wind energy is expected to contribute by a 14%–17%. In fact, two scenarios have been elaborated on the basis of the 2020 target [84], i.e:

1. The “baseline” scenario that assumes a total installed wind power capacity of 230 GW (Fig. 22a), producing 580TWh of electricity and increasing the electricity demand coverage by wind from 4.1% in 2008 to 14.2% in 2020.
2. The “high” scenario where the total installed wind power capacity is assumed to reach 265 GW by 2020, producing 681TWh of electricity and increasing the electricity demand coverage from 4.1% in 2008 to 16.7% in 2020.

Moreover, according to long-term plans [84], 400 GW (250 GW onshore and 150 GW offshore, see also Fig. 22b) of wind power in the EU and 20% of the USA electricity demand covered by wind by 2030 [85], along with China requesting 150 GW installed by 2020 [86], set the scenery of wind power prospects and challenge the target of 1000 GW globally by 2030. In this context one should also note that:

- In India, existence of a domestic industry and 65–70 GW of assessed wind potential along with 10% of RES capacity and 4–5% of RES energy shares by 2012 are the main drivers of wind energy with estimations calling for 2 GW/year in the following period.
to be taken including the following: the wind energy industry[87], with the main directions and actions mentioned goals to be realized, R&D targets set must be put forward by 100%

Fig. 21. Social acceptance of various electrical power technologies (Source: [80]).

- Wind potential for onshore wind energy capacity in Brazil has been assessed at 143 GW (at 50 m high).
- At the end of 2008, Australia’s expanded the country RES target to 20% by 2020.
- South Africans turn to wind, since the bulk part of the 100TWh produced by RES up to 2025 is to be assigned to wind power.

Finally, what is important to consider is that for the aforementioned goals to be realized, R&D targets set must be put forward by the wind energy industry [87], with the main directions and actions to be taken including the following:

- New wind turbines need to reduce their overall costs
  - Large scale turbines of 10–20 MW going offshore (R&D programmes for prototypes already initiated)
  - Improved design and reliability of components (Testing facilities to assess efficiency and reliability of wind turbines)
  - Development of innovative logistics (Cross industrial programmes)
  - Deeper waters and larger turbines for offshore
  - Development and industrialization of support structures for sea installations, both fixed and floating (Structure concepts to be developed and tested at different depths and under different conditions)
  - Achieve grid integration for even greater wind energy penetration
  - Introduction of large-scale energy storage systems and high voltage alternative and direct current (HVAC-HVDC) interconnections (Offshore farms connected with more than one grid, long distance HVDC, R&D of energy storage systems)
  - Resource assessment and spatial planning
  - More sophisticated assessment of wind resources (High quality measurements and databases for wind data as well as short-term wind speed forecasting with the use of neural networks)
  - Spatial planning through social and environmental considerations (Development of planning tools and methodologies).

7. Conclusions

A review of the wind energy history undertaken in the current work emphasizes on the main issues of global market facts, technology, economics, environmental performance, prospects and R&D of wind power, providing some insight and presenting the highlights for each of the fields. From the review undertaken, the dynamics of wind power at the global energy scene during the last thirty years is illustrated, while according to the targets set, the perspective of exceeding 1 TW of wind power installations by 2030 seems feasible, especially if considering the challenges introduced by the need of each country to safeguard security of supply and promote clean power technologies.

Besides that, although the leading role of the EU throughout the period of wind energy development has been designated, the return of the USA and the tremendous growth of the wind energy industry in China are also reflected. On top of that, of special interest is also the gradual adoption of wind energy by several countries of the developing world, this clearly demonstrating both the catholic character of wind power and its ability to largely substitute fossil-fueled power generation in the years to come.

References


