Wind turbines: current status, obstacles, trends and technologies

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Abstract. The last decade the installation of wind farms around the world is spreading rapidly and wind energy has become a significant factor for promoting sustainable development. The scope of the present study is to indicate the present status of global wind power expansion as well as the current state of the art in the field of wind turbine technology. The RAM (reliability/availability/maintenance) section is also examined and the Levelized Cost of Energy for onshore/offshore electricity production is presented. Negative consequences that go with the rapid expansion of wind power like accidents, environmental effects, etc. are highlighted. Especially visual impact to the landscape and noise pollution are some factors that provoke social reactions. Moreover, the complicated and long permitted process of a wind power plant, the high capital cost of the investment and the grid instability due to the intermittent nature of wind, are also significant obstacles in the development of the wind energy production. The current trends in the field of research and development of onshore and offshore wind power production are analyzed. Finally the present study is trying to achieve an estimation of where the wind industry targets for the years to come.

1. Introduction
The increasing energy demand globally together with the emission of harmful gases (NOx, SOx etc) caused by the conventional fossil fuel resources, have made the need of increasing the use of renewable energy sources in the energy balance of each country imperative. Surely, green growth should not be perceived as a turn to an irrational and at any cost use of renewable energy sources, but as an investment in policies and technologies which would turn renewable energy sources into competitive and sustainable energy sources. According to the European Energy Roadmap 2050 [1] the share of renewable energy rises substantially in all scenarios, achieving at least 55% in gross final energy consumption in 2050, an increase of 45 percentage points from today's level of around 10%.

Wind power, i.e. the kinetic energy of the wind, is a renewable energy source that is used among others mainly for the production of electrical power. The global wind resources (land and near-shore) are estimated to be 72 TW which is seven times the world’s electricity demand and five times the world’s energy demand. In contrast to the global pollution issues and the significant cost of fossil fuels, wind seems to be a clean, affordable and inexhaustible source of energy and its exploitation can meet directly both the global demand for renewable and clean energy and the need to secure new energy sources. The wind turbines are installed either onshore (on land) or offshore (beyond the...
coast). Offshore wind farms seem to be advantageous due to the enormous energy potential associated with the large continuous areas and the stronger winds that imply greater power generation, even though they have higher initial investment, operation and maintenance costs.

2. Wind power in numbers
By the end of 2015 the global cumulative installed wind capacity has reached 432 GW (Figure 1) with offshore installations to have a total power of 12 GW [2]. In the same time there is 142 GW of installed wind power capacity in the EU: 131 GW onshore and 11 GW offshore [3].

![Figure 1. Global cumulative installed wind capacity 2000-2015](Source: Global Wind Energy Council)

According to a Caduff et al. study [4] the bigger the wind turbine is, the greener the produced electricity is. Of course a bigger wind turbine means mainly producing more power more efficiently. The last decade the wind turbine size has more than doubled. In 2005 the maximum operational wind turbine was 3.6 MW and now is 8 MW. The largest operational wind turbine models based on capacity and their manufacturers, are the following: Vestas V164 8MW (with 164m rotor diameter), Enercon E126 7.5MW, Samsung S7.0 171 7MW, MHI SeaAngel 7MW, Repower 6M 6.2MW, Siemens SWT-6.0 150, Alstom Haliade 6.0MW, Sinovel SL6000 6.0MW, Areva M5000 5.0MW, Gamesa G5MW [5]. According to BTM Navigant survey [6] regarding wind turbine installation market share, in 2014 Vestas (Denmark) had 12.3% of the wind energy market, Siemens (Germany) 9.9%, GE Wind (USA) 9.1%, Goldwind (China) 9%, Enercon (Germany) 7.8%, Suzlon (India) 5.8%, United Power (China) 5.1%, Gamesa (Spain) 4.7%.

The largest operational onshore wind farm in the world is Gansu Wind Farm in China. It has a current capacity of power of 6,800 MW and a target capacity of 20,000 MW by 2020. The first world’s offshore wind power plant was installed in Vindeby (Denmark) in 1991 and had a total capacity of 4,95 MW (11 X 0.45 MW – BONUS wind turbines). At this moment the largest offshore wind farm in the world (and the largest wind farm in Europe by megawatt capacity) is the London Array. It is a 630MW wind farm consisted of 175 Siemens Wind Power SWT-3.6 turbines and located 20 km off the Kent coast in the United Kingdom. In February 2016 Dong Energy has announced the Hornsea project, a 1.2 GW offshore plant which will be made up of 7 MW turbines and will occupy more than 400 square kilometers, situated about 120km off the Yorkshire coast also in the United Kingdom.

Among the EU members, Germany remains the country with the largest installed capacity (45 GW), followed by Spain (23 GW), the UK (14 GW) and France (10 GW). The total wind power capacity installed at the end of 2015 could produce 315 TWh and cover 11.4% of the EU electricity consumption in a normal wind year [3].
3. Wind turbine technologies

There are two main types that modern wind turbines can be categorized in: the horizontal axis wind turbines and the vertical axis wind turbines. The majority of the large scale wind turbines are horizontal axis due to their greater efficiency and power output. The main parts that a large scale horizontal wind turbine consists of are: rotor (blades, hub and pitch system), nacelle (rotor shaft, bearings, gearbox/ generator, mechanical brake and yaw system), tower, foundation and the electrical (power feed cables, lightning protection, power converter, transformer) and control system (sensors, actuators, system consisting of hardware and software).

There are two different drive systems for converting rotational power into electrical: indirect and direct drive. Indirect drive system uses a gearbox to increase the rotational speed of the shaft that drives the generator. The indirect drive configuration often uses asynchronous squirrel-cage induction generator (SCIG), wound rotor induction generator (WRIG) or doubly fed induction generator (DFIG). The direct drive does not use gearbox because there is a full-scale power converter with multi-pole generators: excited synchronous generator (EESG) or permanent magnet synchronous generator (PMSG). There are also configurations that use gearboxes with a full-scale power converter and thus, bigger and more expensive generators are unnecessary. These indirect drive types use smaller generators: wound rotor synchronous generator (WRSG), permanent magnet synchronous generator (PMSG) and asynchronous squirrel-cage induction generator (SCIG). The configuration uses an excited synchronous generator (EESG) is the most reliable, powerful and expensive configuration. Wind turbines with DFIG configuration is the most commonly offered type by the major manufacturers. The trend is towards full scale power converter configurations with multi – pole permanent magnet synchronous generator (PMSG), because they reduce losses and they are lighter than types with excited synchronous generator [7].

The condition monitoring systems, which comprise combinations of sensors and signal processing equipment, are used to monitor the status of operating major components. Monitoring may be: on-line (and thus provide instantaneous feedback of condition) and off-line (the data are collected at regular time intervals using measurement systems that are not integrated into the wind turbine). A detailed view of a wind turbine condition monitoring system will typically present the following data: wind turbine data (wind speed, active and reactive power, yaw angle, etc. and command, operational and fault status), electrical and mechanical data, meteorological data, grid data, statistical data. Different monitoring techniques in wind turbines are used in order to prevent damage or failure of components. The most common condition monitoring techniques that are used are the following: process parameters, performance monitoring, vibration analysis, acoustic emission, ultrasonic testing (UT), oil analysis, strain measurement, electrical effects, shock pulse method, radiographic inspection and thermography [8].

![Figure 2. Fixed bottom foundations and floating offshore concepts [9]](image-url)
There are different types of foundations that are used for offshore wind turbines (Figure 2). The two main categories are the fixed bottom (for depths up to 50 m) and the floating concepts (for deeper waters). The monopole is the simplest and cheapest type of foundation that is used commonly in the North Sea into the sea bed to a depth of 0–25 m. A gravity-based foundation is normally fabricated in reinforced concrete with ballast and it uses its own weight to anchor to the seabed at water depth between 0 and 25m. An alternative to these two is the suction caisson, in which by removing the water from a caisson onto which the turbine is situated the suction force thus created is used to promote easy installation. A tripod structure is a relatively lightweight three-legged steel structure, in which the frame is submerged in the water, providing good stability and stiffness and it is used for depths between 20 and 50m. Jacket is often used in water depths of about 20–50 m and usually consists of a three or four-legged lattice structure made from tubular steel.

The need for higher quality wind resources unconstrained by water depth has turned the wind industry developers in the direction of floating support options (which were already experienced in the offshore Oil and Gas industry). The main floating concepts are: the spar buoy, the tension-legged platform, the buoyancy stabilized and the semi-submersible. Statoil together with Siemens Wind Energy installed in 2009 the world’s first full-scale floating spar type wind turbine (Hywind) of 2,3 MW power output at the coast off Norway and at a depth of 200m [10]. This wind turbine survived 11 meter waves with seemingly no wear. In summer of 2015 a 7MW floating offshore wind turbine (semi-submersible concept) developed by Mitsubishi Heavy Industries (MHI) has been moored at the Fukushima demonstration site, 20 kilometres offshore. [11]

4. Maintenance issues and wind power related costs
Wind turbines, just like every other technical asset, must be serviced regularly and repaired in case of defects. The main reasons that make the maintenance of wind turbines of special significance are the ambient conditions that are unusually tough and the extremely high dynamic loading of the components. These two factors are considered carefully in the design and selection of materials, but conventional components still require maintenance. Common causes of wind turbines failure can be: components failure, control system failure, high wind, waves, lightning, grid failure, icing, etc. The commonest reason which is responsible for wind turbines failure is components breakdown. Figure 3 presents the average failure rates for wind turbine components from different sources [7].

![Figure 3. Average failure rates for WT components from different studies [7]](image)
To achieve the best possible power production efficiency of the installed wind turbine, a high reliability level should be reached. The objective is to increase the turbine availability, by improving the wind turbine reliability or their maintainability or both, if this is possible. The wind turbine reliability is a pivotal factor in the successfully function of a wind power plant. High reliability can be achieved by understanding and minimizing the failures of the system. The reliability of a wind turbine does not depend exclusively on the reliability of its subsystems, but also on external, indirect factors like the maintenance strategy used, the existence of spare parts, the time needed to repair, the existence of control systems of the subsystems, the type of wind turbine related to the operational environment (onshore, nearshore, offshore) and the training of the personnel. Maintenance planning could make maintenance more efficient and could lead to a reduction of failure events. In order to decide the most effective maintenance strategy, the most critical components of the wind turbines, which are prone to failures, should be identified. The maintenance strategy should take into account both the reliability improvement and the reduction of maintenance cost. The operation and maintenance strategy of wind turbines is directed towards enhanced condition monitoring systems.

The levelized cost of energy (LCOE) is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yield a lower return on capital, or even a loss. According to IRENA (International Renewable Energy Agency) [12] for 2014 the LCOE range was for onshore projects 0,06-0,12 USD/kWh and for offshore projects 0,10-0,21 USD/kWh. The regional weighted average installed costs in 2014 for onshore wind range from around 1,280 USD to 2,290 USD/kW (with China and India having weighted average installed costs 35% to 44% lower than in other regions). The average installed cost ranges in 2014 for offshore wind projects was 2,700-5,070 USD /kW. The variable operation and maintenance costs for onshore wind projects in 2014 for Austria was 0,04 USD/kWh, for the Netherlands 0,013 - 0,018 USD/kWh, for Norway 0,021 - 0,039 USD/kWh, for Spain 0,028 USD/kWh, for Sweden 0,010 - 0,035 USD/kWh, for Switzerland 0,045 USD/kWh, for the United States 0,01 – 0,024 USD/kWh and for Denmark 0,015 - 0,019 USD/kW.

5. The less popular side of wind power and the obstacles
Visual impact, noise pollution, ecosystem-related issues (environmental hazards for flora and fauna), health hazards (electromagnetic fields, possible cause of accidents), impact on tourism and agriculture, the reduction in the value of land and the end of life (wind turbine waste treatment), are the main drawbacks of wind farms. These effects are also sources of rejection of wind turbine installation from the inhabitants of the planned wind farms. Noise pollution and the degree of visual disturbance could be avoided by selecting wind turbine sites far from residential areas. Offshore wind farms seem to be advantageous as they have reduced noise impact and visual impact. From a visual disamenity point of view, the socially optimal location for installing offshore wind farms is unlikely to be greater than ca 18 km from the shore [13].

Caithness Windfarm Information Forum published a detailed table that includes all documented cases of wind turbine related accidents and incidents which could be found and confirmed through press reports or official information releases up to 31 March 2016 [14]. The data include human accidents (fatal, injuries, human health related), fire accidents, wind turbine components failures that result in severe damages (structural components failures, blade failures etc), construction and transportation damages, ice throw, environmental damages (wildlife damages, pollution from oil leakages etc). This data clearly shows that blade failure is the most common accident with wind turbines, closely followed by fire. Figure 4 shows a chronological summary of the previous mentioned accident table. The trend is as expected - as more turbines are built, more accidents occur.

In a survey of Zimmerling et al [15] based on 2,955 installed turbines (the number installed in Canada by December 2011), an estimated 23,300 birds would be killed from collisions with turbines each year in Canada; (c.a.270 million birds died each year in Canada, ~200 million were killed by cats and ~25 million by building collision [16]). The problem of bird mortalities due to wind turbine
collision could be reduced by careful site selection, the use of brightly colored sections of rotors or the use of some night time lighting (for the bats).

![Wind turbine accidents and incidents](image)

**Figure 4. Wind turbine accidents and incidents [14]**

Nevertheless, the average general attitude towards any kind of renewable energy installations (including wind power) is positive. The majority of people support any action which yields to cleaner environment and to sustainable development. Despite the general approval of wider society with respect to wind power, when it comes to local communities, the negative reactions have often been especially intense. A major cause for these reactions has been a fear of property values falling due to proximity to a wind farm because of the visual impact, noise and other issues mentioned before. Public information, consulting and allowance of the local people (local community organisations, environmental societies, wildlife trusts, local politicians) for participation and involvement in the planning and decision making procedures, could considerably contribute in the prevention of local resistance towards wind power investments.

The wind turbine end of life is an issue that is going to be of high importance in the near future. A large amount of already installed turbines will reach the end of their service life shortly. A modern wind turbine is designed to work for an estimated time of 20 years. After this point it has to be either renewed or recycled. The main problem regarding wind turbines decommissioning process is that except steel, copper and aluminum which are fully recyclable, the glass reinforced plastics (based on polyester or epoxy) used in the rotor blades have proven challenging to recycling. Options of blade material waste treatment are: mechanical recycling (which is a labor intensive process and uses the produced material as a filler in artificial wood, cement or asphalt production), incineration, pyrolysis and landfill, which is the worst option [17].

The complicated and long permitted procedures of a wind power plant in many countries, together with the long planning phase (including among others environmental, engineering, feasibility and site-specific studies) that are required, are challenges that an investor has to face in the early beginning of a wind power project. The high investment cost and the high levelized cost of wind energy compared to energy market prices are also characteristics that have to be taken into consideration for estimating the viability of the investment. Of course the high feed-in tariffs and the policies of subsidies that most of the governments follow in order to promote wind energy, make wind a competitor with the existing conventional energy sources. The grid instability due to the intermittent nature of wind is another disadvantage as this practically means power losses in transmission lines. Additionally the variable or the intermittent nature of wind supply is probably the biggest obstacle wind power has to overcome, as the power grids require a reliable energy supply and energy companies are often forced to apply a cost
of the extra gas turbine plant required to make up the missing guaranteed supply to intermittent of suppliers, in order to ensure integration of variable renewables sources like wind into a grid [18]. Alternatives to the instability of wind power production would be implementing energy storage configurations and also the use of wind forecasts for preparing grid operators for extreme events which power generation is unusually high or low.

6. Research & Development trends and the future of wind industry

The large offshore models constructed for extreme weather and sea conditions and designed to reduce installation time and maintenance frequency, is the field of research and development (R&D) competition for the wind turbine developers. These huge constructions will logistically force in the next decade the supply chain towards the establishment of coastal manufacturing and assembly facilities to avoid constraints associated with road/rail transport. The floating offshore models are also something that the wind turbine manufacturers focus. The floating wind turbines have the advantage that all construction (and also maintenance) could be done on land and then transported and hooked up to the seabed. Advanced drivetrain designs, enhanced condition monitoring systems, larger rotors made by light-weight advanced materials and taller towers with new design architectures and materials, suggest a whole new field for innovations in the near future. Totaro [19] highlights that the new technologies and their patents will be likely directed towards six core areas: reducing component weight and manufacturing costs, transport and assembly, monitoring and control, turbine reliability, grid integration and optimizing performance. The most ambitious R&D is trying to create a rotor blade longer than 200m for a 50-MW offshore wind turbine. This is 2,5 times longer and 6 times more powerful than the largest blades and turbines currently in operation [20].

7. Conclusions

The last decade the installation of wind turbine farms around the world is spreading rapidly onshore as well as offshore. The present study has examined the current status of wind power and presented the related technologies, the maintenance issues, the costs, as well as the negative effects and obstacles of the wind industry. Despite some local negative reactions, the majority of people embraces and supports renewable energy installations. In the future we will see taller towers with larger rotors from advanced materials that could capture greater amounts of wind energy. The wind turbine technology will be focused on higher reliability with the implementation of advanced control and monitoring systems. The operation and maintenance strategy will be directed towards enhanced condition monitoring systems and advanced maintenance strategies. The annual amount of waste from wind turbines due to their end of life will grow substantially and should be managed sustainably.

As an epilogue to this study it should be emphasized that the domination of environment friendly energy sources, which are economically competitive against fossil fuel energy sources, is something the whole mankind could benefit from.

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