APPLICATION NOTE
INTRODUCTION TO WIND POWER

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CONTENTS

SUMMARY

Wind Power generation has been a key contributor to the recent development of renewable energy.

The associated technologies are being steadily improved to ensure reliable operation and to minimize any adverse impact upon the electricity distribution system. It has now been clearly demonstrated that a very high penetration of wind power is feasible, albeit in some cases challenging.

Significant cost reductions have been achieved, lowering the cost of wind power to a level that in many cases is competitive with current conventional generation, even when the low environmental impact of wind power is not taken into account.

This technical note discusses the basics of wind power technology, its integration into electric power systems and its evolution in recent markets.

INTRODUCTION

COMPARISON WITH OTHER TECHNOLOGIES

The steady development of the associated technologies, markets, and projects and the significant cost reductions have in many cases made wind power generation a competitive alternative to conventional electricity generation.

The main strengths of wind power include:

- Low environmental impact
- Increased energy independence, especially in countries lacking fossil fuel or hydroelectric resources
- A modular nature that enables its adaptation relatively quickly to changing needs and a low financial risk compared to generation technologies such as nuclear power that only make sense in large scale projects.
- Low enough costs to make it the best alternative in many cases.

There are of course also some drawbacks that have to be taken into account, especially the following:

First, energy production from wind power shows a high variability, and is not fully dispatchable. Nevertheless, large shares of wind power have been successfully integrated into many electric power systems. It is true that the integration of wind energy represents an added cost for the distribution system. However the progressive sophistication of the power system operation is reducing this impact to reasonable levels.

Second, it is not possible to install wind power plants everywhere, unlike some other power generation technologies which have fewer limitations regarding location. When selecting a suitable location to build a wind power production facility, several site specific factors need to be taken into account:

- Wind resource has to be abundant. Its estimation will be the focus of the next section.
- Administrative permission has to be obtained. Power system planning objectives or environmental issues may render the project unviable.
- The location has to be accessible. This is a common problem since locations with high wind speeds are often in remote or mountainous areas.
- The location has to be reasonably near a suitable connection point with the existing power grid. Otherwise the cost of building the interconnection line may render the project unviable.

Third, wind power is no longer the only viable renewable energy. Recent cost reductions in photovoltaic generation make it an excellent alternative in some cases. Moreover, photovoltaic technology is simpler to install and to maintain. It is even more modular and it can be installed almost everywhere provided that there is enough sun. Photovoltaic power is, however, only capable of producing energy during the day.

Even taking into account the drawbacks, wind power generation is certainly one of the best alternatives for electricity generation currently available. This fact is clearly demonstrated by its steadily growing market share. The year 2015 established a record for wind power, as we will demonstrate with figures in a later section.

BASIC PRINCIPLE OF OPERATION

Wind turbines extract energy from the wind by transforming some of the kinetic energy of moving air into mechanical energy. Turbine blades are similar to airplane wings: the wind creates a pressure difference between the sides of the blade that in turn creates a mechanical torque in the rotor. The resulting mechanical energy is used by the generator to produce electric energy, which is delivered to the grid through a power interface, as shown in *Figure 1*.

Optionally, a gearbox can be included in the drivetrain to match the operating speed of the turbine with the generator speed.

In recent designs, a control system is used to optimize the operation of the turbine and the power interface.

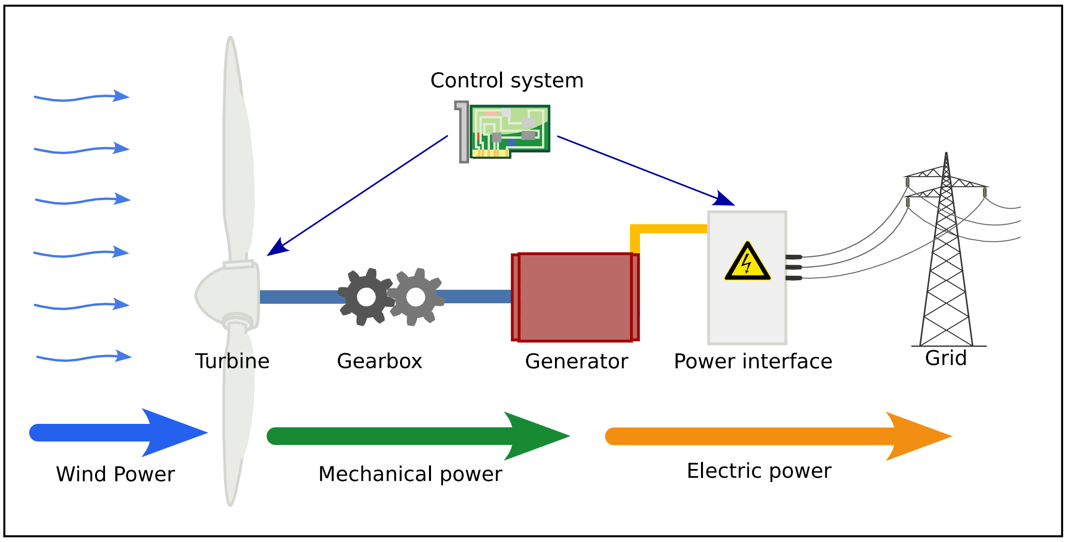

Figure 1—Principle of operation [7]

The characteristic behavior of a wind power system, meaning the amount of energy that can be extracted from wind at a given time, and the ability to control and regulate this extraction, will mainly be determined by:

- The kinetic energy that is available from the wind
- The efficiency of the conversion of wind energy to mechanical energy

Other significant losses, such as mechanical losses in the drivetrain, generator losses, electrical losses, constant consumptions, et cetera will just reduce the output by a certain factor but will not determine the global behavior of the system. The only exception is the capacity to regulate reactive power, which depends upon the type of generator and power interface employed.

WIND RESOURCE ESTIMATION

AVAILABLE POWER FROM WIND

For a given mass M of air, the kinetic energy is $E = \frac{1}{2}MV^2$, being V the wind speed.

In the case of a wind turbine, the air mass m that flows through the area that is swept by the turbine blades is, in kg/s:

$$m = \rho \cdot A \cdot V$$

With ρ = density of air (kg/m^3)

A = area swept by the rotor blades (m^2)

V = wind speed (m/s)

Therefore, the kinetic power that is available for conversion is

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A \cdot V^3$$

Only a fraction of this power will be converted to mechanical energy in the rotor. This fraction is the power coefficient C_p, which will be discussed in detail later. For now, the important idea to be noted is that the power that is available for conversion will depend upon:

- The area swept by the rotor blades: Longer blades imply more power, and this area is proportional to the square of the blade length.
- More importantly: the available power will depend on the **third power of wind speed**: Doubling wind speed multiplies the power by eight.

This has a strong influence on how the wind resource has to be estimated in order to predict the power output of a wind turbine:

- The mean of the wind speed is not particularly meaningful. It is necessary to estimate the frequency at which each wind speed occurs, since high wind speeds, even if they are not frequent, can represent a significant share of the energy production.
- Small errors in estimating wind speed are amplified and can cause large errors in the estimation of the energy production.
- A rather low variability in wind speed can still translate into a large variability in energy production.

MAIN CHARACTERISTICS OF WIND

One of the most important characteristics of wind is that it is both a **highly local** and a **variable** phenomenon. Wind speed changes over time and within various time frames, depending upon the seasons and the weather conditions. Moreover, the wind near the ground is affected locally by the terrain topology and roughness.

- Mountains, valleys, canyons and other terrain configurations and objects can either block the wind in certain areas or act as a funnel and multiply its speed. The result is that significant differences in wind speeds can be found within a hundred meters, or even less. It will be extremely important to choose the right location for a wind turbine, especially in complex topography.
- Wind is slowed down at ground level by terrain “roughness”. Buildings, trees, and even low vegetation or a smooth surface such as large bodies of water will affect wind speed close to the

ground, creating a wind speed gradient. Therefore, the higher the wind turbine, the higher the wind speed.

- Wind speed shows a significant variability at several time scales: from seconds to years. This will have a number of impacts, both on how the wind resource has to be estimated and on how to successfully integrate wind generation into the electric power system.

MEASUREMENT CAMPAIGNS

When trying to assess the potential profitability of a wind power system, the first step is to choose an appropriate location and to estimate the available wind resource at that specific spot. Candidate areas can initially be chosen with the help of available wind maps, or with the help of individuals with extensive experience in the locale. However, in any event there will be no option but to undertake a measurement campaign in order to obtain a reliable estimation of the expected wind resource. One or several meteorological measurement masts (met masts) are usually installed in the selected location. They include anemometers, wind vanes and logging equipment, in order to record the speed and direction of wind over at least a one year span so as to take into account seasonal variations. Large wind farms can economically justify a higher number of masts and a longer campaign to increase the precision of the estimation. The height of the masts will be ideally the height of the rotor that will be installed, although a compromise can be made to lower installation costs.

DETAILED WIND MAPS

The expected wind in the vicinity of the masts can be estimated with the help of specialized software once the measurement campaign is completed. The measurements are then extrapolated to estimate the distribution of wind speeds and its direction at each point, taking into account the roughness coefficient and elevation of the surrounding region as well as existing obstacles.

This is shown in *Figure 2*: On the left, a map including the elevation and surface irregularity of each point can be seen. There are two measurement masts (met masts). A wind rose is represents the measured wind power for each direction at these two locations. By running the modelling software, the map shown on the right is obtained, on which the available wind power is represented by colors (colder colors represent lower wind power). Points separated by less than 1 km can have power differences of 3 to 1. Out of these measurements, the yearly average power, the expected power for any given time of the year, or any other statistical magnitude can be derived. The only limit is the time resolution of the measurement campaign and its duration.

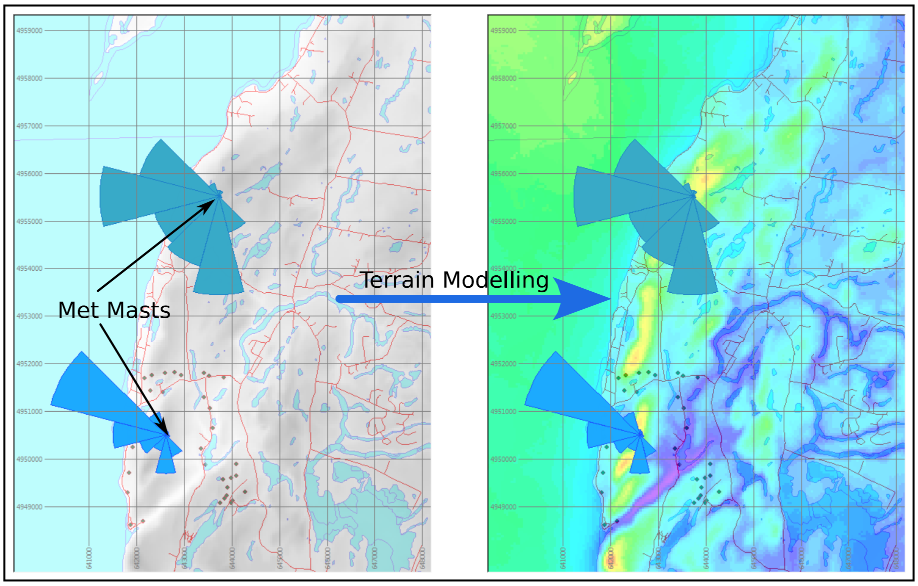

Figure 2—Local wind map from met masts measurements.

Once the estimation of the wind power that is available for the selected location is matched with the characteristics of the wind turbine system intended for that location, a confident estimate the electric energy production can be made.

WIND POWER TECHNOLOGY

Figure 3 shows the main components of a wind turbine and the basic structure of a wind farm composed of several wind turbines. The turbines shown are three-blade, horizontal rotor turbines which are currently the most commonly used system.

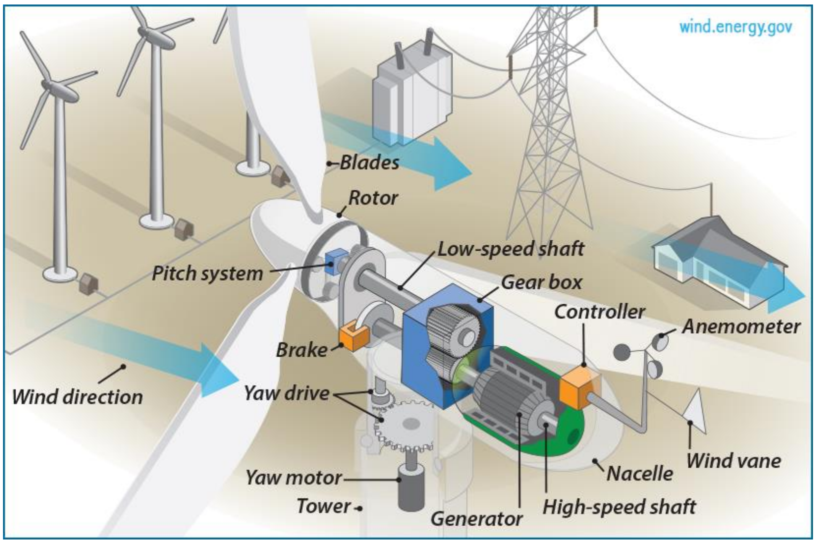

Figure 3—Wind turbine components. (Source: U.S. Department of Energy)

A wind turbine is composed of a tower, usually made of steel, which supports the nacelle, in which most of the main components are placed.

The nacelle is kept oriented toward the wind thanks to the yaw system. This will usually maximize energy production although other designs exist where the nacelle is oriented in the opposite direction.

ROTOR AND BLADES

The rotor and blades are responsible for converting the wind power into mechanical rotating power at the low-speed shaft. The conversion efficiency is given by the power coefficient C_p, so that

$$P_{mechanical} = C_p \cdot P_{wind} = \frac{1}{2} \cdot C_p \cdot \rho \cdot A \cdot V^3 \text{all}$$

The theoretical limit for C_p (known as the Betz limit) is roughly 59%. Real world wind turbines generally achieve lower efficiencies. In modern three-blade turbines, C_p typically peaks at 44-47%. Other turbine designs have lower efficiencies. This is one of the reasons for the success of three-blade designs, although recently some manufacturers have indicated that they are reconsidering two-blade designs for economic reasons.

The power coefficient C_p depends mainly on the aerodynamic design and number of blades, but for a given design, it depends on:

- The angle of the blades relative to wind direction
- The ratio of the wind speed to the rotation speed (more precisely the tip-speed ratio: the ratio of the wind speed to the speed of the blade tips)

Variable pitch-turbines have a motorized pitch system enabling the angle of the blades to be changed during operation, thereby altering C_p. There are other turbine designs available which employ a fixed pitch with the blades fixed relative to the rotor, and therefore their angle cannot change.

Likewise, the rotation speed cannot be changed in all turbines. Some are fixed-speed and others are variable-speed. This is determined by the type of generator and power interface.

POWER CONTROL

The power that is available from wind needs to be controlled for two primary reasons.

The first is to enable maximization of energy production. Since C_p will change if wind speed or rotation speed changes, it is beneficial to be able to operate with the optimum C_p at all times.

The second is that it is necessary to limit the incoming power from wind. Wind power depends roughly on the cube of wind speed. As wind speed increases, the available power risks exceeding the rated power of the mechanical and electrical components and thereby damaging them.

The capabilities of wind turbines regarding power control will depend on their capacity to change C_p. This in turn will depend on whether they are fixed or variable speed and fixed or variable pitch turbines. From a practical point of view, not all combinations are used. Wind turbines are generally either fixed speed and fixed pitch, or variable pitch and variable speed.

FIXED PITCH/FIXED SPEED TURBINES

In this turbine type, there is no control over the power coefficient C_p. Therefore, the turbine has to be carefully selected before installation so that the values of C_p are reasonably high and within the range of wind speeds that are expected in the selected location

In order to avoid damaging the turbine components, power is limited by the design of the blades. The blades will naturally stall as the wind speed increases, and therefore they will automatically reduce their efficiency, effectively limiting the mechanical power that reaches the shaft. These turbines are also called stall-controlled wind turbines.

This design has the advantage of simplicity and low cost primarily in regard to the generator and power interface as it will be seen later. However it has a lower overall efficiency due to the lack of control over C_p.

VARIABLE PITCH/VARIABLE SPEED TURBINES

In this case, there are two ways to influence C_p. Usually, for lower wind speeds, the pitch angle is kept constant and the rotation speed is controlled to maximize energy production. In order to limit power for higher wind speeds, the pitch angle is increased while keeping the rotation speed constant.

This design is more complex and the corresponding costs are higher, but the overall efficiency is also higher. Most of the wind turbines that are currently being installed fall into this category, not only because of the higher efficiency, but also because of other capabilities that are required by most current grid codes.

GEARBOX, GENERATOR AND POWER INTERFACE

Figure 4 shows the main wind turbine topologies regarding the gearbox, the generator type and the power interface.

In turbine types A and B, the generator is an induction machine directly connected to the grid. The only power interface is a soft-starter and a transformer. The rotation speed of the generator is determined by the electric grid frequency. High speed generators are commonly used, and therefore a gearbox is needed since the optimal rotating speed for the turbine rotor is much lower than the generator speed. Type A is a pure fixed speed/fixed pitch turbine, while Type B has a wound rotor machine with rotor resistances that enables changing speed, although only over a very narrow range (10%).

Type A turbines were very successful in the early days of Wind Power development, due to their simplicity. However, their efficiency is lower than that of other alternatives. Due to the machine and connection type they are not able to regulate reactive power, and they do not withstand voltage sags. Type B was an evolution of type A. They enable a slightly higher efficiency but it shares the rest of the drawbacks and has a higher cost. By 2013, the non-compliance with most grid codes had reduced their market share to less than 2%.

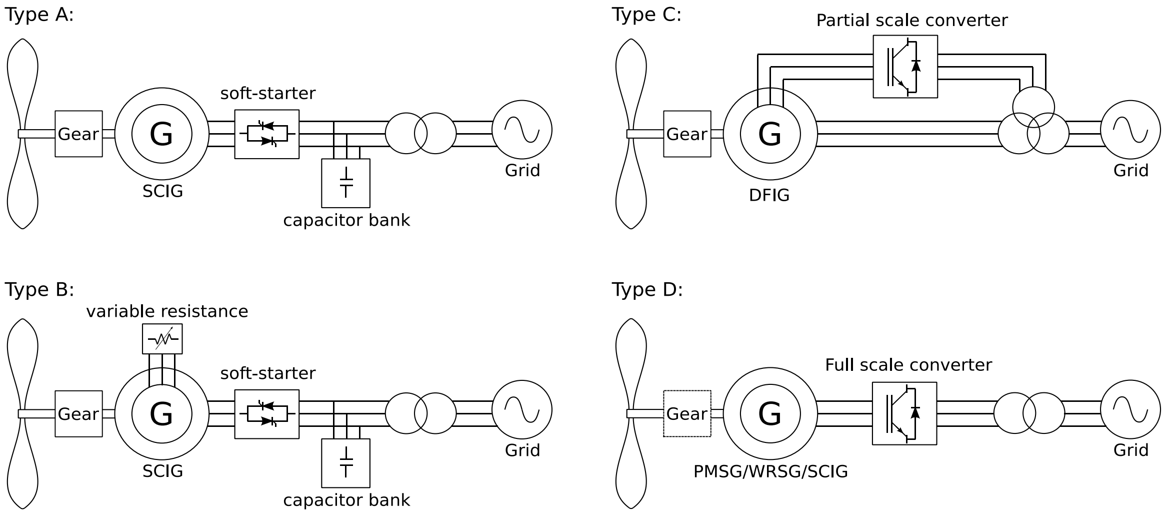

Figure 4—Main wind turbine topologies

Type C turbines use a doubly-fed induction generator (DFIG) whose rotor is fed by a frequency converter that does not need to be rated for the full power of the turbine, but rather for only for roughly 1/3 of the power. This enables changing the rotating frequency over a large range; approximately 30% around the synchronous speed. This is enough to optimize energy production. They are variable speed/variable pitch turbines. These turbines offer high efficiency and they are able to comply with the most stringent grid codes regarding reactive power and LVRT. They have been the most popular choice in recent years, although Type D turbines are being increasingly used. Type C turbines represented over 57% of the turbines installed in 2013.

Type D turbines are characterized by a full scale converter that completely decouples the generator from the grid. In this case almost any type of generator can be used, and since the generator speed does not depend upon the grid frequency, rotating speed can be controlled over a wide range. They are variable speed/variable pitch turbines. In some cases, multipole medium or low speed generators can be used so that the gearbox can be either simplified or eliminated. If the gearbox is eliminated, the turbine is said to be Direct Drive.

These turbines offer high efficiency, full control over active and reactive power, and compliance with grid codes. The drawback is the high cost of the full-scale power converter, although its cost has been steadily decreasing in recent years.

The most common subtypes for Type D are direct-drive with electrically excited synchronous generators (13.5%), direct-drive with permanent magnet synchronous generators (16.3%), geared permanent magnet synchronous generators (6.9%) and geared squirrel cage induction generator (4.1%). Figures are for onshore turbines in 2013.

ELECTRIC ENERGY PRODUCTION

Figure 5 shows the typical power curve for variable speed/variable pitch (solid blue line) and fixed speed/fixed pitch (dashed red line) wind turbines. Taking into account the capabilities regarding power regulation, the size of the blades, as well as accounting for other inefficiencies, a curve can be built that shows the electric energy output as a function of the wind speed. This curve is used to estimate the electric energy production from the wind measurements.

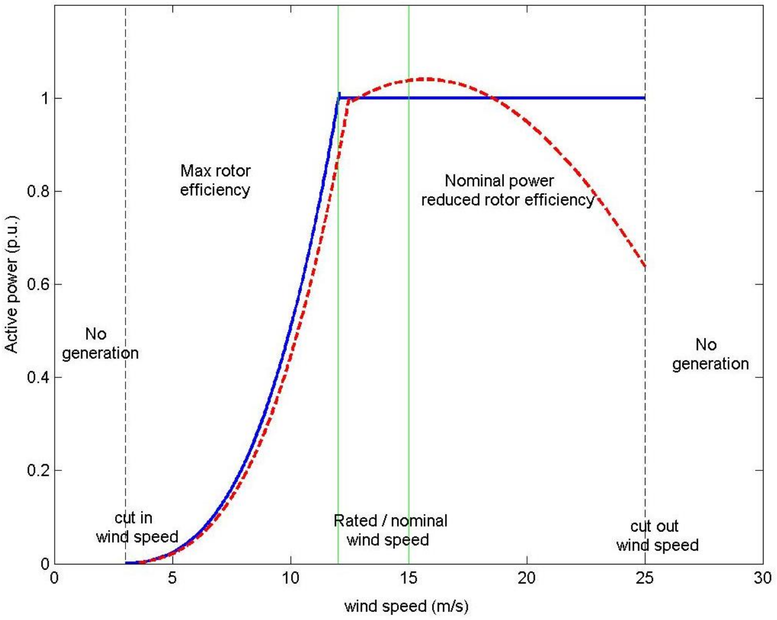

Figure 5—Power production vs wind speed

However, this curve only takes into account the production of a single wind turbine. It is common practice that several wind turbines are built near each other to form a wind farm, with a power line that connects the farm to a common grid connection point that is usually a substation. This was schematically shown in *Figure 3*.

In a wind farm, other effects need to be taken into account when estimating production. The most important is the wake effect: each turbine creates a wind shadow behind it that reduces the wind and creates turbulence. This reduces the energy production of any wind turbine situated within that shadow. This effect can be mitigated by leaving enough space between turbines and by placing the turbines in a pattern that avoids such an overlap or placing them in a row aligned with the dominant wind direction.

The wake effect is usually taken into account by modelling tools (e.g. tools used to build the local wind map). The modelling tool selected should provide algorithms to optimize the placement of the turbines given the wind measurements and the desired wind turbine model.

SELECTION OF WIND TURBINES

Once the wind resource is estimated, a wind turbine should be selected that is suitable for the location. A broad range of factors should be considered in the selection of the turbine including ease of maintenance, logistics and accessibility.

A wind turbine needs to withstand the mechanical forces related to the highest expected wind speeds. The components also need to withstand the mechanical fatigue that is caused by the expected turbulence levels. The latter is determined by the wind class, stating the maximum wind speed (classes I-IV) and the turbulence level (a or b).

A decision has to be made regarding wind turbine size: rated power, hub height and blade length. This is a complex techno-economic decision involving multiple factors.

- For a given wind farm rated power, it is possible to have a higher number of lower power wind turbines, or a lower number of higher power wind turbines.

    - More turbines mean more trenches for interconnection cables
    - Higher WT power usually means higher tower height and longer blades, which in turn can increase installation costs. Depending on the location, especially in remote mountainous or otherwise inaccessible areas, consideration must be given to transporting the largest components or the required building machinery, such as cranes.
- For a given WT rated power, manufacturers offer different tower/blades combinations to adapt the turbine to different wind resource types:
    - A higher tower will allow reaching higher wind speeds, and therefore the production will increase
    - Longer blades will increase swept area, and therefore the production will increase
    - Higher tower and/or longer blades will however increase the turbine cost and the installation costs. The wind turbine output will most often be limited by the rated power, and therefore not all the extra available wind power will be converted to energy production.
- A limited number of WT models are available. Their availability and cost may depend on multiple factors, including location.

Regarding turbine size selection, there is a clear trend of increasing turbine nameplate capacity and size to reduce costs. Currently, typical wind turbines are rated at 1-4 MW, have rotor diameters and hub heights of around 60-130 meters, with an average of 1.7-3 MW depending on the region. Manufacturers offer increasingly large wind turbines, especially for offshore applications where the benefits from larger turbines are higher, with nameplate powers currently of up to 8 MW and rotor diameters up to 180 meters.

A wind farm has to comply with the local grid codes, which can vary widely depending on the country. Depending on the wind turbine technology selected and the applicable grid code, it may be necessary to include additional equipment at wind turbine level or at wind farm level.

OFFSHORE WIND

In recent years there has been a significant development of offshore wind technology. The lack of obstacles and the relatively unimpeded wind flow over the sea surface tends to result in relatively high and uniform wind speeds in many areas. However, offshore construction and maintenance operations are generally extremely expensive, in that they require large ship cranes and highly specialized personnel, and are often limited by weather conditions. Due to the increased maintenance costs, the reliability of the wind turbines is of the highest importance in offshore locations. The interconnection lines between turbines, to the substation and to the onshore connection point are made by subsea cables, which are expensive to install. The connection to the shore is usually made by an AC line for smaller wind farms that are located near the shore. For larger wind farms that are located further offshore (60-80 km), the preferred option is usually an HVDC connection.

Figure 6—Offshore wind farm [8]

GRID INTEGRATION OF WIND POWER

In some power systems, wind power is reaching significant penetration levels. In Denmark for example, wind power contributed 42% of the electric energy in 2015 and was able to provide 100% of the required electric power for 60 days in a row. Other countries have also shown high penetrations in 2015. These include Spain, with 19% of the total electric energy and instantaneous penetrations of around 50%. Overall, wind power covers over 11% of the EU electricity consumption in a normal wind year.

This increasing penetration is a challenge for electric utilities, the main problem being the variability of wind.

The balance between production and consumption in a power system has to be kept steady at all times. Since there is only a very small storage capacity available, the power that is being generated has to be equal to the power that is consumed at any given time. Most conventional generation technologies are able to regulate their power output at will over a certain range. This enables production to follow demand variations. However, wind power is usually not capable of increasing its production since it is already trying to extract the maximum power from the available wind at that time in order to reach maximum efficiency.

In order to mitigate this effect, there is a need to have power reserves that are capable of supplying the demand when wind production decreases. These reserves can come either from conventional power plants, from interconnections with other countries, or from storage facilities.

These reserves of course represent a cost for the system, which has to be minimized. This can be done in several ways.

- Wind power prediction: having a good power prediction enables assigning the required production to conventional power plants in advance, which is less expensive than allocating reserves. Short-term prediction methods (24h or less), which are crucial for electric system operation, have significantly improved over the last decade.
- Strongly interconnected power systems: Having strong power lines enables averaging the wind power production over a large territory, so that the available wind power in a certain region can supply remote loads. Wind generation in a given wind farm has a much higher variability than the overall generation from a large territory, and extreme production levels (both low and high) are much less likely to occur, as can be seen in Figure 7. Strong interconnections also enable sharing the power reserves over a larger area.

- Specialized control centers have been built to remotely control and monitor wind farms in order to predict and optimize their contribution.

Grid codes have been adapted to take into account the integration of wind power however they are becoming increasingly stringent. They usually include requirements regarding reactive power control and LVRT capabilities. They have also recently begun including requirements regarding frequency regulation, thereby forcing the reduction of active power output in the case of over-frequency. In some special cases they even require increasing active power output in case of under-frequency, therefore forcing the wind farm to operate below its rated power even in normal conditions.

Another recent requirement that is being introduced in some grid codes is related to inertia emulation. Conventional generation technologies (thermal, nuclear, hydroelectric) are usually connected to the grid via large synchronous generators. These generators provide some inertia to the system frequency, helping stabilize its operation. A larger share of the conventional generation is being displaced by technologies (such as photovoltaic and wind) which do not provide this stabilizing inertia. This will cause the system to become more prone to larger frequency variations which may bring stability problems. Some grid operators may therefore require that renewable generators implement an emulation of the inertia that is needed by the system.

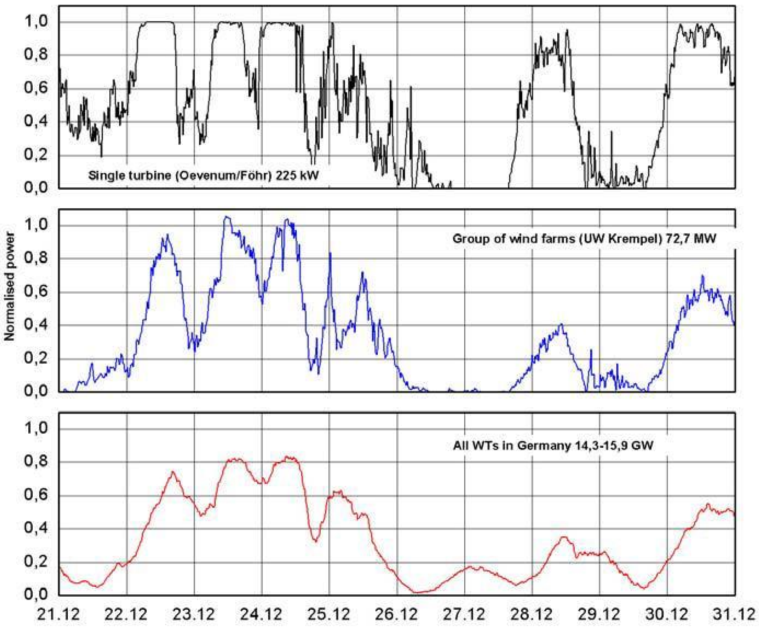

Figure 7—Examples of wind production variability. (Source: REnKnow.Net)

ECONOMICS OF WIND POWER

WIND POWER COSTS

Wind power is a highly capital-intensive activity. **Error! Reference source not found.** shows typical values for total capital cost in recent wind farms. It must be noted that there is a wide range for total installed costs which depends primarily upon the region. The global weighted average cost for onshore wind farms was probably around 1,560 USD/kW in 2015, while in China and India they were 1,270 and 1,325 USD/kW respectively, the lowest in the world [5]. These costs can be compared to average costs of 4,766 USD/kW in 1983, showing the great reduction that has taken place in recent decades. It is expected that this trend will continue in the future.

	Onshore	Offshore
	Cost share (%)	
Wind turbine (incl. installation)	64-84	30-50
Grid connection	9-14	15-30
Construction	4-10	15-25
Other capital	4-10	8-30
	Capital cost (USD/kW)	
Total cost	1,200-2,300	2,700-6,000

Table 1—Capital cost for onshore and offshore wind farms (source: IRENA [5,6]).

O&M costs for onshore wind power are relatively low, mainly due to the fact that the fuel (wind) is free, in contrast to thermal electricity generation. Data for O&M costs are not widely available. However, it can be said that O&M costs represent roughly 20-25% of the LCOE, and that this cost is decreasing. It is estimated that full-maintenance contracts prices fell by 27% from 2008 to 2015. The range of reported O&M costs is very wide, ranging from 0.005 USD/kWh to 0.04 USD/kWh, although it appears that many recent projects will fall in the 0.01 to 0.02 USD/kWh range.

O&M cost in offshore wind farms is much higher, probably in the range of 0.03 to 0.06 USD/kWh, but there is a significant reduction potential since the maintenance procedures and infrastructure are still being developed.

There is also a wide range regarding the cost of energy. The best wind projects in 2014 and 2015 delivered energy at a LCOE between 0.04 and 0.05 USD/kWh, with weighted averages of 0.053 USD/kWh in China, 0.06 USD/kWh in North America, 0.07 USD/kWh in Europe, and 0.08 USD/kWh in Eurasia and India. Significant cost reductions of around 25% are still expected by 2025.

LCOE in offshore wind farms is also much higher than for onshore wind farms. Weighted average in 2015 was probably around 0.17 USD/kWh, but with a wide range of 0.10 to 0.25 USD/kWh. Large reductions of around 35% by 2025 can be expected, with a LCOE decreasing to 0.11 USD/kWh.

COMPENSATORY SCHEMES

In the recent past, wind power costs were too high to enable the deployment of wind generation without some kind of support scheme, such setting a feed-in tariff, granting a premium over market prices, direct subsidies, tax incentives, soft loans, setting mandatory quotas to utilities or guaranteeing priority access to the grid. Feed-in tariffs and market premiums are usually determined either by an auction mechanism or by setting a fair price based on current costs.

Wind power costs have been decreasing steadily to the point where it is competitive with conventional technologies in some cases. However, support schemes are still in place in many regions in order to accelerate the penetration of renewable energy and to meet certain renewable generation targets. The current trend is to progressively reduce these support schemes in most cases and to advance toward competitive market integration as soon as possible.

MARKET TRENDS

2015 was a record year for wind power generation, with an installed capacity of 63 GW worldwide, for a cumulative installed capacity of 433 GW, and total investments of almost 300 bln EUR. Cost reductions and renewable targets seem to be accelerating market development as can be seen in *Figure 8*.

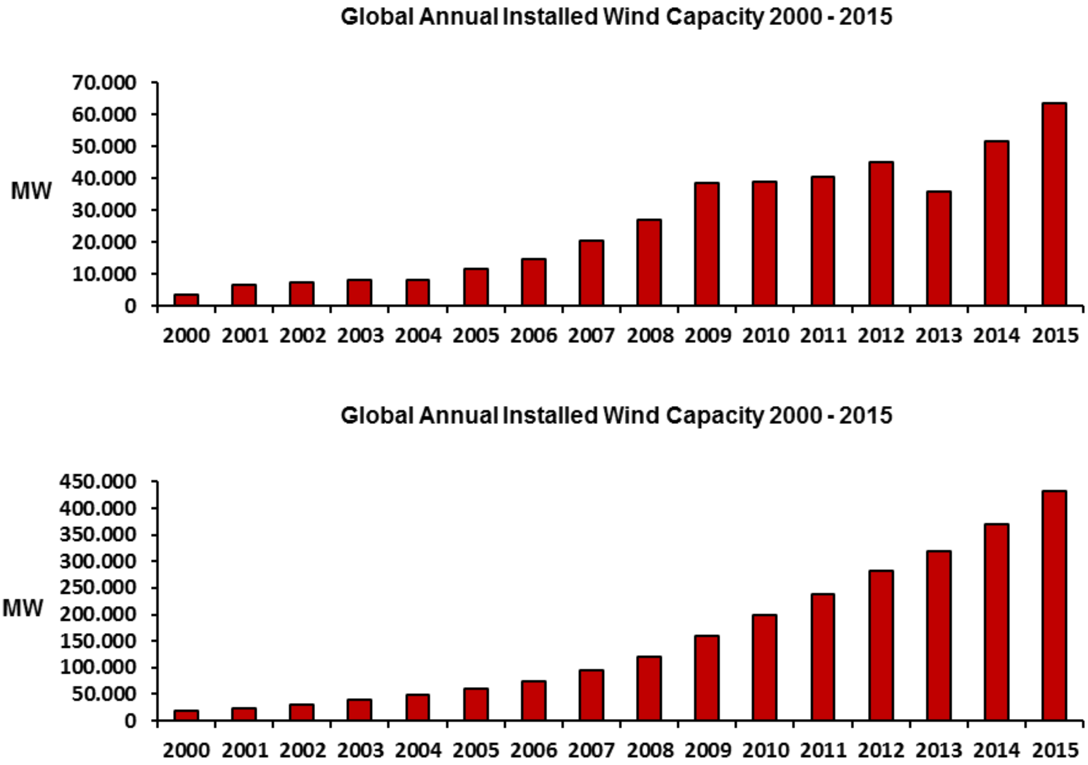

Figure 8—Installed worldwide wind capacity [4].

However, the evolution of the market has been very uneven in recent years, as it can be seen in *Figure 9*. The figures for newly installed capacity are rather constant and slightly accelerated in Europe. North America shows a very irregular market growth. Asia has been the fastest growing market, representing roughly half of the total market in 2015. In the rest of the world the market is much smaller, although in Latin America there are recent signs of a take-off.

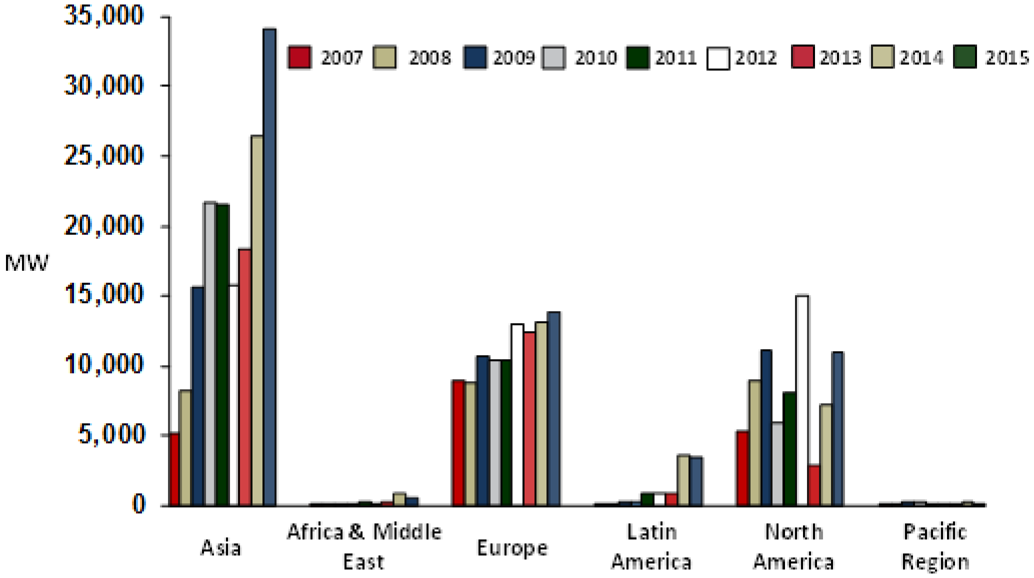

Figure 9—Annual installed capacity by region [4].

Within Europe the largest market is still clearly Germany (6 GW in 2015) followed by France and UK with each installing 1 GW in 2015. Regarding cumulative capacity in Europe, Germany still leads with almost 45 GW, followed by Spain with 23 GW, UK with 13 GW and France with 10 GW.

Cost reductions and renewable targets are expected to continue driving market growth in the upcoming years.

Offshore wind power still represents a marginal share of total wind power. However, in 2015, 3.4 GW of new capacity was added for a total cumulative capacity of 12 GW. In all, 91% of the capacity that was installed in 2015 corresponds to waters off European countries, the rest being located in Asia, mainly in China.

LOCAL ENVIRONMENTAL IMPACT OF WIND POWER

Wind power generation is largely seen as a clean energy source compared to conventional generation, especially thermal power plants. It reduces the GHG emissions as well as other environmental contaminants. However, it does have some impact on the local environment. Detailed planning can limit the impact of wind power consequences to an acceptable level.

BIRD POPULATIONS

Birds can collide with turbine rotor blades or get caught by the turbulence behind the rotor. Research has shown that the risk of collisions is relatively small. The estimated number of so-called collision-victims, at an installed power of 1, 000 MW is approximately 21,000. On an annual basis this seems to be a high number, but this is a small amount when compared to the number of birds that get killed by traffic (2 million) or that die because of power lines (1 million). All of these numbers pale when compared to the more than 1 billion wild birds killed annually by domestic cats in the United States.

Most wind turbine casualties are caused at night, during twilight or in bad weather situations. Birds know their forage, migratory and resting grounds very well; they avoid wind turbines. When installing turbines, the breeding and foraging areas of birds must be carefully considered.

OFFSHORE WIND AND FISH

Offshore wind turbines have shown positive effects upon the surrounding fauna. Over-fishing is a well-known problem; the stocks of many species of fish are threatened. The navigation of ships and fishing vessels is prohibited in and around wind farms. Recent research by marine biologists confirms that these areas are developing into breeding grounds for several species of fish with a resultant positive effect on fish stocks.

NOISE LEVEL

Wind turbines produce noise when in operation. The rotor makes a reoccurring sound and the generator and gearbox can also be heard. Carefully designed rotor blades, a limited revolution speed, and effective sound insulation of the gearbox and generator limit noise emission. Rotors with larger diameters rotate more slowly and are less likely to be a disturbance. By maintaining a sufficient distance from residential or other sound-sensitive areas, noise pollution can be avoided.

MOVING SHADOWS

Sunshine creates moving shadows when the rotor of a turbine rotates. In winter, when the sun is low, the shadow can be annoying when it falls into a window. Giving wind turbines an appropriate orientation in relation to residences is sufficient to prevent this problem. If a small number of hours periodically create sufficient inconvenience, the turbine can be stopped at these moments without a significant loss in energy production.

BLENDING INTO THE LANDSCAPE

Wind turbines are striking structures in the landscape. They can be used to great architectural effect, for example, by arranging them in lines along a dike or waterway. In doing so, the lines of the landscape are taken into account. Research has shown that positioning wind turbines in clusters has greater public acceptance when it is clear to neighboring inhabitants that this situation yields great value. The effect of man-made structures on the landscape has always been a matter of taste.

CONCLUSIONS

Wind energy technology has experienced a continuous development in cost efficiency, energy efficiency, reliability and size since the 1980s.

Over recent years, sophisticated methods to measure and estimate the wind resource have been developed and refined, reducing the uncertainty on the expected energy output and therefore the investment risk as well.

A variety of mature turbine designs are readily available on the market, each one with its own characteristics. This makes it possible to find a suitable design for a variety of locations, markets and technical limitations.

Thanks to its mature technology and low environmental impact, wind power has become highly successful. It represents an increasing share of the electricity production worldwide.

REFERENCES

1	Jenkins, N. et al. *"Wind Energy Handbook (2nd ed)"*. John Wiley & Sons. 2011.
2	Ackermann, Thomas. *"Wind Power in Power Systems (2nd ed)"* John Wiley & Sons. 2012.
3	European Wind Energy Association. *"Wind in power - 2015 European statistics"*. 2016.
4	Global Wind Energy Council. *"Global Wind Report - 2015 Annual Market Update."* 2016.
5	International Renewable Energy Agency. *"The Power to Change: Solar and Wind Cost Reduction Potential to 2025."* 2016.
6	International Renewable Energy Agency. *"Renewable Power Generation Costs in 2014: An Overview."* 2015.
7	Illustration: https://commons.wikimedia.org/wiki/File:Wind_turbine_schematic.svg
8	Photo: https://commons.wikimedia.org/wiki/File:Sheringham_Shoal_Wind_Farm_2012.jpg