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Introduction to wind energy systems

Zhen Zhang Design Dept.No.1 Electrical Design Office Electric Engineer, SHANGHAI WAIGAOQIAO,China

Research Article

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Summary. — The main ideas of wind energy are explained in this piece, along with the science and mechanics of how they work. It talks about how wind energy is turned into the spinning of a rotor and the important factors that determine how well this change works. Then it gives an outline of the different bits and pieces that make up windmills. Other things that will be thought about are how to connect to the power source, how common it is to use wind energy to make electricity around the world, how much it costs, and what research and development needs to be done.

– Different wind turbine types: An overview

There are different kinds of wind mills in use today (see fig. 1 for an outline). The horizontal-axis wind turbine is the most popular type. This turbine only has a few rotor blades that are designed to be as aerodynamically efficient as possible. These blades can be turned around their long axis to change the speed (Pitch-regulation). Another, less expensive way to control it is to make the blades so that air moving along them will become turbulent at a certain speed (Stall-Regulation). Power from these engines can range from 10 kW to several MW. The biggest windmill on the European

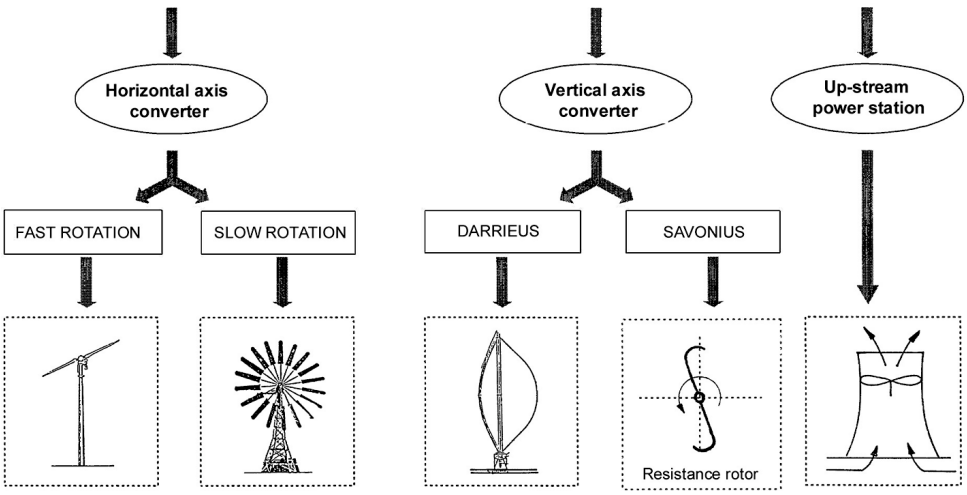


Fig. 1. – Overview of the different types of wind turbines.

The market has 7.6 MW of power, and tests are being done on bigger machines. There is a lot of power in this type of engine. Because of this, it is only used to make power, which needs "high-speed engines" to keep the generator and gear drive small and cheap.

Another common (older) type of horizontal-axis rotor is the wind turbine with multiple blades. It was built for the first time around 100 years ago. Because these windmills have a high starting force, they can be used to power water pumps. The blades are made from simple sheets with an easy shape, and there aren't many turns. There is no need for a spinning controlling system when pumping water, but there is a mechanical safety system in place to keep the rotor from getting damaged by storms. The rotor is turned in the direction of the wind with the help of a "wind-sheet in lee direction." In order to make this type of turbine turn more often, aerodynamically better blades were added, which made it easier to make power. In this case, the area of a blade is smaller.

These kinds of "slow-speed turbines" are very mechanically stable; some have been used for more than fifty years.

The third kind of turbine is called DARRIEUS, and it has a vertical axis. The good thing about them is that they don't depend on which way the wind blows. To start, they need either a generator that can be used as a motor or a SAVONIUS rotor that can be put on top of the vertical axis. In the 1980s, a good number of DARRIEUS turbines were put in place in California. However, there has been no further growth in the higher-power range or in the European markets. Because they make more noise than horizontal-axis rotors, that could be one reason. Another problem is that wind speed goes up a lot with height, which makes horizontal-axis wheels on poles more cost-effective. Still, some companies make DARRIEUS turbines with very low power levels, like a few kilowatts, so that areas without energy lines, like rural areas of emerging countries, can get their own electricity.

It is not used to make electricity; the Savonius rotor is only used for study purposes, like as a tool for measuring wind speed. Because of this, it will not be talked about in length in this work.

Up-Stream Power Station, also called a thermal tower, is the last method we will talk about. It can be thought of as a cross between a wind machine and a sun catcher. A wind wheel on a vertical plane is at the top of a tall, narrow tower. It is moved by warm air rising into the tower. The sun collection that was put around the base of the tower heats the air. A simple collector is made up of a circle of clear plastic foil that is glued to the ground a few meters above the tower. The station needs a lot of room, and the tower needs to be very tall. This kind of method is very inefficient—it only works about 1% of the time. So far, only one Up-Stream Power Station has been

built in the whole world. It was made by a German company. At the Manzarenas site in Spain, it worked well for a few years, but bad weather ruined it in the mid-1980s. This station had 20 kW of electricity, the tower was about 200 m tall, and the collector was about the same size in diameter. Australia had plans for a second Up-Stream Power Station that would produce 200 MW of electricity, but they haven't come true yet. The collector area should be about 7000 m across, and the tower should be about 1000 m tall. So far, no new Up-Stream Power Station has been planned or put in place. Because solar farm stations and horizontal-axis wind turbines have come a long way in terms of technology in the last ten years.

– Physical basics

Section 2.1: The energy in the wind. This part will use math to show where the energy in the wind comes from and what things affect it.

Power is given by (1) P = E = 1 · A · ρ · v3, t^2 a, where E is kinetic energy, A is area, ρa is air density, and v is wind speed.

Because of this, it is also related to the cube of the wind speed, v3.

It is clear from Fig. 2 that the rotor blade's power output per m2 is not directly related to the wind speed, which is what the theory above showed. This means that it makes more sense to put a wind machine somewhere where the wind speed isn't always very low than somewhere where the wind speed is always very low. A Weibull-equation can be used to get a good idea of how the wind speed changes over the course of a year based on measurements taken in different places. What this means is that the top third of wind speed will make at least two thirds of the energy.

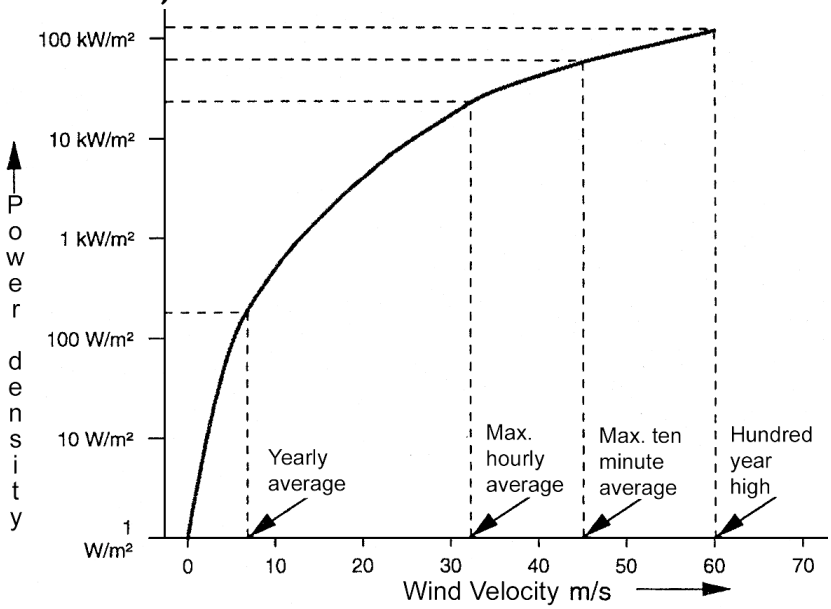


Fig. 2. – Relationship between wind velocity and power output (yearly average valid for Ger-many). Figure taken from [1], p. 241.

From a technical point of view, the power density range grows by 1,000 times for every 10 m/s change in wind speed, which causes a problem with building limits. To get the most power from the wind, windmills are built to only work with high wind speeds.
The next question is how much of the energy in the wind can be used to move the blade. This is called the power coefficient.

The law of Betz and cp
Following Betz's law, a wind machine can only turn up to 59% of the kinetic energy in the wind into mechanical energy. At this point, the wind on the back of the rotor needs to be moving fast enough to push other wind through the plane of the rotor.
The power coefficient cp shows how the power of the rotor blade PR goes up or down with the highest power PR max.

(2) $PR = P1 - P2 = cp \cdot PR\ max.$

When you set the ratio v2/v1 and the highest power coefficient, you get

to zero by deduction.

16/1 cp max = 17 = 0.593 with v2 = 3 · v1.
By Bezout's law, an ideal rotor will slow the wind down to two thirds of its original speed.
The problems talked about in the theory can be summed up and linked to the design of a wind turbine by the following "cooking recipe":
"Cooking recipe" for how wind blades should be built.

1. An aerofoil with a high form ratio has a high tip-speed ratio, which means it has a high power coefficient (cp).
Modern turbines that have a good efficient shape spin very quickly.
2. Profiles that are simple and have small profile form ratios have a small tip-speed ratio. In order to raise the power rate, the area of the rotor radius that the blades cover needs to be raised.
Turbines that spin slowly have a lot of blades and bad aerodynamic shapes.
3. The size of the shape and the speed of the tip have a much bigger effect on the power coefficient than the number of blades.
When compared to a high-speed engine, the quality of an aerofoil is not as important.

– Technical design of wind turbines
What this means is that the power density range grows by 1,000 times for every 10 m/s change in wind speed, which makes setting limits hard. There must be a lot of wind for a windmill to work, so it can get the most power from it.
How much of the wind's power can be used to move the blade? That's the next question. The power coefficient is the name for this.
The Betz law and cp
Betz's law says that a wind machine can only use up to 59% of the wind's kinetic energy to power a machine. The wind on the back of the rotor needs to be moving fast enough to push other wind through the rotor's plane at this point.
When the power of the rotor blade PR goes up or down, the power coefficient cp shows it. The power coefficient cp is set to 1.

(2) PR = P1 - P2 = cp · PR max.

You get when you set the top power value and the ratio v2/v1.

to zero by taking away.
16/1 cp max = 17 = 0.593 with v2 = 3 · v1.
Bezout's law says that a perfect rotor will slow the wind down to two thirds of its speed.
This "cooking recipe" can be used to sum up the problems that were talked about in

the theory and show how they relate to the design of a wind turbine:
""Cooking recipe" for putting together wind blades.

1. An aerofoil with a high form ratio also has a high tip-speed ratio, which means it has a high cp.
These days, blades that are well-designed to work well spin very quickly.
Small tip-speed ratios are found in profiles that are simple and have small profile form ratios. To increase the power, the blades need to cover a bigger area of the rotor's radius.
Turbines that spin slowly have a lot of blades and aren't shaped well for air flow.
3. The amount of blades doesn't have much to do with the power coefficient. The shape's size and pitch speed do.
The quality of an aerofoil is not as important as the quality of a high-speed engine.

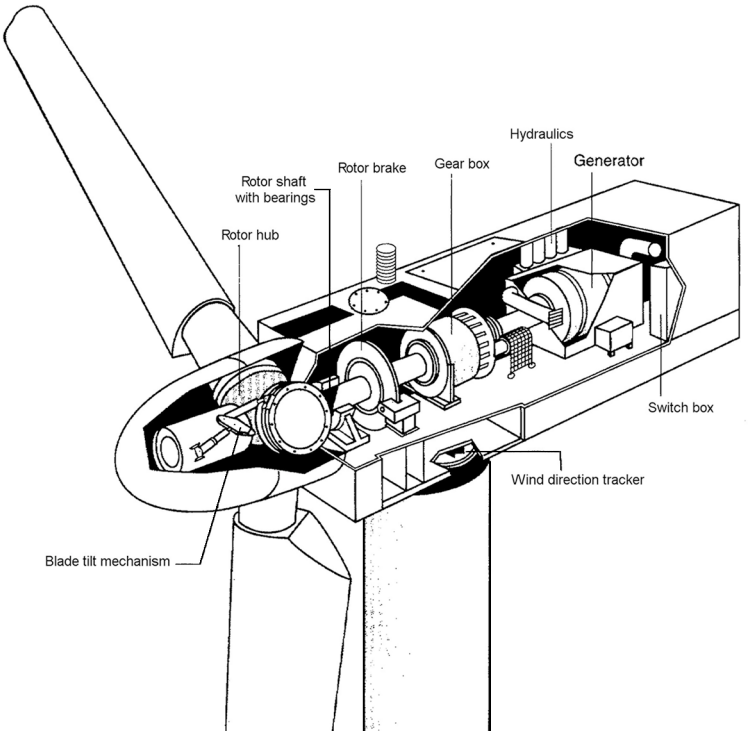


Fig. 3. – The design with gearbox.

3.1 The design without the gearbox. – Some companies, like the German En-ercon, create a different type of turbine that doesn't have a gearbox. As you can see in fig. 4, the main parts of this type of turbine's design are easy to see.
This arrangement only has one shaft that stays in place. On this shaft are both the

spinning blades and the engine. The generator is a big wheel with spokes on it. Around the outside, there are 42 sets of poles, and around the wheel are stators placed on a fixed arm. The wheel is attached to the blade frame, so it turns slowly with the blades. So, there's no need for a disk stop, a clutch, or moving wheels. Cutting down on the number of mechanical parts makes the turbine easier to maintain and make.

The whole system is automatic. A central computer runs the small directed motors and controls the pitch and direction of the hub.

3.2.Aspects of design and growth. – When designing a wind turbine, there are a number of important things that need to be thought about to make sure that the turbine will be functional and last a long time.

The tower

The tower should be as tall as it can be because the wind speed rises with height.

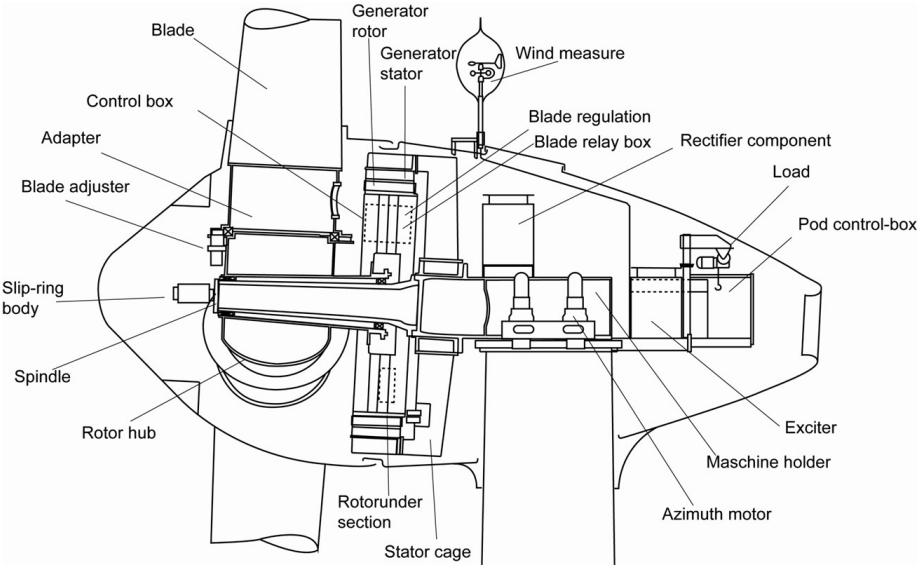


Fig. 4. – The design without gearbox (Enercon E-66).

with height. However, the height is limited by the cost; adding 10 meters to the tower height costs an extra 15,000 dollars, and a tower height of more than 100 meters needs an expensive airplane warning signal.

Heat power

Generators with large engines (> 1 MW) work about 98% of the time. Parts of the machine that are mechanical, like the springs and gear box, also make heat. In other words, about 40 kW of power are lost because the engine gets hot while it's running. To keep the machine parts from breaking, this heat energy needs to be kept in check.

A big fan system is attached to the back of a turbine's hub. Its job is to pull cool air through the hub and get rid of the heat that it produces while it's running.

Keep an eye on and control

The following parts of a wind machine need to be controlled and watched over to make sure they work properly and within the law:

–By big engines; amounts of shaking.

–The pitch angle and speed of spinning of the rotor blades.

–The speed and direction of the natural wind.

–How much power and frequency the electricity has.

–The angle between the output phase and the grid phase.

—How constantly the electricity is sent out.

–Getting electricity data and storing them.

–Equipment for changing signals for the directing motors.

–Rotational speed at night to lower the noise level, since the noise is proportional to the speed of the blade tip to the power six.

Stability through mechanics

The mechanical system is less stable when the following forces act on it:

—Gravity.

–Frictional pressure on the blades of the rotor.

the tower casts shadows on the blade, which changes the pressure on it.

–The turbine's power output is unpredictable because the amount of wind energy is always changing.

–The sound of the blades.

Set up for wind direction

It is possible for a wind machine to be built so that it faces either the wind or the sun. The good thing about a leeward turbine is that it can find its own direction. The bad thing is that the tower can change the wind speed profile before it reaches the plane of the rotor blades. As the blade goes by the tower, it experiences changes in pressure and speed that put stress on the hub. To relieve this stress, an extra device needs to be added to the hub so that the rotor blades can move out of their normal plane of spin.

3.1. Technical drawings of two new wind mills. – A 7.6 MW turbine from the company Enercon was the biggest machine put on the market up until 2012.

The information in Table I gives you an idea of what 3 MW wind mills are made of. They picked a version with and without a gearbox to show how their engines work in different ways.

– Connection to the electrical grid

The main power grid always has the same frequency, like 50 Hz or 60 Hz, and the same phase angle. In order to connect to the main grid, a wind machine must make energy with the same steady numbers.

The wind speed affects how much energy a wind machine takes in, but the wind speed changes all the time. The rotor rotates at a certain speed for each wind speed. The most power is made at these speeds. This highest point is reached at different wind speeds.

TABLE I. – *The technical figures of two different multi-megawatt wind turbines for onshore.*

	Enercon E-182 E3	REpower 3.2 MW
Design	without gearbox	with gearbox
Hub height	80–130 m (onshore)	100–130 m (onshore)
No. of blades	3	3
Rotor speed	6–18 rpm	6.7–12 rpm
Rotor diameter	82 m	114 m
Material of blade	Fibreglass (reinforced epoxy)	Fibreglass (reinforced epoxy)
Blade regulation	Pitch	Pitch
Rated power	3 MW	3.2 MW
Transmission ratio of gearbox	None	approx. 99
Generator	Multi-pole	Asynchronous, few poles
Grid connection	Via frequency converters	Via frequency converters

as they spin at different speeds. But the speed of spinning has to stay the same to get the needed steady output frequency. Either that, or the wind turbine needs to be linked to the power grid using an electronic frequency converter or a twice fed asynchronous generator.

At 0.4 kV, a small rotor can be hooked up straight to the grid. When the wind turbine is connected to the grid, the homes on that network section should not see any changes, oscillations, or flickers in the power. By making the wires wider, you can stop the power loss caused by resistance in the cables. To cut down on power fluctuations, it is often necessary to build a new network branch and connect it to the transformer. This makes the cost of installing the rotor go up.

Megawatt windmills can't join to the grid at 0.4 kV. Instead, they need to be linked at

10–30 kV, which is the normal amount for sharing energy in a city. In remote places where there isn't already a 30 kV link, the people who are building the wind farm must make one and pay for it. A lot of Megawatt wind farms can also be hooked up to the power grid, for example at the 110 kV level in Germany.

Like we already said, the peak power flow is only reached a few times a year. Figure 5 shows how the load is usually spread out. It was taken in Germany.

In the future, when there are bigger wind farms, this uneven spread means that traditional power systems will need to be able to regulate more power.

Connecting offshore wind farms to the power grid is hard from both a technical and a financial point of view for both wind turbine and grid owners. In the beginning, because early test farms still don't have a lot of power, a normal three-phase AC link to the shoreline can be used.

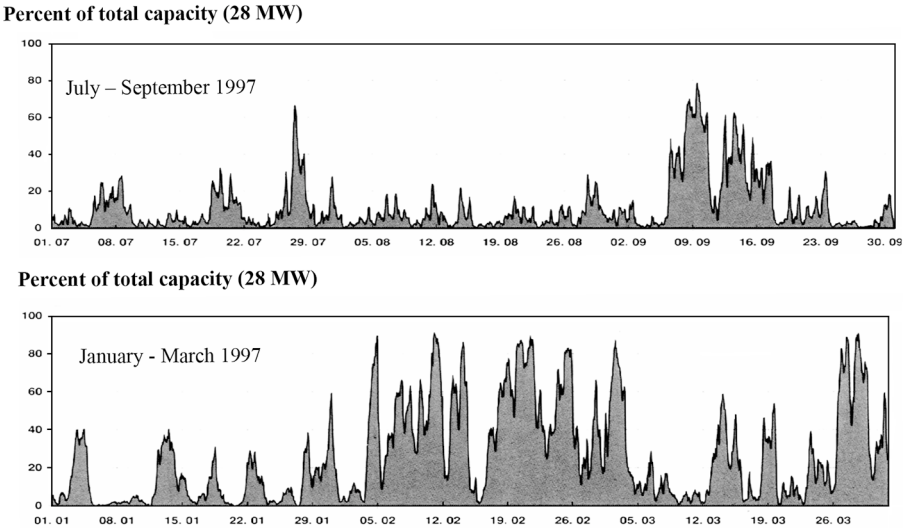


Fig. 5. – Load distribution measurement (Germany).

grid system, which is a cheap and well-known tool. Since these wind farms were also close to the coast, using AC meant that not too much energy was lost.

Using AC underwater lines to connect distant wind farms to the mainland grid is hard because the sites are far away and the farms have large capacities. In the future, losses, the production of reactive power, and the fact that sea lines can only carry so much may become important. A option could be to send high-voltage direct electricity to land, but this is more difficult to do and costs more.

At the time, there are plans to link wind farms in the ocean to the grid on land. Some lines, which are powered by both AC and DC, are already up and running, and plans are being made for more. To protect the nature at sea, several wind farms are linked together on a single wire.

An interior grid is needed to connect the ocean wind farm to the grid on land. The

power that is made has to be sent to a transformer center abroad. A voltage of about 30 kV connects wind blades to it through wires that go under the water. The power is sent to land after being stepped up to the voltage of the transfer line.

– Use of wind energy

5.1. Global status: The United States of America was the first country to develop wind farms in the 1980s. They activated more than 10,000 turbines, each producing 80–200 kW. Denmark was the primary pioneer of wind energy in Europe. Up until 2008, Germany produced around one-third of the world's wind-generated power, making it the world leader at the end of the twenty-first century.

Many governments have started creating incentive programs to boost the economy.

TABLE II. – *World wind power production. This statistic is taken from* [2].

Land/Region	Total installed rated power up to the end of 2013 [GW]
China	91
USA	61
Germany	35
Spain	23
India	20
UK	11
Italy	9
France	8
Canada	8
Denmark	5
Remaining countries	48
Total	319

wind turbines' viability. Paying extra for wind-generated power and contributing a percentage of the original building expenses are two examples of incentives. Because wind energy reduces the demand for fossil fuels and is sustainable and ecologically friendly, governments in industrialized nations or those with significant power use are keen to support it (table II).

By the end of 2014, the world's total rated power was around 370 GW. This represents around 1.6% of the installed capacity of power plants (water, coal, natural gas, and nuclear) globally.

5.1. Operating and investment expenses. The design, size, and placement of the new turbine all affect the installation costs. By building wind parks, where many new turbines are placed on the same site, the infrastructure expenses may be reduced. Table III provides an example of the investment expenses for a wind park on German property.

An typical wind park on land loses value over the course of 10 years. In addition to loan repayments and insurance charges, setup and installation expenses are considerable at this time. The expenses then start to decline after this time. When the government sets the price of power per kilowatt-hour at a high level, the investment may then provide a profit over the following 10 years. This indicates that it is cost-effective to guarantee the longevity of the installed turbines in order to minimize maintenance expenses beyond the ten-year term and provide investors with a favorable return on their investment.

TABLE III. – *(a): The typical investment costs of a* 2 MW *onshore wind power station in Ger-many, (b): The typical operating costs of a* 2 MW *onshore wind power station in Germany (Status 2013). Data are taken from WindGuard GmbH, Germany.*

(a) Investment plan	Costs [¤/kW]	
Hub height	< 120 m	> 120 m
Wind power station, transport, installation	1150	1340
Foundation	70	
Grid connection	70	
Site development (lanes)	40	
Planning, environmental measures, concession, others	190	
Total	1520	1710

Operating costs: 5.1 ct/kWh (b) (Average over 20 years operating time)	
Service, reparation, others	50%
Rent	20%
Management (technical and business)	20%
Reserve for unforeseen events	5%
Insurance	5%

The investment costs shown here for wind farms on German soil are not transferable to other nations. In particular, there are significant differences in the finance structure and labor compensation for wind farms. However, electricity generated by wind

turbines is three to four times more expensive than power generated by conventional power plants in industrialized nations with an established electrical system and enough installed power.
Although the wind offer is greater at sea than on land, wind farms at sea need larger particular expenditures. An offshore wind farm results in increased power production costs (status 2012). In the next years, it is anticipated that the cost of new offshore wind farms would decrease. Through assistance programs, several nations are encouraging the construction of wind converters.

5.1. Environmental factors. Since wind energy is renewable, it has numerous benefits over fossil fuels, whose supplies are running out. When it comes to harmful pollutants, wind energy is clean. As a result, it doesn't exacerbate issues with acid rain or global warming.
The environment may be impacted by wind turbines in both aesthetically pleasing and obtrusive ways. This is due to the fact that they need to be placed in conspicuous places and that the spinning of their blades causes visual distortions, such as flickering shadows and a humming sound. If all of the access routes are taken into account, the amount of land needed to see a wind park might be deemed significant. However, they seldom ever call for community relocation, which is an issue with things like big hydroelectric power plants. Although it has been questioned if the revolving blades provide a threat to birds, it has been discovered that the birds alter their flight patterns to avoid the blades. It has also been questioned if the development of plants is impacted by the decreased wind speed at ground level. The fact that many wind parks have animals grazing between the turbines provides a solution to this.
– Research and development needs
For many years, the wind converter industry has been associated with high-level technological development activities. In 2012, the European Commission's "Wind Energy Thematic Network" initiative published its first report [4], which detailed certain topics that are also pertinent in:
1. Impacts on the environment and society (e.g., improving local incentives by creating participation models):
Techniques for visually integrating wind turbines into the environment; minimizing effects on bird populations, habitats, and flight pathways; reducing noise impacts; designing turbines with life cycle analysis in mind; and analyzing social implications such local employment, investment, taxation, etc.
2. Problems with wind turbine and component design (such as fundamental studies in aerodynamics, structural dynamics, structural design, and control):
-feasibility studies of new wind turbine designs and innovations; -integration of

demand site needs in the design of the turbine, such as electrical control system interaction with grid requirements; -new materials with increased strength, such as carbon fiber for the blades.
3. Testing, standardization, and certification (such as well recognized certification processes for wind farms and turbines):
-standards for offshore wind converter service and maintenance ideas; -identification of standards that are absent; and -initiation of relevant activities for new standards.
4. Grid integration, energy systems, and resource forecasting (wind resourcing forecast, for example):
Energy management and storage systems for standalone applications; the creation of scenarios for revamping the grid system with substantial wind penetration; and the improvement of power quality and consistency.

5. Maintenance and operation (such as sophisticated condition monitoring):
-development of early failure detection and condition systems; -development of preventive maintenance; -standardization of components for simple replacement; -certification of service and maintenance ideas; -resource evaluation for cold and freezing climates.
6. Offshore wind technology (such as studies on the management and effectiveness of extremely large wind farms and more economical foundations, transportation, and installation methods):
-development of deep water foundation structures (fundamental wind turbine design research); -offshore meteorology; -special designs of systems and components for transportation, erection, access, and maintenance of offshore wind turbines; -investigation of the use of energy storage; -improvement of corrosion protecting systems regarding the offshore conditions; -monitoring of environmental impacts (effects on birds, effects of noise and vibration on marine life, especially by installation of wind converter etc.).
In addition to these factors, several R&D projects involving the operation and commercial introduction of wind turbines have been completed, such as:
enhanced understanding of the dynamic forces acting on the drive train; increased accessibility to gearboxes; optimization of control units and control systems; and creation of central lubrication systems.

– Outlook
The market for wind energy has expanded because to financial incentives provided by various governments as well as the environmental benefits of using a clean, limitless energy source. However, greenhouse emissions and air pollution will increase during the construction phase of a new turbine since energy is needed from other generating techniques. When a wind turbine's life cycle is examined, more

pollutants are conserved during operating than are released during construction.

A wind turbine cannot generate electricity on its own. This implies that when the turbine isn't working, backup power production is required. These days, the established fossil fuel power plants provide this backup. In order to maintain a stable electrical grid, more investment in backup generating technologies will be required as the number of wind turbines rises. In this instance, the difficulties stem from the fact that current power plants will produce less energy than they did before. Due to a shorter load period than before, the cost of producing energy in new power plants is rising.

See [3] for more details, particularly on ecological and technical factors (life time aspects).

In some situations, these extra investments will need subsidies.

Nonetheless, wind energy remains one of the most significant renewable energy sources for the future as it can be used in a clean and limitless way with the use of highly developed and effective technology.

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