3 Wind energy conversion

[H.-J. Wagner]

3.1 History

Wind energy is one of the oldest sources of energy used by mankind, comparable only to the use of animal force and biomass. Ancient cultures, dating back several thousand years, took advantage of wind energy to propel their sailing vessels. There are references to windmills relating to a Persian millwright in 644 AD and to windmills in Persia in 915 AD. In Alexandria one can still see the remains of wind mills which are about 3000 years old. These early wind energy converters were essential for pumping water and grinding cereals.

In Europe wind wheels were introduced around 1200 BC probably as an after-effect of the crusade to the orient. These European wind mills were mainly used for grinding, except in the Netherlands where wind wheels supplied the power to pump river water to the land located below sea level.

Between 1700 and 1800 AD the art of windmill construction reached its peak. The construction knowledge was relatively high and improved through trial and error. Later on, theories were developed, e.g. those by Euler, providing the tools to introduce new designs and thus to substantially improve the efficiency of energy conversion.

Many windmills were built and operated in Denmark, England, Germany and the Netherlands during the eighteenth century. In 1750, the Netherlands alone had between 6000 and 8000 windmills in operation. The number of windmills in Germany has been estimated at about 18000 in 1895, 11400 in 1914 and between 4000 and 5000 in 1933.

Around the beginning of the century, windmills were further improved and the design of a multiblade farm windmill originated in the USA. By the middle of the century, more than 6 million windmills were in operation in the USA. Overseas as well as in Europe, many of these wind wheels were used to produce mechanical power or as decentralized electricity suppliers on large farms. When the central electricity grid reached every farmhouse, the use of electricity produced by wind mills rapidly decreased and the converters were taken out of operation as soon as the next repair job was due.

In the nineteen fifties pioneers like Huetter at the University of Stuttgart, Germany, took up developing and testing modern wind wheels again. Their design is quite different from the previous one; there are only two or three blades with very good aerodynamic parameters, able to rotate at high speed. Due to the high number of rotations, only a small and cheap generator is needed to produce electricity. Nevertheless, it was not possible to break even economically selling wind generated electricity in the fifties and sixties.

In the aftermath of the so called oil crisis in the seventies, there was a surge to enforce the development and marketing of wind wheels, especially in the USA, Denmark and Germany. This was based on the understanding that ultimately, additional energy sources emitting less pollution would be necessary. Due to favorable tax regulations in the eighties, about 12000 wind converters supplying power ranging from 20 kW to about 200 kW were installed in California. In Europe, a lot of tax money was spent on the development of bigger wind converters and on marketing them. Now, in 2005, Germany has taken over the leadership: 2.5 MW converters are on the market, 3-5 MW converters are into testing and market introduction and the share of electricity produced by wind amounts to more than 5% in Germany.

3.2 Different converter types: an overview

Today there are various types of wind energy converters in operation (Fig. 3.1 gives an overview). The most common device is the horizontal axis wind energy converter. This converter consists of only a few aerodynamically optimized rotor blades, which for the purpose of regulation can usually be turned about their long axis (Pitch-regulation). Another cheaper way to regulate it consists in designing the blades in such a way that the air streaming along the blades will go into turbulence at a certain speed (Stall-Regulation). These converters can deliver power ranging from 10 kW to some MW. The largest converter on the European market has a power of 2.5 MW, bigger machines are under construction. The efficiency of this type of converter is very high. Therefore, it is solely used for electricity generation which needs "high speed engines" to keep the gear transmission and the generator small and cheap.

Another conventional (older) type of horizontal axis rotor is the multiblade wind energy converter. It was first built about one hundred years ago. Such wind mills have a high starting torque which makes them suitable for driving mechanical water pumps. The number of rotations is low, and the blades are made from simple sheets with an easy geometry. For pumping water, a rotation regulating system is not necessary, but there is a mechanical safety system installed to protect the converter against storm damage. The rotor is turned in the direction of the wind by using a so called wind-sheet in lee direction. In order to increase the number of rotations, this type of converter had been equipped with aerodynamically more efficient blades facilitating the production of electricity, where the area of a blade is smaller. The mechanical stability of such "slow speed converters" is very high; some have had operation periods of more than fifty years.

A third type of converter is known as DARRIEUS, a vertical axis construction. Their advantage is that they do not depend on the direction of the wind. To start, they need the help of a generator working as a motor or the help of an SAVONIUS rotor installed on top of the vertical axis. In the nineteen eighties, a reasonable number of DARRIEUS-converters had been installed in California, but a further expansion into the higher power range and in the European markets has not taken place. One reason may be that they are noisier than horizontal axis converters. Another disadvantage is that wind velocity increases significantly with height, making horizontal axis wheels on towers more economical. Nevertheless, there are some companies producing DARRIEUS-turbines in the very low power range of a few kilowatts for decentralized electricity supply in areas without electrical grids, e.g. rural areas of developing countries.

The SAVONIUS rotor is used only for research activities, e.g. as a measurement device especially for wind velocity, it is not used for power production. Therefore it will not be discussed in detail here.

The last technique to deal with is known as Up-Stream-Power-Station or thermal tower. In principle, it can be regarded as a mix between a wind converter and a solar collector. In the top of a narrow, high tower is a wind wheel on a vertical axis driven by the rising warm air. A solar collector installed around the foot of the tower heats up the air. The design of the collector is simple; a transparent plastic foil is fixed several meters above the ground in a circle around the tower. Therefore, the station needs a lot of space and the tower has to be very high. Such a system has a very poor efficiency, only about one percent. Worldwide, only one Up-Stream-Power-Station, designed by a German company, has been built so far. For some years it worked satisfactorily at the location of Manzarenas in Spain, but in the mid eighties it was destroyed by bad weather. This station had an electrical power of 20 kW, the tower was about 200 m high and the collector had a diameter of approximately the same size. A second Up-Stream-Power-Station with an electrical performance of 200 MW has been planned in India. The tower height is about 1000 m and the diameter of the tower is about 200 m. The project should be sponsored by the European Union, yet the project is not realized. The advantage of such a design is its technical simplicity, which may enable developing countries to construct it by themselves. But since there has been tremendous technical progress over the last ten years regarding solar farm stations as well as horizontal axis wind converters, no new Up-Stream-Power-Station have been designed and installed so far.

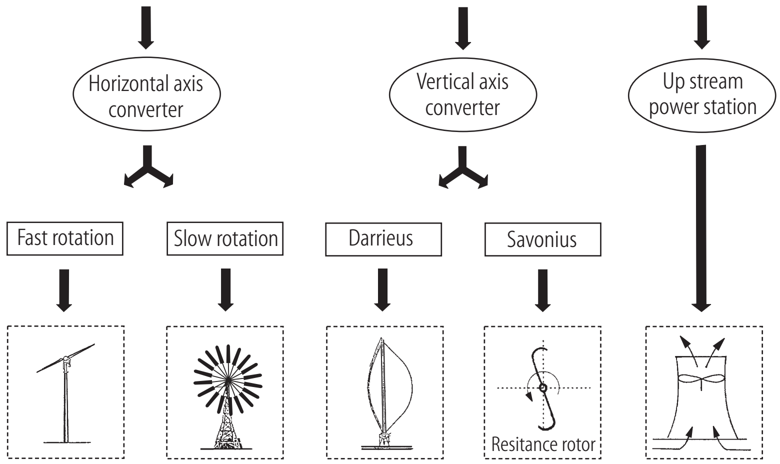


Fig. 3.1. Overview of the different types of wind energy converters.

3.3 Physical basics

3.3.1 Origin of wind energy

Large differences in the solar flux onto the surface of the earth lead to different air temperatures all over the globe. In regions with strong solar radiation, heated air expands and gives rise to a high pressure zone. In places with less radiation, air stays cooler and gives rise to a low pressure zone. Pressure differences cause the movement of air particles from one place to another; from high pressure to low pressure zones. This movement results in what we call wind.

A second force determining the direction of the wind, resulting from the rotation of the earth, is superimposed onto the first one. This force is known as the Coriolis force. In the northern hemisphere, this force works in such a way that the moved air is deflected towards the right, relative to its initial direction. In the southern hemisphere just the opposite happens: the moved body of air is deflected towards the left.

As a result of pressure differences, air is first moved in the direction of low pressure zones and the Coriolis force adds a movement towards the right (in the northern hemisphere). This drifting to the right continues until there is an equilibrium of the two forces, the force due to the pressure difference and the Coriolis-force. Up to this point, the air particles will travel along isobars. The layer of air closer to the earth's surface is slowed down due to the friction caused by the uneven surface of the land. One consequence of this is that the wind velocity will increase relative to the height above ground. Above a height of about 1000 m only so called geostrophic or cyclostrophic winds occur which are free of friction.

The general wind system around the globe is determined by two components: The HEADLY-circulation near the equator and the ROSSBY-circulation in the upper and lower parts of the globe. The operating energy for Headly-circulation comes from the strong solar insulation in the tropic zones. Air is heated, rises upwards and is deflected towards the North or South. At the same time it deviates to the East due to the Coriolis force. The air cools down and starts sinking at about 30° latitude north or south, respectively. In the areas of higher latitude north and south, the Rossby-circulation determines the outcome. This circulation has a wave form character and is driven by the temperature differences between the 30° and 70° latitude. Near the earth's surface, the Rossby-circulation generates a west wind belt. At a certain height this wind belt has considerable strength and is known as a Jet Stream. Due to its impact, airplanes crossing the North Atlantic need less time in one direction than in the other.

The general circulation system described in this chapter in a very short and simplified form is often superimposed by other atmospheric turbulences. The wind field near the earth surface can therefore change drastically over time and from place to place.

3.3.2 Energy content of the wind

If we take an area A and apply a wind velocity v, the change in volume with respect to the length l is

$$\Delta V = A \cdot \Delta l\ , \tag{3.1}$$

$$v = \frac{\Delta l}{\Delta t} \tag{3.2}$$

$$\Rightarrow \Delta V = A \cdot v \cdot \Delta t\ . \tag{3.3}$$

The energy in the wind is in the form of kinetic energy. Kinetic energy is characterized by the equation

$$E = \frac{1}{2} m v^2\ . \tag{3.4}$$

The change in energy is proportional to the change in mass, where

$$\Delta m = \Delta V \cdot \rho_a \tag{3.5}$$

and ρ_a the specific density of the air. Therefore, substituting for ΔV and Δm yields

$$E = \frac{1}{2} \cdot A \cdot \rho_a \cdot v^3 \cdot t\ . \tag{3.6}$$

From (3.6) can be seen that the energy in the wind is proportional to the cube of the wind speed, v^3. The Power P is defined as

$$P = \frac{E}{t} = \frac{1}{2} \cdot A \cdot \rho_a \cdot v^3\ . \tag{3.7}$$

Therefore, it is also proportional to v^3. From Fig. 3.2, it can be seen that the power output per m^2 of the rotor blade is not linearly proportional to the wind velocity, as proven in the theory above. This means that it is more profitable to place a wind energy converter in a location with occasional high winds than in a location where there is a constant low wind speed. Measurements at different places show that the distribution of wind velocity over the year can be approximated by a Weibull-equation. This means that at least about 2/3 of the produced electricity will be earned by the upper third of wind velocity. From a mechanical point of view, the power density range increases by one thousand for a wind speed change of just 10 m/s, thus producing a construction limit problem. Therefore, wind energy converters are constructed to harness only the power from wind speeds in the upper regions.

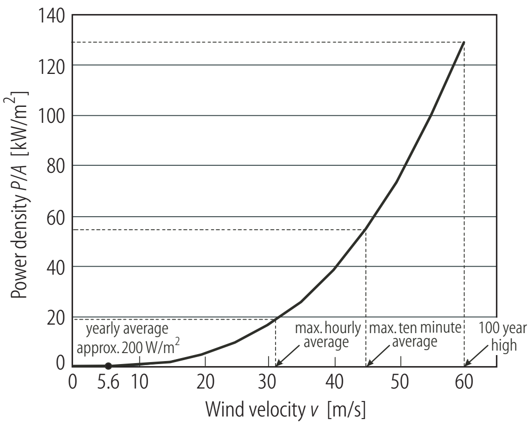


Fig. 3.2. Relationship between wind velocity and power of the wind (Maximum values for German coast).

3.3.3 Energy conversion on a blade

Figure 3.3 shows the velocities and forces at the profile of a rotating blade. The blade itself moves with an average circumferential velocity u in the plane of the rotor. The wind flows perpendicular to the plane of the rotor, thus creating a resultant velocity vector w. This velocity is then the relative approach or flow velocity of the rotor blade.

The two main forces acting on the rotor blade are the lift force $\boldsymbol{F}_\mathrm{A}$ and the drag force $\boldsymbol{F}_\mathrm{R}$. The drag force acts parallel to the initial direction of movement and the lift force acts perpendicular to it. The lift force is the greater force in normal operating conditions and arises due to the unequal pressure distribution around an aerofoil profile. The pressure on the upper surface is lower than that on the under side, therefore the air has a higher velocity when passing over the upper surface of the profile. The lift force is determined from the following formula:

$$F_\mathrm{A} = \frac{1}{2} \cdot \rho_\mathrm{a} \cdot c_\mathrm{A} \cdot w^2 \cdot A\,, \tag{3.8}$$

where c_A is the lift force coefficient. The drag force is determined from a similar formula,

$$F_\mathrm{R} = \frac{1}{2} \cdot \rho_\mathrm{a} \cdot c_\mathrm{R} \cdot w^2 \cdot A\,, \tag{3.9}$$

where c_R is the drag force coefficient, and is caused by air friction at the surface of the profile. The relationship between the two forces is given by the ratio E_G of their coefficients,

$$E_\mathrm{G} = \frac{c_\mathrm{A}}{c_\mathrm{R}}\,. \tag{3.10}$$

It can be seen from Fig. 3.3 that the resultant force $\boldsymbol{F}_\mathrm{RS}$ of the lift and drag forces can be divided into two components: the tangentially acting component $\boldsymbol{F}_\mathrm{T}$ and the axially acting component $\boldsymbol{F}_\mathrm{S}$. It is the force $\boldsymbol{F}_\mathrm{T}$ that causes the rotation of the rotor blade and makes power delivery possible.

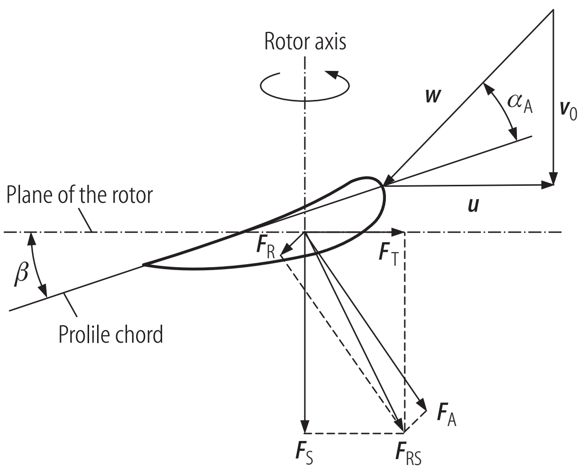


Fig. 3.3. The velocities and forces acting on a blade.
Legend: α_A - Angle of attack;
β - Pitch angle;
u - Average circumferential velocity;
v_0 - Wind velocity in the rotor plane;
w - Relative approach velocity;
F_R - Drag force;
F_A - Lift force;
F_RS - Resultant force;
F_T - Tangential component;
F_S - Axial component.

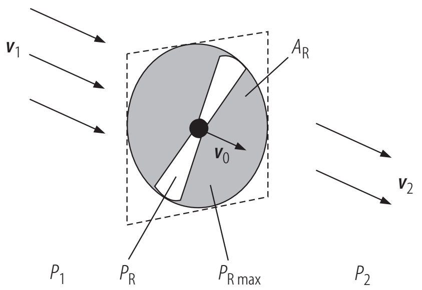


Fig. 3.4. Wind energy change at the rotor.

3.3.4 Power coefficients

Now the question is how much of the wind energy can be transferred to the blade as mechanical energy.

3.3.4.1 Betz‘ law and the power coefficient c_p

Betz‘ law states that you can only convert a maximum of 59% of the kinetic energy in the wind to mechanical energy using a wind turbine. This is because the wind on the back side of the rotor must have a high enough velocity to move away and allow more wind through the plane of the rotor.

The energy uptake of the rotor reduces the wind velocity from v_1 to v_2 as shown in Fig. 3.4. The average wind speed in the plane of the rotor can be assumed to be

$$v_0 = \frac{v_1 + v_2}{2} . \tag{3.11}$$

By conservation of momentum, the mass flow rate must be consistent throughout the plane:

$$\dot{m} = \dot{m}_1 = \dot{m}_{\mathrm{R}} = \dot{m}_2 . \tag{3.12}$$

If there is no energy uptake from the wind, the maximal power $P_{\mathrm{R\,max}}$ of the wind with a velocity of v_1 in the plane of the rotor is

$$P_{\mathrm{R\,max}} = \frac{1}{2} \cdot \dot{m} \cdot v_1^2 . \tag{3.13}$$

Then

$$\dot{m} = \rho_{\mathrm{a}} \cdot v_1 \cdot A_{\mathrm{R}} \tag{3.14}$$

$$\Rightarrow P_{\mathrm{R\,max}} = \frac{1}{2} \cdot \rho_{\mathrm{a}} \cdot A_{\mathrm{R}} \cdot v_1^3 . \tag{3.15}$$

The relationship between the power of the rotor blade P_{R} and the maximum power $P_{\mathrm{R\,max}}$ is given by the power coefficient c_{p}:

$$P_{\mathrm{R}} = P_1 - P_2 = c_{\mathrm{p}} \cdot P_{\mathrm{R\,max}} . \tag{3.16}$$

A long calculation finally yields

$$c_{\mathrm{p}} = \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right) \cdot \left[1 - \left(\frac{v_2}{v_1}\right)^2\right] . \tag{3.17}$$

The maximum power coefficient is determined by the ratio v_2/v_1; setting the derivation to zero leads to

$$c_{\mathrm{p\,max}} = \frac{16}{27} = 0.593 \quad \text{with} \quad v_2 = \frac{1}{3} v_1 .$$

Therefore, an ideal turbine will slow down the wind by 2/3 of its original speed.

3.3.4.2 Tip speed ratio

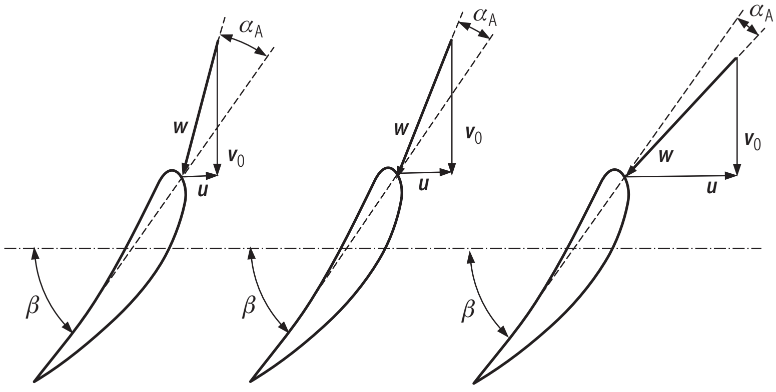
A wind energy converter is classified through the characteristic tip speed ratio λ_S. This is the ratio (as a scalar) of the circumferential velocity of the rotor at the end of the blade (maximum velocity u_e) and the wind velocity v_0 in front of the rotor blade:

$$\lambda_S = \frac{u_e}{v_0} . \tag{3.18}$$

The tip speed ratio has a strong influence on the efficiency of a wind energy converter (Fig. 3.5). When λ_S is small, the circumferential velocity is also small which results in an increase in the angle of attack α_A. When the angle of attack increases past a critical angle, the flow breaks from the profile and becomes turbulent, thus dramatically reducing the lift force. If the tip speed ratio is too large, the lift force will reach its maximum value and decrease afterwards, thus reducing the power efficiency of the converter.

3.3.4.3 Power efficiency

The power efficiency of a rotor blade can be determined by investigating the relationship between the power coefficient and the tip speed ratio. Figure 3.6 shows that for every pitch angle β, there is a tip speed ratio λ_S which corresponds to the maximum power coefficient and hence the maximum efficiency. It can be seen that the power efficiency significantly depends on the pitch angle and the tip speed ratio. Therefore, the pitch angle of the blade has to be changed mechanically in respect to the actual tip speed ratio. It can also be seen that the rotor blades can be damaged by using high pitch angles. This means that a disk brake on the main shaft is not necessary in most modern converters by using pitch control.



a **b** **c**

Fig. 3.5. Influence of the tip speed ratio λ_S [93Kle, p. 241ff].
(a) λ_S too small, flow breaks from the profile top side: c_A small, c_R big, c_p small.
(b) λ_S optimal, correct flow over the profile: c_A very big, c_R small, c_p maximum.
(c) λ_S too big, negative angle of attack: c_A small, c_R big, c_p small.

Besides the power coefficient c_p which can be interpreted as the efficiency between the rotor blade and the wind, there are also energy losses in the mechanical components of the rotor and gear system and in the turbine and generator connection. Therefore, the efficiency can be defined as

$$\eta = c_p \cdot \eta_m \cdot \eta_{ge} , \quad (3.19)$$

with η_m the mechanical efficiency and η_{ge} the efficiency of the coupled generator and the electrical auxiliary equipment. The efficiency η is also defined by the relationship of the electrical power to the power potential in the wind:

$$\eta = \frac{P_{el}}{\frac{1}{2} \cdot \rho_a \cdot A \cdot v^3} . \quad (3.20)$$

The issues discussed in this chapter can be summed up and related to the design of a wind energy converter through the following principles:

Principles for the design of wind energy converters

1. A high aerofoil form ratio c_A/c_R leads to a high tip speed ratio and therefore a large power coefficient c_p.

   ⇒ Modern converters with a good aerodynamic profile rotate quickly.

2. Simple profiles with smaller profile form ratios have a small tip speed ratio. Therefore, the area of the rotor radius that is occupied by blades must be increased in order to increase the power coefficient.

   ⇒ Slow rotating converters have poor aerodynamic profiles and a high number of blades.

3. The profile form ratio and the tip speed ratio have a considerably greater influence on the power coefficient than the number of blades.

   ⇒ For modern converters with a good aerodynamic profile, the number of blades is not so important for a large power coefficient c_p.

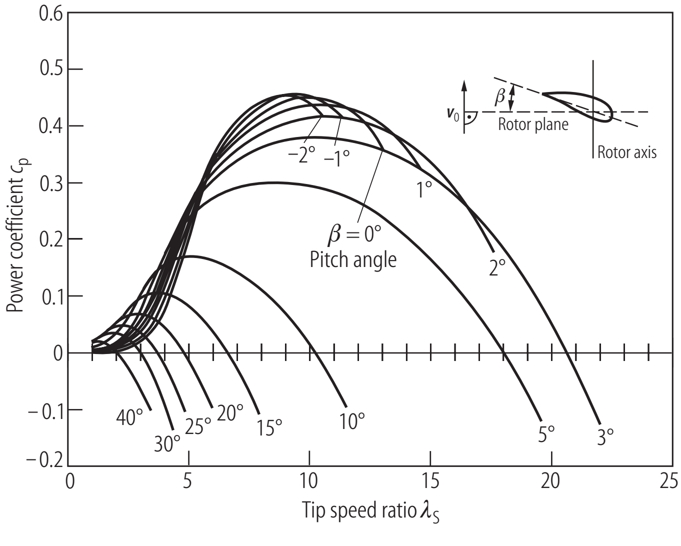


Fig. 3.6. Relationship between the power coefficient and the tip speed ratio; $+\beta$ is measured in the direction of v_0 from the rotor axis, for its definition see Fig. 3.3 [93Kle, p. 241ff, translated from German into English].

3.4 Technical design of converters

3.4.1 The design with gearbox

The details of a design with gearbox, also called the Danish design as this is where its history lies, are shown in Fig. 3.7. The main aspect of this design is the split shaft system, where the main shaft turns slowly with the rotor blades and the torque is transmitted through a gearbox to the high-speed secondary shaft that drives the few-pole pair generator. The transmission of torque to the generator is shut off by means of a large disk brake on the main shaft. A mechanical system controls the pitch of the blades, so pitch control can also be used to stop the operation of the converter, e.g. in stormy conditions. The pitch mechanism is driven by a hydraulic system, with oil as the popular medium. This system needs almost yearly maintenance and constant pressure monitoring, along with the gear box which is lubricated with oil. For constructions without a main brake, each blade has its pitch angle controlled by a small electric motor. Wind speed and direction measuring devices are located at the back of the hub head. A rack-and-pinion mechanism at the joint of the hub and the tower allows the hub to be rotated in to the wind direction and out of it in stormy conditions.

3.4.2 The design without gearbox

Some companies, e.g. the German company Enercon, design another converter type without gearbox. The scheme of such a converter is shown in Fig. 3.8, where the main design aspects can be clearly seen. This design has just one stationary shaft. The rotor blades and the generator are both mounted on this shaft. The generator is in the form of a large spoked wheel with e.g. forty-two pole pairs around the outer circumference and stators mounted on a stationary arm around the wheel. The wheel is fixed to the blade apparatus, so it rotates slowly with the blades. Therefore, there is no need for a gearbox, rotating shafts or a disk brake. This minimizing of mechanical parts simplifies the maintenance and production of the converter. The whole system is automated; pitch control and hub direction are controlled by a central computer which operates the small directional motors

3.4.3 The Multibrid design

In this design, a new combination of approved techniques has been used. It is operated in the M5000 design of the research and development company Multibrid® and was developed especially for offshore use. This design is a combination between a special gearbox and a multi-pole generator. The concept is based on a single-leveled planetary gear. The hub is directly connected to the hollow wheel of the planet and the inner raceway of the rotor bearing through a hollow shaft. There is no high-speed transmission included, which is critical to failure. The selection of a special type of planetary gearing achieves a high transmission allowing the use of a generator with up to 150 rpm. The bedding of the generator rotor on the main shaft reduces the number of bearings. A permanent magnet-excited synchronous generator with water-cooling, high efficiency and wide speed range is used. Due to the compact design, the construction has a reduced weight.

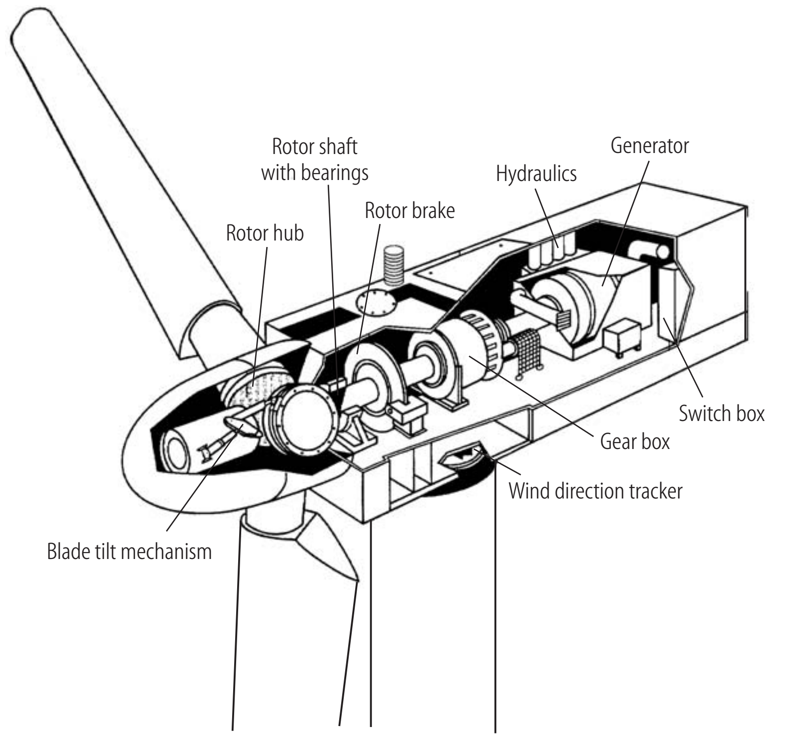


Fig. 3.7. Design with gearbox.

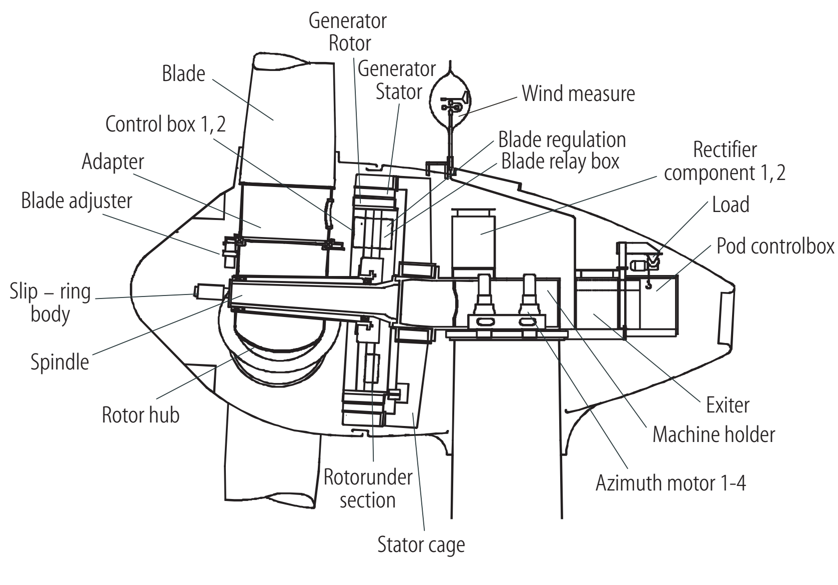


Fig. 3.8. Design without gearbox (Enercon E66).

3.4.4 Aspects of design

There are several critical aspects of a wind energy converter that need to be considered in the design phase to ensure that the converter will be economic and durable.

3.4.4.1 The tower

In principle, the tower needs to be as tall as possible, because the wind speed increases with height. However, the height is limited by cost issues (an increase in tower height of 10 m costs an extra fifteen thousand Dollars) and a tower height of over 100 m requires an aircraft-warning beacon, which is again expensive.

3.4.4.2 Heat energy

Large converters (>1 MW) have an average generator efficiency of 98%. Heat is also generated in the mechanical parts of the machine including the bearings and the gear box. This means that around 40 kW of power are lost to the heating up of the generator during operation. This heat energy needs to be controlled to prevent damage to the machine parts. A large fan system is mounted on the back side of the hub of the converter and is used to draw cool air through the hub and remove the heat energy emitted during operation.

3.4.4.3 Control and monitoring

The following aspects of a wind energy converter need to be controlled and monitored to ensure effective operation:

- Vibration levels (for large converters);
- Speed of rotation and the pitch angle of the rotor blades;
- The natural wind speed and direction;
- The voltage and frequency of the produced electricity;
- The output phase angle compared to the grid phase angle;
- The consistency of the electrical power output;
- The acquisition and storage of electrical signals;
- Signal conversion equipment for the directional motors;
- Rotational speed at night to reduce the noise levels, as the noise is proportional to u_e^6.

3.4.4.4 Mechanical stability

The following forces affect the stability of the mechanical system:

- Gravity;
- Centrifugal forces on the rotor blades;
- Pressure changes on the blade due to the shadow effect created by the tower;
- Stochastic power output of the converter due to continually changing wind energy levels;
- Resonance of the blades.

3.4.4.5 Wind direction set-up

A wind energy converter can be designed to face the wind (windward) or away from it (leeward). A leeward converter has the advantage of being self orientating, but the disadvantage of the tower disturbing the wind velocity profile before the wind has reached the plane of the rotor blades. The pressure and speed differences experienced by the blade as it passes the tower result in stresses on the hub which requires the use of an extra mechanism in the hub to allow the rotor blades to move out of their usual plane of rotation.

3.4.5 Technical figures for two modern wind converters

Table 3.1 gives an idea of the size of the common features of wind energy converters. A design with gearbox and a design without gearbox have been chosen to show the different operation of their generators.

Table 3.1. The technical figures of two differently designed wind energy converters (taken from Enercon and Nordex company brochures).

	Enercon E70	**Nordex N80**
Electrical power [MW] / wind velocity [m/s]	2 / 13.5	2.5 / 15
Design	without gearbox	with gearbox
Height of tower [m]	64-113	60-80
Number of blades	3 blades	3 blades
Speed of rotation [rpm]	6-22	11-19
Diameter of blade [m]	71	80
Material of blade	fiberglass (reinforced epoxy)	fiberglass (reinforced epoxy)
Blade regulation	pitch	pitch
Transmission of gearbox	none	1:68 ratio
Generator	multi-pole	few poles
Grid connection	via frequency converters	via frequency converters

3.5 Connection to the electrical grid

3.5.1 Requirements of the grid

The main electrical grid has a constant frequency, e.g. 50 Hz, and a constant phase angle. Therefore, a wind energy converter must produce electricity with the same constant values in order to be integrated into the main grid. The input energy of a wind energy converter is proportional to the wind speed, but the wind speed is never constant. Each wind speed has a corresponding rotor rotation speed at which the maximum power is produced, as shown in Fig. 3.6. This maximum occurs at different rates of rotation for different wind speeds. However, the rate of rotation must be kept constant in order to achieve the required constant output frequency. Solutions to this problem of maximizing the power output of converters are discussed in Sect. 3.5.2.

A small converter can be directly connected into the grid network at 0.4 kV. Once the wind energy converter is integrated into the grid network, there must be no voltage change, voltage oscillation or flicker experienced in the homes on that network branch. The loss of voltage due to resistance in the cabling can be avoided by increasing the diameter of the cables. It is often required that a new network branch is constructed and linked to the transformer in order to reduce the voltage disturbances. This increases the installation costs of the converter.

Mega-Watt converters cannot be connected to the grid at the 0.4 kV stage, but have to be connected at 10-30 kV which is the usual level of the city electricity share distribution. In remote areas, where a 30 kV connection is not established, the connection must be created and financed by the wind park developers. Wind parks with a lot of Mega-Watt converters must be connected into the electrical grid at a level of about 100 kV and higher.

As mentioned earlier, the maximum power output is obtained only in few hours during the year. Figure 3.9 shows a typical load distribution, measured within the German 250 MW program. With larger wind energy installations, this uneven distribution leads to the need of higher regulation capacities by conventional power systems in the future.

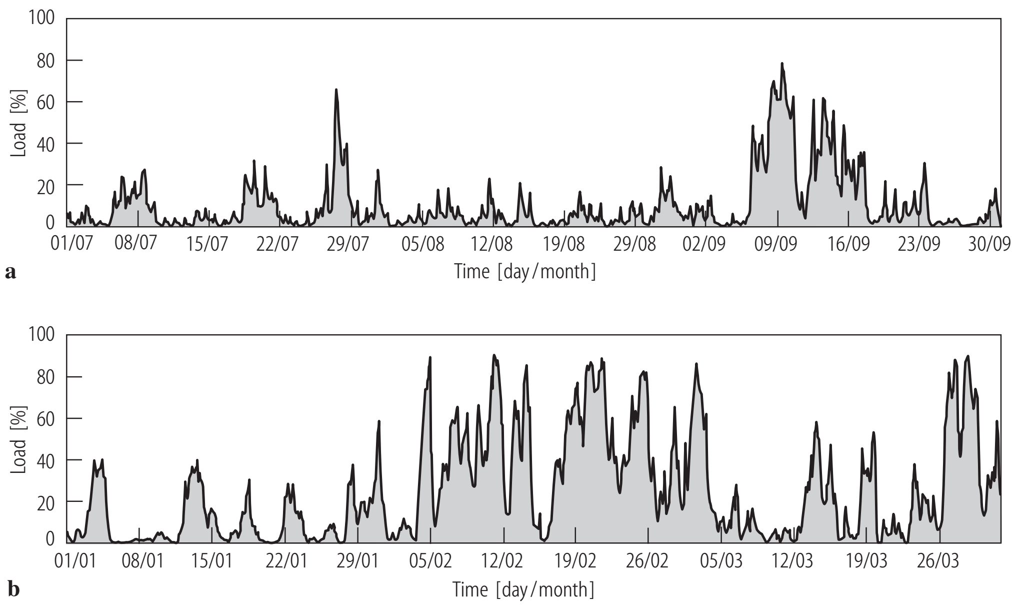


Fig. 3.9. Load Distribution of a wind park with a total capacity of 28 MW in Germany [98ISE]. **(a)** July - September 1997. **(b)** January - March 1997.

3.5.2 Adaptation of grid frequency and speed of electrical generator

There are several methods in operation that ensure an output of electricity to the grid at a constant frequency, e.g. of 50 Hz, whilst also achieving maximum efficiency in the operation of the converter:

- *Mechanical:*
  The rate of rotation at the generator can be controlled by the use of a gearbox, allowing the blade shaft to rotate at slow variable speed, while the generator shaft rotates at a constant higher speed.
- *Electrical by pole pairs:*
  The number p of controllable electromagnets in operation in the generator, so called pole pairs, can be switched, allowing the generator to rotate at different speeds n but produce the same output frequency f, where $n = f / p$.
- *Electrical by generator:*
  An asynchronous generator is characterized by the difference of the rotation speed between the mechanical part of the generator and his internal electro-magnetic field, the so called generator slip. Special types of asynchronous generators have such big generator slips that they can be used for operating the motor with variable speed at a constant frequency of the electrical output voltage of the generator.
- *Electronical:*
  A system of electronic frequency converters at the output of the generator can be used to regulate the varying frequency of the generator to be exactly 50 Hz in the grid. A Synchronous Generator (SG) is used in this type of system set-up (Fig. 3.10). A system that has no electronic converters but relies on one of the four mentioned principles to regulate the output frequency can employ either the use of a synchronous generator (SG) or an Asynchronous Generator.

For more technical details see [98Hei]. The method chosen is often dependant on the economics. For a 10 kW converter, the installation of an electronic system would extremely increase the investment costs, but for a 2.5 MW converter it is the most reliable and easiest control option.

3.5.3 Special aspects of the connection of offshore wind parks

Grid connection of offshore wind farms is a technical and economical challenge to both wind turbine and grid operators. In the initial phase, the still quite limited capacity of early pilot farms allows the use of a conventional three-phase AC connection to the onshore grid system which is a well known and inexpensive technology (currently: 175 kV, tendency in the future: 240 kV). Greater capacities and remote offshore sites make it technically difficult to connect offshore wind farms to the mainland grid by using AC undersea cables. Losses, reactive power production and limited capacity of the sea cables may become important in the future. High-voltage direct current transmission to land could be a solution, but it is technically complicated and expensive.

An internal grid is necessary to connect the offshore wind farm to the onshore grid. The produced power has to be fed to an offshore transformer substation, to which wind turbines are connected via undersea cables by a voltage of e.g. 30 kV. After stepping-up to the transmission line voltage, the power is conveyed to the shore.

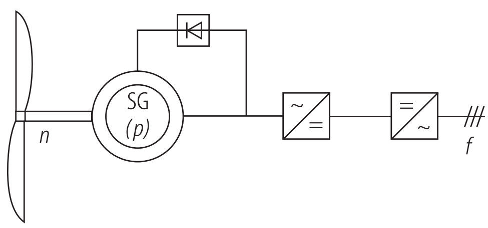


Fig. 3.10. Grid connection with frequency converters.

3.6 Use of wind energy

3.6.1 World-wide status

In the nineteen eighties, it was the USA that took the lead in establishing wind farms. They set over 10000 converters into operation, each generating between 80-200 kW. In Europe, Denmark was the main pioneer of wind energy. Today, in the twenty-first century, Germany has taken the world lead, producing about a third of the world's wind produced electricity.

Many governments have begun to produce initiative schemes to increase the economic feasibility of wind energy converters. Some initiatives used include paying more for wind produced electricity and providing a proportion of the initial construction costs. Governments of industrial countries and those with high power consumption are eager to promote wind energy because it is environmentally clean and sustainable and limits the need for fossil fuel usage. This attitude has resulted in five countries leading the way in world wind energy usage and supplying 76% the world's wind power today, as seen in Table 3.2. The development in Europe has been aided by the European commission which has set renewable energy usage targets to be met for the future.

3.6.2 Federal Republic of Germany

Very early, the German government had started a program to support and promote the development of wind energy converters. The program provided grants for the installation and operation of wind turbines and financed up to 40% of the investment costs as far as a capacity of 250 MW in total. The last grants were approved by the end of 1996. Afterwards, different legal acts supported electricity generation by renewable energies.

Table 3.2. World wind power production [06WWE].

World total and selected countries	Approx. total installed power up to the end of 2005 [MW]
World total	59000
Germany	18400
Spain	10000
USA	9100
India	4400
Denmark	3100
Italy	1700
United Kingdom	1400
China	1300

Table 3.3. Status of wind energy use in Germany [05DEW] (status 31.12.2005).

Number of installations	17600
Installed Capacity [MW]	18400
Average Installed Power [kW/installation]	1049

Since the year 2001, the Renewable Energy Sources Act is valid. It regulates the feed-in of electricity, the legal obligation of utilities to take off all electricity generated from renewable energy sources as well as the scope of prices paid for it. The feed-in tariffs are paid by the grid operators whose grid is closest to the location of the wind installation. The tariffs paid are not generated from taxes but from the revenues of the grid operators. Therefore, the Renewable Energy Sources Act is legally not a subsidy or state aid. To support the connection of the converters to the main grid, the government has set the feed-in tariffs relatively high (status: end of the year 2005):

- Onshore Wind: 8.7 €-ct/kWh for at least five years; followed by at least 5.5 €-ct/kWh.
- Offshore Wind: Turbines installed before 2011 up to 9.1 €-ct/kWh for the first nine years of operation, followed by 6.19 €-ct/kWh.

There are discussions to change the feed-in tariffs. Due to these figures and the installed capacity of wind energy, the consumer had to pay about 0.5 €-ct/kWh plus tax for wind energy in the year 2005. Table 3.3 shows the status of wind energy use in Germany in December 2005.

In 2001, the largest wind energy converters installed in Germany were 2.5 MW converters. End of 2005, converters up to 5 MW had come on to the market.

Nowadays off-shore wind parks are in a planning status along the coast and in a distance of 30 km and more from the coast. The first of them will be constructed as a testing park in a water depth of 30 m. It will be erected until 2008 to test different types of big wind energy converters. The advantage of offshore plants will be a higher capacity factor up to about 50% (up to 4325 h/a load duration) due to higher wind velocities. They measure about twice as much as the ones in onshore locations. The disadvantages are higher investment costs for the founding of the wind mills in the sea and for the electrical connection to the grid.

The costs involved in installing a wind energy converter vary depending on the design, size and chosen location of the new converter. The infrastructure costs can be minimized by constructing wind parks, where a number of new converters are installed on the same sight. An example of the investment costs for a wind park in Germany is shown in Table 3.4.

For most wind parks, the invested money comes from banks and private investors. The money invested in an average wind park depreciates over about a ten year period. During this period, the set-up and installation costs are high, along with the loan repayments and insurance costs. After this period, the costs decrease. Over the next ten years, a financial return can be made on the investment if the price for the electricity per kilowatt hour is set at a high tariff by the government. This means that it is economic to ensure the durability of the installed converters to keep maintenance costs after the ten year period low and allow the investors to receive a good return on their investment.

Table 3.4. Investment costs of a wind park of ten 1.5 MW converters in Germany (source: public investment brochure, status: end 2003).

	Invested costs [10^6 €]	Percent of total [%]
Wind Park (ten 1.5 MW converters) including transport, assembly, cabling, starting-up, grid connection, reinforcement, infrastructure	16	83
Technical planning, foundation soil analysis, survey and grid connection fee	2.0	11
Raising of capital	0.5	3
Others	0.5	3
Grand total	19	100

3.7 Economical and environmental aspects

3.7.1 Environmental comparison

Wind energy is a renewable energy source; therefore it has many advantages compared to fossil fuels which have diminishing reserves. Wind energy is clean in regard to toxic emissions and therefore does not add to global warming or acid rain problems.

Wind energy converters can affect the environment in aesthetic and human intrusive ways as they must be sited in prominent locations and, by the rotation of their blades, produce optical and acoustic distortions such as flickering shadows and a humming noise. The land required for a wind park can be considered large, if all the access routes are also taken into consideration. However, they very rarely require the resettlement of communities, which is a problem associated with e.g. large hydro-electric power stations. The danger of the rotating blades to birds has been questioned, but it has been found that the birds change their flight paths to avoid the blades. It has also be questioned whether the reduced wind speed at ground level affects the growth of flora. But here as well, no influence could be found.

3.7.2 Energy payback time

The energy payback time of a system is the time required to recover the total energy investment made. The definition of the energy payback time (Fig. 3.11) as well as the energy yield ratio (ratio of produced energy to total cumulative energy demand) can be helpful for the final evaluation of energy systems. The total cumulative energy demand can be understood as an indicator of environmental impacts as far as the depletion of energy resources is concerned. To obtain, for instance, the cumulative energy demand for the production of a power plant, the whole facility has to be split up into components, sub-components and their respective materials. Combining this material balance with specific data for material and energy intensity allows the calculation of the cumulative energy demand.

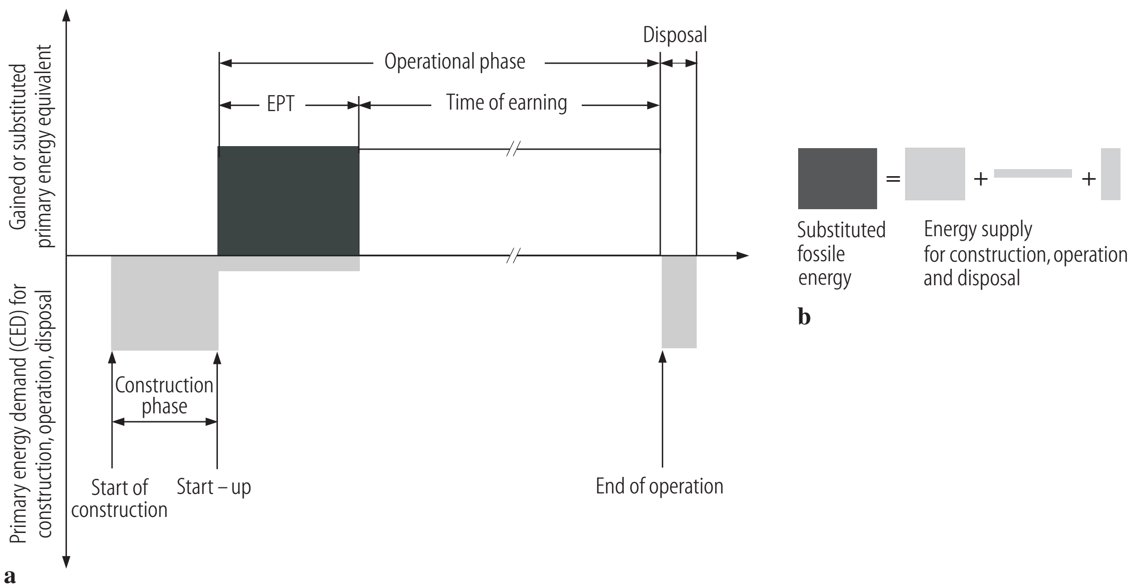


Fig. 3.11. (a) The scheme of energy payback. **(b)** Definition of the Energy payback time (EPT).

For calculating the yearly energy output of a wind energy converter, three locations have been selected: Coastal, near coastal and inland. Large wind energy converters of 500 kW and 1.5 MW with a hub height of 67 m and a rotor blade diameter of 66 m, as produced in Germany, have been chosen. It has been found that the variation of the energy yield ratio is within 10% only for the different types (500 kW and 1500 kW) of wind energy converters [98Pic]. The most important assumptions for the calculations are:

- Wind velocity distribution within a year and within a month follows Weibull's distribution;
- The velocity profile of wind velocity with altitude is exponential in shape;
- All the components except the foundation are made at a plant situated in northern Germany;
- The machinery is transported by truck to the site;
- Lifetime of one plant is 20 years;
- Maintenance of rotor blades (coating) is required after 10 years.

The cumulative energy demand of the wind energy converters including production, utilization and disposal varies from 13800 to 13900 GJ. The tower has the biggest share of about 27%. Another important component group, due to a high content of energy-intensive materials, is the generator with a share of about 21%. The rest of the machinery holds a share of about 13%, while foundation and grid connection hold 10%. For assembly, maintenance and transportation, about 8% of the total cumulative energy demand are needed.

Also, an energy payback time for an offshore system was evaluated. The assumptions for the evaluation were similar to the ones for onshore designs, except for the following additions:

- Transportation to the site and erection of the wind energy converters are realized by special ships from the nearest port;
- For the foundation, the tripod has been selected;
- Lifetime of the offshore foundations is approximately 40-50 years. Therefore, the foundation has been taken into account only for 50% of the cumulative energy demand calculation;
- Service travels are necessary three times a year;
- A general overhaul of the wind energy converter is made after 10 years;
- Credits for recyclable materials were not granted.

Here, the total cumulative energy demand sums up to 85000 GJ. The foundation has the biggest share of about 31%. Another important component group, due to a high content of energy-intensive materials, is the machinery with a share of about 17%. The tower holds a share of about 15% while rotor and hub blades together account for about 11%. The maintenance during the lifetime of the wind energy converter contributes about 22% to the total cumulative energy demand. The major share of maintenance goes into replacement of components (e.g. gear box). Associated transportation and mounting have also been considered. For transportation and mounting in the construction phase as well as for dismantling after the operation phase only 2% each is needed.

To calculate the energy payback time, the net harvest of energy has to be appraised. Using the installed load of the wind energy converter and the expected capacity factor of 50% and considering the system's efficiency factor to be about 80%, a net electrical power output of 17.5 GWh/a can be found. Using the German average primary energy conversion factor of electricity of 0.33, the net harvest has been converted to equivalent primary energy. Thus the Energy Payback Time is about 4 months.

The calculations of the cumulative energy demand or the energy yield ratio are not very accurate as compared to economical cost and benefit analysis, where decimal figures have to be exact. Nevertheless, the results show clear tendencies. Therefore both cumulative energy demand and energy payback time – and therefore the payback time for CO_2 as well – might be seen as indicators for environmental impacts, as far as the estimation of depletion of energy sources is concerned.

Finally, it can be summarized that from a sustainable point of view the use of wind energy for power generation makes sense.

3.8 Outlook

Wind energy is one of the oldest techniques used by Man to harness energy. The simple windmills are now a thing of the past, and today, 100 m high horizontal converters are appearing on the landscape around the world. The level of power conversion has risen from 200 kW in the nineteen eighties to 5 MW in the year 2006. Research and development is still continuing.

The wind energy market has grown because of the environmental advantages of harnessing a clean and inexhaustible energy source and because of the economic incentives supplied by several governments. However, energy is required from other generation methods during the building phase of a new converter, so greenhouse gases and air pollution will be added in this period as well. If the life cycle of a wind energy converter is examined, more pollutants are saved during operation than are emitted during the building phase.

The world wind energy potential is very large, but today, in 2006, it has very low usage levels; Germany is the largest producer and wind energy accounts for about 6% of the country's electricity. In many countries, wind energy conversion is still very uneconomic compared to the fossil fuel power stations. It has been made economic in countries like Germany because the government has recognized it as a clean source of energy and has therefore set the price that the grid operator pays per kWh for wind generated electricity very high and provided further investment incentives.

A wind energy converter is not a self-sustainable power station. This means that back-up power generation is needed at the times when the converter is not in operation. This back-up is nowadays supplied by the established fossil fuel power stations. If the number of wind energy converters increases in the long term to produce about 10% of the electricity, the need for extra investment in the back-up generation systems will arise in order to maintain a stable electricity grid system. These additional investments will need to be met by the wind energy conversion companies.

However, wind energy is still one of the most important renewable energy resources for the future, because it can be harnessed in a clean and inexhaustible manner through the application of technically advanced and efficient machinery.

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