WIND ELECTRICITY GENERATION

Introduction

Windpower technology dates back many centuries. There are historical claims that wind machines which harness the power of the wind date back beyond the time of the ancient Egyptians. Hero of Alexandria used a simple windmill to power an organ whilst the Babylonian emperor, Hammurabi, used windmills for an ambitious irrigation project as early as the 17th century BC. The Persians built windmills in the 7th century AD for milling and irrigation and rustic mills similar to these early vertical axis designs can still be found in the region today. In Europe the first windmills were seen much later, probably having been introduced by the English on their return from the crusades in the middle east or possibly transferred to Southern Europe by the Muslims after their conquest of the Iberian Peninsula. It was in Europe that much of the subsequent technical development took place. By the late part of the 13th century the typical 'European windmill' had been developed and this became the norm until further developments were introduced during the 18th century. At the end of the 19th century there were more than 30,000 windmills in Europe, used primarily for the milling of grain and water pumping.

Figure 1: Wind power generators are now common worldwide. Great Orton Windcluster ©Wind Prospect / Cumbria Wind Farm

Modern wind generators

The first wind powered electricity was produced by a machine built by Charles F. Brush in Cleveland, Ohio in 1888. It had a rated power of 12 kW (direct current - dc). Direct current electricity production continued in the form of small-scale, stand-alone (not connected to a grid) systems until the 1930's when the first large scale AC turbine was constructed in the USA. There was then a general lull in interest until the 1970's when the fuel crises sparked a revival in research and development work in North America (USA and Canada) and Europe (Denmark, Germany, The Netherlands, Spain, Sweden and the UK). Modern wind turbine generators are highly sophisticated machines, taking full advantage of state-of-the-art technology, led by improvements in aerodynamic and structural design, materials technology and mechanical, electrical and control engineering and capable of producing several megawatts of electricity. During the 1980's installed capacity costs dropped considerably and windpower has become an economically attractive option for commercial electricity generation. Large wind farms or wind power stations have become a common sight in many western countries. In 2001 Denmark alone had 2000 Megawatts of electricity generating capacity from more than 5,700 wind turbines, representing 14% of their national electricity consumption (Source: www.windpower.dk). Wind is a clean, safe, renewable form of energy.

To a lesser degree, there has been a parallel development in small-scale wind generators for supplying electricity for battery charging, for stand-alone applications and for connection to small grids. Table 1 shows the classification system for wind turbines.

Scale	Rotor diameter	Power rating
Micro	Less than 3 m	50 W to 2 kW
Small	3 m to 12 m	2 kW to 40 kW
Medium	12 m to 45 m	40 kW to 999 kW
Large	46 m and larger	More than 1.0 MW

Table 1: The classification system for wind turbines. Source: Spera, 1994 and Gipe, 1999

Wind generation for developing countries

Unlike the trend toward large-scale grid connected wind turbines seen in the West, the more immediate demand for rural energy supply in developing countries is for smaller machines in the 5 - 100 kW range. These can be connected to small, localised micro-grid systems and used in conjunction with diesel generating sets and/or solar photovoltaic systems (see hybrid systems section later in this fact sheet). Currently, the use of wind power for electricity production in developing countries is limited, the main area of growth being for very small battery charging wind turbines (50 - 150 Watts). In Inner Mongolia there are over 30,000 such machines used by herders for providing power for lighting, televisions, radios, etc. (Spera 1994). Other applications for small wind machines include water pumping, telecommunications power supply and irrigation.

Technical

The power in the wind

The wind systems that exist over the earth's surface are a result of variations in air pressure. These are in turn due to the variations in solar heating. Warm air rises and cooler air rushes in to take its place. Wind is merely the movement of air from one place to another. There are global wind patterns related to large scale solar heating of different regions of the earth's surface and seasonal variations in solar incidence. There are also localised wind patterns due the effects of temperature differences between land and seas, or mountains and valleys. Wind speed generally increases with height above ground. This is because the roughness of ground features such as vegetation and houses cause the wind to be slowed.

Windspeed data can be obtained from wind maps or from the meteorology office. Unfortunately the general availability and reliability of windspeed data is extremely poor in many regions of the world. However, significant areas of the world have mean annual windspeeds of above 4-5 m/s (metres per second) which makes small-scale wind powered electricity generation an attractive option. It is important to obtain accurate windspeed data for the site in mind before any decision can be made as to its suitability. Methods for assessing the mean windspeed are found in the relevant texts (see the 'References and resources' section at the end of this fact sheet).

The power in the wind is proportional to:
- the area of windmill being swept by the wind
- the cube of the wind speed
- the air density - which varies with altitude

The formula used for calculating the power in the wind is shown below:

Power   = $\dfrac{\text{density of air x swept area x velocity cubed}}{2}$

P   = $\frac{1}{2}.\rho.A.V^3$

where, P is power in watts (W)
ρ is the air density in kilograms per cubic metre (kg/m^3)
A is the swept rotor area in square metres (m^2)

V is the windspeed in metres per second (m/s)

The fact that the power is proportional to the cube of the windspeed is very significant. This can be demonstrated by pointing out that if the wind speed doubles then the power in the wind increases by a factor of eight. It is therefore worthwhile finding a site which has a relatively high mean windspeed.

Wind into watts

Although the power equation above gives us the power in the wind, the actual power that we can extract from the wind is significantly less than this figure suggests. The actual power will depend on several factors, such as the type of machine and rotor used, the sophistication of blade design, friction losses, and the losses in the pump or other equipment connected to the wind machine. There are also physical limits to the amount of power that can be extracted realistically from the wind. It can been shown theoretically that any windmill can only possibly extract a maximum of 59.3% of the power from the wind (this is known as the Betz limit). In reality, this figure is usually around 45% (maximum) for a large electricity producing turbine and around 30% to 40% for a windpump, (see the section on coefficient of performance below). So, modifying the formula for 'Power in the wind' we can say that the power which is produced by the wind machine can be given by:

$$P_M = \tfrac{1}{2}.Cp.\rho.A.V^3$$

where, P_M is power (in watts) available from the machine
C_p is the coefficient of performance of the wind machine

It is also worth bearing in mind that a wind machine will only operate at its maximum efficiency for a fraction of the time it is running, due to variations in wind speed. A rough estimate of the output from a wind machine can be obtained using the following equation;

$$P_A = 0.2 \, A \, V^3$$

where, P_A is the average power output in watts over the year
V is the mean annual windspeed in m/s

Principles of wind energy conversion

There are two primary physical principles by which energy can be extracted from the wind; these are through the creation of either lift or drag force (or through a combination of the two). The difference between drag and lift is illustrated by the difference between using a spinnaker sail, which fills like a parachute and pulls a sailing boat with the wind, and a Bermuda rig, the familiar triangular sail which deflects with wind and allows a sailing boat to travel across the wind or slightly into the wind.

Drag forces provide the most obvious means of propulsion, these being the forces felt by a person (or object) exposed to the wind. Lift forces are the most efficient means of propulsion but being more subtle than drag forces are not so well understood.

The basic features that characterise lift and drag are:
- drag is in the direction of air flow
- lift is perpendicular to the direction of air flow
- generation of lift always causes a certain amount of drag to be developed
- with a good aerofoil, the lift produced can be more than thirty times greater than the drag
- lift devices are generally more efficient than drag devices

Types and characteristics of rotors

There are two main families of windmachines: vertical axis machines and horizontal axis

machines. These can in turn use either lift or drag forces to harness the wind. The horizontal axis lift device is the type most commonly used. In fact other than a few experimental machines virtually all windmills come under this category.

There are several technical parameters that are used to characterise windmill rotors. The *tip-speed ratio* is defined as the ratio of the speed of the extremities of a windmill rotor to the speed of the free wind. Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios (up to 13:1) and hence turn quickly relative to the wind.

The proportion of the power in the wind that the rotor can extract is termed the *coefficient of performance* (or power coefficient or efficiency; symbol C_p) and its variation as a function of tip-speed ratio is commonly used to characterise different types of rotor. As mentioned earlier there is an upper limit of C_p = 59.3%, although in practice real wind rotors have maximum C_p values in the range of 25%-45%.

Solidity is usually defined as the percentage of the area of the rotor, which contains material rather than air. Low-solidity machines run at higher speed and tend to be used for electricity generation. High-solidity machines carry a lot of material and have coarse blade angles. They generate much higher starting torque (torque is the twisting or rotary force produced by the rotor) than low-solidity machines but are inherently less efficient than low-solidity machines. The windpump is generally of this type. High solidity machines will have a low tip-speed ratio and vice versa.

There are various important wind speeds to consider:
- Start-up wind speed - the wind speed that will turn an unloaded rotor
- Cut-in wind speed – the wind speed at which the rotor can be loaded
- Rated wind speed – the windspeed at which the machine is designed to run (this is at optimum tip-speed ratio
- Furling wind speed – the windspeed at which the machine will be turned out of the wind to prevent damage
- Maximum design wind speed – the windspeed above which damage could occur to the machine

The choice of rotor is dictated largely by the characteristic of the load and hence of the end use. Some common rotor types and their characteristics are shown in Table 2 below.

Type	Speed	Torque	C_p	Solidity (%)	Use
Horizontal Axis					
Multi blade	Low	High	0.25 - 0.4	50 - 80	Mechanical Power
Three-bladed aerofoil	High	Low	up to 0.45	Less than 5	Electricity Production
Vertical Axis					
Panemone	Low	Medium	less than 0.1	50	Mechanical Power
Darrieus	Moderate	Very low	0.25 - 0.35	10 - 20	Electricity Production

Table 2: Comparison of Rotor Types

Anatomy and characteristics of the wind generator
A typical small wind generator has rotor that is directly coupled to the generator which produces electricity either at 120/240 volt alternating current for direct domestic use or at 12/24 volt direct current for battery charging. Larger machines generate 3 phase electricity. There is often a tail vane which keeps the rotor orientated into the wind. Some wind-machines have a tail vane which is designed for automatic furling (turning the machine out of the wind) at high wind speeds to prevent damage. Larger machines have pitch controlled blades (the angle at which the blades meet the wind is controlled) which achieve the same function. The tower is of low solidity to prevent wind interference and are often guyed to give support to the tower.

Figure 2: The Practical Action small wind turbine
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The specifications for the Practical Action small wind turbine are shown in Table 3 below.

Type	3 blade upwind
Rotor diameter	1.7 metres
Drive	Direct
Rated Power	100 Watts
Start-up wind speed	3.5 m/s
Cut-in wind speed	3.5 m/s
Rated wind speed	8.0 m/s
Furling wind speed	14.0 m/s
Generator	Permanent Magnet Alternator
Max. Power Output	200 Watts

Table 3: Practical Action Small Wind Energy System for Battery Charging
Turbine Specifications

Grid connected or battery charging

Depending on the circumstances, the distribution of electricity from a wind machine can be carried out in one of various ways. Commonly, larger machines are connected to a grid distribution network. This can be the main national network, in which case electricity can be sold to the electricity utility (providing an agreement can be made between the producer and the grid) when an excess is produced and purchased when the wind is low. Using the national grid helps provide flexibility to the system and does away with the need for a back-up system when windspeeds are low.

Micro-grids distribute electricity to smaller areas, typically a village or town. When wind is used for supplying electricity to such a grid, a diesel generator set is often used as a backup for the periods when windspeeds are low. Alternatively, electricity storage can be used but this is an expensive option. Hybrid systems use a combination of two or more energy sources to provide electricity in all weather conditions. The capital cost for such a system is high but subsequent running costs will be low compared with a pure diesel system.

In areas where households are widely dispersed or where grid costs are prohibitively expensive, battery charging is an option. For people in rural areas a few tens of watts of power are sufficient for providing lighting and a source of power for a radio or television. Batteries can be returned to the charging station occasionally for recharging. This reduces the inconvenience of an intermittent supply due to fluctuating windspeeds. 12 and 24 volt direct current wind generators are commercially available which are suitable for battery charging applications. Smaller turbines (50 -150 watt) are available for individual household connection.

Other issues

Environmental concerns

Wind power is a clean renewable energy source. There are, however some environmental considerations to keep in mind when planning a wind power scheme. They include the following:

- Electromagnetic interference - some television frequency bands are susceptible to interference from wind generators.
- Noise - wind rotors, gearboxes and generators create acoustic noise when functioning; this needs to be considered when siting a machine.
- Visual impact - modern wind machines are large objects and have a significant visual impact on their surroundings. Some argue that it is a positive visual impact, others to the contrary.

Cost - economics

The cost of producing electricity form the wind is heavily dependent on the local wind regime. As mentioned earlier the power output from the wind machine is proportional to cube of the windspeed and so a slight increase in windspeed will mean a significant increase in power and a subsequent reduction in unit costs. Capital costs for windpower are high, but running costs are low and so access to initial funds, subsidies or low interest loans are an obvious advantage when considering a wind-electric system. If a hybrid system is used a careful cost-benefit analysis needs to be carried out. A careful

Figure 3: Crockahenny Windcluster with installed capacity of 5 MW supplying 4200 homes
©Wind Prospect

matching of the load and energy supply options should be made to maximise the use of the power from the wind - a load which accepts a variable input is ideally matched to the intermittent nature of windpower.

Local manufacture

Local production of existing designs is a far simpler process to get started than development of new machines, and can be carried out in many developing countries. The production of small and medium sized machines locally is a great deal cheaper than imported machines and, during the production process, it enables manufacturers to make minor modifications in order to match systems with desired end-uses and to the conditions under which they are expected to operate. Depending on the availability of materials, rotor blades can be made locally from laminated wood, steel, plastics or combinations of these materials, whilst some of the machinery components can be made by small engineering workshops. Other parts, including special bearings, gearboxes, generators and other electrical equipment may have to be imported if they are not available in the country of assembly. Towers can be made of welded steel, preferably galvanised, which can be manufactured in many local engineering works, whilst the foundations can be cast from reinforced concrete on site.

Source: Renewable Energy Technologies, IT Publications, 1991.

References and resources

S. Dunnett: Small Wind Energy Systems for Battery Charging.
Practical Action Technical Information Leaflet,

Hugh Piggott: It's A Breeze, A Guide to Choosing Windpower.
Centre for Alternative Technology, 1998

E. H. Lysen: Introduction to Wind Energy, basic and advanced introduction to wind energy
with emphasis on water pumping windmills.
SWD, Netherlands, 1982

Smail Khennas, Simon Dunnett & Hugh Piggott: Small Wind Systems for Rural Energy
Services ITDG Publishing, 2003, ISBN 1 85339 555 2

Jack Park: The Wind Power Book.
Cheshire Books, USA, 1981

Hugh Piggot: Windpower Workshop, building your own wind turbine.
Centre for Alternative Technology, 1997

E. W. Golding: The Generation of Electricity by Wind Power.
Redwood Burn Limited, Trowbridge, 1976

David, A. Spera: Wind Turbine Technology, fundamental concepts of wind turbine
engineering.
ASME Press, 1994

Paul Gipe: Wind Energy Basics, a guide to small and micro wind systems.
Chelsea Green Publishing Company, 1999

T. Anderson, A. Doig, D. Rees and S. Khennas: Rural Energy Services - A handbook for
sustainable energy development. ITDG Publishing, 1999.

L.A. Kristoferson, and V. Bokalders: Renewable Energy Technologies - their application in
developing countries. ITDG Publishing, 1991.

S. Lancashire, J. Kenna and P. Fraenkel: Windpumping Handbook.
I T Publications, London, 1987

Windpumping.
Practical Action Technical Brief

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Home Power Magazine
http://www.homepower.com/

Wind Prospect Ltd.
http://www.windprospect.com/

Danish Wind Turbine Manufacturers
Association
http://www.windpower.dk

National Renewable Energy Laboratory of the
U.S. Department of Energy
http://www.nrel.gov

James and James
http://www.jxj.com/suppands/

Hugh Piggott
http://homepages.enterprise.net/hugh0piggott/

African Windpower
http://www.power.co.zw/windpower/

Centre for Renewable Energy and Sustainable
Technology
http://www.solstice.crest.org

Institute for Global Communications. A good
source for wind energy links
http://www.igc.apc.org/energy/wind.html