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EXPERT GROUP MEETING ON DESIGN,
DEVELOPMENT, MANUFACTURE AND APPLICATION OF
WINDMILL IN ENERGY GENERATION ENGINEERING



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TECHNICAL PAPER

AN OVERVIEW OF WIND-POWER DEVELOPMENT

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AN OVERVIEW OF WIND-POWER DEVELOPMENT

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1. BACKGROUND TO WINDMILL DEVELOPMENT

It is known that the ancient Egyptians used wind power five thousand years ago on the Nile to propel boats. The earliest detailed written records of windmills, with which the wind was used to drive machinery on land, date from the first century AD, although some sources suggest windmills were used in China and Japan much earlier. During the following thousand years the Mediterranean horizontal axis sail windmill evolved and by the 12th century windmills with rigid sails had reached northern Europe, in particular England and Holland, where they were mainly used for corn grinding and water pumping respectively.

The onset of the industrial revolution and the invention of first the steam engine and later the internal combustion engine during the nineteenth century almost halted the incentive for continued development of wind energy systems. But interest in the technology survived and expanded strongly in the USA from the 1850s onwards where a reliable means of water pumping was required for water supply, as the livestock industry developed on the Great Plains of the Mid-West. In fact, as the railroads spread across the North American prairie, many of the essential water points for replenishing the steam locomotive's water supplies were also powered by windmills.

Today, despite the wide-spread use and availability of petroleum fuels and the extension of rural electrification, there are still hundreds of thousands of windpumps used in the livestock industries of the USA, Australia, South America, and South Africa for water supply. The main reason they are still used is simply because they are less troublesome than diesel engines in areas lacking mains electricity. Over fifty enterprises throughout the world are known still to manufacture windpumps at the present time.

By the 1930s interest had developed in the use of wind power for the generation of electricity. Small wind generators for charging lead-acid batteries were the first systems to be produced. During the second world war many Danish farms employed wind generators and although cheap oil in the 1950s and 60s led to a decline in interest, legislation and fiscal incentives have helped Denmark to become once again one of the leading users and exporters of wind electricity generating technology today.

2. OVERVIEW OF PRIMARY APPLICATIONS

Wind power lends itself best to applications that can accept a substantially variable energy input. In all cases some element of storage is inevitably involved; this can be high grade energy storage such as electrical energy in rechargeable storage batteries, or it can be storage of a product such as pumped water held in a tank from where it can be taken at times of little or no wind.

So long as a wind powered system is designed to have sufficient storage capacity to cover the periods when the supply is unable to meet the full level of demand, then an output is always available. The one exception where direct storage is not involved, is grid-connected wind electricity generation where the grid replaces the need for storage. In this situation, the randomness of wind generated electricity need be no more of a complication than the randomness of the demand pattern in a sizeable electricity grid, providing the level of wind generated electricity penetration of the grid is no more than around 20%.

Wind power is in regular and practical use at present for a number of applications and it has the potential to be used for various others which remain at the experimental stage. Some known applications and their current status are indicated in Table 1.

Table 1: Wind Power Applications and Status

System	Application	Status
Battery charging	Boats/caravans lights	Commercial
	Electric fences	Commercial
	Expeditions	Commercial
	Navigation aids	Experimental
	Telecommunications	Experimental
Grid connected	Mains supply	Commercial
Wind-diesel	Remote settlements	Experimental
	Irrigation pumping	Experimental
	Sea water desalination	Experimental
Windpumps	Drinking water supply	Commercial
	Irrigation pumping	Commercial
	Dewatering	Commercial
	Sea-salt production	Commercial
	Seawater desalination	Experimental
Miscellaneous	Ice production	Experimental
	Cooling/air condit.	Experimental
	Heating	Experimental
	Milling grain, etc.	Obsolete

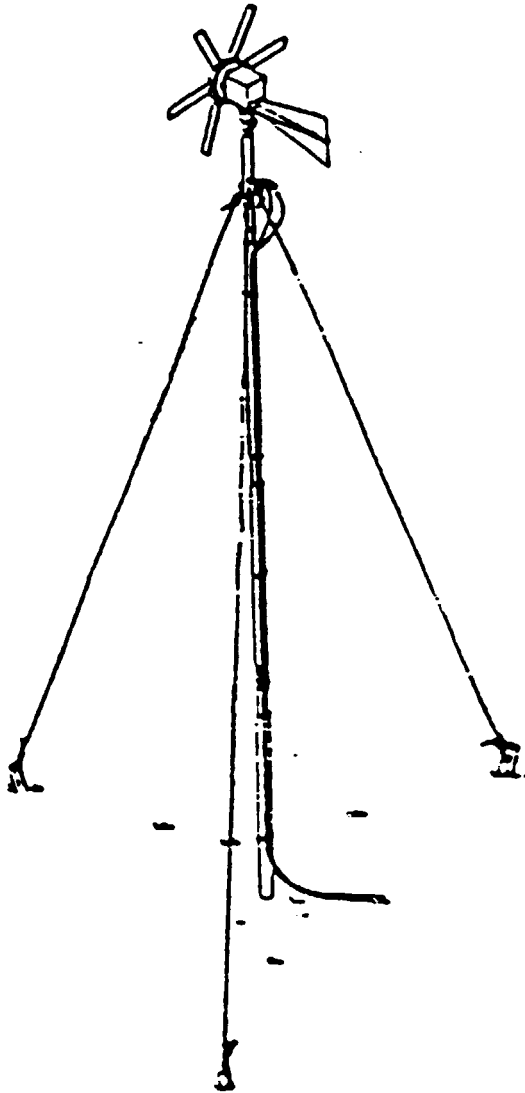


Figure 1 Typical Small Battery Charging Wind Generator
(50kW Marlec 'Rutland' Windcharger)

Due to the wide variability of the level of energy input to a wind system, the potential for mismatches with the demand makes wind system design a technically complex process. However wind power has been successfully used for many decades, so a wealth of experience as well as theory has been evolved to cope with this problem and satisfactory systems with high levels of reliability have been developed.

3. REVIEW OF PRIMARY APPLICATIONS

The following sections review the status of some of the primary wind applications in general use.

3.1 Battery Charging

The most common type of small wind electric system involves the use of a wind generator to maintain an adequate level of charge in an electrical storage battery. The battery in turn can provide electricity on demand for electrical applications such as lights, radios, telecommunications or electric livestock fencing. A typical small modern battery charging wind generator is illustrated in Figure 1.

Usually a brushless, permanent-magnet alternator is used for generating electricity, as these are more efficient and more reliable than the traditional dynamo which has brushes and a segmented commutator. However an alternator produces alternating current (AC) which is not immediately usable for charging a battery that requires direct current (DC). Therefore a set of diodes are used to rectify the AC output into DC, in much the same way as with modern motor vehicle electrical systems. The rectifier system usually uses five diodes in a bridge circuit, as this offers much smoother DC than a single diode. Other additions may include electrical filters to take out the remaining ripple which can interfere with telecommunications applications.

The most efficient and simple battery charging systems use large diameter permanent magnet alternators designed to run at low speeds. These have the major advantage that they can be driven directly by the windmill rotor, so that a gear box is not necessary. Larger systems and some of the more old fashioned types require a speed-increasing gearbox to drive the generator fast enough.

Generally, most battery charging systems require a charge regulator to prevent overcharging of the batteries which could damage them. This is an electronic device that is capable of sensing the battery voltage so that when it reaches a certain level the charge regulator uses a relay to switch most of the current from the wind turbine through a shunt resistor where surplus energy is dissipated as heat. It is also possible to have additional control circuitry to prevent excessive battery discharge, for example, by sensing low voltage and isolating the battery or

switching on a warning indicator, but although this is a desirable feature, this is still unusual since it is generally quite costly to install (low battery charge is more difficult to detect reliably than overcharge and requires much more sophisticated electronics).

Batteries are nearly always of the lead acid type and although car batteries or lorry batteries can be used for very small systems, they are not really suitable for such purposes and deep discharge or traction batteries should preferably be used. This is because vehicle batteries are not tolerant of deep levels of discharge and will rapidly deteriorate if not maintained at a high state of charge. Nickel-cadmium (Ni-Cad) batteries can be used successfully, but they tend to be more expensive per unit of electricity stored; they are however to be recommended under extremely cold conditions as they are much more resistant to freezing than lead-acid batteries. Other types of battery are under development but are not at present in general use.

The battery directly feeds the load and so long as it is adequately charged can supply power at any time on demand irrespective of whether or not the wind is blowing. A single lead-acid battery cell is generally rated at a nominal 2 volts, but most battery systems are arranged for a nominal voltage of 12, 24 or 48 volts (with six, twelve or twenty-four cells in series).

The lower the voltage the greater the cable thicknesses required to minimise power transmission losses, so professional applications such as telecommunications most commonly are rated at 48 volts to minimise resistive losses in the cables. High DC voltages (above 120V) are not commonly used as they are potentially lethal (DC is more likely to kill than AC).

The charge-discharge cycle of a battery is typically 70% efficient, so that in other words, 30% of the energy that is input to a battery is lost as heat, etc., and only 70% can be recovered as useful electricity.

In many cases, especially if standard AC mains appliances are required, an inverter can be used to convert the low voltage DC output from batteries to a mains voltage at 50Hz (or 60Hz) AC output. Inverters are solid state electronic devices. The cheaper and cruder types are relatively inefficient (they absorb a significant percentage of the energy that is input, especially at part load) and they also tend to have crude square wave outputs that can cause radio interference and overheating of some small AC appliances such as electric motors. Better quality inverters are normally necessary for serious wind-battery charging applications; these need to have a quasi-sine wave output (a wave-form more nearly approximating to conventional mains AC), combined with circuitry designed to minimise power losses, especially at part load or no load. Another vital requirement with inverters (and other electronic devices) used with stand alone wind electricity generators is that they have an adequate overload capacity for brief periods; eg. typically twice the nominal

rating for one minute and up to six times the nominal continuous rating for say 10 seconds.

Before the advent of power electronics, rotary inverters were used to produce AC from a DC source. These consist of a DC motor driving an AC generator, often combined on the same armature. A rig of that kind can easily be improvised from a suitably matched motor and alternator. However solid state inverters are preferable as they are significantly more efficient, quieter and at least theoretically more reliable and long lasting. The word 'Theoretically' was used advisedly as solid state electronic inverters can be problematic and unreliable, although the few well established manufacturers with well-tried mass-produced models do have reliable ones available. It is always advisable only to use inverters (and other electronic devices) that have been produced and used in some numbers. This is because inverters offered for wind applications (especially ones with large power ratings) tend to be relatively new, untried and hence potentially unreliable.

Small wind battery charging systems are most commonly rated at between 25-100W in a 10m/s wind speed, and are quite small with a rotor diameter of 50cm to 1m. A few machines of this kind are in relatively large scale production notably in the UK, the Peoples Republic of China and the USA. Around 150,000 such systems are in use today and annual production has been increasing. It is probably in the range 20,000 to 30,000 units per annum.

The main use in the western developed countries is for lighting or powering small electronic devices in remote buildings, caravans (i.e. residential trailers), yachts and other small leisure vessels. They are being taken up in developing countries for remote settlements, especially in the Mongolia region of China and in the independent Mongolian Peoples Republic (Outer Mongolia) where nomadic herdsmen use them for lighting and powering radios in their portable "yurta" homes.

A UNDP/UNDTCD project in the Mongolian Peoples Republic, provides an interesting insight into the application of wind electricity generators in a development application. Initially three different wind electricity generators were tried: -

- the Rutland 50W wind generator, supplied by Marlec Engineering from the UK
- the Dyna Technology 200W Wind Charger (a long established design, no longer in production, from the USA)
- the Electro 5kW Wind Generator (a more recent Swiss manufactured design, but also no longer in production)

The Marlec machine is the only one that remains in service (or in production); the Dyna Technology 200W Wind Charger was significantly more expensive and found to have a lower energy capture than the Marlec machine despite having a power rating four times greater, due to its high cut in wind speed. The

Electro 5kW Wind Generator proved to be too large, troublesome and expensive. This illustrates the probable reason for the success of the small 50W machines; they have a high "load factor" (i.e. they can extract energy from light winds) and in addition they are relatively inexpensive and reliable in operation.

Larger wind electricity generators that can be used for stand-alone applications, including battery charging, also exist. Typical sizes are 250W, 500W, 1kW, 2kW, 5kW and the largest that can generally be considered for battery charging applications is around 10kW.

Battery charging with a wind turbine rated at one or more kilowatts requires relatively large and expensive batteries. The minimum size of a battery regardless of the storage capacity required is dictated by the maximum acceptable charging current - the higher the current the larger the area of battery plates necessary if damage is to be avoided. Therefore larger wind turbines result in unattractively expensive systems. Also the larger systems have only been manufactured and supplied in small numbers, so, at the time of writing, they tend to remain semi-experimental and although some brands have an excellent reputation many have proved to be inadequately tested and have misbehaved under field conditions. Such problems may be expected to be less prevalent in future as more experience is gained and the products improve.

3.2 Grid-connected systems

Experiments with large wind turbines linked to the electricity grid were carried out as long ago as the 1930s in the USSR, and repeated in the 40s and 50s notably in France and the UK. A 1MW wind turbine was even developed and installed in the USA during the Second World War and remained by far the largest wind turbine ever built until the late 1970s. Serious development of the technology only really began in the late 1970s after the "oil shock" of 1973-4. At that time, Denmark and the USA became the prime contenders for large wind turbine development (mainly because they had significant home markets for the equipment) but most of the OECD countries initiated some kind of experimental wind programme as did a number of developing countries, in particular India and China.

A grid-connected wind-turbine uses an alternator or an induction generator. The latter is akin to an induction motor. It works on similar principles and is less costly than conventional synchronous alternators. In both cases the generator is driven by the wind turbine rotor, via a gearbox, housed in the nacelle. A typical nacelle is illustrated in Figure 2. Sometimes two gearboxes in series are needed, because large wind turbine rotors rotate at less than one hundred revolutions per minute while the alternator needs to be driven at around one thousand five hundred revolutions per minute. A mechanical brake is also necessary, not for stopping the machine but to lock the rotor when the machine is not in use and prevent an unintended run-away.

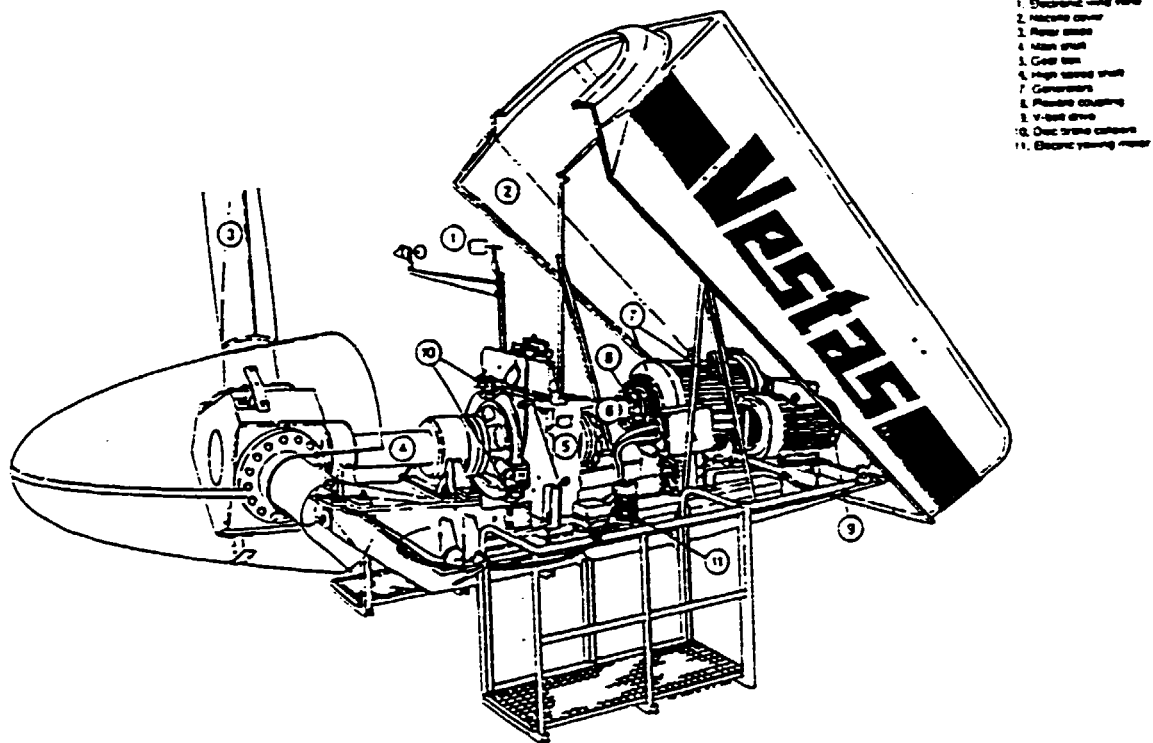


Figure 2
 Wind Generator Nacelle and Related Components

The wind generator rotor is normally orientated by a small electrical servo system which drives the slewing ring via a worm wheel and pinion. This is activated by a wind direction sensing transducer.

The alternator is linked to the grid via an interface for connection and isolation. Isolation is required to protect the generator from the grid, i.e. when the wind speed is not high enough for the turbine to produce a positive output. It is also needed to protect the local grid from the turbine, i.e. to prevent electrocution of maintenance staff working on the lines if a section of the grid needs to be shut-down for maintenance or repairs. The wind turbine output also needs to be maintained reliably within the voltage and frequency limits allowable by the local electricity utility.

Generally the present generation of grid-connected wind turbines use induction generators running at synchronous speed with the grid, so the windmill rotor runs at constant speed. There has been some controversy about whether to use pitch controlled blades to improve efficiency, but on balance it appears that the added cost and complication does not pay off in improved cost-effectiveness. Another area of controversy is whether to use rigid or teetered blade roots for the rotor; again the simpler solution of a fixed blade root tends to predominate at present.

The impetus of wind turbine development began in Denmark and California during the early to mid 1980s largely because effective fiscal incentives to encourage wind electricity generation were legislated in both areas. The Danes developed a wind turbine industry slightly ahead of all their competitors, partly thanks to having a significant home market developing even in the late 1970s combined with an earlier background of experimentation with grid connected wind turbines in the 40s and 50s. Danish wind turbines tend to use a "simple and robust" approach, with fixed pitch three-bladed rotors and fairly rigid structures, while the US industry tended to favour pitch-controlled compliant designs, which, whilst having a small edge in performance over Danish technology, tended in practice to be over-complicated and relatively unreliable in operation.

At the same time as the industry developed in Denmark and California, focussing initially mainly on machines in the 50 to 100kW size range, several governments initiated experimental programmes to promote the development of much larger megawatt sized machines. Notably the MOD series in the USA of the early 1980s culminated in the 3MW Boeing MOD 3, the German programme culminated in the 5MW "Growian" wind turbine and the UK programme produced a 3MW machine installed in Orkney. However these large machines proved less cost-effective and much more troublesome than the smaller machines being commercially manufactured and sold for use on wind-farms.

In the early 1980s the wind-farms (sometimes known as wind-parks) used 50 and 100kW machines. Gradually the size for optimum cost-effectiveness crept up, until today many new wind-farms, especi-

ally those being developed in Europe, tend to favour 250 to 750kW machines.

At the same time, the cost-effectiveness of grid-connected wind turbines increased markedly during the last decade. The capital cost fell from approximately US \$3,000 per kW of installed capacity in the early 80s to around US \$1,000 per kW by 1990. Not only did the costs of wind turbines fall, but reliability improved and so did the efficiency of wind energy capture. In the early 80s most Californian wind turbines had capacity factors in the region of 15% (i.e. they actually produced, on average, 15% of what they would in theory if the wind blew continuously at the rated power wind speed), but by 1990 it was common for capacity factors of 25% or more to be achieved, some have recently even exceeded 30%. Another way of looking at this is that in the early 1980s energy capture of 50kW machines was typically 500-700kWh/m²/yr at a good site, but this has steadily increased to a maximum of 1200-1400kWh/m²/yr by 1990 with the current generation of 250 to 750kW machines. Evidently energy capture has practically doubled while costs have been reduced by two thirds, resulting in considerable reductions in unit electricity output costs such that they are currently somewhere in the region of US 10c/kWh.

The trend at present is towards wind-farms utilising wind turbines sized from 250kW to 750kW, since larger machines require less space for a given installed capacity, e.g. the space required for a 5MW wind-farm consisting of seven 750kW machines is much less than for twenty-five 200kW machines. This is because wind turbines need to be deployed so as to minimise interference with neighbouring machines located down wind, since the wake behind a wind turbine is not only depleted in energy but also turbulent and capable of damaging the rotors of machines downstream if they are exposed to it. Also the cost overheads for cables and interfacing with the grid are of course significantly lower for a smaller number of larger machines.

Although wind-farms need to be large in land area in relation to their rated power, (compared with a conventional power station), they have the unique advantage among power generation methods that the same land can be used for other purposes, such as livestock grazing or agriculture, because the wind turbines themselves and service roads only take up a small fraction of the land required, typically less than 5%.

Some controversy exists in the industrial countries on the environmental acceptability of wind-farms, in particular with respect to "visual intrusion"; in some cases objections have been registered against planned wind-farms for this reason. Other potentially negative factors that have been raised, like the risk to bird life and electromagnetic interference with television and radar, have tended to prove relatively unimportant or even practically non-existent in many cases.

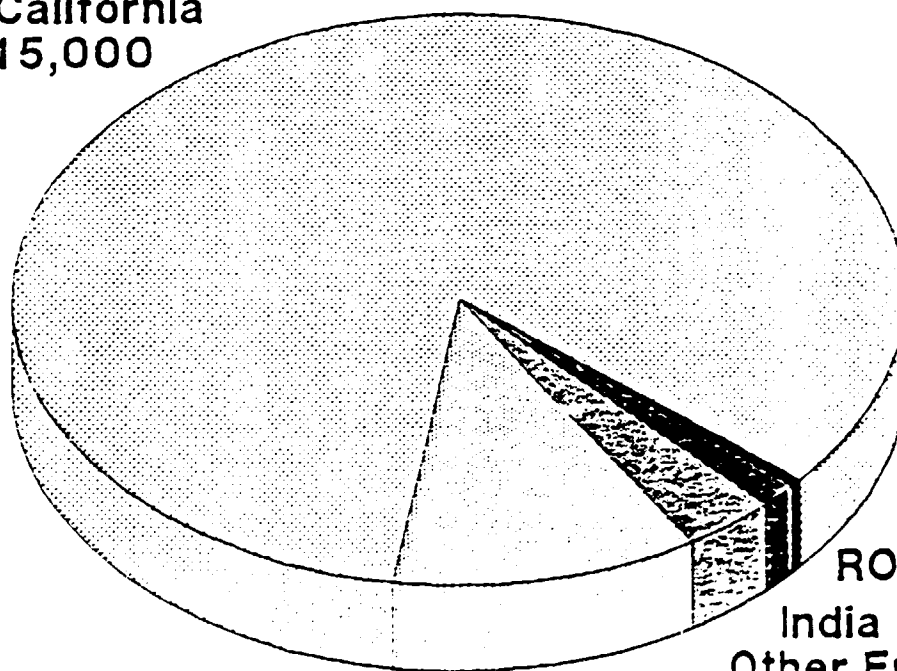
Figure 3 indicates the distribution of wind turbines installed in grid connected applications world-wide. Although California

still dominates in terms of sheer numbers (Table 2 details the California wind-farm break-down), wind-farms are beginning to be developed in numerous other countries, including the Netherlands, Germany, Spain, the UK and India. Japan is also becoming a major supplier of wind turbines for wind-farms.

Table 2: California Wind-Farms in 1990

Total turbines installed up to 1990	15,114
Total capacity installed	1,398 MW
Total investment up to 1990	US\$2,600 million
Total land area used	2,300 ha
Annual energy production	2,124 GWh
Annual income from wind-farms	US\$ 159 million
Expected additional installations 1990	1,175
Expected capacity added in 1990	190 MW

California
15,000



ROW 80
India 250
Other Europe 600

Denmark 2,000

Figure 3 1990 World-Wide Distribution of Installed Grid Connected Wind Turbines

3.3 Wind-diesel systems

Wind-diesel systems can range from a single 5kW diesel generating set operating in conjunction with a 10kW wind turbine at the lower end of the size range, to several megawatts of diesel capacity (normally involving several generating sets) running a mini-grid system, with perhaps a megawatt or more of wind electricity generation. Obviously there is a wide spectrum of intermediate possibilities and the costs, engineering details and complications relating to these extremes are considerably different.

The rationale for wind-diesel systems is that diesel-generated electricity is generally more expensive than wind generated electricity. The unit cost of diesel generated electricity is approximately US \$0.15-0.20 per kWh for megawatt sized diesel generating sets up to US \$1.00 (or more) per kWh for the smallest sizes of generating set (taking all costs into account). In contrast, a medium sized wind turbine, given a favourable wind régime, can generate electricity at US \$0.10-0.20 per kWh.

Consequently where a diesel generating set would be used a wind-diesel system can (in theory) reduce the average unit cost of electricity, and save diesel fuel. It can also reduce diesel operating hours and thereby lower the maintenance requirements and increase the life of the engine. However, in practice, the effective substitution of windpower for diesel power is not straightforward.

Operating strategies for smaller systems are much more difficult than for bigger ones, but the rewards are potentially greater. Systems utilising several diesels, several wind turbines and a large number of loads tend to operate more smoothly because a multiplicity of wind and diesel inputs offer considerable scope for power modulation and larger systems have user demand patterns which are much smoother and which change less quickly than for small systems. The smallest systems, where the cost of diesel electricity is especially high, are especially difficult to integrate with a wind turbine as they can suffer rapid power demand peaks (for example when someone switches on a 3kW kettle on a 5kW system) and similarly with only one engine and one wind turbine it is difficult to devise strategies to cope with a sudden lull in the wind which can cause the wind turbine power output to fall for a few seconds to less than 25% of what it had been earlier.

With small systems little is gained unless the diesel can be shut down for extended periods. This is because the part-load efficiency of a small diesel is such that simply taking part of the load onto the windmill will not save much fuel.

Research and development into autonomous wind-diesel systems is quite recent and dates from the late 1970s. At the present time the technology is close to commercial readiness but still remains semi-experimental, with a number of pilot projects in various parts of the world and numerous technical papers on the topic being regularly presented at conferences (e.g. Avolio, Lipman and

Yundog). An example of one such project is located in Italy, a 20kW wind - diesel demonstration plant which has been designed for autonomous supply of electrical power for remotely located consumers, realised under CEC sponsorship, it now powers a small factory. A number of other successful wind - diesel systems have been installed for island communities, particularly around the UK, but also in Greece, China and Ireland.

In contrast, the largest autonomous wind - diesel systems are effectively a small diesel powered grid with a wind - farm attached to it. As long as the wind energy system penetration remains small, (i.e. no more than 20%), standard wind - farm wind technology is applicable.

With the smallest systems either load control has to be used, where the wind turbine is over - sized so that in medium to strong winds a high proportion of wind - generated electrical power is dumped into a heat sink, or some form of short - term energy storage is needed to bridge lulls in the wind.

Load - control is the most well - developed type of system at this stage. It is a concept where only a small fraction of the rated output of the wind turbine is considered as "firm power" to be used for priority loads as lights, televisions or computers, which cannot tolerate occasional outages. Most of the rated output is taken up by non - priority loads such as water heating, refrigerators and freezers or other applications which can stand occasional gaps in power availability. Therefore slight lulls in the wind are handled by cutting off most of the non - priority load, e.g. a 50kW system would often require 45kW of non - priority load. In such a case, if a lull is such that the wind falls to a level which is not sufficient to generate 5kW for the priority loads, then the diesel is automatically started and will take over the priority loads plus some share of the other load. Load switching is handled by a programmed controller utilising a micro - processor, i.e. a small computer, fed with information by wind speed sensors. In effect the diesel component of a load - controlled system is more a back - up system to a stand - alone wind system in which the turbine is considerably over - sized (or de - rated) for the priority electrical load. Therefore normally either the wind system or the diesel will handle the bulk of the load, and rarely both together.

On the other hand, a fully integrated wind - diesel system is configured to run the wind turbine(s) and diesel engine(s) in parallel. With such systems some form of energy storage is essential to cater for brief lulls in the wind and to buffer sudden peaks in wind energy availability during gusts. The types of storage that have been tried are batteries, flywheels and hydraulic or pressurised gas accumulators. Batteries are not really practical except for the smallest of systems, due to their high cost. Flywheels look promising but have a limited storage capacity, as do hydraulic pressurised gas accumulators. However this technology is still largely under development.

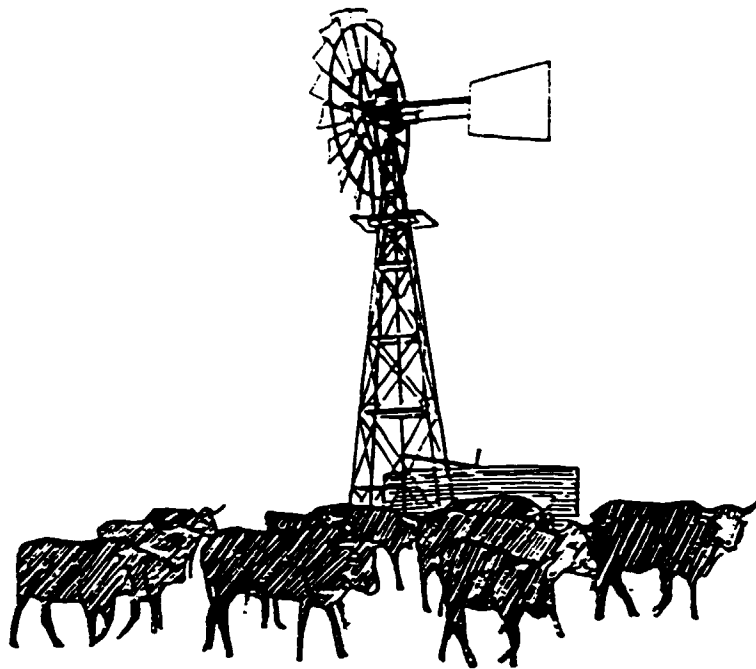


Figure 4 Multi-blade American Farm Windpump

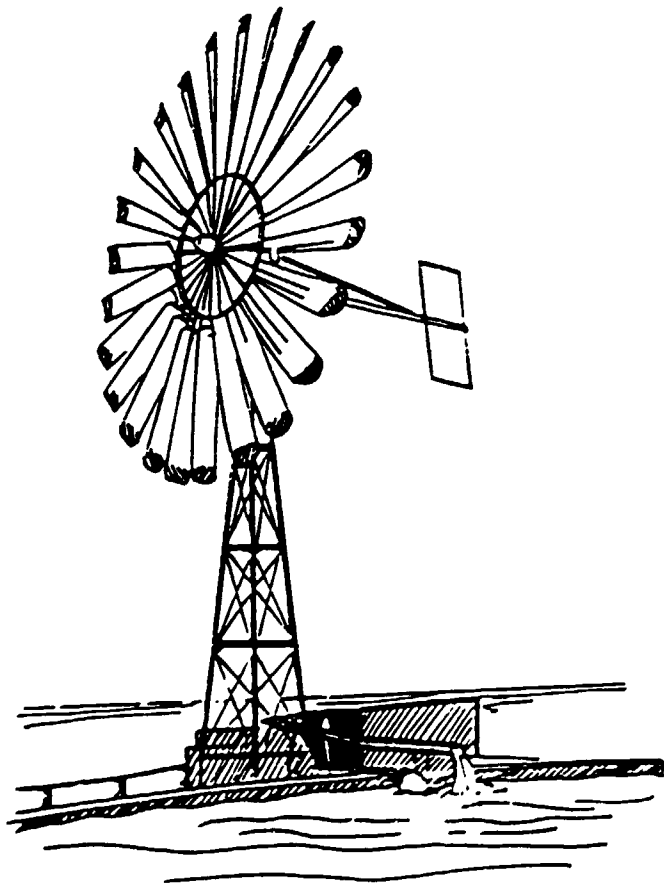


Figure 5 The IT Windpump

3.4 Windpumping Systems

History and General Overview

Windpumps remain the most common application in the world for windpower in terms of sheer numbers of windmills.

Windmills were used for pumping water many centuries ago. One of the most notable applications has been in recovering much of the polderland of Holland for farming, this reclamation commenced in the early 17th century. Today the main applications for windpumps are in arid regions where they are used to provide essential water where previously there was none, for drinking and crop irrigation.

The widespread use of windpumps for water supplies originated a century ago in the USA. At that time there was a great migration westwards across the US Great Plains and water was required for people and cattle. As a result, settlers began producing crude windmills for pumping water from the 1860s onwards. By the mid-1880s the more bizarre devices invariably failed and development converged towards the so-called "American farm windpump", the ubiquitous multi-bladed wind-pump with its slowly rotating fan (Figure 4). These were so successful that they remain in commercial production over a century later in almost unchanged form; in fact it is hard to think of any other technology that originated so long ago and has been in production for so long with so few changes.

The windpump was probably one of the most important technological factors to assist the successful development of the US livestock industry which in turn led to the huge and successful exploitation of the natural prairie lands in that country. Without windpumps large areas of the Great Plains would have been almost useless for cattle ranching. The so-called "American farm windpump" spread through the world so that by the end of the last century manufacturing took place in many other countries including Australia, the UK, France, Germany, Russia, Argentina, South Africa; in fact in almost anywhere with a significant livestock industry.

Production quantities of windpumps are difficult to establish. It has been estimated (Eldred) that over 6,000,000 windpumps were manufactured in the USA in the period between 1900 and the present day and it is likely that the rest of the world must have come close to equalling that number. Although numbers have declined since those days, so many remain in regular use that some of the surviving manufacturers maintain a significant business selling spare parts for the still active machines which have been sold over many decades. Windpumps frequently survive in regular daily use for a quarter of a century or more. Some have been in regular use for more than 50 years.

Review of types of windpumps

Windpumps sub-divide into four main categories:-

- traditional mechanical "American" farm windpumps
- modern lightweight steel windpumps
- wind-electricity generators with electric pumps
- miscellaneous minority types not fitting the above three categories

The first category represents more than 90% of all windpumps in present-day use and several million such machines are currently in use world-wide.

The so-called "American Farm Windpump" consists of a multitude of bolted together steel sections, and massive cast-iron transmission components running in plain bearings. It evolved originally over a hundred years ago and continues in regular production with few concessions to modern engineering in many countries. It seems certain that many of these traditional windpumps of a design hardly changed since the nineteenth century will remain in production well into the 21st century. It is hard to think of any other engineering products which have achieved such a long run of regular commercial success with so little in the way of modifications.

The modern lightweight windpump is fabricated from "cut and welded" steel components and uses ball-bearings and lighter machined transmission components. Grease rather than oil is used as a lubricant. It is a relatively new development from small manufacturers and research institutions, often seeking to achieve better performance than from the traditional farm windpumps, and/or to use more modern small-scale manufacturing processes. The achievement of adequate reliability has proved uncertain with many of these recent designs, although a few, especially in the smaller sizes, show promise. Once this kind of technology improves, it seems likely to gradually become more widely used in future. At present, probably less than 10% of existing windpumps in regular use come into this category.

Wind electricity generators have been occasionally marketed with electric pumps for windpumping duties. Unfortunately it has generally been found that, even though they tend to be more efficient as wind turbines than traditional windpumps, they are less efficient as wind pumping systems and less cost-effective.

The main reason for this is because most utilise electrically powered small centrifugal pumps, which are only about half as efficient as comparable piston pumps, used by mechanical wind-pumps. This and the losses associated with going from shaft power to electricity and back again (and mismatches between components) result in poorer system efficiencies than with traditional mechanical windpumps. A mechanical windpump can

achieve an overall efficiency of 15-20% whereas most of the published results relating to wind electric pumping showed system efficiencies no better than 7-12%. Also a low solidity wind electricity generator usually requires a significantly higher wind speed than a traditional high solidity rotor windpump before it produces a useful output, and wind electricity generators cost per square meter of rotor swept area are typically twice as great than for traditional mechanical windpumps.

As a consequence of the above factors the cost-effectiveness of wind electric pumping systems is significantly worse than mechanical windpumps. However, it can be said in favour of wind electric pumping that: -

- it permits the wind generator to be located at some distance from the pump (which may be an essential requirement and can allow better access to the wind which in turn can compensate for poorer efficiency)
- if large power levels are needed then there may be no other option, since the largest mechanical windpumps have a rotor diameter of 8m but much larger wind electricity generators can be procured
- wind electricity generators can power a network of pumps or a hybrid load consisting of pumps and other useful electrical applications such as lights.

There are also some unconventional windpumps. For example, one American manufacturer markets a pneumatic windpump, in which the rotor is coupled to an air compressor which in turn energises a pneumatic pump using compressed air via a plastic tube. This concept seems to have some merits (it is not efficient but it is potentially of low cost) but the product in question was not effectively optimised, so its rotor characteristic was ill-matched to the load and it needed high winds to start it. Hence although this has some of the merits of wind-electric pumping in permitting the wind turbine to be located at some distance from the pump it has not yet been effectively demonstrated although it has the potential to be cost-effective, with a better designed system.

Mention should be made of traditional "self-build" windpumps used in coastal villages in SE Asia (especially Thailand and China). These are of low cost and are used for low head paddy irrigation, or for sea salt production, commonly with dragon spine or ladder pumps. These traditional windpumps are tending to be replaced with engine pumps or electric pumps as the mains extends and in any case they are not part of the commercial manufacturing sector.

Applications for windpumps

There are three main applications for windpumps: -

- drinking water supply (for livestock or human settlements)
- small scale irrigation of crops
- pumping sea water for sea salt production.

These three main needs and the physical, technical and economic requirements to meet them, are very different. As a result a windpump developed for water supply duties is usually unsatisfactory for irrigation or sea-salt production and vice-versa.

Drinking water supply usually demands relatively high static heads (typically in excess of 10m and commonly in the 30-80m range) and the demand tends to be substantially constant throughout the year in most situations. Irrigation, on the other hand, is a seasonal requirement, often only for two to three months of the year and also it tends to use surface water or water from shallow water sources. Hence a windpump for irrigation commonly needs to earn a whole year's return on the investment in only a few months. This is difficult because the economic value of irrigation water is typically two or three orders of magnitude less than for drinking water (irrigation applications require cubic metres of water delivered to the field at a similar cost to litres of water used for drinking).

It follows from this that windmills are generally much better suited to drinking water supply duties where the value of the product is relatively high, it is needed all the year around and the unique advantage of windpumps in needing little human intervention as specially useful.

Specialised traditional designs of windmill, usually hand-built at village level from basic materials, have evolved for irrigation pumping in a few places such as Thailand and China. However such devices are invariably designed for low head, high volume pumping using traditional pumps such as ladder or dragon spine pumps and they are economic through being relatively inexpensive (in any case they demand labour rather than cash).

In recent years a number of development orientated aid projects have attempted to introduce windpumps manufactured in the industrial sector of developing countries specifically for irrigation, but with limited success, largely because they proved too expensive and also sometimes (where excessive cost reductions had been sought) too unreliable.

A further problem with wind powered irrigation is that considerable volumes of water need to be stored in surface level tanks to guarantee water when there is little or no wind (typically running to hundreds of cubic metres instead of at most a few tens of cubic metres normally required for drinking water supply systems). Consequently, adequately sized storage tank costs for irrigation become prohibitive.

At the other end of the technological spectrum, serious work was carried out in Texas to investigate and test the use of scientifically optimised large wind electricity (and other) turbines for larger scale irrigation (Gilmore). The United Nations also commissioned a study on using wind and solar energy to irrigate 10,000ha in the southern desert of Egypt (I.T. Power and Euroconsult). In both cases the indications were that large scale wind powered irrigation (requiring hundreds of kilowatts or megawatts) is nearly but not quite economic in comparison with diesel at the time of these studies. Therefore, improvements in the technology combined with any increases in real terms in diesel fuel costs seem likely to make it a serious contender for irrigation pumping in the future.

The most promising economic way of using basic farm windpumps for small-scale irrigation at present or in the near future may be to over-size a system designed for drinking water supply in an arid region and use the surplus water for supplementary irrigation, (i.e. a hybrid water supply and irrigation system). The marginal cost of over-sizing such a system is relatively small and therefore surplus water for irrigation is relatively cheap to produce (assuming the well or borehole has the capacity). This seems a most promising approach but has received little serious study so far by agencies concerned with water supplies for development.

Recent Experiences with Windpumps

A number of small manufacturers in Third World countries attempted to get into the windpump business during the late 1970s and the 80s with mixed success. Several tried copying traditional American windpump designs, and almost without exception abandoned the effort. A more successful approach was to synthesise something akin to an American Farm Windpump, but fabricated from steel stock using conventional modern cutting and welding. Several manufacturers in such countries as Thailand, the Philippines, India and Pakistan had some limited success from this approach, although limited R&D ability and design capacity often meant such designs were not well optimised and in some cases performed worse and less reliably than the traditional American windpumps.

During the mid-1970s two projects were initiated to develop novel windpump designs specifically for small scale manufacture in developing countries. These were by the CWD, previously the SWD, (a consortium of researchers from universities and a consulting engineering company based in Amersfoort in the Netherlands, but which ceased operations in June 1990) and the UK-based Intermediate Technology Development Group (ITDG) which handed the work over to IT Power Ltd in 1982. Both projects were supported financially by their respective government aid programmes and involved probably the most sophisticated windpump R&D so far.

The Netherlands project aimed to develop relatively low solidity, fast-running windpumps, with direct drive, fabricated from standard steel stock by cutting and welding (with a few machined components). It was hypothesised that a low solidity fast

running windpump would be lighter and more efficient, and hence more cost-effective. A range of such machines was developed with rotor diameters from 2.5 to 3.0m. As they were all direct drive, fast-running machines, all except the largest required special pumps capable of being driven at higher than usual speeds to accommodate this.

The CWD fast-running windpumps were limited to relatively shallow boreholes due to their speed of operation. Projects to test-manufacture variations on this theme were initiated in Sri Lanka, Pakistan, Sudan, Tunisia and Morocco but it is believed that only one example remains in limited production, in a modified form, in Tunisia.

The UK based project, was initiated by the Intermediate Technology Development Group (ITDG) and taken over by IT Power. In this case a high speed machine was initially considered for low-lift pumping duties for the same reasons given by the CWD. However experience in the field soon suggested a high solidity multi-bladed rotor, similar to the American wind pump, would not actually be significantly more expensive and the slow rotational speeds would result in a much more reliable machine capable of functioning on deep boreholes with conventional piston pumps. Also it was concluded that the main application for windpumps is water supply, where a slow running, reliable machine capable of working on deep boreholes is an essential requirement.

The IT Power windpump, like the CWD machines, was designed to be fabricated (mainly cutting and welding) from standard steel stock and used ball and roller bearings with grease lubrication, which today is a more cost-effective solution than oil-lubricated plain bearings as used on traditional windpumps. Since it is a direct drive machine, the minimum rotor diameter to avoid excessive pumps speeds is 3.75m, but the main design diameter is 6m.

The IT Windpump, Figure 5, is now in commercial production in Kenya, Pakistan, and Zimbabwe and prototypes have been tested to date also in Botswana, India, Oman, Nigeria and Egypt. A major reason for its success was a form of intensive "post production" R&D implemented by the Kenyan manufacturer, Bobs Harries Engineering Ltd., of Thika which rapidly identified the weaknesses. These were corrected as a result of a research grant provided for IT Power by the UK Overseas Development Administration.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 General conclusions

Although wind energy can be used for a wide spectrum of system sizes and applications, and a variety of research and experiment-technology, in practice it is only used on any significant scale in a limited range of applications and countries.

The main applications and locations are: -

- windpumps for drinking water supply; Argentina, Australia, South Africa, Namibia, New Zealand and the USA
- windpumps for sea salt production; China and Cape Verde
- windpumps for small-scale irrigation; China, Thailand, India, Colombia and Crete
- small wind electricity generators for battery charging; China, the UK, the USA and the Netherlands
- medium to large grid-connected wind turbines; Denmark, the USA, the Netherlands, Germany, the UK, Spain, Italy and India

The use of wind technology has several potential environmental and developmental advantages: -

- it is environmentally benign. If adopted on a large scale it will contribute to delaying the effects of global warming (the greenhouse effect)
- it is more suitable for technology transfer for small-scale local manufacture in developing countries than most energy technologies
- in areas with a favourable wind regime, wind power is generally the least cost option
- village level operation and maintenance (VLOM) is possible with the simpler technologies such as windpumpers
- it has the potential to reduce drudgery. Windpumps in particular can improve the situation for women who are expected to carry water in many rural societies
- wind systems generally have long operational lives, so they offer a long-term solution to rural energy needs.

It should also be mentioned that wind power has some potentially serious disadvantages if poor planning/implementation is employed. These have, in some cases, limited its successful usage. Some examples of common problems are as follows: -

- the selection and correct sizing and siting of wind turbines and associated systems, e.g. storage tanks or batteries, requires judgements that are not widely available (but local manufacture helps to overcome this by introducing the necessary know-how into the region)

- wind systems have relatively high capital costs in comparison with fossil-fuelled engines, although their low running costs frequently more than compensate for this. However, lack of capital can be a serious barrier to their take-up
- wind power technology (especially for smaller systems) remains relatively immature, there is significant risk of deploying inadequately developed and unreliable systems which, when they fail, give the whole idea of using wind power a bad reputation
- wind power systems require an adequate wind regime, and reliable data often remains difficult or impossible to obtain in some regions. Misjudgements with regard to the mean wind-speed can result in serious errors of judgement in procurement of systems

4.2 Conclusions and Recommendations - Windpumps

Many developing countries with large, windswept open plains and arid or semi-arid conditions could undoubtedly apply windpumps on a large scale for rural water supplies to meet both human and livestock drinking water requirements, to the general benefit of the rural populations. Any such development will in many places be a least cost solution so far as government agencies concerned with the provision of water supplies are concerned. But a detailed study is necessary in all such cases, to review the likely size and nature of the market for windpumps and to develop a workable strategy by which they may be initially introduced, demonstrated and then (if successful) the technology may be transferred into the local manufacturing sector.

It is therefore hoped that the UN system might consider developing a more closely co-ordinated and strategic approach to the promotion of windpumps for development. This should include:

- identification of countries and regions that can best benefit from the technology
- detailed studies to develop a windpump strategy in short-listed countries, involving collation and assessment of wind data, end-users and their detailed requirements, identification of actual and/or potential manufacturers, technical support agencies, etc., resulting in project formulation activities
- financial support (with some risk taking) for properly planned and justified programmes to deploy windpumps in practical water supply applications, and subsequently (where it is justifiable) to develop local manufacturing capacity

Finally, a technical development that will greatly enhance the prospects for the wider use of windpumps would be the evolution

of a cost-effective and reliable "remote pumping system" which would allow the flexibility of a wind-electric pumping system, in terms of being able to position the windmill at some distance from the water source but at much lower cost and without such a great loss of efficiency as applies with present day systems. This appears to be a feasible techno-economic goal (ref. Fraenkel - Review of Power Transmission Options).

4.3 Conclusions and Recommendations - Stand-Alone Wind Electricity Generators

The production of very small battery charging windmills (25-50W) has increased significantly during the last five years particularly in China and the UK. This trend is likely to continue but probably mainly in those two countries. Unit costs have fallen to some extent, but not dramatically.

A substantial further fall in unit costs will become possible when the scale of production reaches levels where mass-production techniques become economical.

Various wind turbines in the size range 250W up to as much as 10kW are in production for stand-alone applications but their relatively high costs, complication and the large battery storage needed tend to militate against their widespread usage.

Small wind electricity generators for battery charging compete mainly with solar photovoltaics. They offer a cost advantage wherever wind speeds are greater than 4 to 5m/s and siting is straightforward. This is mainly in deserts, coastal regions and on islands.

There are probably more limited possibilities for using small stand alone wind electricity generators in development projects than for windpumps. Similar barriers exist, such as lack of data on both the wind energy resource, on the technology and on the needs of potential end-users and size of the market.

Small stand-alone wind electricity generators no doubt could perform important specialised roles in development (eg. lighting and telecommunications for remote communities in arid regions and on islands, ice production for fisheries, fresh water production by reverse osmosis, etc). However the potential remains poorly researched and documented so a starting point would be detailed studies in regions where such specialised needs occur to establish if, how and where this technology should be introduced, and what form of the technology would be most appropriate.

In the few areas where a justification for using the technology has already been established (eg. Mongolia), assistance is needed with technology transfer, in particular with regard to the manufacturing process.

4.4 Conclusions and Recommendations - Grid Connected Systems

As discussed in more detail earlier, this technology has made rapid progress from being practically non-existent only ten years ago to providing 2 to 3% of electricity generated in 1990 in the two main areas in which it has been taken up, namely Denmark and California. The most common sizes of wind turbine for use on wind-farms has moved from 50 to 100kW in the early 1980s to 300 to 750kW in the early 90s. Costs (per kW of installed capacity) have declined to around 33% of what they were in the early 1980s and energy capture has practically doubled.

Depending largely on such non-technical factors as the quality of the wind régime, and assumptions on discount rates and amortisation periods for the capital investment, unit costs of wind generated electricity from grid-connected systems are currently as low as US \$0.08-0.20. This makes wind-farms one of the more attractive new renewable energy options for the large scale generation of electricity.

Wind-farms are not generally associated with development assistance projects. In fact the only wind-farms so far to be established on any scale in a developing country are in India. The main countries having well-established wind-farms are Denmark and the USA (State of California) and the technology is currently being introduced in the Netherlands, the UK, Germany, Sweden, Belgium, Finland, Spain, Greece and Italy.

This technology is associated with the energy sector in most countries and consequently tends to be funded from sources dedicated to financing electrical infrastructure rather than rural development. However much of the wind-farm programme in India has been funded under Danish and German bilateral assistance (and tied to products from the donor countries) and Denmark has also funded a small group of grid connected wind turbines in Cap Verde. The UN has provided some support for technical assistance to China in this area too.

Since the main thrust of development of wind-farms has been in the industrial countries few lessons of special relevance to developing countries have been learnt as yet. But perhaps one of the main lessons has been that technical reliability is probably one of the over-riding requirements for the successful implementation of wind-farms and in recent years the quality of wind turbines in this respect has improved markedly.

Since there are clear indications that wind-farms, used in the right circumstances, can generate electricity at competitive costs with conventional power generation (especially compared with the expensive diesel generation used on small grids), there is a good case for an independent (of the industry) assessment of the potential role of wind-farms for developing countries having favourable wind régimes. Such an assessment needs to identify areas and regions possessing suitable wind régimes and siting conditions, the current and projected future requirement for

mains electricity and hence the potential for using wind – farm technology to meet some of this need.

It is possible that wind – farms could perform an important specialised role in strengthening the fringes of the grid (i.e. for loss reduction purposes) where it is common for the utility to have problems in maintaining the voltage within the required limits during times of peak power. This could be particularly important in rural areas of countries like India and China where there can be sudden surges in demand for electricity in particular for such peaky demand patterns as energising irrigation pumps. Since the availability of wind commonly correlates well with crop water demand, it is likely that strategically located wind – farms could assist in meeting widespread irrigation pumping demand through the grid. Any study such as the one recommended in the previous paragraph should of course consider aspects of this kind.

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