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Wind Power Systems

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Wind energy has been used for centuries to drive ships, lift water, grind grain and, more recently, generate electricity. Such devices as the old wind-powered grist mill, the traditional Dutch windmill, the American farm windmill and the modern Darrieus turbine produce useful power from the wind.

Wind energy is inexhaustible. As long as the sun shines and heats the earth's atmosphere, the wind will blow. Wind energy is clean; it does not pollute the environment. Its availability in a general area can be predicted with reasonable accuracy and is not affected by political or social instability.

As a fuel, wind is free, although the equipment used to harness the energy is not. Some simple designs require only time, labor, ingenuity and locally available materials to build, but modern wind power systems can be quite expensive. This publication will help you determine if a wind power system is profitable for you.

Power from the Wind

Power is defined as a force multiplied by a distance and divided by a period of time, or

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

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Wind machines are designed to extract power from a moving body of air. Power in moving air, or "wind," varies with air density and speed, or velocity. Although temperature and altitude affect air density, the effect on wind machines is small. On the other hand, velocity has a large effect on power in the wind. A gentle breeze may have only enough power to rustle leaves on the trees while a hurricane-force wind can destroy buildings.

The amount of power produced by a wind machine is determined primarily by three variables — wind velocity, the size of the rotor or wind area intercepted and the efficiency of the specific wind machine. In theory, about 60 percent of the power in wind can be extracted by wind machines. However, most wind machines actually extract much less than 60 percent — seldom more than 40 percent — of the power available in wind. Power extracted is directly proportional to the wind area intercepted; that is, if the rotor area is doubled, power is doubled.

Wind velocity is the most important variable affecting production of useful power from the wind. Power in the wind varies as the cube of the wind velocity. For example, if the wind velocity increases from 8 to 16 miles per hour, the power does not simply double but increases eight times. Conversely, if the wind velocity is decreased by half, power is only one-eighth of the former amount. Small changes in wind speed have a great effect on power. Site selection for a wind machine to avoid obstructions and gain just one or two miles per hour in wind speed can be very important in the overall success of a wind-power system.

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Wind Conversion Systems

Wind machines in use today vary from the American multiblade farm water-pumping windmill to giant propeller-driven generators. They are classified as drag or lift devices depending on the type of rotor or turbine. The machines are categorized further as vertical or horizontal axis machines on the basis of the turbine's axis of rotation.

Drag devices use flat or curved blades made of wood, steel or other materials. The American farm windmill (Figure 1) has a rotor containing many blades and is the most common example of a horizontal axis, drag machine. The wind pushes the blades, forcing the rotor to turn about its axis. Drag devices produce high starting torque and are well suited for pumping water at relatively low rates. Their overall efficiency is low, typically 20 to 25 percent and rarely over 30 percent. The Savonius rotor (Figure 1) is a vertical axis drag device often made from a split oil drum. It is an example of attempts to improve performance of drag machines.

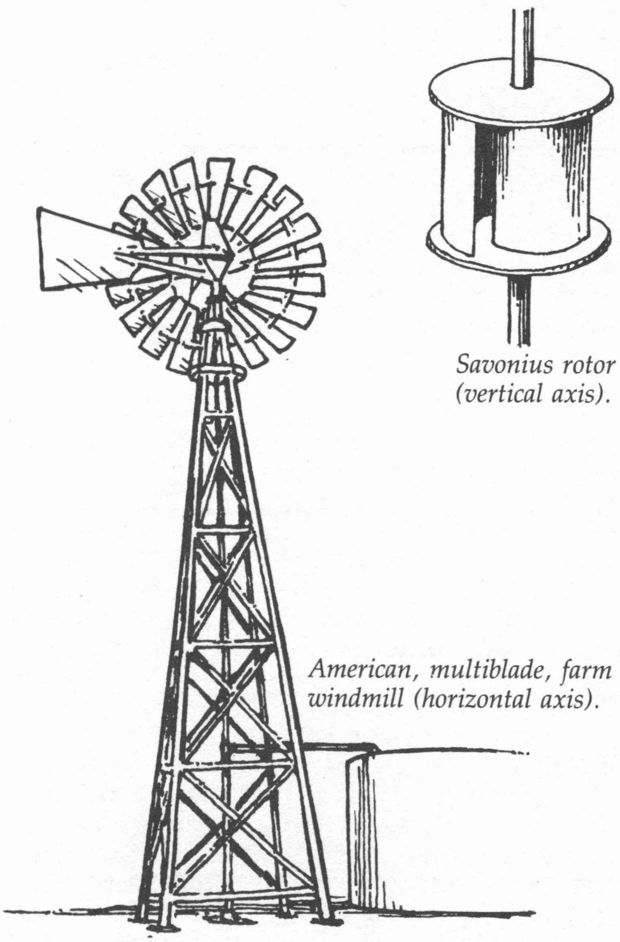

Figure 1. Drag type wind machines.

Lift devices use slender airfoil-shaped blades to capture energy from the wind. When the wind strikes the blades, lift is produced which pulls the blades about the rotational axis. Modern wind turbines usually have only two, three or four blades in contrast to the multiblade American farm windmill. However, turbines with airfoil-shaped blades may achieve efficiencies of 40 to 45 percent, almost twice that of drag machines. Their higher efficiency makes them better suited for generating electricity.

Vertical axis wind turbines have some advantages over horizontal axis turbines. They can convert wind from any direction without special features for orienting the rotor. The vertical axis of rotation also allows placement of the generator near the ground. The most common vertical axis lift device is the Darrieus wind turbine (Figure 2). Darrieus rotors are not self-starting and are somewhat more costly than equivalent horizontal axis machines. Costs of Darrieus machines are expected to decrease with improvement in manufacturing techniques.

Horizontal axis machines require some method to properly orient the rotor to the wind. Some wind turbines use a tail vane or rudder to keep the rotor perpendicular to the wind (Figure 2). Others have downwind rotors with slightly angled or "coned" blades which maintain the desired orientation perpendicular to the wind (Figure 2).

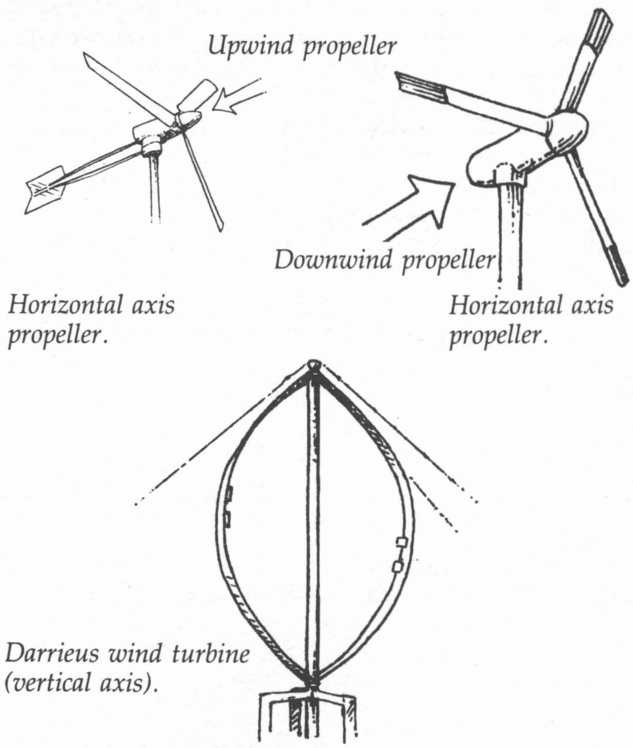

Figure 2. Lift type wind machines.

All wind machines require some provision to prevent excessive rotor speed and possible damage in high winds. Furling devices which turn the rotor out of the wind, governors which change the pitch of the rotor blades and brakes are some of the features used to prevent excessive rotor speed.

Water Pumping Systems

An American multi-blade windmill coupled with a piston pump is the most familiar wind power system for pumping water. Rotary motion of the fan is mechanically converted to reciprocating (up-down) motion to drive the piston pump. The pump cylinder is located below the water level in the well (or other water source) and is driven by a pump rod connected to the windmill. The multi-blade rotor is excellent for this application because it produces the high starting torque needed to overcome the high starting load of a piston pump. Such pumping systems have been used for many years to provide water for livestock and farm or ranch homes at remote locations.

Pumping rates depend upon windmill fan or rotor diameter, the height of lift or head and the wind speed. Approximate pumping rates are shown in Figure 3. Wind speed has an important effect on pumping rate. The pumping rates shown are for windspeeds of 15 to 20 miles per hour. Moderate winds of 10 to 12 miles per hour will run a windmill at about one-fourth to one-third capacity. Overspeed controls begin to limit output when wind speed reaches 22 to 25 miles per hour. Since the wind does not always blow, a water storage tank is essential so water will be available during calm periods.

Economics may not be a factor in a remote location. If electric power is not available and it is not practical to operate an engine-powered pump, a windmill may be the only viable choice. However, the choice between a windmill and existing electrical power for pumping water should be thoroughly analyzed. For comparison, select a windmill and an electric pump that can provide the necessary amount of water. Then compare the cost of owning and operating both pumping systems. Include depreciation, interest on the investment, repairs, the cost of power and electric transmission lines for the electric pump and the cost of water storage for the windmill system.

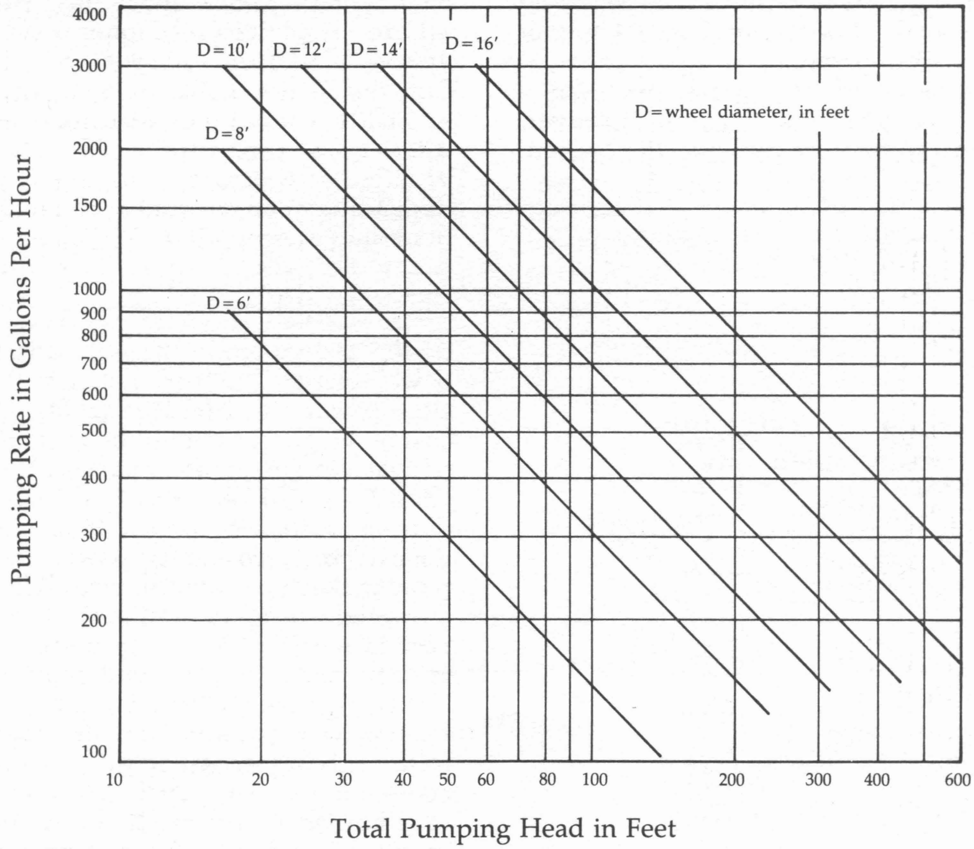

Figure 3. Approximate pumping rates for American, multiblade, farm windmills at windspeeds of 15 to 20 miles per hour (higher speeds for larger wheels).

Irrigation generally requires a higher pumping rate than a multi-blade farm windmill provides. Modern wind turbines are being tested for irrigation pumping by the USDA Agricultural Research Service and West Texas State University in cooperation with the U.S. Department of Energy and the Texas Energy and Natural Resources Advisory Council. A vertical-axis and a horizontal-axis turbine have been tested in a mechanical wind-assist mode and a horizontal-axis, electrical-output turbine has been tested in an electrical-assist mode.

One of the wind-assist irrigation pumping systems tested is illustrated in Figure 4. The system uses a Darrieus, vertical-axis wind turbine and an electric motor to power a vertical turbine pump. The electric motor is large enough to drive the pump without assistance from the wind turbine and runs continuously when irrigating. The wind turbine is coupled to the pump shaft through an overrunning clutch and a combination gear drive. The turbine furnishes power only when windspeed exceeds the cut-in speed, about 13 miles per hour. The wind turbine thus reduces the load on the electric motor but does not replace the motor. A wind-assist system of this type assures a dependable and constant flow of water and is not totally dependent on wind power.

The wind-assist concept works well for a pump driven by an electric motor. However, some problems remain in applying the concept to a pump driven by an internal combustion engine.

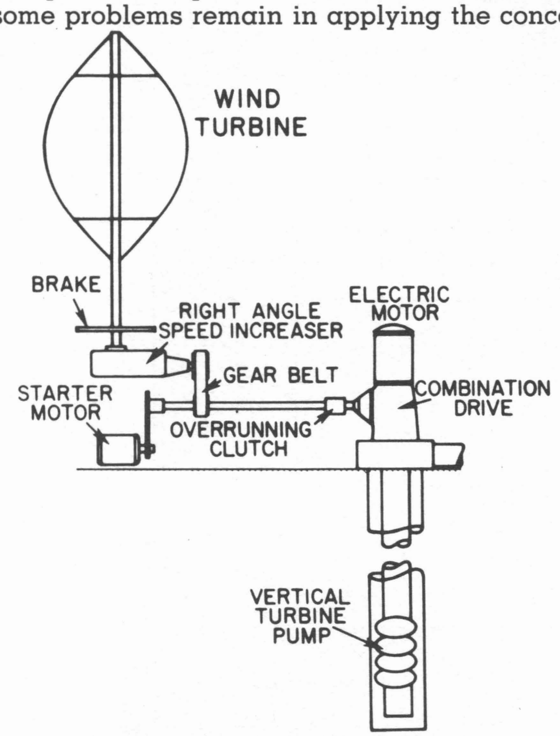

Figure 4. Schematic of wind-assist irrigation water pumping system using a Darrieus vertical axis wind turbine.

Research indicates wind power could provide 40 percent of the energy now used for irrigation in the Southern Great Plains. The economic outlook for wind power is better if it is used throughout the year either for summer and winter irrigation or for generating electricity when irrigation is not needed.

Electric Power Generation Systems

"Wind chargers" were common in many areas of the United States in the 1930s and early 1940s and were the only source of electric power for many rural residents. Then the Rural Electric Cooperative System brought low-cost central station power to all parts of the country and wind-driven electric generation systems practically disappeared. Today, energy shortages and rising utility prices have created renewed interest in the use of wind to produce electric power.

Most wind turbines built today are designed to generate electricity. They may be horizontal-axis or vertical-axis machines, but practically all are lift devices for higher wind energy conversion efficiency. Generating capacities vary from less than 1,000 watts to more than 100 kilowatts. Output may be direct current (DC) or alternating current (AC), 120 to 440 volts, with variable or constant voltage and frequency — depending upon the kind of generator (induction generator, alternator or DC generator) driven by the wind turbine and the controls or "accessories" used.

One of the major disadvantages of wind-driven generators in the past was the need for power storage. Batteries can still be used to store power, but their cost greatly increases the cost of the power generation system. Wind power systems that interconnect with utility power lines have greater flexibility than systems requiring storage batteries. When the generator does not produce enough power, the utility company makes up the difference. When the generator produces more than enough power, the excess is fed into the utility power line. Discuss specific arrangements and requirements with utility representatives before investing in a wind-driven generator on the assumption the utility will buy excess power. Remember, utility companies *will not* pay the same price for power they buy back as they charge for the electricity they sell. Presently, the buy-back rates for on-line wind generators are not well defined in Texas.

Other Wind Power Applications

Use of wind energy is not limited to the pumping of water or generation of electricity, although these are the major applications in use today. Wind is being used to heat water directly by turning a paddle blade or churn in an enclosed drum. Work of the wind is converted directly to heat. Some wind machines are being used to operate air compressors or to pump fluids other than air or water. An additional applicaiton is that of turning a large flywheel which is used to store energy and then to convert it to mechanical or electrical power.

There will be many innovative applications in the future for wind power systems. One should look for those unique situations where the need matches wind availability or site considerations provide economical storage for leveling out the energy output from a variable wind.

Power Production Characteristics

How much electricity can a wind machine generate? This is determined by the wind speed, the size of the machine rotor and the efficiency of conversion by the machine.

Manufacturers of wind machines cannot give a single efficiency number because efficiency varies with wind speed. Instead, manufacturers provide performance curves to describe the power their machine puts out at different wind speeds. These performance curves (Figure 5 and Table 1) may be used to estimate the electrical generating capability of a wind machine. The rated capacity of a wind generator is not an indication of how much electricity it produces under all wind conditions. The electricity produced varies depending on wind speed and hours of wind at that speed.

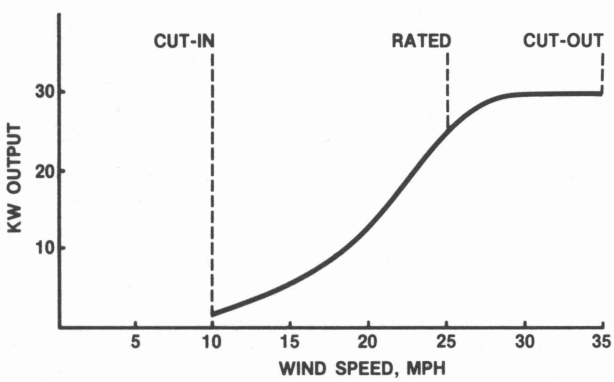

Figure 5. Sample performance curve for wind generator rated at 25 KW at wind speed of 25 MPH.

As shown in Figure 5, power output rises with increasing wind speeds. Even though wind machines start turning slowly in 3 to 4 mile per hour (mph) winds, they do not produce usable power until the wind cut-in speed is reached, usually about 8 to 10 mph. The generator continues to produce more power until it reaches rated capacity at the rated wind speed. As wind speed increases beyond rated wind speed, the power output of the generator is controlled by a governing device to limit rotor speed. If the wind reaches a speed that could damage the rotor, the cut-off speed, the machine automatically shuts down. Most wind machines operate in this manner.

Figure 6* shows the state divided into six wind speed areas. Table 1* gives wind speed distributions at a height of 60 feet, a common wind generator height. These distributions were developed from National Weather Station data and indicate the expected number of hours the wind blows each year at speeds from 0 to 47 mph.

To estimate the electricity produced each year by a wind generator, first select the desired wind distribution region from Figure 6. Next, refer to the wind speed distribution table. For every wind speed, estimate the power output according to the wind generator performance curve. Multiply the hours of occurrence at each wind speed by the KW output and add all these values to find the yearly kilowatt-hours (KWH) of electricity that may be produced. Remember that local conditions within each region may cause differences in wind characteristics from those shown.

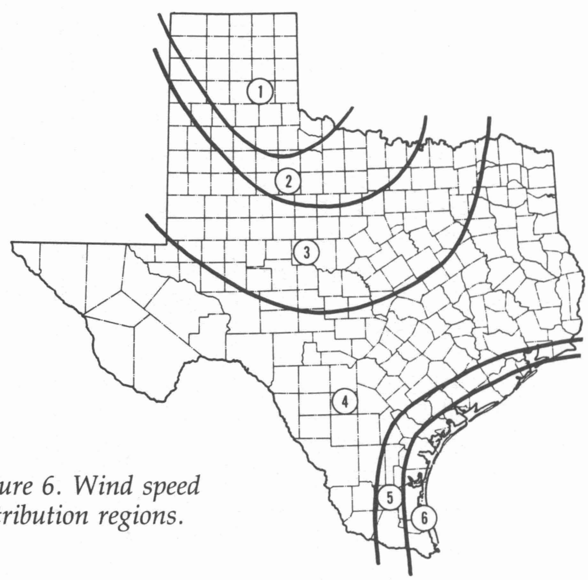

Figure 6. Wind speed distribution regions.

*Adapted from *Guide for Wind Energy in Texas*, published by the Texas Energy and Natural Resources Advisory Council, January 1981.

Table 1. Regional wind speed distribution at 60 foot height.

Wind Speed (MPH)	Annual Hours of Occurrence					
	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
0	9	19	279	281	88	113
1	16	34	51	116	19	17
2	28	88	30	90	58	43
3	57	126	129	196	196	154
4	113	210	297	295	318	252
5	187	283	453	402	435	339
6	268	351	534	480	516	402
7	356	421	576	515	548	431
8	474	481	600	535	560	453
9	560	531	612	549	560	465
10	602	568	608	556	550	472
11	613	584	587	559	535	482
12	593	580	527	555	514	482
13	546	557	467	536	486	461
14	496	503	423	494	444	432
15	445	449	387	447	404	407
16	403	395	357	385	367	386
17	367	347	312	325	331	369
18	339	308	288	274	296	357
19	317	277	225	230	262	336
20	302	249	192	191	232	297
21	292	223	159	156	205	264
22	270	200	132	125	178	243
23	231	180	108	100	151	219
24	190	159	84	79	125	189
25	150	137	69	64	98	158
26	114	115	54	51	73	124
27	86	89	45	40	55	92
28	67	64	33	31	41	69
29	53	46	30	24	30	53
30	43	38	24	18	22	41
31	35	30	21	14	16	33
32	28	27	18	10	12	26
33	24	24	15	7	10	21
34	19	19	12	5	7	16
35	16	14	9	5	5	12
36	13	10	6	4	4	9
37	10	8	3	3	2	9
38	7	5	3	3	1	8
39	5	4	2	3	2	5
40	4	3	1	2	1	3
41	3	2	1	2	1	2
42	3	1	0	2	0	2
43	2	1	0	1	0	1
44	2	0	0	0	0	1
45	1	0	0	0	0	0
46	1	0	0	0	0	0
47	0	0	0	0	0	0

Table 2. Example calculation of estimated kilowatt hours power output in Region 3 of a wind generator rated at 25 KW at wind speed of 25 MPH. See Figure 5 for wind generator performance curve.

Wind Speed (MPH)	Occurrences (HRS)	KW Output	KWH
10	608	2	1216
11	587	2	1174
12	527	3	1581
13	467	4	1868
14	423	4	1692
15	387	5	1935
16	357	7	2499
17	312	8	2496
18	288	9	2592
19	225	11	2475
20	192	13	2496
21	159	15	2385
22	132	17	2244
23	108	20	2160
24	84	22	1848
25	69	25	1725
26	54	27	1458
27	45	28	1260
28	33	29	957
29	30	30	900
30	24	30	720
31	21	30	630
32	18	30	540
33	15	30	450
34	12	30	360
35	9	0	0
Estimated Annual Energy Produced			**39,661**

Example. Estimate the electricity that may be produced by a wind generator rated at 25 KW, given:

- performance as shown in Figure 5.
- location in wind speed distribution region 3.

Table 2 shows the calculation of the estimated power output to be 39,661 kilowatt-hours per year.

Matching Energy Requirements

Wind generators are available in many sizes, ranging from less than 1,000 watts to more than 100 KW. Common sizes are generally less than 10 KW but more are becoming available in the 25 to 40 KW range. Choose a generating capacity based on an economic analysis as well as the purpose for which it is to be used. A wind generator might be selected to provide:

1. A portion of the peak and total power demand.
2. More than the total energy required.
3. Matched output to loads, utilizing storage.

In the first two situations, energy would be either purchased from or sold to an electric utility, requiring a utility interconnection. The third situation may or may not need a utility interconnection. Without a backup supply, power must be used as it is produced or stored.

When sizing electrical generators, determine your peak power requirement as well as your total daily, weekly or monthly power use. Peak power is measured in watts or kilowatts, whereas total use over a period of time is measured in kilowatt hours.

List the wattage of each motor, appliance or lighting system which operates at the same time. Determine your average power use per day, week or month by taking electric meter readings at the desired interval or by estimating daily use of each appliance. Most electric companies can provide average appliance energy-use figures, and the appliance normally shows the wattage rating on the nameplate. Monthly electric bills also show kilowatt hour usage for existing homes. The typical peak electric power requirement for an all electric home may be 15 to 25 KW, particularly if resistance heat is used. Monthly use may range from 1,000 Kwhr, or less, to more than 3,000 Kwhr.

When supplying peak load, a 25 KW wind generator or larger would be required. However, an average capacity of only 8.3 KW would be required for a monthly load of 3,000 Kwhr if the wind blows rather uniformly for 12 hours per day. Of course, some storage would be required in the latter case in the form of batteries, water pressure or other standby generating systems, depending on the particular electrical energy use.

Storage capacity depends on the number of windless days, average energy use and peak energy requirement. For an average energy use of 40 Kwhr per day, with five consecutive windless days per month, storage capacity should be at least 200 Kwhr. Using 12 volt, 200 amp hour batteries would require 84 batteries, a sizeable investment. It may be better to invest in larger equipment and sell excess energy to a utility to offset energy purchased during windless days or days when peak demand exceeds energy produced. Batteries may work well in a remote area where no utility lines exist.

Generators and Utility Interconnection

Wind energy production systems have three components: the wind turbine, the generator and power conditioning equipment. Wind availbility and turbine size determine how much energy can be generated.

There are three types of generators used with wind energy systems and the type of equipment used for utility interconnection and power conditioning varies with each. Several wind power equipment manufacturers use induction generators, which are driven above synchronous speed and produce AC power. These generators are relatively inexpensive and well-suited to automatic operation. However, they require a magnetizing current which may significantly affect utility power factor and will be of interest to the utility company. These generators do not normally backfeed de-energized power lines and thus are safe for utility repair crews. Other potential problems include loss of synchronism which may cause motor damage and light flicker during start-up.

Some manufacturers use alternators with an alternating current frequency that is determined by the number of poles and speed of rotation. When synchronized, these units may be tied to the utility grid and require no VAR support from the utility. However, they represent more of a hazard to utility work crews. Interrupting equipment must be installed to protect linemen when utility outages occur. Some alternators are designed to rectify AC current to produce DC before conditioning for tying into a utility grid.

The third type is the DC generator that has been traditionally used for battery changing. It can feed direct resistance loads such as water heaters or space heaters. This provides an advantage for wind machines operating at varying speeds. Use of solid state inverters can provide an AC current compatible with the utility grid or other use. Different types of inverters require different safety disconnects in case of utility power outage. Thus, one needs to carefully investigate the implications of the system under consideration from the standpoint of cost, effect on utility interconnection and other problems.

Due to the complexity of generator type, operating characteristics, utility system and potential use, it is wise to confer with a qualified technician or electrical engineer and with the utility company before buying wind generating equipment.

Selecting a Site

Place small wind generators as near as possible to the point of power usage to minimize transmission line installation costs. It is also important to locate wind generators to take maximum advantage of prevailing winds.

Windspeeds reach a maximum over long stretches of flat, unobstructed terrain or over rounded hilltops. Trees and buildings or other obstructions reduce windspeeds. Figure 7 shows disturbed wind flows caused by buildings and trees.

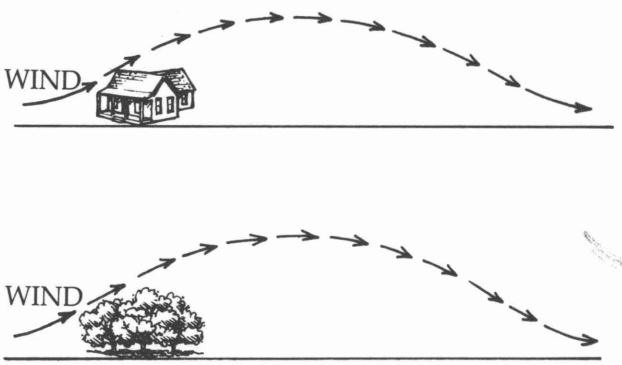

Figure 7. Disturbed wind flows around buildings and trees.

Since windspeeds are higher at higher elevations, taller towers provide increased wind power. Install tall towers if the wind generator must be located near buildings or trees. However, at some point, the increased cost of a taller tower offsets the power generated from the higher windspeeds at greater elevation. Towers 60 feet high are common for wind generators.

A general rule of thumb is a tower tall enough to clear the highest obstruction by 25 feet and located at least 300 feet from the nearest trees and buildings.

Wind Power Formula

Theoretical power, P, in the wind = $\frac{1}{2} \rho A V^3$, where ρ is air density, A is intercepted wind area or rotor area in square feet and V is wind velocity in miles per hour. If air density is considered a constant equal to .0024 slugs per cubic foot, the power formula can be simplified to P = $.0012AV^3$. When appropriate constants are used to convert power to common units, the theoretical power formula becomes:

Horsepower = $.00000688AV^3$, or
Watts = $.0051AV^3$,
where A = intercepted wind area or rotor area in square feet
and V = wind velocity in miles per hour.

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5M—6-82