# CHAPTER 6
# Electric Generation Technologies

The Public Utility Regulatory Policies Act (PURPA) has created a new market for electricity produced by independent, small-scale generating systems. Homeowners, landowners and businesses wanting to generate power on-site no longer have to store the surplus in expensive and inefficient battery systems. These small-scale systems can be connected to the grid to sell electricity profitably and buy back-up power economically. Engineers, inventors and others have designed a variety of small power plants to meet the newly created demand.

The first generation of modern, dispersed power plants made its debut in the latter part of the seventies. By 1982 a second generation appeared, with significant refinements. New designs and materials have been coupled with sophisticated electric technology to increase the efficiency and reliability of the newer systems.

Production facilities have outgrown backyard garages and moved into suburban and rural factories. Higher production runs have lowered equipment costs. Spin-off companies have begun to provide related services, such as site evaluation, servicing and financing. The industry has definitely grown out of its infancy, a little wobbly at first, but then with increasing confidence. Now it walks firmly on two legs.

This chapter surveys the four electric generation technologies that are available for the home and for small commercial enterprises: wind power, hydropower, photovoltaics and fossil-fueled cogeneration plants. The purpose here is not to provide a how-to lesson for building and installing on-site power plants but to discuss the ways small power-producing technologies work and how to estimate the power output one will get from various systems. Detailed books on each of these technologies are available to provide how-to information. Here the objective is more modest: to inform the prospective buyer on how these systems work, how to assess their appropriateness for a particular site and how to choose the proper equipment.

Each of these four technologies has its own unique characteristics and its own jargon. Wind developers speak of power density and

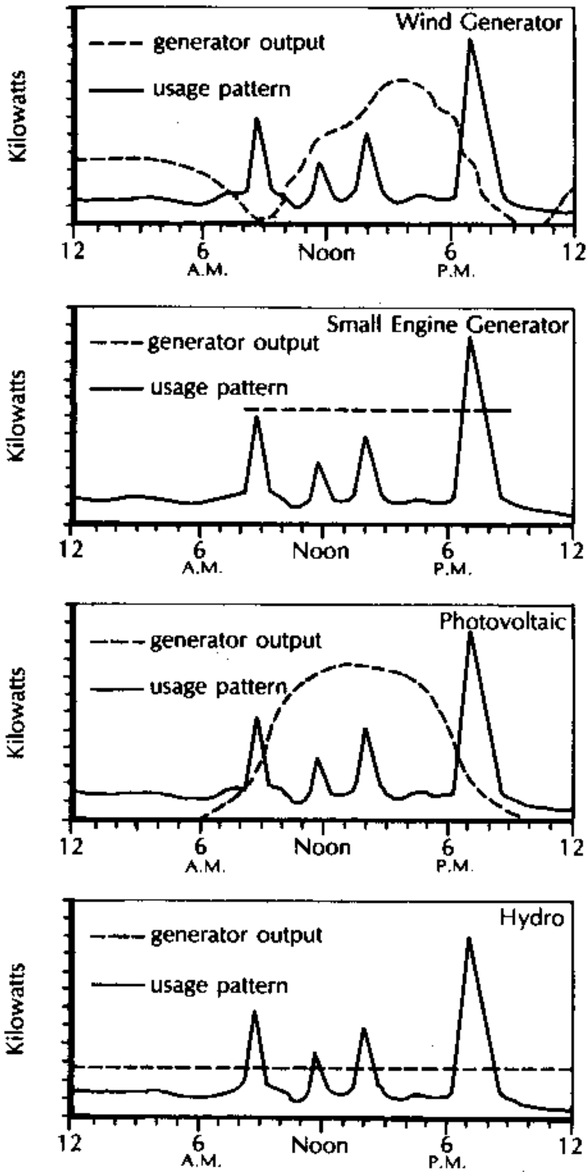



**Figure 6–1:** Notice the sharp spikes for individual residential loads, compared to the diversified load curves seen in previous chapters (see figure 2–2). The loads are the same, but the timing of the electrical output by different systems varies dramatically. Hydro and small engine generation provide the best match. *Redrawn from Terrance D. Paul,* How to Design an Independent Power System, *copyright © 1981, with permission of Best Energy Systems for Tomorrow, Necedah, Wis.*

Rayleigh distributions. Hydro developers talk about feet of head and flow duration curves. Photovoltaics suppliers discuss peak watts and junction barriers. Cogeneration manufacturers discuss heat exchangers, Carnot cycles and Otto cycles.

Each operates on different principles. Wind and hydro machines convert the force of moving air and water molecules into mechanical energy in a turbine and then use the turbine to generate electricity in a generator. Cogenerators use the internal combustion engine to rotate a turbine that turns a generator to produce electricity. Photovoltaic devices have no turbines at all. They capture the energy of tiny bits of sunlight, called *photons*, to create a flow of electrons, an electrical current.

Cogeneration systems generate useful heat as well as electricity (or mechanical power), using the same primary fuel. The concept of cogeneration can be applied to photovoltaics. Silicon-based photovoltaics convert at most about 20 percent of the sunlight striking the cell into electricity. The other 80 percent becomes waste heat, which could be captured if the means to do so become less expensive than the value of the thermal energy captured. In fact, silicon-based photovoltaics are more efficient if they are cooler. Thus, by removing heat by moving air or water over the cells, the electrical output increases as the thermal energy is harnessed.

All four technologies strive to achieve the same objective: to convert the largest portion of potential energy into useful work for the least cost, or to have the highest efficiency and the lowest price per unit of energy produced.

All of the technologies except photovoltaics exhibit economies of scale, meaning the larger the power plant, the cheaper the cost per kilowatt of power produced. Economies of scale are not unlimited. Beyond a certain scale, the increased structural stress on the materials in the wind turbine may outweigh the advantages of large blade diameters. The reliability of several smaller cogeneration systems is greater than that of one large system and can spell the difference between a cost-effective and an unprofitable arrangement.

The most cost-effective system is one sized to fit the available fuel supply and demand. A wind turbine built to function effectively in high-velocity winds will often generate electricity inefficiently in low-velocity winds. A hydroelectric plant sized to the maximum seasonal flow rate will operate very inefficiently during the majority of the year when flow rates are lower. A cogeneration facility sized to satisfy a winter heating load will generate too much heat in the summer months.

Many designers of cogeneration systems avoid the problem of excess waste heat by sizing the facility to meet the annual base load for thermal energy, often the domestic hot water load. If the PURPA buyback rates are high, the cogeneration system will be sized much larger, in order to maximize its electrical output. A great deal of work is now going on in the industry to allow the facility to use the excess heat resulting from this larger-size facility. Some companies are linking absorption air conditioners to their cogeneration systems. The high-temperature waste heat drives the air conditioner in the summer months.

The best advice to anyone entering the field of small power production is also the most obvious: piggyback on the experience of others. Learn from the first- and second-generation entrepreneurs. By late 1982 more than 500 PURPA contracts had been signed with small-scale cogenerators and small power producers. Each contractor often owned more than one power plant, and more than a thousand turbines and generators of all sizes were in operation. Chances are that within 100 miles of where you are there are at least two pioneers selling electricity to the utility. Some are wary of visitors. The mass media publicized their ventures prematurely, and swarms of curious onlookers trespassed on their property or otherwise invaded their privacy. Most will respond warmly and openly to someone who demonstrates a working knowledge of small power plants. Don't expect a small power producer to give you a history of PURPA. Do your basic homework before you visit. Familiarize yourself as fully as you can with the technology you plan to employ.

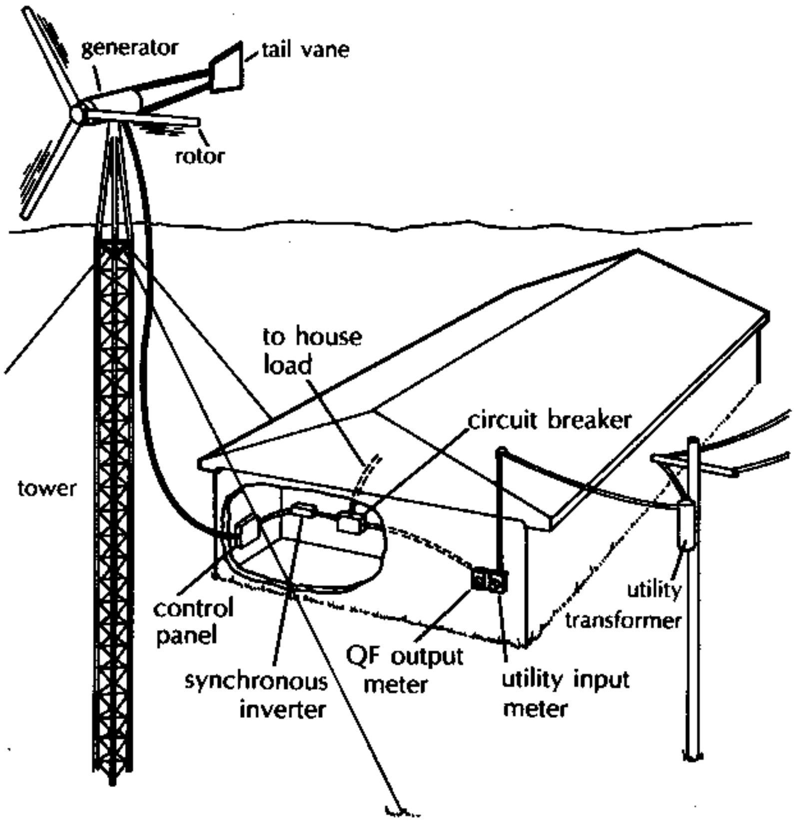
Your time with the owner will be best spent finding out about actual experiences with the technology and with the utility. The lessons he's learned can save you time, trouble and money.

# Wind Power

## The Equipment

A hundred years ago millions of windmills dotted the landscapes of many countries, providing mechanical power for threshing grain or pumping water. These mechanical functions are still economically performed by windmills. This book, however, focuses on twentieth-century wind systems that generate electricity. Wind-electric machines are built somewhat differently from their water-pumping ancestors.

The blades or *rotor* of a wind machine convert the wind's energy into mechanical or rotary power. Modern wind machines are designed to gain an aerodynamic lift from the wind in much the same way that airplanes do. The individual rotor blades of most modern wind genera-




**Utility-Connected System**

**Figure 6–2:** Notice the two meters in this grid-connected wind electric system. One monitors consumption from the utility transformer and the other output to the utility grid.

tors have an airfoil cross section. When the wind hits the blades, the resulting aerodynamic lift causes the blades to move faster than the wind itself. Advances in wind machine blade design have helped to optimize the efficiency with which these systems extract energy from the wind. The relationship of the rotor's speed (measured at the blade tips) to the wind speed is the *tip-speed ratio*. If the blades are moving five times faster than the wind, the tip-speed ratio is 5:1. Windmills with low ratios of about 1:1 are mainly suited for slow-speed, mechanical purposes such as water pumping. High-tip-speed propellers in the

**Inside a Windcharger**

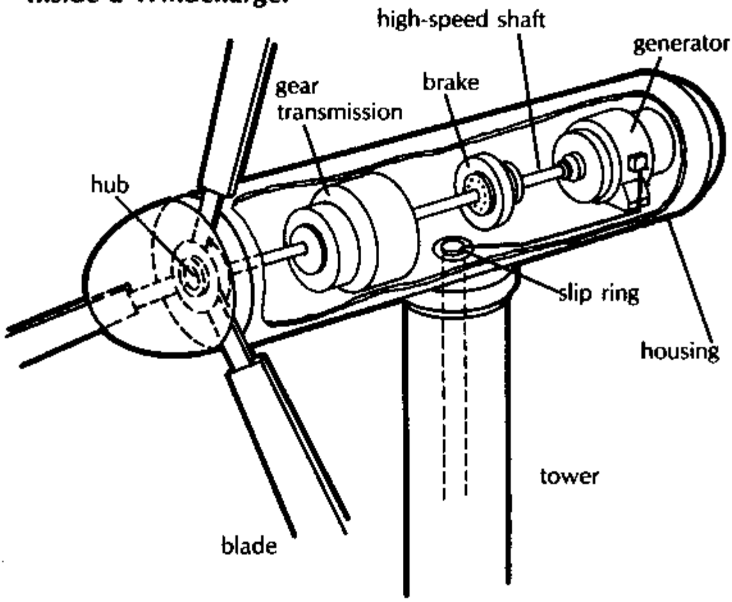



**Figure 6–3:** The wind drives the blades that rotate the shaft inside a windcharger.

range of four to eight times faster than the wind are suitable for generating electricity.

Wind machines are classified according to the orientation of their axis of rotation. They are either *horizontal-axis* or *vertical-axis* machines. At present horizontal-axis machines greatly outnumber vertical-axis designs. The chief advantage of the vertical-axis wind machine is that it is easily able to accept wind from any direction.

Horizontal-axis machines can be further sub-divided into upwind or downwind machines. *Upwind rotors* are steered into the wind by a tail vane. Advocates of the upwind design point out that it avoids the "wind shadow" caused by the tower and therefore operates in a more even wind flow.

*Downwind machines* don't need a tail vane. Some designers, such as Hans Meyer, founder of Windworks in Mukwonago, Wisconsin, believe this is a more economical design for larger machines. He points out that, as the rotor diameter increases, "a tail structure that puts the tail sufficiently clear of the slipstream (the flow of wind) becomes a big and expensive structure."[1]

Besides the rotor or blades, the typical wind machine has a *governor* or controller. Different manufacturers use different methods of

**Photo 6–1:** The Darrieus rotor pictured here is a vertical-axis wind machine that can be driven by wind from any direction. The transmission and generator are located at the base of the vertical mast. *Photograph courtesy of Joe Carter.*

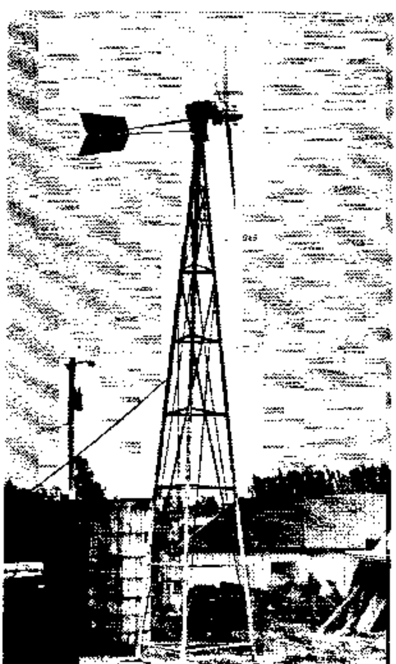


**Photo 6–2:** An upwind horizontal-axis machine uses a tail vane to orient the rotor to face into the wind. *Photograph courtesy of Joe Carter.*

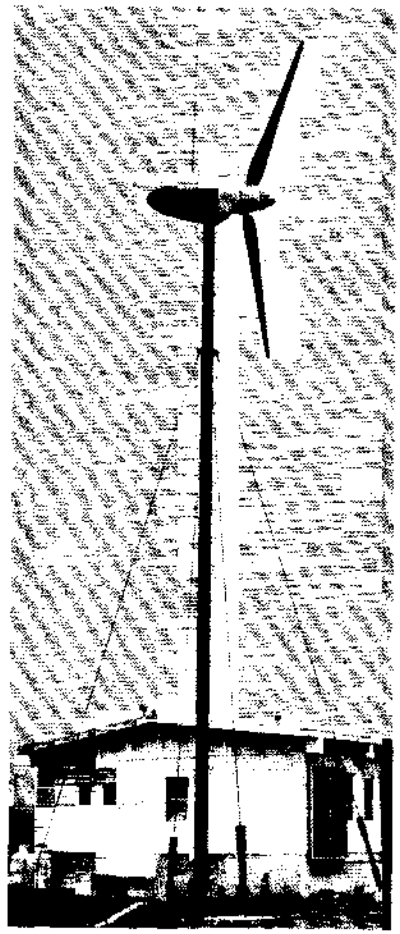


**Photo 6–3:** A downwind horizontal-axis machine operates without a tail vane. The rotor itself is oriented downwind of the tower mast just by the force of the wind. In this photograph the wind is coming from the left. *Photograph courtesy of Joe Carter.*

blade-pitch control and overspeed protection. Turbines with small rotors often use no pitch control or rely on flexing blades to conform to variations in wind speeds. Larger machines, however, require some form of governing to adjust the blade pitch for both efficiency and speed control. Often there is a trade-off between simplicity and increased efficiency in larger machines. As Karl Bergey of Bergey Windpower points out, "High aerodynamic efficiencies are obtained with . . . variable-pitch rotor systems at the cost of mechanical complexity and decreased reliability."[2]

Field data from wind machines supports the view that the most economical machine is the one that can survive infrequent but very high wind gusts. A 100-miles-per-hour (MPH) gust can accelerate the rotor tip from a moderate speed of 175 MPH in a 25-MPH wind to 300 MPH to 500 MPH. When this happens, the machine is almost certain to be damaged unless it has some form of overspeed control. The simplest method is to put a brake on the rotor and run a cable to the ground. In high winds the owner can use the cable to brake the rotor. However, since wind speeds can increase very rapidly, the operator needs to be nearby for this manual system to work well.

Most of the upwind generators have some form of pivoting tail to swing the rotor out of the direct wind at about 30 MPH. This is called yaw orientation. One method allows the rotor and generator assembly to tilt up, out of the wind. Another method positions the rotor so it keeps turning, but at a reduced power output. Some maintain a reduced power output by using a blade pitch control that turns the blade to a pitch angle of 60 degrees. This feature is commonly used in horizontal-axis designs, in upwind and downwind configurations.

Gears, like the transmission in a car, are used to increase the turbine's speed of revolution where it connects with the generator. (Gears also reduce the overall efficiency of the system because of energy losses due to friction.) Most systems have a transmission to get the shaft speed up to the 1,800 revolutions per minute (RPM) of a typical generator. Some wind machines have no gears. These direct-drive designs use special, low-speed alternators that are coupled directly to the rotor shaft.

About half the wind machines sold today can be had with induction generators, the advantages of which were discussed in chapter 4. The primary advantage is that since the magnetizing (or excitation) power for an induction generator comes from the utility line, the generator output automatically matches the frequency and waveform of the utility. This obviates the need for expensive synchronizing equipment. If the line power fails, the generator goes dead, thereby reducing the need for protective relays.

Another advantage of induction generators is their price. A 25-kilowatt (kw) induction generator costs around $450, whereas a 25-kw synchronous generator, sometimes called an alternator, costs $2,000.

Paul Gipe, a technical adviser to wind developers in Pennsylvania and an author of several how-to manuals, offers another advantage of induction generators. Because the generator is tied to the utility power, it maintains a constant rotor rotation at all wind speeds up to the capacity of the generator, at which point the generator fails and the rotor is unloaded. Thus blade-pitch controls aren't needed to obtain a constant rotor RPM, as they are for synchronous generators. Pitch control is needed to prevent overspeed but Gipe says induction control "can be more easily incorporated into a rotor than can an infinitely variable pitch-changing mechanism."[3]

Not all wind machine manufacturers agree, however, that constant rotation is an advantage. Since induction generators are locked into a fixed rotational speed by the power line, they "are usually running too fast or too slowly and do not fully harness the wind energy available," says Marcellus Jacobs, president of Jacobs Wind Electric Company. Jacobs' own alternating current (AC) machine delivers 240 volts (v) through an inverter system, which allows the blade speed to vary with wind speed.[4]

Another disadvantage of the induction generator is that it can act like a motor if the wind speed is too low to spin the turbine fast enough. If this occurs, it will consume rather than produce electricity. The induction generator is essentially identical to an induction motor. The rotational speed of the shaft defines whether it converts electrical energy into mechanical energy or mechanical energy into electrical energy. If rotation of the shaft increases from 1,740 RPM to 1,800 RPM, the motor generates 60 hertz (Hz) electricity. To prevent the generator from acting like a motor, some manufacturers have installed a control box relay that directly couples the generator to utility power only when the wind speed is 10 MPH or greater. This system guarantees that there will be enough wind to drive the induction machine fast enough to produce, not consume, power.

A final disadvantage of the induction generator is its relatively low power factor. Remember, the power factor is an indication of the amount of reactive power consumed by the generator. Reactive power is parasitic. It does no useful work as it circulates through utility lines, but it costs the utility money to supply it. Reactive power exists when the voltage and current waveforms are out of phase, when the peak voltage occurs ahead of the peak current (lagging power factor) or behind it (leading power factor). This out-of-phase condition, or more specifically, the lagging power factor, is an inevitable aspect of induction generations that adds to the utilities' transmission costs.

Some utilities impose penalty charges for poor power factors. Southern California Edison, for example, imposes a 20¢ per kilovar penalty charge when the power factor is below 80 percent. Properly sized capacitor banks can be used to shift the current and voltage into phase with each other to ensure that the minimum acceptable power factor is maintained. However, installing such capacitor banks raises another problem. When the circuit is de-energized, the electricity in the capacitors could be transmitted to the induction generator, thus allowing it to continue to function, eliminating the inherent safety features of a generator that depends on utility electricity for its operation.

It was mentioned before that to prevent damage to the rotor and tower, every wind machine has some form of overspeed protection. This is also used to protect the generators which cannot produce more power than their rated capacity without being damaged. The speed at which the generator produces its rated power is called the *rated wind*

**Simple AC Generator**

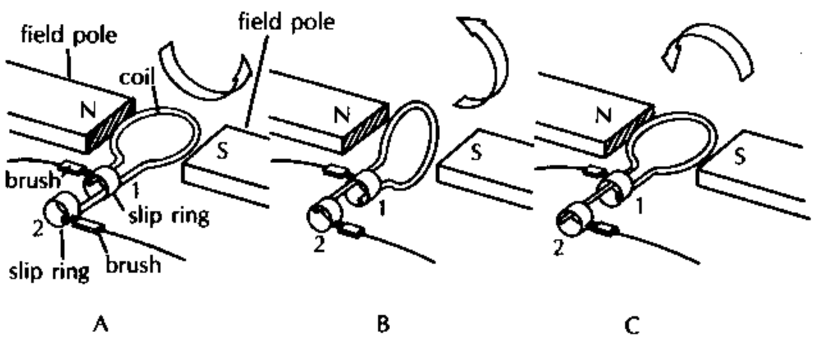



**Figure 6–4:** In an AC generator, as in a DC generator, the current is always flowing in the same direction in the coil when the coil is perpendicular to the field pole. In an AC generator, unlike the DC generator, copper rings called slip rings are used. Carbon brushes make continuous contact with the same respective slip ring, but as the rings rotate, the current reverses. In this illustration current first flows from slip ring 2 to slip ring 1 and then flows from slip ring 1 to slip ring 2. The result is that the current changes direction with each cycle, or in this example, a 180-degree rotation of the coil. Hence we have the term *alternating current*. *Adapted from* Wind Power for the Homeowner *© 1981 by Donald Marier. Permission granted by Rodale Press, Inc., Emmaus, PA 18049.*

## Questions to Ask a Manufacturer

1. How long have you been in business?
2. How well have your products performed?
3. Does your system have a reliable safety system?
4. Is data available from machines at sites similar to mine?
5. Are there owners of this specific machine to whom a prospective customer can talk?
6. What are the skills needed to maintain a particular machine?
7. What type of warranty does the manufacturer provide? What are the warranty limits? Can the owner fix any part of the machine without affecting the warranty?

## Questions to Ask a Dealer

1. How many machines have you installed?
2. Can prospective buyers talk to previous customers?
3. How much experience and training in servicing the machines do you have?
4. What constitutes an adequate site analysis and how long will it take (e.g., hours, days, weeks or months) to have a wind system installed, serviced or repaired if new parts are needed?
5. How long is the test period before the owner takes title?
6. What is the role of the dealer in honoring warranties and guarantees?

SOURCE: Reprinted and adapted from *The Kansas Wind Energy Handbook,* Kansas Energy Office, 1981.

*speed*. For winds that exceed the rated speed, commercial systems are usually designed so the rotor spills some of the wind (overspeed protection: brakes, blade-pitch control, tail vane control); output power thus remains at roughly the rated capacity, preventing damage to the generator. For winds above the cut-out (shut down) speed, the machine must be completely shut down to prevent mechanical or electrical damage.

## Finding the Wind Power at Your Site

The availability of wind power, like any of the solar-renewable energies, is highly site specific. Solar energy can be measured and averaged for a relatively large region. The power available in falling water can be pretty well pinpointed with stable stream conditions (the main variable being the amount of snow and rainfall upstream). Wind power can also be measured and averaged, but it is much more capricious. A 10-MPH average for a given region doesn't necessarily mean a 10-MPH average for a site in that region. It could be more or less, depending on such local factors as the shape of the land in and around the site and larger "macro" factors such as weather patterns for a given season or year. You can't simply assume that a site has adequate wind power just because it "seems" that way. You have to study and measure to find just how much wind power is available.

In this regard it's important to know how power varies with wind speed and what kind of efficiencies are possible in converting available power to electric power. The primary rule of thumb is that the power available in the wind varies with the cube of the wind speed. This is a rather dynamic relationship because, for example, with just a 10 percent increase in average wind speed (say from 10 MPH to 11 MPH) there is a 33 percent increase in available wind power. "Available" means that a given wind power system has that much more "fuel" to convert to electricity. On average, wind systems convert between 16 and 30 percent of the available wind power into usable power. All these factors point to the critical importance of making a *site analysis*.

You can start by collecting existing wind speed data from local weather stations and airports. The U.S. Department of Energy has commissioned detailed studies of wind "regimes" throughout the country. This kind of information is only a beginning that can tell you if your site is in the ballpark of wind power feasibility. The next step is to use anemometers to measure, record and average the wind speed at your site. There are a number of types available for rental or purchase, each with varying degrees of sophistication in what they do with raw wind speed data. The most sophisticated can tell you all you need to know, while others will require you to "boil down" a lot of data manually to get meaningful results.

Average wind speed is but one of several important factors in making assessment of the abundance of your wind resource. You have to get "inside" that average to know how often winds are faster than the average. For example, because of the cube law, with 5 hours of 20-MPH wind and 5 hours of 10-MPH wind (averaging up to 15 MPH),

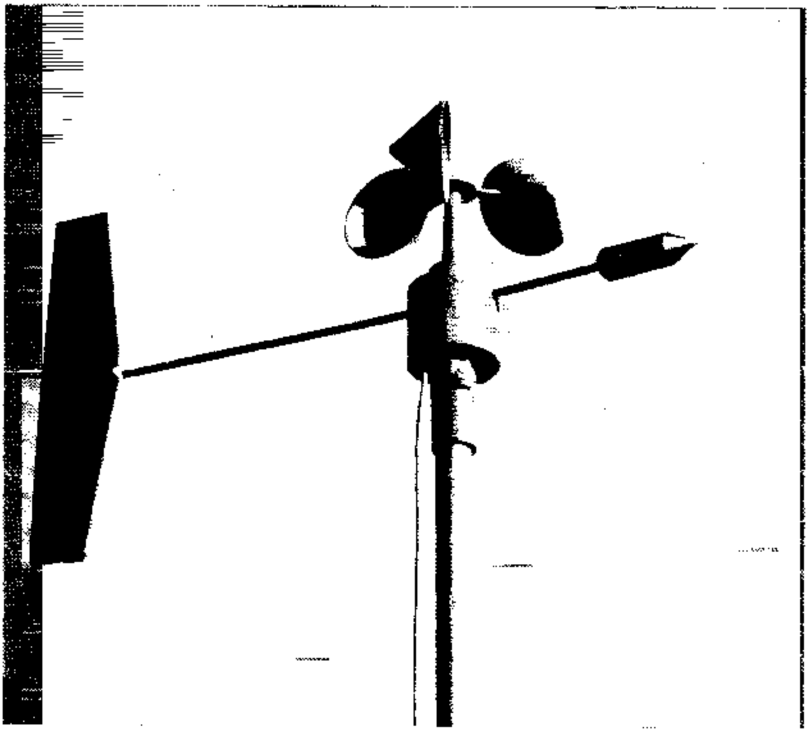


**Photo 6–4:** A simple but important wind-prospecting tool is the anemometer. Connected with a recording device, it can help you collect data about wind speed and direction when making a wind site assessment. *Photograph courtesy of John Hamel.*

there is almost three times more available wind power than there is with 10 hours of 15-MPH wind. Along with daily variations, there are also seasonal variations in average wind speed. There are variations due to the terrain of the site and the height of the anemometer relative to the planned height of the wind machine. If you're looking hard at wind power as a PURPA-type investment, you'll ultimately want your data to tell you just how many kilowatt-hours of electric power different wind machines will produce at your site. Fortunately there is data collection technology and published methodologies, and there are professional concerns that can assist you. The list of publications in Appendix 6 is a good place to start. If you have an idea of the average speed at your site, refer to figure 6–5 for an idea of just what wind machines with different rated outputs can deliver.

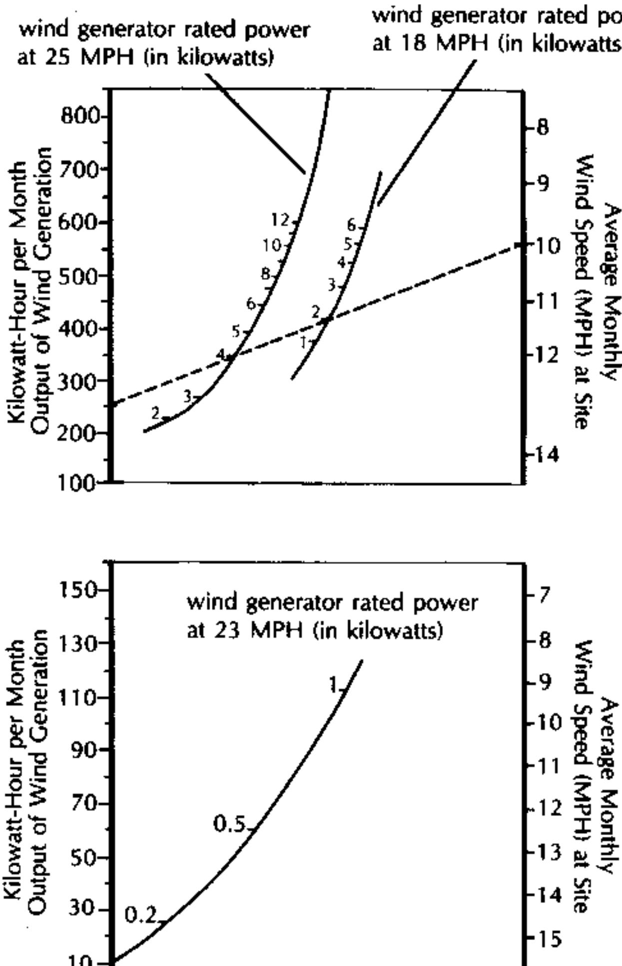



**Figure 6–5:** These nomographs provide estimates of the monthly kilowatt-hour production of wind machines with different power and wind speed ratings operating in different wind regimes. There are three rated wind speeds: 25 MPH, 18 MPH and 23 MPH. Power ratings are 2 kw to 12 kw at 25 MPH, 1 kw to 6 kw at 18 MPH and 0.2 kw to 1 kw at 23 MPH. The dotted line in the upper nomograph shows how to derive an estimate. The machine in question is rated to produce 4 kw in a 25-MPH wind, or 2 kw in an 18-MPH wind. When operated at a site with a 10-MPH average wind speed, the monthly power production is about 250 kwh. Average wind speeds change from season to season, so if you happen to know your site's wind speed average on a month-by-month basis, you can make a more precise estimate of annual power production.

## Keeping the Wind Turbine High

Tower height is a very important factor in the ultimate output of a system. Wind speed increases at higher altitudes, in part because the air moves faster and in part because the wind machine is removed from turbulent air near the ground (where wind is slowed by surface friction). The rough rule of thumb is that wind speed varies by the one-seventh power of the height above the earth's surface. Double the height, and the wind speed increases by the one-seventh power. The cube rule translates this into a profound difference in output. For example, at 10 MPH, a Dunlite 2,000-watt (w) wind system will produce only 280 w; at 15 MPH the same wind system will produce almost 1,000 w, almost four times as much. This leads us to another basic law of wind machines: *The least expensive way to get more power from the wind is to build a high tower*. You can choose the most economical tower height by comparing the cost of the last 10-foot increment of tower with the percentage increase of power you might get from the wind machine. Since the tower is often the least expensive component of a wind system, the height might not be restricted by economic considerations but by zoning provisions or structural requirements.

Commercial towers are built of welded triangular design of high-strength steel tubing and are hot-dipped galvanized after fabrication. In some designs each section is 10 feet long, and all sections simply plug into each another. Two types of towers are available: the self-supporting tower and the guyed tower. Self-supporting towers are about 80 percent more expensive (for example, costing around $2,700 for a 60-foot self-supporting tower, compared to $1,600 for a 60-foot guyed tower). They do, however, take up less ground space. Guyed towers have cables that extend outward, requiring a horizontal distance from ground anchor to base of almost 80 percent of the tower's height. Hence the space required for a guyed tower is much greater.

Another reason for putting a wind plant high is to keep it away from disturbed air. The machine should be a minimum of 50 to 60 feet aboveground and in all cases, the propeller tips must be 25 to 30 feet above all obstacles within a 300-foot radius.

The relationship of the height of the tower to the wind speed will also vary by the nature of the terrain surrounding it. Wind moving over the surface of the earth encounters friction caused by the turbulent flow over and around mountains, hills, trees, buildings and other obstructions in its path. These frictional effects decrease with increasing altitude above the surface. Frictional effects differ from one surface to another depending upon the roughness of the surface. Likewise, the

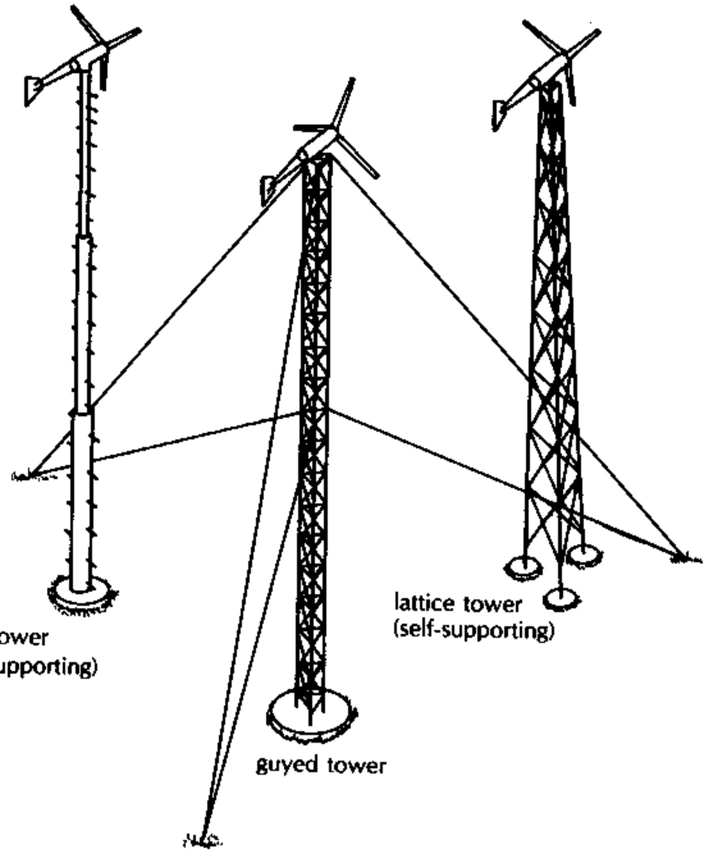



**Figure 6–6:** Towers for wind systems are either self-supporting or secured by guy wires. Notice the land area needed for the wires holding the guyed tower.

rate at which wind speed increases with height varies with the degree of surface roughness. Wind speeds on higher towers increase at the greatest rate over rough terrain, such as that in the Appalachian Mountains and at the least rate over smooth terrain like that of the Great Plains. Because of this, it is more important to use a tall tower when siting in hilly terrain than, say, in the flat Texas Panhandle.

## Comparing Machines

Wind machines are given a *rated output* by the manufacturer, which means simply the output of a particular model at a wind speed

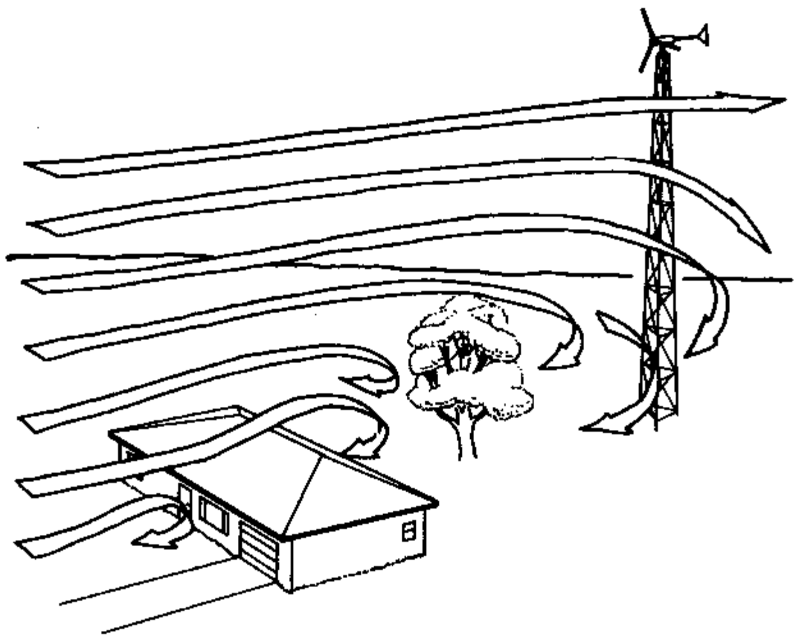


**Figure 6–7:** The higher the tower, the fewer the obstructions to wind speeds. The distortion of wind currents occurs far above the height of the tree.

arbitrarily selected by the manufacturer. As you will see when you examine various models and their specifications, different models are rated at different speeds. How does one compare a wind machine that produces 1 k in 12-MPH winds with another that produces 2.5 k in 28-MPH winds?

Electrical engineer Gil Masters, one of the authors of *More Other Homes and Garbage*, provides a simple method by using the machine's capacity factor.[5] Remember that the capacity factor is the ratio of the energy delivered over a given period of time to the energy that would have been delivered if the generator were supplying rated power over the same time interval. Assume that a 10-kw machine delivers 1,200 kilowatt-hours (kwh) per month. If that machine were operating at full 10-kw-rated capacity for the 720 hours in a month, it would produce 7,200 kwh. Thus it has a capacity factor of 1,200 ÷ 7,200 or 16 percent. Figure 6–8, based on statistical work done by C. G. Justus in 1978, provides for correlations between wind speed, rated wind speeds and capacity factors. The capacity factor here is plotted against

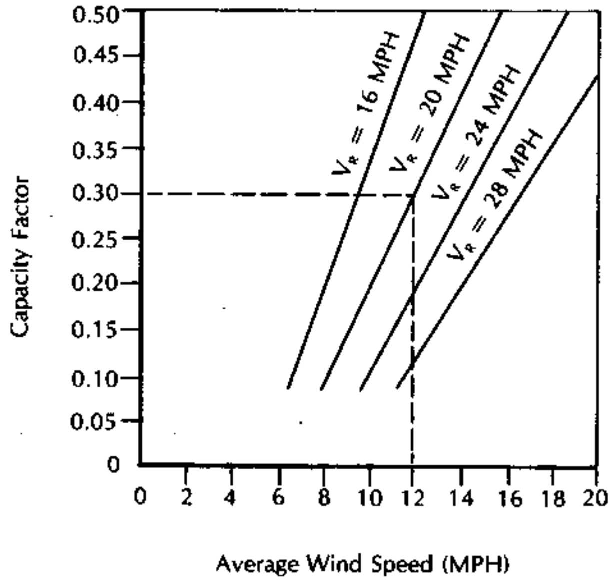



**Figure 6–8:** Capacity factor is a function of average wind speed for different rated wind speeds ($V_r$). This graph is based on a regression analysis done by C. G. Justus. It assumes a cut-in wind speed of 0.4 $V_r$ for all four of the rated wind speeds shown. The capacity factor is the fraction of the hours of the year the machine is operating at the equivalent of full output. To use this graph, you must know the rated wind speed of the wind machine you're considering and the average wind speed at your site. The dotted line shows the capacity factor that results from operating a machine with a $V_r$ of 20 MPH at a site with 12 MPH average wind. Refer to the text to find out how to use capacity factor with a machine's rated power to derive an estimate of kilowatt-hour production. *From* More Other Homes and Garbage, *by Jim Leckie, Gil Masters, Harry Whitehouse, and Lily Young. Copyright © 1981 by Sierra Club Books. Reprinted by permission of Sierra Club Books.*

average wind speed with rated wind speed as a parameter. While the correlation assumes a cut-in speed of 0.4 $V_r$ ($V_r$ is *rated velocity*; for example, an 8-MPH cut-in for a machine with a rated velocity of 20 MPH), if a given machine has a different cut-in speed, it won't change the results significantly.

The example in figure 6–8 shows that a machine with a $V_r$ of 20 MPH operated in a 12-MPH wind regime will have a capacity factor of 0.30. How does that translate into power production? Let's say the wind machine in question is a 4-kw unit. You can estimate monthly kilowatt-hour production by multiplying the capacity factor times the power rating times the number of hours in a month (720). Thus the equation becomes:

$$0.30 \times 4 \text{ kw} \times 720 = 864 \text{ kwh/month}$$

The difference between a machine's rated wind speed and your site's actual average is therefore very significant. If that 4-kw unit were rated at 24 MPH instead of 20 MPH, it would have a capacity factor of about 0.20, which, at a 12-MPH average, would deliver 576 kwh per month. That's quite a difference (33 percent) for just a 4-MPH change in rated wind speed.

James Sencenbaugh, a manufacturer of wind machines (see Appendix 6), adds another word of caution and some arithmetic advice in evaluating manufacturers' claims. He suggests that consumers compare the given machine and its claimed efficiency with those of known machines with long-term operating experience. To do this, one must use the Betz Theorem, which translated into a formula is: power in kw = K × A × V cubed, where K = 0.0000053; A = swept area of propeller = 3.14 × diameter (squared) ÷ 4; and V = rated wind speed of generator in MPH cubed.

The Sencenbaugh Electric Company provides a good example. They computed the average system efficiencies of several wind machines based on the rated wind speed, the rated capacity and the blade diameter. The results are listed below:

| MODEL | EFFICIENCY (%) |
|---|---|
| Aerowatt 24FP7G | 15 |
| Dunlite 2 Kw | 18 |
| Jacobs 3 Kw 100 VDC | 25 |
| Pinson C2E | 22 |
| Sencenbaugh Model 500-14 | 24 |
| Average of five machines | 21 |

SOURCE: James Sencenbaugh. *Sencenbaugh Wind Electric Design Manual* (Mt. View, Calif.: Sencenbaugh Electric Co., 1981).

Assume a manufacturer claims 1.2 kw at 20 MPH, using a 10-foot-diameter blade. Using the formula above, one finds that the manufacturer is claiming to produce 3.3 k at 20 MPH. The claimed efficiency is thus 1.2 kw ÷ 3.3 kw = 36 percent. This manufacturer says he is 1.64 times more efficient than the average of the other six manufacturers. This comparison does not disprove the claim, but as Sencenbaugh cautions, it requires additional investigation.

# Hydropower

A flowing stream contains two kinds of energy: Its velocity gives it *kinetic energy*, and its elevation gives it *potential energy*. The kinetic energy in most streams is not great enough to be useful. It is the potential energy between two sites of differing elevations that are exploited for hydropower. Very simply, the idea is to divert some of the water from a higher, upstream site, transport it via a conduit and then let it fall through a waterwheel or hydraulic turbine located at a lower elevation downstream. The turbine turns a generator that produces electricity, and the "spent" water returns to the stream.

The amount of power obtainable from a stream is proportional to the rate at which the water flows and the vertical distance the water drops (called the *head*). To determine the mechanical power generated, use the following formula: $THP = Q \times H \div 8.8$, where THP equals theoretical horsepower, Q is flow rate of water in cubic feet per second (CFS), H is head in feet and 8.8 is a correction factor for the units. For electrical power the proper formula is $P = QH \div 11.8$ or $P = AVH \div 11.8$, where P is the power obtained from the stream in

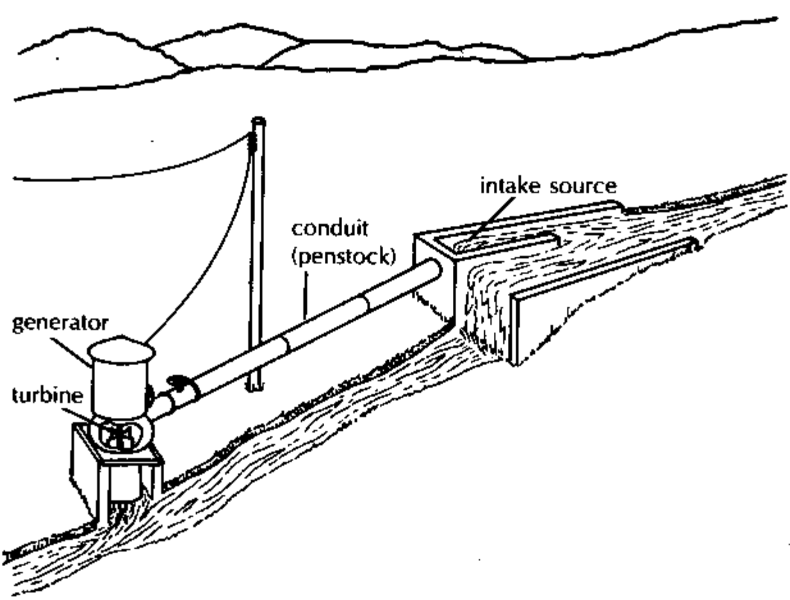



**Figure 6–9:** In this simple hydroelectric system, the flow of water turns the turbine inside the generator just as the power of the wind rotated the shaft inside the windcharger in figure 6–3.

kilowatts, Q is the flow of water in CFS; A is the average cross-sectional area of the stream in square feet; V is the average velocity of the stream in feet per second; H is the height the water falls (head) in feet; 11.8 is a constant that accounts for the density of water and the conversion from foot-pounds per second to kilowatts. Another formula, $P = (Q \times H) \div 709$, gives us the power in kilowatts with a known usable flow rate in cubic feet per minute (Q) and net head, in feet.

Using a flow rate of 10 CFM and a net head of 50 feet, the theoretical power is $P = (10 \times 50) \div 709 = 0.7$ kw.

These formulas give us an indication of the potential power from a stream of given dimensions and head. As in any conversion process, a great deal of potential energy is lost. Turbines themselves are from 60 to 85 percent efficient. Table 6–1 gives representative values for conversion efficiencies of various types of prime movers. Further losses take place in the generator and the gears. Thus the efficiency of the turbine should be multiplied by about 0.75 to give a system efficiency. A system efficiency of 50 percent represents a good preliminary estimate.

Any flowing stream can generate electricity. But below a certain combination of head and flow rate, the capital investment in the hydroelectric device will outweigh the benefits gained from electric gen-

TABLE 6–1

**Typical Efficiency Ranges for Small Water Wheels and Turbines**

| PRIME MOVER | EFFICIENCY RANGE (%) |
|---|---|
| Water Wheels | |
| Undershot | 25–45 |
| Breast | 35–65 |
| Poncelet | 40–60 |
| Overshot | 60–75 |
| Turbines | |
| Reaction | 80 |
| Impulse | 80–85 |
| Crossflow | 60–80 |

NOTE: Reprinted and adapted from *Micro-Hydro Power*, Ron Alward, Sherry Eisenbart and John Volkman (Butte, Mont.: National Center for Appropriate Technology, 1979), p. 13.

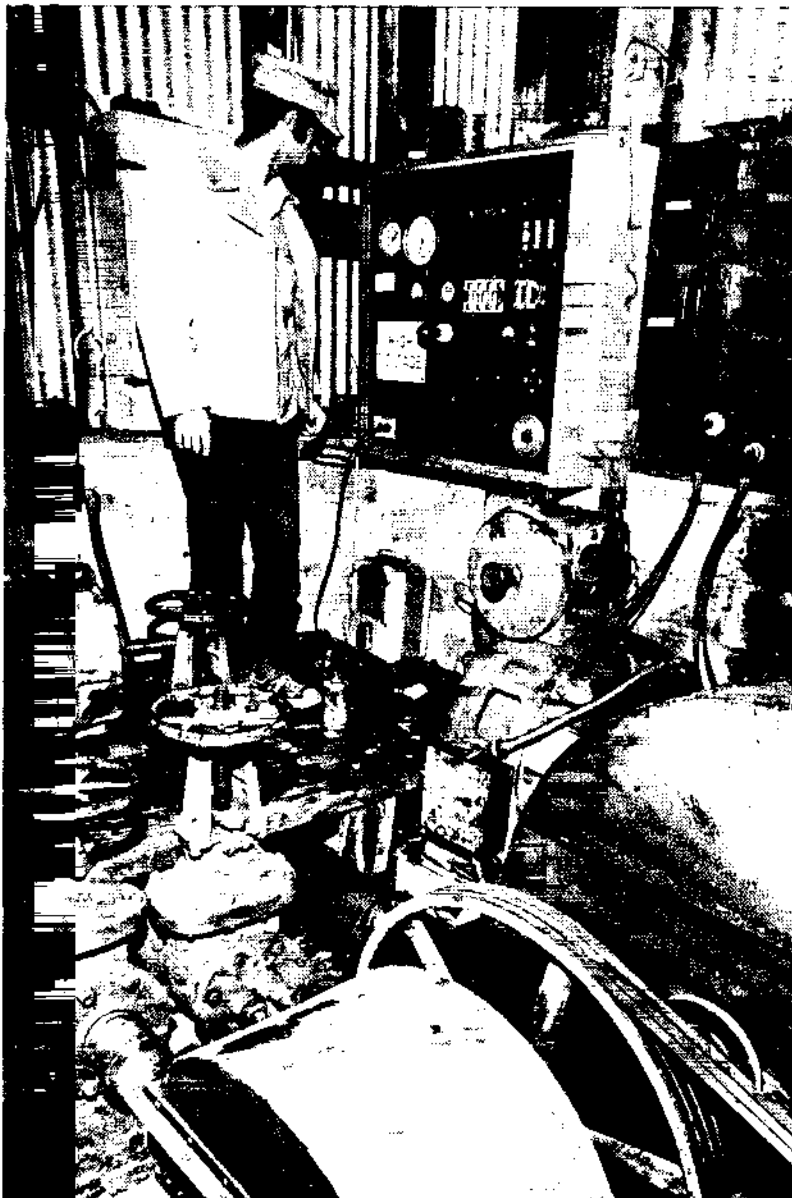


**Photo 6–5:** One important part of a small hydro installation is the powerhouse, which houses the turbine, the generator and electrical and mechanical controls. This system produces 240 kwh per day during times when water flow is normal. During high-water times, it produces 480 kwh per day. *Photograph courtesy of T. L. Gettings.*

eration. Many developers believe that any combination of head and flow rate that produces less than 500 watts (0.5 kw), taking account of the system efficiency, is not worth the time and expense of development. Assuming a 50 percent conversion efficiency, this is about the power output from 450 gallons of water per minute (GPM) falling 9 feet. Or 20 GPM falling 200 feet. Or a flow rate of 1 cubic foot per second and a 12-foot drop, or a 6-foot drop (head) with a flow rate of 4 gallons per cubic foot. A flow rate of 1 cubic foot per second is equal to about 7 gallons per second.

On larger streams and rivers, one may be able to rely on published material to estimate heads and flow rates. The water flow is not constant even on rivers that have large reservoirs. It varies seasonally and in drought periods or periods of heavy rains and flood flows. In order to predict the power available from a particular hydro site, the historical water-flow records must be obtained and put in usable form. The majority of continuous flow data for a given river or stream are gathered and published by the U.S. Geological Survey (USGS). The most useful flow data readily available from the USGS is the average flow rate. Although hydropower equipment is usually rated at greater flow rates, the average flow rate can provide an adequate estimate for sizing the turbine on an initial, very preliminary basis.

In some cases, however, the USGS can provide, upon request, a flow duration curve for any given site. If the duration curve is available, the hydro plant will normally be sized for a 20 to 30 percent exceedance flow—that is, for the flow that is exceeded only 20 to 30 percent of the time. If a USGS gaging station is not located near the power plant site, reasonable approximations can be made using gaging station information, with appropriate adjustments, from a site within the same general rainfall area. The USGS will usually provide assistance in determining an approximate flow.

## Measuring Water Flow

Assuming there is no reliable data for water flow that can be used on your site, and the state does not provide assistance, you will have to take your own measurements. Ron Alward, author of a manual on micro-hydro plants, recommends taking biweekly measurements throughout one complete year to get a good idea of how the flows vary seasonally. Then determine from available data for your watershed (such as precipitation or snow pack data) whether this has been a dry, a wet or an average year. Then make the necessary corrections to your own data to determine the minimum expected flow rates for your stream. This will give you the base capacity that can be counted on during the entire year. If, on the other hand, you are going to use the stream for shaving peak demand during certain months, or just want to maximize the revenue from the stream, you might want to size the system larger even though it will operate at lesser efficiencies during the periods of low flow. Some hydro developers have found it economical to run their systems even though a few months of the year the stream flow is so low that they have no output at all.

You will also need to know the maximum flow rate in order to size spillways adequately for bypassing excess water to prevent damage to your installation. There are three methods commonly used to determine flow rate. To measure the flow of small streams or springs, temporarily dam up the water. Divert the entire flow into a container of known size and carefully count the number of seconds it takes to fill the container. If it takes 40 seconds to fill a 55-gallon drum, the flow rate is 1.375 gallons per second or 82.5 gallons per minute or 11 cubic feet per minute.

For larger streams the *float method* can be used. If done carefully and repeated several times, it can give results accurate enough for most calculations. In order to use this method, you need to know the average cross-sectional area of the stream and the stream's velocity in feet per second. With this data you can find the flow, again in cubic feet per minute (area times velocity). These methods are detailed in the book *Micro-Hydro Power* (see the Bibliography).

A method for determining the flow rate of even larger streams is called the *Weir Method*. It is somewhat more complicated and more expensive than the other methods. You have to build a temporary structure across the stream perpendicular to the flow, with a rectangular notch or spillway of known proportions located in the center section. You then make certain measurements and use established tables to arrive at the volumetric flow rate (refer again to *Micro-Hydro Power*).

## Measuring Head

Along with flow rate, determine the extent to which the water falls, which is where most of the power is created. The greater the vertical drop, the more potentially useful power there is available. In this chapter the general reference is to relatively low head (30-foot drop), as opposed to high head. To measure head you have basically three alternatives. You can hire a good surveyor to determine the vertical distance between your water source or proposed intake location and the proposed location of the power plant. Ron Alward suggests *in Micro-Hydro Power that if your head is less than 25 feet, you may need* such precise measurements that a surveyor should be hired. For those who know how to use standard surveying equipment (a transit or a surveyor's level and leveling rod), borrow or rent the appropriate pieces and get a friend to help you make the necessary measurements.

Once you have the total, or *gross head,* there are various losses to be considered before you can make any theoretical power calculations. The *net head* is required for these calculations. Losses will occur for several reasons. Whenever water flows through a pipe there are *friction losses*. These friction losses are greater for increased flow rates and for smaller pipe diameters. Elbows and bends in the pipe will also increase friction losses. Polyvinyl chloride (PVC) pipe, for example, offers low friction loss, rarely exceeding 8 percent of the gross head.

Other losses might occur that depend on the type of turbine you use, and there are power losses in the flow of water to and from the turbine. All these losses subtract fractionally from the *gross head* (what you measured) to give you the *net head*. When you know both the flow rate and the net head, you can make a determination of the available power in the stream (see figure 6–10).

# Equipment

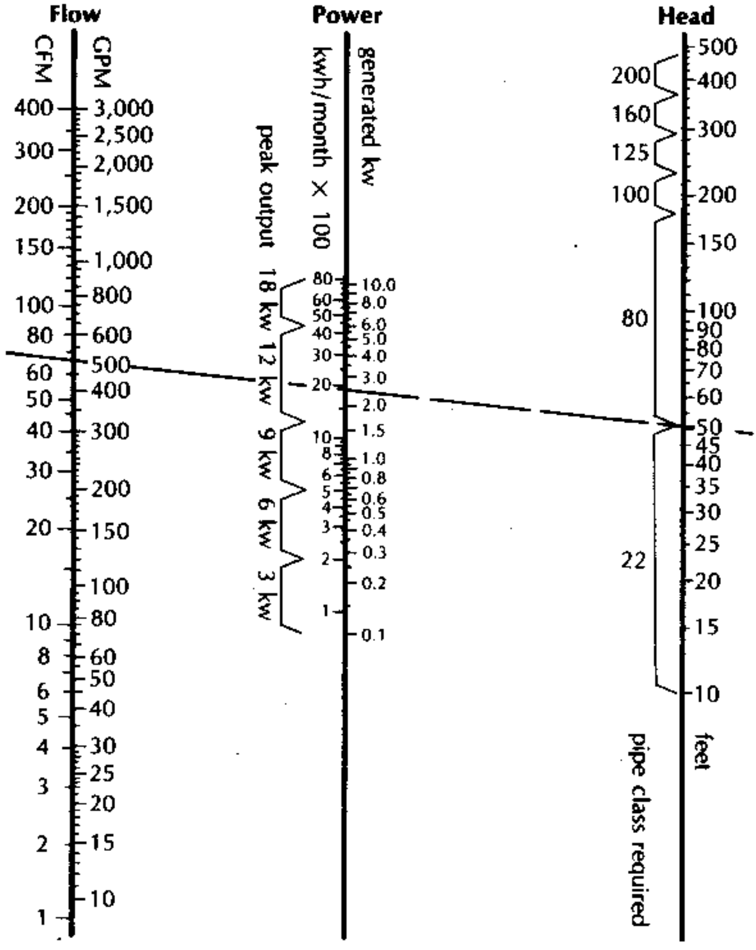
Most equipment suppliers can give you a rough estimate of the cost and type for your system if you can supply them with the following information: usable flow rate, length of pipe required from take-off to generator location (location of the dam with respect to the generator location), power demand (alternating current or direct current) and what you want to do with the surplus power.

There are two basic types of hydro turbines used to generate electricity: impulse turbines and reaction turbines. A third type, the Schneider Lift Translator, will be discussed because of its peculiar characteristics. Waterwheels will not be discussed here because their efficiencies are extremely low (about 15 to 25 percent), and it is unlikely that they would be the technology of choice for generating electricity. Each type and brand of turbine has its own variation in peak efficiency, efficiency at maximum load, efficiency at minimum load and ratio of maximum load to minimum load. Each of these variables affects the recoverable annual energy at a given site. Hence, knowledge of turbine types and manufacturers' data is necessary for the final turbine selection process.

## Impulse Turbines

*Impulse turbines* are generally the simplest of all common turbine designs and are widely used in very small-scale hydro applications. Impulse turbines have a series of radial buckets that are driven by one or more water jets, each directed by a needle valve. Flow and power

*(continued on page 212)*




**Nomograph to Determine Typical Output Power from a Micro-Hydro System**
(assumed system efficiency of 53%)

**Figure 6–10:** Once you know the usable flow of your stream and the net head, you can use a nomograph (on facing page) to determine the power you can expect from your turbine. For example, suppose you have a usable water flow rate of 500 GPM through a net head of 50 feet. To determine the power you can expect from the turbine, locate the flow rate, 500 GPM on the Flow line, and the head, 50 feet, on the Head line. Join these two points with a straight line. The point where this line cuts the Power line is the power output of the turbine. The Power line gives three pieces of information. The continuous power output in generated kilowatts is 2.5. This turbine will put out a constant 2.5 kw if the water flow conditions remain the same. At a continuous power output of 2.5 kw, you can expect to produce nearly 2,000 kwh per month, as indicated on the first scale on the left side of the Power line. If you are using a DC system, feeding into storage batteries, then your system can have a peak power output of 12 kw, as shown. *Redrawn from Alward, Eisenbart and Volkman,* Micro-Hydro Power, *p. 15.*

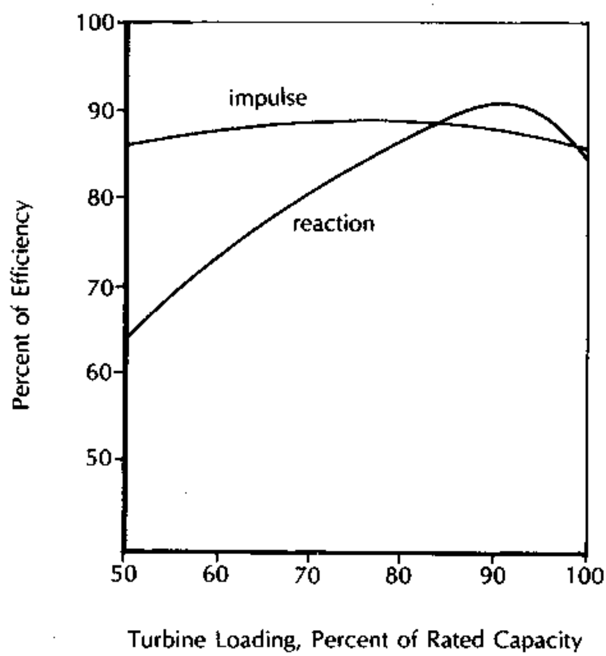
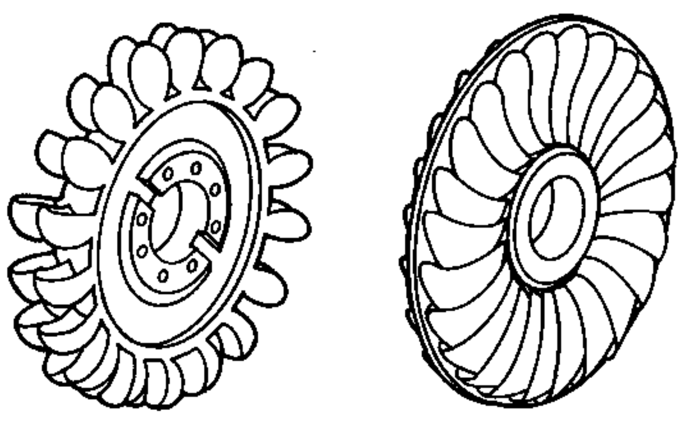



**Figure 6–11:** This graph compares impulse and reaction turbine efficiencies at different loads. Notice the relative stability of impulse turbines at partial loads, whereas reaction turbine efficiencies drop substantially at partial loads but are slightly higher than impulse turbines at 90 percent loads. *Redrawn from D. V. MacDonald and E. G. Raguse,* Technical and Economic Aspects of Pipeline Hydroelectric Projects *(Newport Beach, Calif.: Engineering Science), by permission of Engineering Science.*

are regulated by opening or closing the needle valve. The runner may be mounted with the shaft either vertical or horizontal and must rotate in air above the downstream water surface. Impulse turbines can maintain good efficiencies over a wide range of flows. These turbines are normally described by design head, power, speed and number of water jets.

*Micro-Hydro Power* succinctly describes the Pelton wheel: "In general terms a *Pelton wheel* is a disc with paddles or buckets attached to the outside edge. The water passes through a nozzle and strikes the paddles one at a time, causing the wheel to spin. The buckets are shaped so that the water stream is split in half and caused to change direction, heading back in the opposite direction to the original water stream for the greatest efficiency. The shape and smoothness of the buckets is important. Because the power developed by the Pelton wheel is largely dependent on the velocity of the water, it is well suited for high head/low flow installations."[6] Pelton wheels operate best on heads over 50 feet. Operating efficiencies of 80 percent are common.

Another impulse turbine is the *Turgo impulse turbine*, designed and built by F. Gilbert Gilkes and Gordon Ltd. of England. It is similar to the Pelton wheel but theoretically operates at a higher speed and thus can be used successfully at lower heads.



Pelton wheel Turgo

**Impulse Turbines**

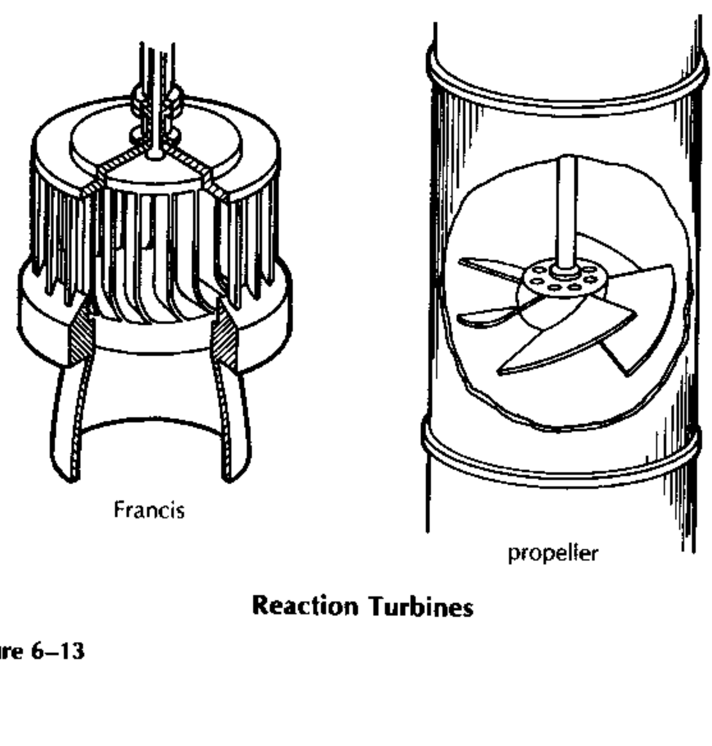
**Figure 6–12**

## Reaction Turbines

*Reaction turbines* work differently from impulse turbines. The runner is placed directly in the water stream, and the power is developed by water flowing over the blades rather than striking each individually. Reaction turbines use pressure rather than velocity. The function is more like that of a centrifugal water pump running in its reverse mode. Reaction units tend to be very efficient at specific designed-for situations, and their efficiency falls sharply with any variation. Reaction units are usually used in very large installations.

The *Francis turbine* is a reaction turbine. According to Bill Johnson, editor of *Currents* magazine, it was the undisputed turbine of choice for nearly 100 years. Therefore, in the majority of cases where persons are rebuilding an existing turbine, they will be working with some variation of the Francis turbine. By the same token, nearly every used unit offered for sale will be a Francis. Francis turbines must be mounted in a fashion that allows the water to enter its rotors from all sides. It can be mounted horizontally or vertically. It has been used for heads from 3 to 300 feet.

The *propeller turbine* is a simple machine, closely resembling a boat propeller in a length of pipe. As with the Francis, the water




**Reaction Turbines**

**Figure 6–13**

contacts all of the blades constantly, and it is thus imperative that the pressure in the cross section of the pipe be uniform. If, for example, the unit were operating horizontally, and the pressure at the top of the tube were less than at the bottom, the runner would be out of balance. The propeller turbine is an axial-flow reaction turbine in which the water moves parallel to the runner axle and turns the blades as it passes. Large versions of this are sold by Allis Chalmers under the trade name TUBE Turbine. The *tube turbine* bends the penstock just before or after the runner, allowing a straight-line connection with the generator, which is located outside the pipe. Another variation is the *bulb turbine*. In this case, the propeller drives a gearbox and generator in a pod or "bulb" within the tube holding the propeller. This makes for a very compact, self-cooled unit without the problems inherent in other types of sealing the axle where it leaves the tube. However, it also requires a high degree of precision to make the gears and generators as small as possible and involves some difficulty in servicing because of the lack of easy access. The bulb turbine places the turbine and generator in a sealed unit directly in the water stream. Another variation, the *straflow*, attaches the generator directly to the perimeter of the turbine. The *Kaplan* has adjustable blades on the propeller to allow for variations in flow rates.

## Cross-Flow Turbine

The *cross-flow* turbine is midway in style between an impulse and a reaction turbine. Manufactured primarily by the Ossberger organization of West Germany, the cross-flow turbine has a horizontal axle with an attached drum composed of curved blades parallel to the axle. A nozzle directs the water stream into the blades from the outside, after which the water passes through the drum and out via the blades opposite where it entered. It was apparently invented as an impulse wheel similar to the Pelton wheel but has been refined to have a reaction component by using a two-element nozzle. The cross-flow turbine is not capable of the efficiencies of a well-tuned Francis or variable pitch propeller turbine, but has the potential of maintaining efficiency over a wide range of flows in its more sophisticated forms. It also has the advantages of two axle ends on which to attach generators, pumps, and so forth and has no thrust bearings or cavitation to contend with. The Ossberger cross-flow turbine can work effectively on heads of less than 20 feet.

Several companies have been examining the feasibility of using pumps as turbines. Pumps offer the advantage of being off-the-shelf items, while most turbines must be custom designed. They cost about half the price of a turbine of equal capacity. On the other hand, they

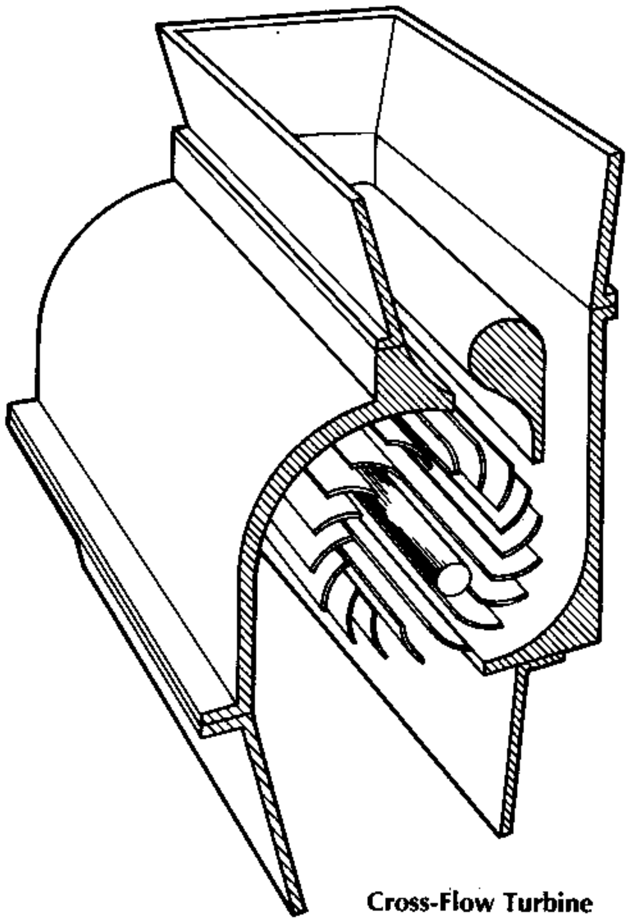
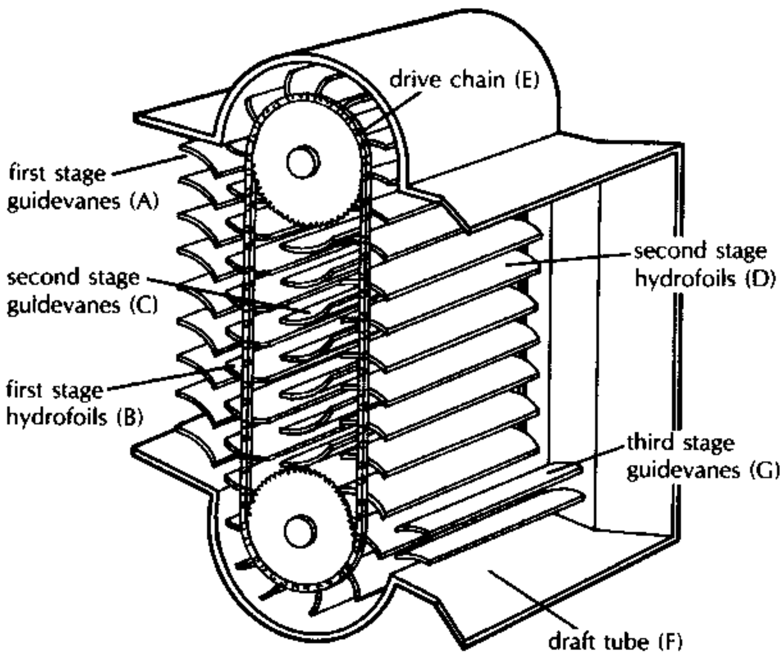



**Figure 6–14**

are about 5 percent less efficient than turbines, and they are less capable than turbines of operating over a variety of flows. Therefore, several pumps might be necessary to satisfy the flow requirements of a particular site. Costs should be less by about 50 percent. *Centrifugal Pumps as Hydraulic Turbines for the Small Hydropower Market,* by L. Shafer and A. Agostinelli, is an excellent publication on the function of centrifugal pumps as water turbines (see the Bibliography).

## Schneider Hydroengine

A recent development in hydro-turbine technology is the Schneider Lift Translator or Hydroengine. Daniel J. Schneider, a




**Schneider Hydroengine**

**Figure 6–15:** *Adapted by permission of Schneider Engine Co. from Daniel J. Schneider and Emory K. Damstrom,* Schneider Hydroengine.

physician-turned-physicist, was seeking a very low head hydropower plant that could harness the vast majority of water flowing in the United States without high dams that flood thousands of acres. Picking up on the work of another physician/physicist, the eighteenth-century Swiss Bernoulli, he examined the principles of fluid flow dynamics. Schneider used the principles of flow dynamics that apply to wind machines. Indeed, he first designed his machine to be used as a wind turbine. Historically, lift translators have been used for sailboats, airplane wings and hydroplane foils.

Figure 6–15 illustrates the operation of the patented Schneider Hydroengine. The energy converting process begins as the water flows into the entryway. The design of the entryway causes the water to strike the cross section of the Schneider Hydroengine at a uniform velocity. "As the water flows into the throat section, it contacts the first stage guidevanes (A). The first stage guidevanes direct the water flow to lift downward on the first stage hydrofoils (B) by directing the flow to optimally match the velocity of the hydrofoils. This velocity matching achieves a high recovery efficiency. Once the water flow leaves the first stage hydrofoils, it comes in contact with the second stage guidevanes (C). The second stage guidevanes redirect the water velocity in an upward direction, lifting the second stage hydrofoils (D), at a matched velocity. The hydrofoils' linear movements are transferred to drive chains (E) attached to each end of the hydrofoils. The drive chains turn sprockets located at the top and bottom of the engine. The top sprockets are attached to a shaft leading to the speed increaser [transmission gearbox], and the shaft's torque/rotation drives the generator. After leaving the second stage hydrofoils, the water flow simultaneously enters the draft tube (F) and the third stage guidevanes (G) for its return to the channel. The third stage guidevanes and draft tube are designed to minimize head losses. The draft tube is horizontally flared and the outlet is at an elevation so that the top margin is never less than six inches below the lowest operating water level in the afterbay."[7]

This machine will economically derive 80 percent of the power output from a given flow of water from a head substantially less than that needed by a conventional machine. It can operate well in heads of only 3 feet and is presently available in sizes ranging from under 1 kw to 1 megawatt. The Schneider Hydroengine is available from the company in Justin, Texas (see Appendix 6).

## Governors, Generators, and Powerhouses

With today's technologies and the ready availability of utility interconnection, the conventional mechanical or hydraulic *governor*, a device to change the speed of the machine, is seldom necessary for systems below 200 kw. If an induction generator is used, no governor is necessary. If you are considering an isolated system, one not tied to a utility grid, several types of electronic governors are available. Most of these use the surplus energy to generate heat, often for hot water heating, in effect generating at a constant rate and shedding excess as heat.

Generator choices in the 1-kw to 5-kw range are limited. The ultimate choice will depend to some extent on the RPM of your turbine. Generators generally run at 900 RPM, 1,200 RPM or 1,800 RPM, with 1,800-RPM being by far the most common and the cheapest. Direct-drive generators are normally only used for either very high-speed installations such as high-head Pelton wheels or very large low-head turbines. Otherwise geared transmissions are used to step up shaft speed to the generator.

J. George Butler, author of *How To Build and Operate Your Own Small Hydroelectric Plant*, describes several key factors for deciding on the location of the powerhouse. First, it should be located so as to obtain the greatest possible amount of head. Second, it should be as close as possible to the house, given the winter snows that would make walking to the powerhouse difficult. Third, it should be located high enough off the stream so as not to be damaged by spring runoffs. The powerhouse must be large enough for the turbine, generator, main breaker box, inverter and battery storage, if any. Its design need not be sophisticated, but it must be weatherproofed and have a dry floor. The cost of the completed structure should be in the range of $10 to $20 per square foot, depending on how much salvaged materials were used and how much of the work is done by the owner.[8]

# Photovoltaics

The most decentralized of all electric technologies is the photovoltaic (PV) cell, more popularly known as the solar cell. Unlike the other three technologies discussed in this book, the solar cell doesn't convert mechanical energy into electrical energy.

The vast majority of solar cells today are made from silicon. The silicon is reduced from silicon dioxide, ordinary sand. The silicon used in solar cells is very pure, on the order of one atom per billion impurity. The silicon atom is called a *semiconductor* because it has four electrons in its outermost shell. Those elements with only one or two electrons in their outer shell have weak holds on the electrons. These tend to move easily from one atom to another. Elements composed of such atoms are called metallic. They readily conduct electricity—which is itself nothing more than a flow of these outer shell electrons. If an element has as many as six or seven electrons in its outer shell, the material is called nonmetallic. The electrons are tightly bound, and the material is a poor conductor of electricity.

Elements whose atoms have three, four or five electrons in the outer shell, are called semiconductors because their outer electrons can be freed, but only if given some additional energy, or push, from an outside force or energy. Silicon is a semiconductor.

Sunlight is composed of tiny bits of energy called *photons*. A silicon atom readily absorbs a photon, and the added energy "excites" or activates one of the outer electrons and frees it. (This occurs most easily when silicon atoms are lined up in precise rows or positions, which they are in their crystalline state. In any crystal the atoms or molecules are arranged in perfect geometric formations. The opposite is the *amorphous state*, in which atoms or molecules are jumbled together in no regular pattern.)

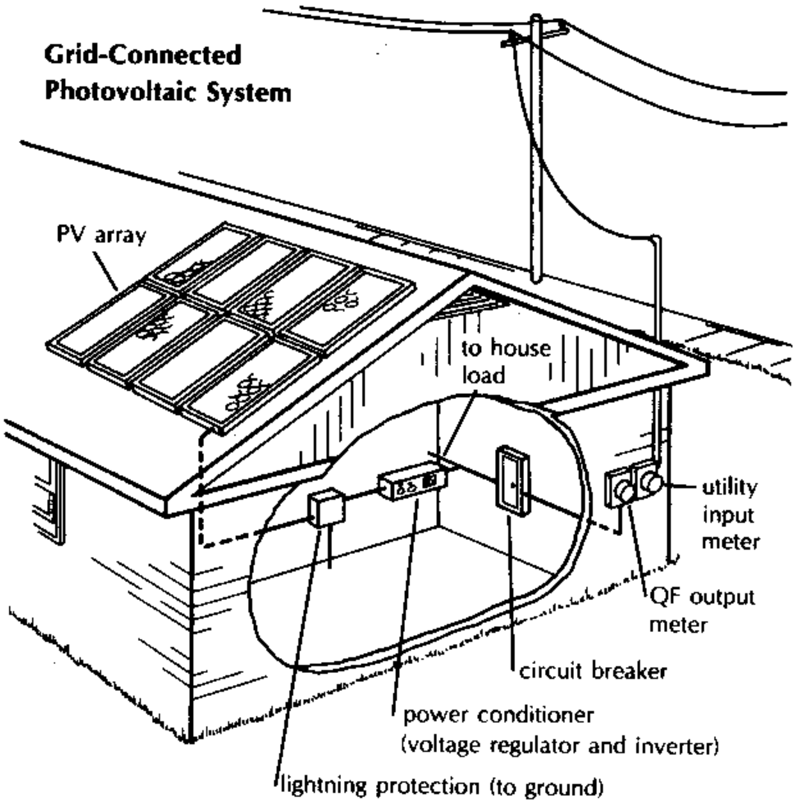



**Figure 6–16**

The silicon atom loses its outer shell electrons when struck by sunlight, but this alone does not generate electricity. To do that, the flow of these electrons must be channeled. In the cell, a junction or barrier is formed within the wafer of silicon so that when the photon moves the electron out of orbit, it moves into a wire that is part of a circuit, at which point it creates with other electrons a channeled current of electric power.

This barrier is created by adding infinitesimal amounts (no more than one atom per million atoms of silicon) of two elements: boron, which has three outer shell electrons, and phosphorus, which has five. The two surfaces of the cells are treated with impurities, creating dissimilar electrical properties from side to side. In the process, the cells are arranged on a rack and inserted into a heated chamber. One side of the cell is exposed to positively charged boron atoms and the other

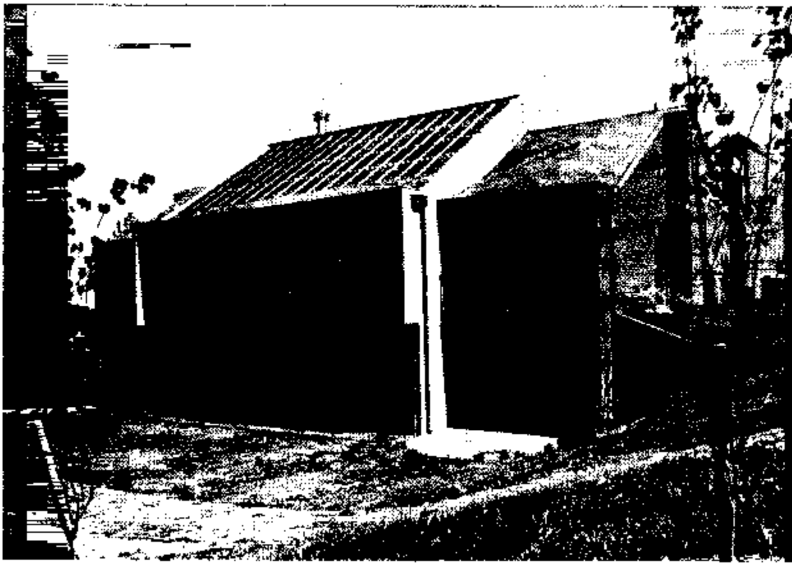
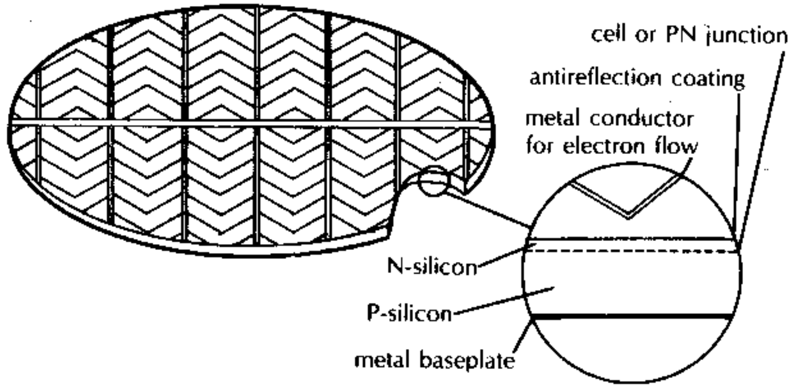


**Photo 6–6:** Future I, a solar research house sponsored by Georgia Power Company, uses 544 square feet of photovoltaic panels to provide electricity for the house. Future I is connected to the Georgia Power Company utility system so that at night and on cloudy days electric service is available. When the photovoltaic cells are producing more electricity than the house needs, the homeowner sells the excess to the utility. *Photograph courtesy of Georgia Power Company.*

is exposed to negatively charged phosphorus or arsenic atoms. This negative charge forms "holes," as they are called, to attract electrons from the boron atom. As the wafer is heated, these elements are allowed to penetrate the surface of the cell. The amount of penetration is a highly controlled process. As the two sides of the cell are exposed to the desired depth with these different materials, a neutral area is left between the sides. This neutral area is called a *PN junction*. It gets its name from the positive and negative sides that it separates. The side of the cell treated or doped with boron needs electrons and tends to absorb them, much as a sponge soaks up water. The side treated with phosphorus atoms has an excess of electrons, which creates a negative charge.

When light falls on the cell, photons are absorbed and electrons are set free. The surplus electrons accumulate in the phosphorus-treated side. If one end of a wire is attached to this top layer and the other end connected to the layer beneath, electrons will leave the




**Crystal Silicon Solar Cell**

**Figure 6–17**

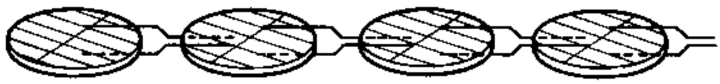
upper layer, flow through the wire, and be absorbed by the boron-doped silicon, completing the circuit.

The final production step for the solar cell consists of an etching process that applies a metal coating. A metallized grid is applied to the surface of the cell to gather up the electrical charges. The lines of this miniature grid are extremely thin so as not to shade the cell from sunlight. On the other hand, the grid must cover all parts of the cell. If its lines were spaced too far apart, the electron might not have the energy to travel all the way from its orbit to the grid. The grid appears like a system of roads all leading to a highway.

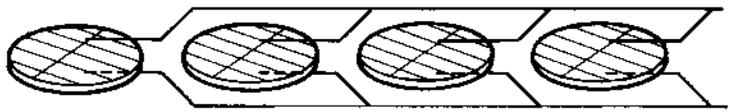
Finally, the top side of the cell containing the grid is covered with a special antireflective coating to prevent sunlight from being reflected off the cell. This increases the amount of sunlight absorbed and improves the overall efficiency of the cell. This antireflective material also has a textured surface, which further increases the amount of light absorbed by the cell.

Yet despite all technological refinements and extreme quality controls, solar cells typically convert a fraction of the available solar energy into electricity. The maximum theoretical efficiency of the silicon solar cell is 23 percent. Efficiencies of 20 percent have been achieved in the laboratory, though commercial, single-crystal silicon solar cells typically convert 13 to 15 percent of the sunlight falling on them into electricity.

The finished cells are then packed into modules, which consist of several cells connected in series until the desired voltage or amperage



solar cells in series (increases voltage)



solar cells in parallel (increases current)

**Figure 6–18:** When wired in series, each solar cell voltage output is added together. When wired in parallel, the currents are added together.

is achieved. These cells are then housed in a protective covering, usually glass on top with silicon rubber holding the cells in suspension. A rigid frame is placed around the glass to protect it as well as to provide some means of mounting.

## Electrical Characteristics

The amount of current (amperage) produced by a photovoltaic cell is proportional to the amount of light falling on the cell. Current also increases with the area of the cell. The voltage, on the other hand, is fairly constant, about 0.45 v in silicon cells regardless of cell area. Unlike conventional generators, the cell current decreases with increases in cell voltage. Also, the output of a silicon-based cell is reduced by about 10 percent for each 45°F rise in cell temperature.

Based on the application and load requirements, the main terminals of a solar cell array are connected to various power conditioning equipment. The direct current produced by the array can be used directly or converted to standard 120-v alternating current.

Because the array is an active power source by day, care must be taken during servicing and maintenance. The National Electrical Code recommends that in the interest of safety, maximum voltage should be no higher than 50 v to 60 v. If a higher voltage is required, switches should be installed between cell modules at 50-v to 60-v intervals. These switches can then be disengaged during maintenance to limit the voltage anywhere on the array.

## Cost of Solar Cells

Solar cells have been included among the four technologies discussed here even though they are not yet economical for most grid-connected applications. They are, however, already competitive for many stand-alone applications. When a house is located far from the grid system, the cost of laying in cable may be more than the cost of a PV system. More than 1,000 homes in the United States had solar cells as of the end of 1982. And although still in the demonstration stage, at least a dozen grid-connected, solar-cell-powered homes are operating.

Before 1973 solar cells were used only in the space program. They were manufactured for the highest possible reliability. Their first market

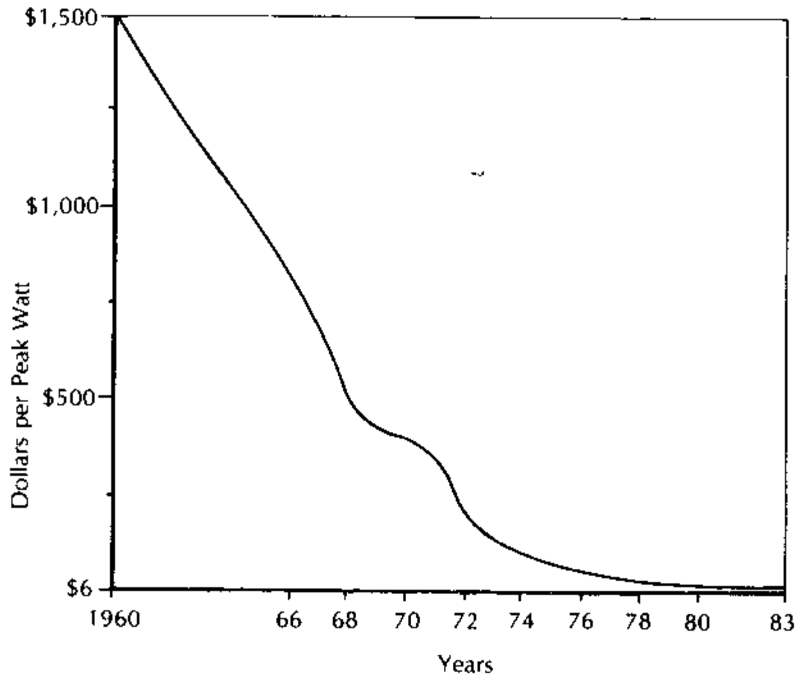



**Figure 6–19:** This graph shows how the prices of photovoltaics have fallen over the years. The prices indicated here are prices per peak watt of capacity for large quantities of photovoltaic modules. Prices are factory costs, not retail or wholesale prices. For a large quantity of photovoltaics, such as 1 megawatt's worth, which equals $10 million in hardware, the price can be as low as $6 per peak watt.

on earth was for extremely remote applications, at the North and South Poles or in deserts or on mountaintops where their high cost was less than that of heavy-duty batteries or diesel generators that had to be serviced regularly. But the more the cost of cells drops, the more they will become an increasingly popular consumer item.

The price is in fact dropping quickly. In 1974 a photovoltaic system big enough to make a household energy self-sufficient would have cost $2.5 million. Today it costs $50,000, a fiftyfold reduction in less than ten years. Some members of industry and government predict that solar cell electricity will be competitive for grid-connected applications by 1985 or 1986, assuming a continuation of the business and residential tax credits. At that time a household system would cost between $10,000 and $15,000, and would be economical as a grid-connected system.

Another type of cell, the *concentrator*, is nearly cost-competitive right now. These use lenses or mirrors to focus the sunlight on very high efficiency cells made of single crystal silicon or gallium arsenide. The concentrators are made of plastic, glass or aluminum. These materials are cheaper than semiconductor-grade silicon, and as concentrators they cost-effectively reduce the required cell area. Unfortunately, concentrating sunlight on solar cells increases their temperature and thus decreases their efficiency if the cells are formally cooled. But efficiencies do not drop at higher temperatures for cells made out of materials such as gallium arsenide. Several companies are also investigating the possibility of solar cogeneration systems that generate heat as well as electricity. The heat gained from cooling the cells (to maintain efficiency) could be used in industrial processes.

In fact, even the flat cell models that we used on rooftops may be somewhat more cost-competitive when thermal as well as electrical energy is captured. By using air or water to cool the cells and using the resulting heat for space and water heating, solar cogeneration can raise overall efficiencies from 15 percent to more than 50 percent, with a theoretical upper limit of 70 percent.

Finally, scientists have discovered a way to achieve relatively high efficiencies even with very "dirty" silicon. Some manufacturers have produced thin film solar cells from amorphous silicon with efficiencies of 8 percent. Since a very small amount of material is used, and the crystallization step is avoided, amorphous silicon cells are very inexpensive. Since 1981 the Japanese electronics industry has routinely used amorphous silicon in watches and calculators. Solar arrays using such devices will generate less electricity per square foot, but they might become competitive as early as 1984.

## Measuring the Sun's Energy

Manufacturers sell photovoltaic systems on the basis of the cost per peak watt of the cell. A *peak watt* is the electricity generated from a solar cell under peak solar gain conditions. But the sun doesn't shine all day and neither does it shine at full capacity even during daylight hours. A typical clear day will contain 4 to 6 hours of full sunlight equivalent. A very rough rule of thumb is that to get 1 average watt of power, one needs 4 to 6 peak watts worth of installed cells. An average watt is the amount of power one cell would generate if operating continuously over the year. Thus to generate an average of 720,000 watt hours (WH) or 720 kwh per month, 1,000 watts (w) per hour times 24 hours times 30 days, a system would need 4,000 to 6,000 peak watts of installed capacity.

This power requirement ultimately translates into some number of square feet of cells covering a roof or arrayed on the ground. But that number is highly variable depending on cell efficiency, cell shape and the level of solar gain at a given site. Another rough rule of thumb has that in the United States 1 square foot of cells will deliver 7 to 10 peak watts.

The power generated by the solar cell array varies depending on the tilt of the array. If the tilt angle is equal to the latitude of the installation, the noon insolation will be the same in winter as in summer. However, the array will produce a great deal of electricity in the summer due to the longer summer days, and a small amount of electricity in the winter. By varying the tilt of the array one can even out the differences between winter and summer sun angles. The extent to which the solar cell owner will do this depends on the buyback rates of the local utility under PURPA and whether there is a seasonal and time-of-day component to them. For example, a more horizontal tilt will gather more energy during the summer months, but little insolation during the winter when the sun lies low in the sky. But daylight hours are longer during the summer, and if the summer rates are higher than winter rates (probable in most of the country, which is served by summer peaking utilities) the solar cell owner could have a great incentive to lower the tilt of the array.

The optimum tilt of the array for year-round generation is usually given as 15 degrees plus latitude. Thus for Memphis, Tennessee, it would be 35 degrees latitude plus 15, or a 50-degree tilt.

Table 6–2 shows the electricity in kilowatt-hours (rounded off to the nearest watt hour) generated per square foot per month in Memphis for two array tilts. Option 1 has a tilt of latitude plus 15 degrees. In

TABLE 6–2
**Kilowatt-Hours of Electricity Generated per Square Foot per Month (10% efficiency)**

| | JAN. | FEB. | MAR. | APR. | MAY | JUNE | JULY | AUG. | SEPT. | OCT. | NOV. | DEC. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Option 1 | 1.0 | 1.1 | 1.3 | 1.4 | 1.5 | 1.4 | 1.5 | 1.5 | 1.4 | 1.3 | 1.0 | 0.8 |
| Option 2 | 0.8 | 1.0 | 1.3 | 1.6 | 1.8 | 1.8 | 1.9 | 1.8 | 1.5 | 1.3 | 0.9 | 0.7 |

NOTE: Option 1 has an array tilt of latitude plus 15 degrees; option 2 of latitude minus 15 degrees.

Option 2 the array tilt is latitude minus 15 degrees.

The first option gives a more balanced generation pattern. The ratio of lowest to highest month is less than 2:1. The second option generates more electricity but is more unbalanced. The ratio of lowest to highest month is almost 3:1.

A 1,000-square-foot array under the first option would generate 15.2 kwh × 1,000 = 15.2 megawatt-hours (Mwh) per year. Under the second option, a 1,000-square-foot array would generate 16.3 kwh × 1,000 = 16.3 Mwh per year, or 7 percent more. Assuming a seasonal or time-of-day rate differential for a summer peaking utility, the second option is even more favorable, generating 20 to 25 percent more electricity in the May-through-August peak air-conditioning load months.

# Cogeneration

Cogeneration systems produce both electrical (or mechanical) energy and thermal energy from the same primary energy source. The automobile engine is a good example of a cogeneration system. It provides mechanical shaft power to move the car, produces electric power with the alternator to run the electrical system and uses the engine's otherwise wasted heat to warm the inside of the car in the winter. Cogeneration systems capture otherwise wasted thermal energy, usually from a heat engine producing electric power (i.e., a steam or combustion turbine or diesel engine), and use it for applications such as space conditioning, industrial process needs, or water heating, or as an energy source for another system component.

Among the four technologies discussed here, cogeneration is unique because it is not necessarily based on renewable fuels

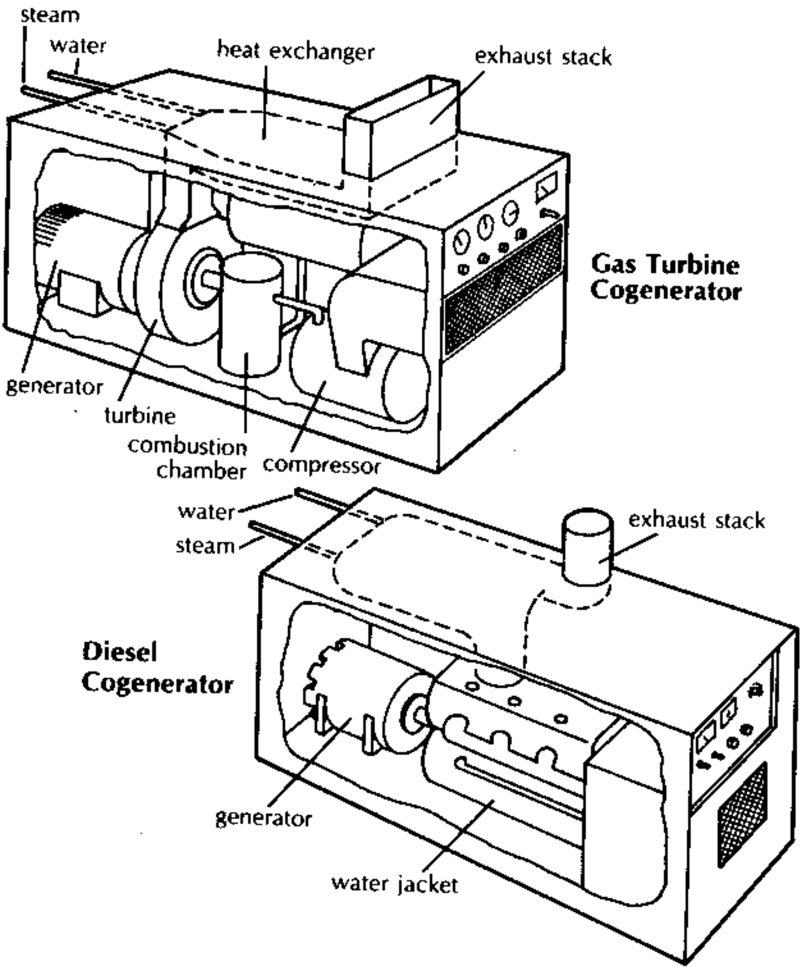



**Figure 6–20:** Shown here are the two basic types of cogeneration systems: the gas turbine and the diesel engine.

(although it can be if fueled by wood, solid waste or methane). In fact a political battle took place over whether to include it at all in PURPA. Some utilities argued that encouraging gas or oil-fired cogeneration could actually increase the amount of domestic and imported fossil fuels burned to generate electricity, a result clearly antithetical to the objectives of the legislation. Some argued that many small cogeneration facilities that burned oil could represent a potentially greater pollution agent than a few large, oil-fired power plants because the latter have taller smokestacks, are located far from population areas and have more sophisticated antipollution devices.

The Federal Energy Regulatory Commission (FERC) decided to include oil- and gas-fired cogenerators under PURPA but only after delaying for more than a year before concluding that the environmental impact would be benign. The FERC argued that even if slightly more fossil fuels were used for a cogenerator than for either a boiler or a conventional power plant, the amount of fossil fuel used would be less than the *combined* amount of fuel burned to generate the same amount of electricity and thermal energy in both the power plant and the boiler. A typical power plant operates at 30 to 35 percent efficiency. A typical boiler operates at 50 percent efficiency. Cogeneration systems operate at 70 to 95 percent efficiencies. For every 100 barrels of oil burned in a cogeneration plant, about 10 percent less electricity would need to be generated than in a conventional power plant and in addition, the cogeneration system would supply almost as much heat as would be generated in a conventional boiler.

There are two types of cogeneration systems: topping cycle and bottoming cycle. A *bottoming-cycle* system uses reject steam to generate electricity. The *topping-cycle* system generates electricity as the primary product and recovers the waste heat. This chapter discusses only topping-cycle cogeneration systems, since only these are available with outputs of less than 200 kw. Commercially available cogeneration systems within this size range are diesel or gas turbines or reciprocating piston engines.

Cogeneration systems consist of three primary components: the engine, the generator and the heat recovery equipment. Very few companies sell a complete, packaged system. Almost all companies combine the best individual components into the most cost-effective system.

The gas in gas turbines does not refer to the fuel, but rather to the gases that provide the force to spin the turbine. The fuel may actually be oil or natural gas. In a simple gas turbine, the air is compressed and then pushed into a combustion chamber. Fuel then enters the chamber and burns, raising the temperature of the gases. As the gas expands and escapes through the nozzle, it rotates a turbine. The spinning shaft turns a generator, and also provides the power for compressing additional air. In gas turbine cogeneration, the hot exhaust gas can heat water in a boiler to produce steam. Gas turbines have a lower electrical efficiency than diesel engines (20 to 30 percent) but the total recoverable energy is about the same. The electrical-to-thermal ratio for simple gas turbines is between 0.5 and 0.7 (50 to 70 percent of the output is electric power). This means that as much as twice as many Btu of heat energy are recovered for every Btu of electrical energy generated. The

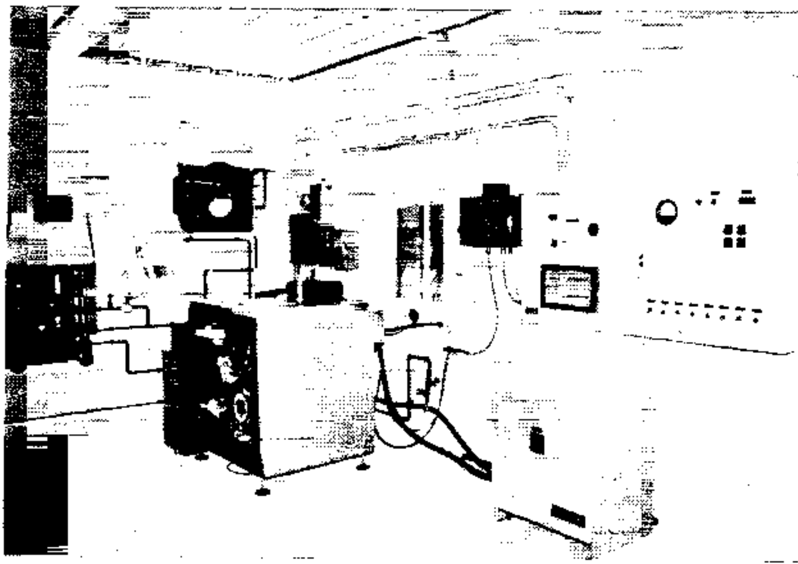


**Photo 6–7:** A small-scale cogeneration system such as this one can operate independently to supply the energy needs of an office building, an apartment building or several homes, or it can be grid connected. In the latter case, any surplus electricity produced can be sold to the local utility under PURPA regulations. *Photograph courtesy of Agway Research Center.*

waste heat in gas turbines can be recovered at a higher temperature, in the range of 900°F to 1,000°F.

In sizes much smaller than 1,000 kw, the fraction of primary energy converted to electricity is very low, often less than 20 percent, compared to 30 percent for larger systems. Also, the electrical conversion efficiency of gas turbines drops significantly in part-load applications. Thus an oversize system will operate much more inefficiently for a gas turbine than would be the case for a diesel-based system. The result is that for the size of systems discussed in this book, gas turbines are usually uneconomical. However, advances in the technologies could change this conclusion.

The high-temperature gas turbine exhaust heat can be used to increase power generation. Turbine exhaust temperatures would be reduced several hundred degrees for this purpose and would still be hot enough to meet most domestic and commercial thermal requirements. One way this can be done is to run turbine exhaust through a regenerator, which transfers heat to the air coming out of the compressor before it goes to the combustor. General Electric predicts that the electrical efficiency of cogenerating regenerative gas turbines could reach 38 percent by the mid-1980s. These systems produce lower-temperature heat and also less net heat (in Btu) than simple gas turbines, so the percentage of primary fuel converted into useful thermal and electrical energy declines. But since the proportion of electrical energy goes up, the economic value of the output rises. The electric output of cogeneration systems is the real money-maker. At 5¢ a kilowatt-hour, the value of the electricity is about $15 per million Btu. The value of thermal energy at a fuel oil cost of 90¢ per gallon or a natural gas price of 60¢ per therm is about $7.50 and $6.00 per million Btu respectively.

The gas turbine can be modified to operate on methane as long as this low-Btu gas (usually 600 Btu per cubic foot compared to 1,000 for natural gas) is clean enough for gas turbine operation. The primary modification entails increasing the fuel gas flow rate fivefold to tenfold to make up for the lower heating value of the fuel compared to natural gas. Gas turbines operating on low-Btu gas can actually be 10 to 20 percent more energy-efficient than when operating on natural gas. Moreover, a given gas turbine would also have a higher power output when operated on low-Btu gas. It is also possible to modify gas turbines for dual fuel operation so that a low-Btu, gas-burning gas turbine might be switched to oil or natural gas, depending on fuel price differences and availability.

The other basic type of cogeneration system involves diesel engines driving a reciprocating piston. Once again the name is misleading. Diesel engines, which can be as small as 15 kw, can be fired by natural gas or oil. Diesel engines can either be spark-ignited like an automobile gasoline engine or compression ignited. Spark-ignited stationary engines are usually fueled with natural gas, while compression ignition engines are usually fueled with diesel fuel or residual fuel oil, although there are a number of dual fuel engines available. When switched to low-Btu gas, the diesel will produce less power and may be less efficient in its electrical conversion efficiency, in contrast to the situation with gas turbines.

Diesels convert a higher fraction of the primary fuel to electricity than do gas turbines, about 35 percent versus 30 percent. Diesel cogeneration provides by-product heat at both high and low temperatures. Diesels use a water jacket to cool the cylinders in which water is heated to 150°F to 250°F. Exhaust gases are emitted at about 700°F. Even though less waste heat is usually recoverable with these engines than with gas turbines, the higher electrical conversion efficiency makes their total output (thermal and electrical) more economically valuable.

There are no household cogeneration systems yet available. The smallest one is the Total Energy Module System (TOTEM) distributed by the Fiat motor company. Yet it has been used primarily in Europe as a

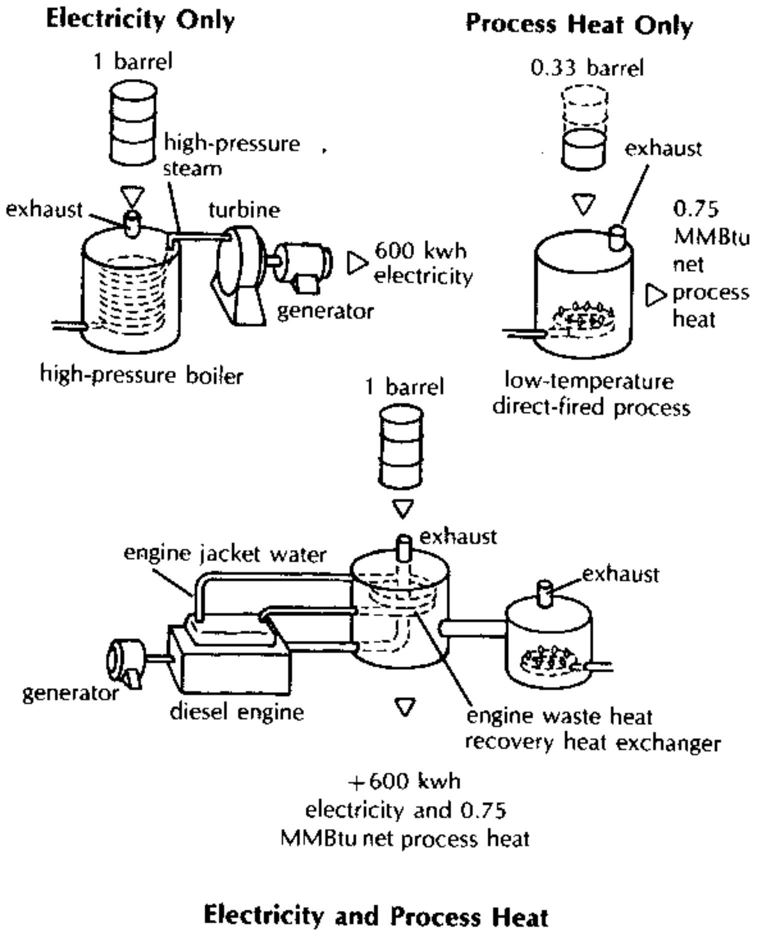



**Figure 6–21:** This illustration shows that diesel cogeneration can result in significant oil savings. The figures at the top (electricity only and process heat only) show that the production of 600 kwh of electricity and 0.75 million Btu of low-temperature process heat consume a total of 1.33 barrels of oil. The lower figure (electricity and process heat) shows that the same output results when the two processes are combined, but the consumption is 1 barrel of oil. The use of waste energy results in saving one-third of a barrel of oil. *Adapted from Governor's Commission on Cogeneration,* Cogeneration: Its Benefits to New England *(Boston: Massachusetts Energy Office, 1978).*

peak-shaving device. It is turned on rarely to meet the peak needs, thereby reducing the heavy demand charges utilities impose year-round for customers that have sharp demand spikes for only a few minutes a year.

If the TOTEM were used as a baseload facility operating 90 to 100 percent of the time, it would generate at rated capacity about 130,000 kwh per year and almost twice that amount in useful thermal energy. This could meet the needs of almost a dozen homes. Thus if homeowners are to gain the advantages of cogeneration, they should form collectives, possibly homeowner associations, to own and operate the system, much the way they now own and operate swimming pools or other recreational facilities.

The problem with operating the TOTEM system as a baseload technology is its high maintenance cost. Automobile engines are not made to operate under a high, constant torque. The 450-horsepower (HP) engine under the hood of the Cadillac may need a great deal of power to get the car going. But on the highway, cruising at 60 MPH, it probably needs only 15 HP to move the vehicle. Automobile engines, unlike truck engines, are not made to operate under high torque on a sustained basis. Thus the TOTEM system must be completely torn down and maintenanced every six months at a cost of several thousand dollars.

About a dozen TOTEM systems are operating currently in the United States. Several are on farms, where they operate from methane generated from animal wastes. If the system can overcome its high maintenance costs, it has several attractions. It is a complete system. All electrical controls and heat recovery equipment come in one package. Because of this, the space required for that equipment is much smaller than for a system assembled from parts from different manufacturers.

Two companies at present sell and install cogeneration systems in the 75-kw to 200-kw range: Cogenic Energy Systems, of New York, and Re-Energy Systems, Inc., of Media, Pennsylvania. Re-Energy Systems is discussed in more detail here, primarily due to its claimed higher efficiency and the five-year warranty the company provides. Moreover, Re-Energy Systems is more oriented to smaller commercial users than Cogenic Energy Systems.

Re-Energy Systems uses a Mack truck engine and operates it at about half the rated horsepower to give it a longer life. The engine runs at about 900 RPM to 1,200 RPM compared to TOTEM's 3,000 RPM.

The generator is made by a local firm in Pennsylvania and matched to the engine. A 100-HP engine will run a 75-kw generator.

Three heat exchangers are mounted in a heavily insulated, all-steel enclosure. One exchanger reclaims the heat from the lubricating oil, heated air, the generator's resistance losses and heat radiated from the engine block. Another takes heat from the cooling jacket of the engine. The third absorbs sensible heat from the exhaust system and from the condensation process as well. One reason Re-Energy can claim an efficiency of 96 percent compared with an average 80 percent for their competitors is that its units capture the waste heat from exhaust gases. The temperature coming out of the engine is 1,200°F while the temperature of the fluid finally dumped is 90°F. The unit achieves 96 percent thermal recovery from the generation of electricity. The company claims the unit when fully loaded converts 38 percent of the primary fuel to electricity and 58 percent of the primary fuel to recovered thermal energy.

Depending on the type of cogeneration equipment used, one can maximize heat recovery or electrical generation or maximize the recovery of high-temperature heat. Most cogeneration systems produce twice as much heat as electricity.

Until PURPA, a cogeneration system was invariably sized to meet the internal base electrical load of the building, unless it was used for emergency backup. (All hospitals, for example, are required to have standby generators to power life-support systems in case the utility lines go dead.) Sizing a system for the internal base electrical load allows the owner to use all of the electricity internally and to dump a small amount of the waste heat during summer months. Often the cogenerator was used as a peak-shaver, turned on during peak times of the year to reduce expensive demand charges.

PURPA's more favorable standby and buyback rates encourage larger cogeneration systems because surplus electricity can be sold to the utility. At an average buyback rate of 5¢ per kilowatt-hour, the value of the electricity is $15.00 per million Btu (MMBtu). At a price of $1.25 per gallon of fuel oil, the value of the heat energy generated (assuming one can use all of it on-site) is $10.00 per MMBtu. When buyback rates are high in proportion to the cost of the fuel for the cogenerator, the incentive is to maximize the electrical output. On the other hand, if the buyback rate is derived from a coal-fired utility with no new power plants under construction, the buyback rate might be only 2¢ per kilowatt-hour, for a value of $6.00 per MMBtu for the electricity. If fuel oil is priced at $1.25 per gallon, the value of usable thermal energy is still $10.00 per MMBtu. In that case the cogenerator would be sized only to meet the internal electrical base load.

Assuming high buyback rates, the trade-off then is between the higher cost of a larger system and the higher amounts of waste heat generated during the nonwinter months, unless that heat can somehow be used. The advantage of a cogenerator is only fully captured when the full thermal as well as electrical output is used. At total thermal plus electrical efficiencies of 80 percent, a cogenerator will be burning slightly more fuel to produce the same amount of heat plus a great deal of valuable electricity. The electricity is thus "free" (discounting the higher cost of the cogeneration equipment than the conventional boiler) but it is not free if the thermal energy is not used. Indeed, because the electrical efficiency of most cogenerators is the same or less than that of peaking power plants and their cost per kilowatt of capacity is greater, the cost of electricity generated in this fashion will be higher than the marginal cost of electricity to the utility.

The conclusion is that on-site power plants cannot compete with central power plants without recovering a significant percentage of their waste heat. The only time that this might not be true is where the central power plant burns expensive fuel, such as oil, and the on-site power plant uses methane, waste wood or some other local fuel source at relatively little collection expense.

Thus, when sizing a system, there is a trade-off between the amount of electricity one can export to the grid system and the amount of heat that can be usefully captured internally. As a result, much of the research in cogeneration systems is designed to figure out ways to use the excess heat energy beyond meeting space, water and process heating loads. Martin Engine Systems of Topeka, Kansas, a Caterpillar distributor, offers a 100-kw cogeneration system coupled to a Yazaki 15-ton absorption chiller. Re-Energy Systems is also coupling its 125-kw cogenerator with an absorption chiller. Thus the waste heat generated by a larger cogenerator during the summer can be used to power a large space-cooling system.