A Guide to Sustainable Energy Options for Green Residential Housing

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I. Motivation and Introduction

The UN-affiliated Intergovernmental Panel on Climate Change (IPCC) unanimously agreed in January 2001 that new evidence shows more clearly than ever that temperature increases are caused mostly by pollution, not natural fluctuations. As a result of this, snow cover has decreased, the duration of river and lake ice is shorter, and heat-trapping CO_2 has more than tripled since 1750. The panel concluded that global temperatures were expected to rise between 1.4 and 5.8 degrees Celsius over the next century [ENS 2001] resulting in coastal flooding, droughts, and worldwide decreased agricultural production.

Contrary to common myth, the third world energy producers are not the key culprits. One quarter of the world's air pollution is generated in the United States, a country with less than 5% of the world's population. There are many activities that contribute to air pollution; however, **making electricity causes more air pollution than any other industry** [ENS 2001]. The United States consumes nearly three and a half trillion kilowatt-hours of electricity annually. The next largest consumer is China with around 1 trillion kilowatt-hours and more than four times the population.

To counter these encroaching dangers, some people have begun converting their homes to be nearly or even completely electrically self-sufficient. Unfortunately, the challenges involved with making good renewable energy choices can be daunting. This paper is intended as a resource manual for the novice home renewable energy enthusiast. The focus is on the construction or remodeling of houses designed for a small number of occupants. Typical energy loads discussed will be in the neighborhood of one to five kilowatts. Each section includes an informative discussion on various technologies, their histories, economics, and ecological impacts. Brief histories of each technology are provided as a special interest, but also to facilitate discussion of trends in the development of renewable energy generation. A basic knowledge of physics and electricity is assumed.

The technologies and designs that are appropriate for any given house vary tremendously with geographic location and resource availability. Clearly no one design or energy suggestion can effectively accommodate all houses equally. For this reason, much emphasis has been given to form this paper in the shape of a guide to help planners make good decisions. Charts that shows local variability in wind and solar resources have been provided and explained. Additionally, energy policy legislation varies greatly from state to state. Resources for determining the policies that directly affect the building site have been included and discussed.

The first step in designing any electricity generation system is to assess the requirements of the home. This document only rudimentarily discusses the procedure for energy need calculations; however, there are many available documents (even whole texts) that can assist in this process. In addition to determining their needed baseline power, one should also characterize their power usage schedule. For example, if you know that very little power will be used in the house after dark, this can make incorporation of a solar electric system much simpler. It is essential to know the requirements before deciding on which systems should be purchased.

II. Generation

Over the last three hundred years people have developed and refined thousands of methods for generating electricity. Many of these methods involve dangerously unrenewable processes with malicious chemicals and emissions. Fortunately, many clean and environmentally unburdening techniques for electricity generation also exist; These represent one piece of the entire energy resource known as *sustainable energy*.

Sustainable electricity generation is an old, well-refined process. Modern technologies make the harvest of electrical energy from wind, solar, and other sources easier, more efficient, and cheaper than ever. For many rural homes far from the electrical grid, renewable energy sources are the only type that are practical. However, increasingly renewable sources are challenging fossil-based energies on economic grounds in addition to environmental grounds.

This section will explore the small homeowners options for exploiting wind and solar resources. In nearly all circumstances, the location of the home is the key factor in determining the appropriate technology to utilize. The tools for this decision making process will be laid out in full detail.

Wind

Harvesting non-electrical energy from the wind is not a new concept. The earliest known exploitation of wind energy was manifested in sails for boats. From sails, wind technology has developed over millennium to stationary contraptions ranging from simple wooden drag machines to complex composite airfoil machines. Many people praise wind power as being one of the only truly clean and safe energy sources.

Wind power is the world's faster growing energy source. The 2100 MW of wind power added in 1998 was 35% more than 1997 (Chiras, 2000). Although, Europe is leading the world in new wind machines, the U.S. is slowly pursuing the exploitation of this resource. Most of the new wind power installed is in the form of monstrous multimegawatt generators, the market for small household systems is still developing. One nice thing about wind is that it is available practically everywhere.

The Early Beginnings of Wind Power

The evolution of wind machines took three basic steps: 1) simple, light machines using drag force, 2) heavy material-intensive drag machines, 3) light, material-efficient aerodynamic lift devices. Wind harvesting designs can be divided into two basic orientations: vertical and horizontal axis machines. The first wind machines were vertical axis grain mills used by the Persians [Dodge 2001]. These relied on simple differential drag forces creating a torque around a vertical pole [Figure 2-1]. Independently, the Chinese supposedly build vertical axis windmills around 2000 years ago; however, the first documented vertical axis Chinese windmill was constructed by the Chinese statesman Yehlu Chhu-Tshai in 1219 AD. Here the primary applications were grain grinding and water pumping [Inglis 1978].

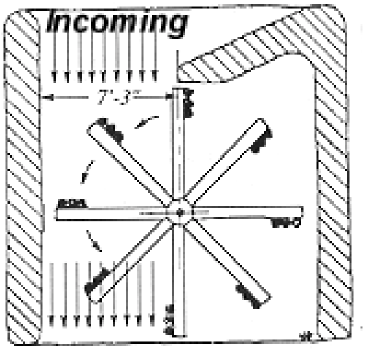


Figure 2-1: Persian vertical axis drag machine design. *From Dodge 2001*

The first documented horizontal axis machines originated in Europe around 1270 AD. These mills were much more efficient than their Persian vertical-axis predecessors, which only had half of their blade area exposed to the wind at any given time. As early as 1390, the Dutch had refined this *post mill* into a multistory building complete with blades on the top floor and several stages of grain grinding and conditioning on lower floors. An improvement in the later European designs was the development of lift forces. The physics concepts behind lift were not understood or analyzed until much later; however, the improvement in power output of these Dutch windmills was significant. Tens of thousands of these windmills with rotor diameters up to 30 meters (5-30 kW) were constructed in the 12th through 19th centuries.

In the middle 19th century, the multi-blade drag windmill energized the American Midwest [Figure 2-2]. Between 1850 and 1970 over 6 million small (1 horsepower or less) windmills were installed in the U.S. alone. Most were used for pumping water for livestock in places too remote for grid electricity.

Figure 2-2: Midwest drag machine used for pumping water. *From Dodge 2001*

The first use of a large windmill to generate electricity was a system built in Cleveland, Ohio, in 1888 by Charles F. Brush. The Brush machine had a rotor with a 17 meter and step up gear box to turn a generator. This machine was capable of producing 17 kW (compared with 70-100kW for a comparable-sized modern wind generator). The first commercial electric power machine was constructed in Vermont starting in 1939. It's large size (rotor diameter 53 m. and full power rating 1.25 MW) was not enough to keep it in commission after WWII when cheaper alternatives flooded the market. Fossil fuels became so inexpensive that the less convenient wind generator technology was essentially put on hold.

Technologies

There are two main types of modern vertical axis wind machines: Savonius rotors and Darrieus rotors. Savonius rotors were officially invented by Sigurd J. Savonius of Finland in the early 1920's; however, they were probably used shortly prior to that time by others [Park 1981]. This type of wind machine is a drag device typically with a cup to catch the wind on one side of the rotational axis and a aerodynamic shape on the other side of the axis, thus creating a torque [Figure 2-3]. The Darrieus rotor, invented by a Frenchman, G.J.M. Darrieus in the middle 1920's, is a slightly more sophisticated device utilizing lift forces rather than drag forces. Sometimes called an Eggbeater Rotor, the Darrieus Rotor uses long curved blades to generate lift such that a torque about a vertical axis is created [Figure 2-4]. Some large scale wind generation facilities employ Darrieus rotors; however, in general vertical axis machines are only seldomly used in modern electricity production.

Small commercially available modern wind generators are almost strictly horizontal axis, propeller machines. Some people have designed and constructed their own vertical axis machines from old barrels and the like; however, finding non-conventional wind machines on the market is difficult. Additionally, there is not much variety among the horizontal axis machines available for small production. They are typically comprised of a propeller with 3 (occasionally 2) blades between half a meter and 2 meters and a gear box/generator that sits immediately downwind of the propellor.

New incremental improvements in blade design over the past decade have slightly increased the efficiency of wind machines and greatly reduced the associated noise pollution.

Figure 2-3: Crude Savonius rotor constructed from old barrels. *From Park 1981*

Calculating the Potential for Wind Energy

Winds on Earth are generated by uneven solar heating; thus, in essence wind energy is a form of solar energy. Although locally variable, a general pattern of global winds has been identified. The different wind regions tend to follow layers that run parallel to the latitude lines. Straddling the equator is a band of typically very low velocity winds (The Doldrums) on top of which is a band of northeast trade winds to about 30N followed by another low velocity layer (The Horse Latitudes). Above the Horse Latitudes to about 60N are typically westerlies followed by polar easterlies. The southern hemisphere is a mirror image of the northern hemisphere.

Much more useful than this general worldwide data are wind resource maps compiled from data collected over a couple of decades. Figure A-1 has a wind resource map for the United States. These maps identify regions in terms of energy per meter squared of area. Often regions are divided into seven categories of wind speed (not used in this paper). In general, as can be seen from this map, winds are typically strongest near the coasts and the Great Plains region.

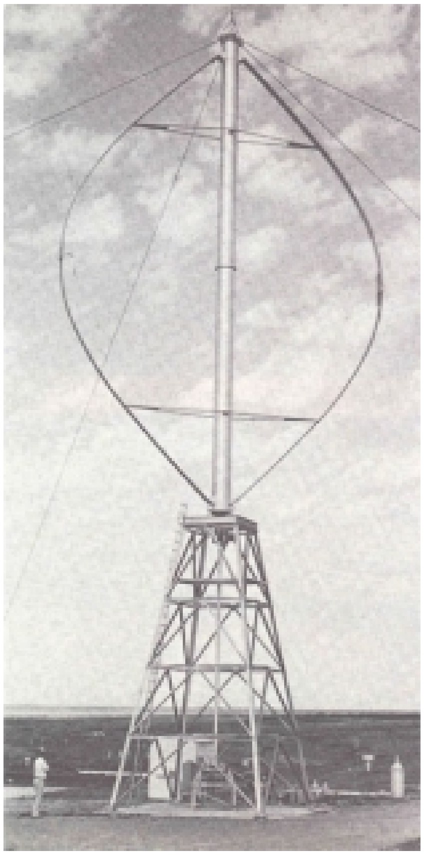


Figure 2-4: Darrieus rotor used for irrigation in Bushland, TX. *From Park 1981*

Wind power has a cubic dependence on wind speed (Eqn 2-1). In this equation, ρ is the density of air; V is the wind speed (converted from mph to m/s with Equation 2-2); A is the area of the rotors (calculated from the rotor diameter by Equation 2-3); E is the efficiency of the wind machine (typically 0.1 to 0.5).

$$P = \frac{1}{2} \text{ x } \rho \text{ x } V^3 \text{ x } A \text{ x } E \tag{2-1}$$

$$V_{m/s} = .447 * V_{mph} \tag{2-2}$$

$$A = \Pi/4 * D^2 \tag{2-3}$$

At sea level and 60F, the density of air is 1.226 Kg/m^3. Because this density varies with temperature and altitude, correction factors should be multiplied by this density to adjust for these variations (Table 2-1).

		Temperature in Fahrenheit (Celsius)					
		0 (-17.8)	**20 (-6.7)**	**40 (4.4)**	**60 (15.6)**	**80 (26.7)**	**100 (37.8)**
Altitude in feet (meters)	**0**	1.130	1.083	1.040	1.000	0.963	0.929
	2500 (762)	1.031	0.988	0.949	0.912	0.878	0.847
	5000 (1524)	0.940	0.901	0.865	0.832	0.801	0.773
	7500 (2286)	0.854	0.819	0.786	0.756	0.728	0.702
	10000 (3048)	0.776	0.744	0.715	0.687	0.662	0.638

Table 2-1: Air Density Correction Factors for Temperature and Altitude

Example problem: The manufactures of the Whisper 175 (with a 4.26 meter diameter) specify that their product will generate a peak 3000W in a 27mph wind at sea level at 60F. What is efficiency at which they estimate their machine?

To solve this problem, we will begin by calculating the power potentially available to the wind machine under the conditions. The density of air at sea level and 60F is $\rho = 1.226*1.000 = 1.226$ Kg/m^3 where 1.000 is the correction factor from the Table 2-1 (sea level and 60F are the standard conditions at which to write wind machine specifications). The velocity of the air at 27mph (from Eqn 2-2) is V = 12.07 m/s. The area of the rotors (from Eqn 3) is $A = \Pi/4*(4.26)^\wedge 2 = 14.25$ m^2. Now everything is in place for the potential power calculation: $P = .5 * 1.226 * (12.07)^3 * 14.25 = 15360$ Watts.

If the Whisper 175 were 100% efficient at capturing the energy in wind (thermodynamically impossible), it would generate more than 15 kW under these conditions. This machine has an efficiency of E = 3000/15360 = 0.19, a reasonable value for small wind generators.

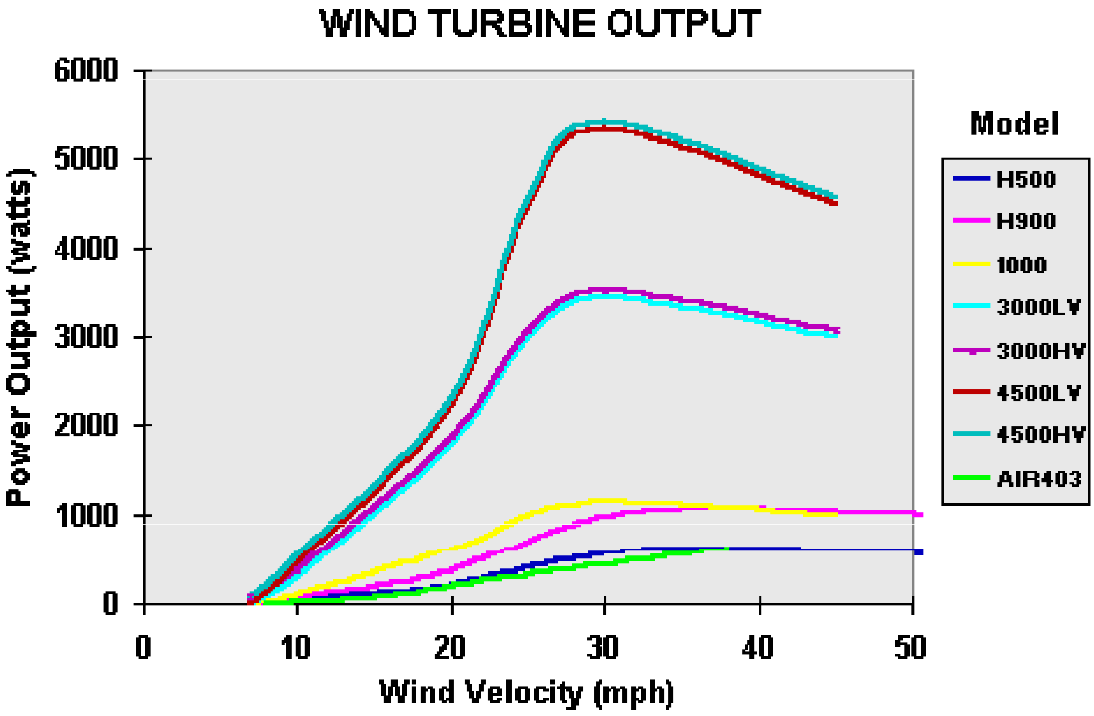


Figure 2-5: Output for selected wind turbine models. *From NoOutage 2001*

Positioning Considerations

Correctly positioning a wind generator relative to its surrounding is as important as choosing a good, windy geographical location. The available wind energy varies significantly with height above the ground due to increased wind speed. The amount of change between the wind speed at the ground and the wind speed some distance above the ground depends on the *surface friction coefficient*, a measure of the roughness of the terrain. The appropriate coefficient for an area can be taken from Table 2-2. With this information, the adjusted wind speed can be calculated (Equation 4) where V is the wind velocity, H is the height above the terrain (not the ground), and α is the surface friction coefficient.

Description of Terrain	**α**
Smooth, hard ground; lake or ocean	0.10
Short grass on untilled ground	0.14
Level Country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22-0.24
Wooded county; small towns and suburbs	0.28-0.30
Urban areas, with tall buildings	0.40

Table 2-2: Surface Friction Coefficients
From Park 1981

$$V_B = V_A * (H_B/H_A)^{\alpha} \tag{4}$$

Therefore, if a generator in an area with trees and buildings (say $\alpha = 0.24$) is positioned 20 meters above the trees instead of 10 meters, then the average wind speed would be $(20/10)^{0.24} = 1.18$ or 18% higher. Since the power goes as the cube of the speed this would result in 65% more available energy. If you use an anemometer on the site to observe wind data, this approximation can help correct for height differences between the anemometer location and the actual wind generator location.

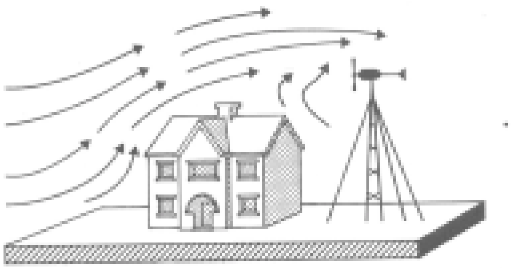


Figure 1a. The house is diverting the wind stream above the generator, which should either be raised or moved.

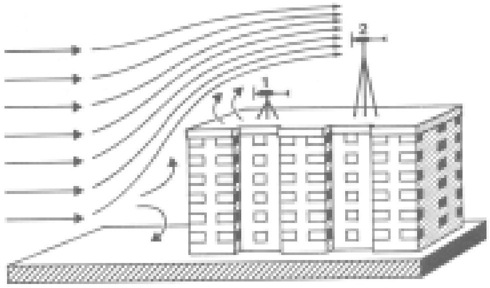
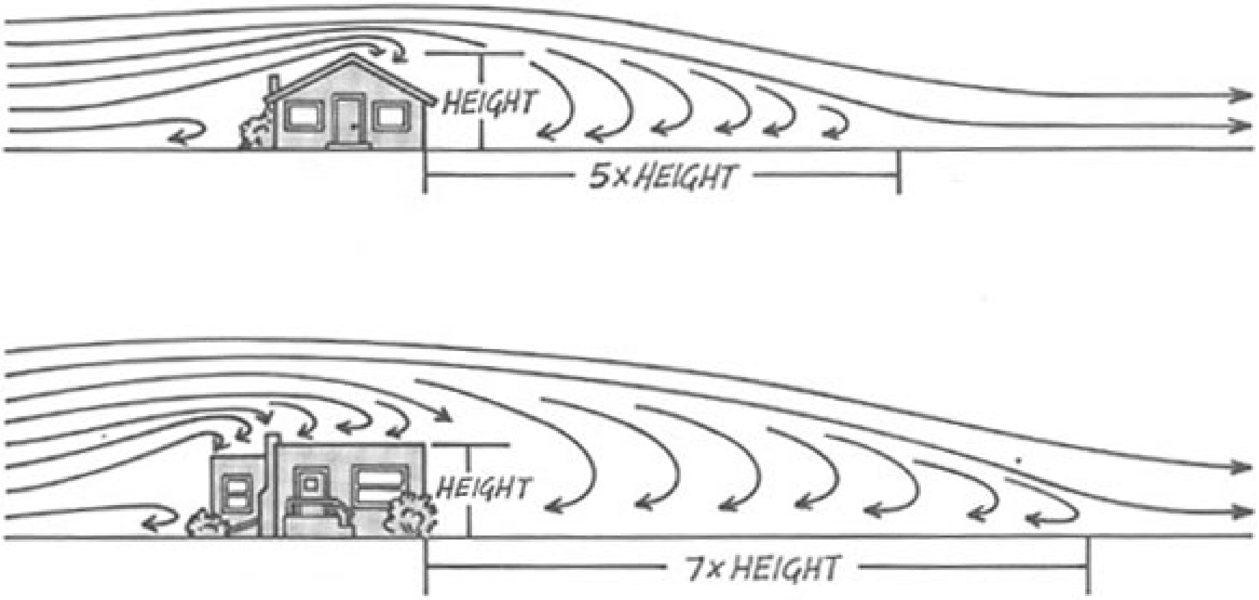


Figure 1b. Again, the building is diverting the wind stream from generator 1, but actually increases the wind speed for generator 2.

Figure 2-6: Wind flow patterns around buildings.
From McGuigan 1978

Turbulence is caused by wind blowing around or over obstacles. Often stall zones and eddy currents will be created, which significantly impact the wind speed in a specific location. To best minimize the potential impacts of nearby wind blocks, a general rule of thumb for best results is to place a windmill 10m above anything within a 100m radius. When this isn't possible, there are many considerations for placement of a wind turbine to minimize the effects of adjacent buildings and structure. Figures 2-6 and 2-7 highlight some of these considerations; for further information, the texts by McGuigan and Park are recommended.



Substantial turbulence occurs on the downwind side of buildings. This turbulence is greater for buildings with sharp edges.

Figure 2-7: Turbulence around sharp edged buildings.
From Park 1981

Economics

On large scales wind generators are beginning to become very competitive with other forms of electricity generation. On smaller scales, one needs motivations outside of economics to justify the purchase. However, compared to other small scale renewable energy sources, wind power is cheap. As fossil fuel prices continue to rise, the economic justification for small-scale wind energy becomes closer to possible.

In Appendix C, is an incomplete list of wind harnessing products available on the market as April 2001. Prices should naturally be expected to fall. In general the going price for wind energy is around $2/peak Watt [Figure 2-9] ranging from $1 to $3/peak Watt depending on the quality of the machine. The curves in Figure 2-10 were taken from an unverified internet site; however, back calculating the required wind machine efficiency to make these curves (as done in the first example problem) yields reasonable results and thereby gives validity to the lines.

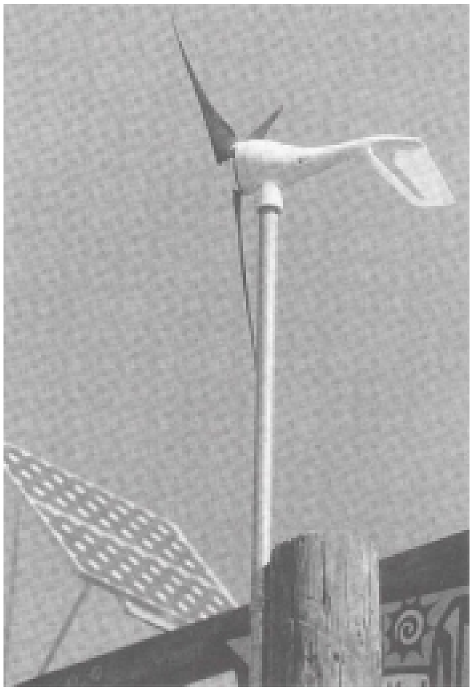


Figure 2-8: AIR403, a small 400W wind generator

The wind machines covered by this survey have only 2 to 3 year warranties. Wind machines tend to be high maintenance (especially in comparison with solar products which usually sport 20+ year warranties).   Keep this in mind when considering an economic comparison of products.

Often the number that most interests potential wind generator purchasers is the *time to payoff*. Naturally, this calculation will require many assumptions about the lifetime of the machine, the reliability of the wind resource, and the stability of the local economics (i.e. energy prices and inflation rates). However, despite the assumptions, a reasonable and useful guess can be calculated to give consumers a notion of how long term their investment is.

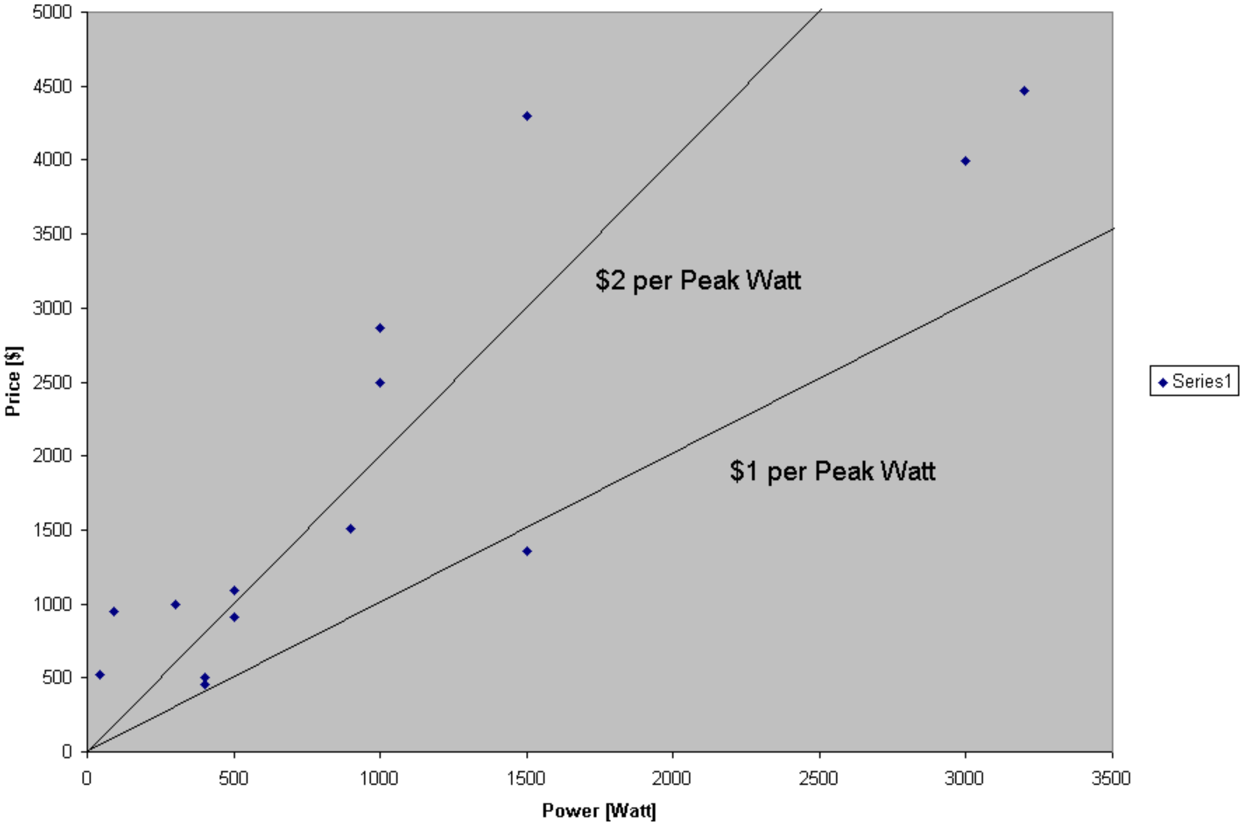


Figure 2-9: Distribution of price versus peak power for selected wind generators.

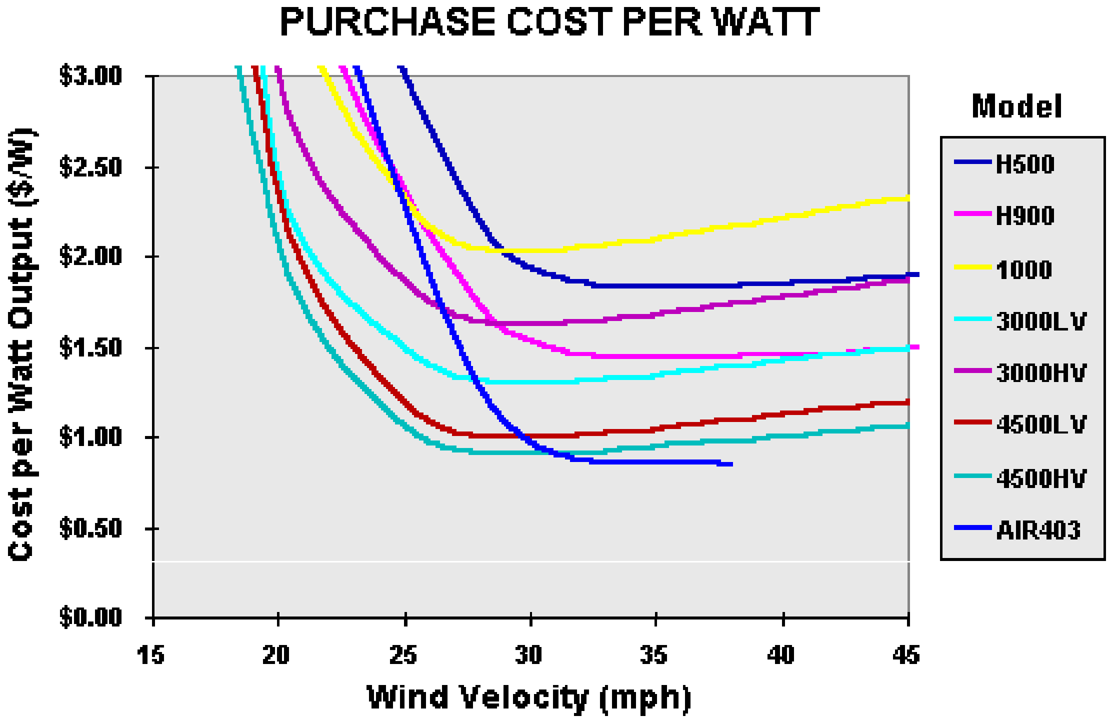


Figure 2-10: Cost per watt as a function of wind velocity for selected wind turbines. *From NoOutage 2001*.

The first step in calculating the payback time is to estimate the number of kilowatt hours that the wind generator will produce annually. To do this, first find the annual average power per square meter from the charts in Appendix A for the specific location in question. Then, using Table A-1, take this number with the rotor diameter and find the corresponding kWh/year number on the table. This table assumes a 0.2 efficiency for the rotor. If you know the rotor to have a significantly different efficiency, multiply the number from Table A-1 by (eff/0.2). This number is your kWh/year.

The next step is to calculate the expected annual income from the energy production. This is as simple as multiplying the kWh/annum by the going rate for a kWh. If you are simply turning the meter backward (see the section on Connecting to the Grid), then this rate is the same as the rate at which you are billed (often between 7 and 15 cents/kWh). Since the payoffs will be coming in the future, they must be adjusted for inflation. Equation 1-4 gives the expected time to payoff, N, in years where I is the inflation rate (usually assumed at 5%), C is the capital cost of the generator, and A is the annual income as calculated above. Table A-2 has the payoff times for a few selected values of capital cost and annual electricity production.

$$N = -(2/I) * \ln[1 - (C/A) * (1-e^{(-I/2)})] \qquad (1\text{-}4)$$

Example Problem: A World Power 3000 (rotor diameter 4.57m) is sold for \$4470 to a farmer in central Kansas. According to the specification sheet, in a 27mph wind it will generate 3200W of electricity. Assuming \$0.10/kWh payback and 5% interest, how many years will it be until the wind generator has paid itself off?

The solution begins by finding the generator efficiency as demonstrated in the previous example problem. Reproducing that calculation suggests a total potential power of 17.7 kW, yielding an efficiency of E = 0.18. From Appendix A, central Kansas receives an annual average of 300W/m^2. From Table A-2, a 4.5m diameter rotor (slightly conservative) with 0.2 efficiency and an annual average of 300 W/m^2 can be expected to yield 8365 kWh/year. This rotor with 0.18 efficiency should be expected to yield

0.18/0.2 * 8365 = 7529. At $0.10/kW this is $753/year. Now, one simply needs to substitute into equation 1-4 to find the number of years until payoff (C = $4470; A = $753; I = .05). The generator should be expected to pay for itself in 6.3 years. With a little care, this rotor will probably last well more than 6 years; however, the manufacturers warranty is only for 2 years.

Environmental Impacts

The environmental impacts of wind energy are very minimal compared with most forms of energy production. The impacts can be broken down into two categories, production costs and operation costs. The production costs consist mostly of materials and energy of assembly. For small, home wind generators casings are typically high density plastics and occasionally carbon fibers. Steel and copper are the major constituents of the windings and circuits. In general, the hazardous waste content in a wind generator is very low. The energy involved with assembly is not more than might be expected for a machine of its size (unlike solar cells).

The operation costs consist of land usage impacts and disruption of avian life. Both of these are really only issues for large wind turbines, which do occupy large spaces and are notoriously responsible for the death of birds. Wind generators on the order of a few kilowatts present no significant threats in either of these areas. Noise pollution has been a persistent problem for wind generators; however, new models have significantly reduced this issue. Nevertheless, it is recommended that generators be installed securely (to prevent rattling) and in a place sufficiently distant from sleeping quarters.

Solar

If you were asked to design an ideal energy source, it would be pretty difficult to come up with something better than the photovoltaic (PV) cell. Comprised of almost entirely silicon, the most abundant element on earth, it captures sunlight, the most abundant energy source on earth, and converts it directly into electricity, the most versatile form of energy known. The total solar energy input to the earth is more than 15000 times greater than the earth's current production of energy from all sources (Boyle 1996). One would only have to cover less than 10% of Kansas with solar panels to supply all of the U.S. with electricity (more on that later).

In the United States, typical direct sunlight is around 800 to 900 W/m^2 and diffuse sunlight is around 100 to 200 W/m^2. An "hour" of sunlight is defined as the number of effective hours during a day at a nominal 1kW. Most places in the US receive between 4 and 6 "hours" of sunlight per day, perhaps up to 8 "hours" in the desert areas.

Because of its reliability and low maintenance, photovoltaic cells are becoming increasing popular for harvesting the sun's energy. 400,000 families in less-developed nations rely on PV. 40,000 homes in the U.S., mostly in remote locations, use PV (Chiras, 2000). Increasingly PV systems are popping up in areas where electrical lines run nearby. These cells are connected to the electrical grid to decrease the demand from other electrical power stations. Solar power is the world's second fasting growing energy source at a growth rate of 16 percent per year since 1990 (Chiras, 2000).

Passive solar has been around since the beginning of human existence. Technologies for more efficiently capturing and utilizing this solar heat energy are conceptually diverse and geographically widespread. This paper will focus on the much more contemporary subject of solar *electricity* generators, namely photovoltaics. In all fairness, however, if the goal of the energy generation system is to produce heat, it is *much* more sensible to use solar thermal energy, not solar electric energy.

Figure 2-11: Edmond Becquerel first discovered the photoelectric effect

History of Photovoltaics

French physicist Edmond Becquerel [Figure 2-11] first described the photovoltaic effect in 1839, but it remained unexplored until the 1870s when Heinrich Hertz produced the first PV cells that converted light to electricity at 1% to 2% efficiency. Solar cell efficiency is defined as the proportion of solar radiation energy incident on its surface that is converted to electrical energy. The next big step in the commercialization of PV cells was the creation of the Czochralski process in the 1940s, which generated high purity silicon. But it was not until 1954 when Bell Laboratories set into motion the development of modern, high-efficiency solar cells (initially up to 4% efficiency) with the development of semiconductor technology.

The efficiency of the best silicon solar cells has now reached 24% in laboratory test conditions (Boyle 1996) and new prism techniques suggest a potentially higher efficiency cell could be created soon. Production of PV modules has increased significantly in the past three decades with the result of increasing efficiency and reducing costs [Figure 2-12].

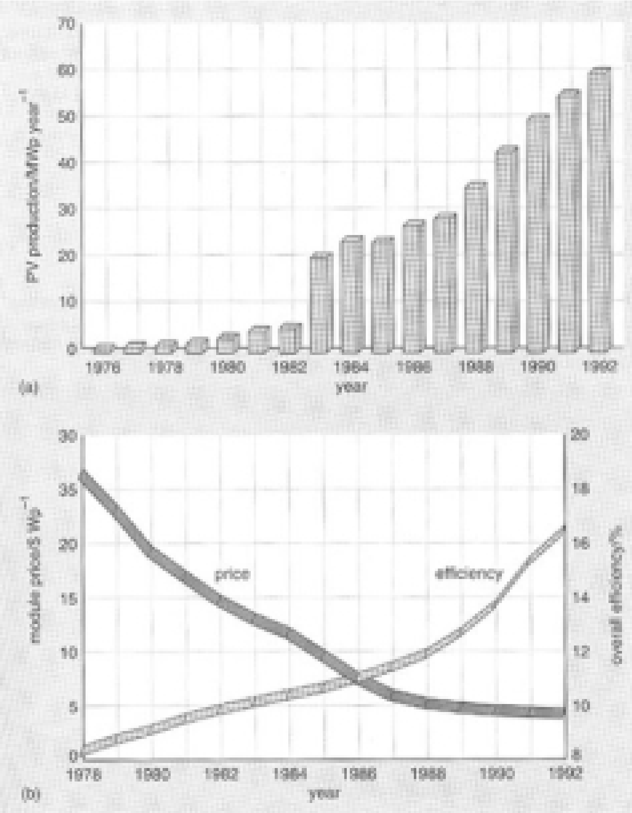


Figure 2-12: Growth of PV 1976-1992
From Boyle 1996

Technologies

The anatomy of a PV cell is rather simple, consisting of basically a piece of silicon doped to be n-type on the top layer and p-type on the bottom [Figure 2-13]. Doping is a process of impregnating the silicon with small quantities of other elements such as Germanium or Arsenic. A single silicon cell produces up to 2.5 amperes at around 0.5V. As standard practice, solar panels incorporate 36 solar cells in series to create a nominal output of around 18 volts.

Photovoltaic cells on the market today come in three main varieties defining a tradeoff between efficiency and cost. The three varieties are categorized by the quality of their silicon crystals. Originally only **monocrystalline** silicon cells (i.e. large single crystals of silicon) were used for collecting solar energy. These cells can generate electricity at up to 16% efficiency (available on the market); however, their production is energy and time intensive and therefore expensive. **Polycrystalline** silicon PV cells consist of many crystals from a few millimeters across to several centimeters in diameter. They can obtain efficiencies around 10% and are the most common choice for home PV energy systems. Another advantage of polycrystalline silicon is that it can be easily formed to fit a square shape. Monocrystalline PV cells are formed in cylinders and cut into circles. They can either fill a panel as circles (waste of space) or be cut into squares (waste of crystallized silicon). **Amorphous** silicon (a-Si) PV cells have no large scale crystal structure and can be produced relatively quickly and cheaply; however, they have a lower efficiency of around 5%. The real advantage of a-Si cells is the capacity to produce thin films for lightweight applications.

The world of PV cell production is constantly advancing and new techniques under development now promise to make future solar cells even cheaper. Some companies such as Evergreen in Massachusetts are refining ways to pull polycrystalline silicon in a ribbon directly out of a batch of molten silicon. This technique would avoid some of the energy, time, and waste involved with slicing up large ingots of silicon crystals.

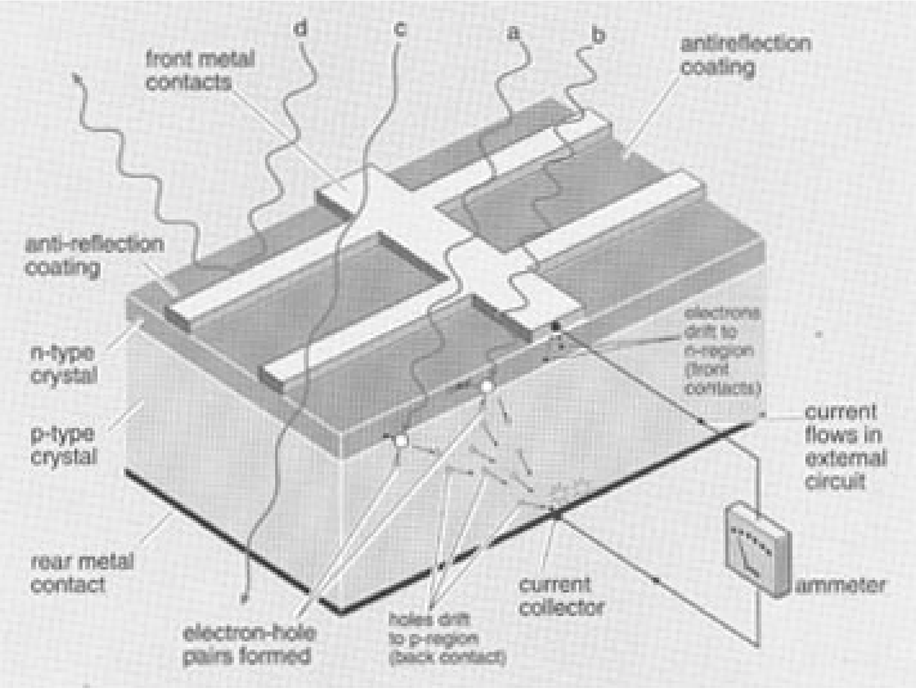


Figure 2-13: PV cell diagram
From Boyle 1996

Calculating the Potential for Solar Energy

Due to variation in incoming solar radiation, the capacity to generate solar power varies tremendously with location. Appendix B should give a rough approximation to the expected solar influx for a given location. The first chart [Figure B-1] shows annual radiation averages for areas in the United States. This chart is particularly useful for people choosing a location for building a new solar house. It is also useful for solar systems that will be connected to the main power grid. However, this chart will not help specify a minimum size for a PV array such that sufficient power will be available year round. For that information, the seasonal charts [Figure B-2] will help. From these charts one can find the minimum solar influx (usually during winter) and make arrangements to have enough power even under these conditions.

Converting the numbers on the insolation charts to usable power numbers is straightforward. The power capacity rating given to solar panels by the manufacturer is calculated by multiplying the area times the efficiency times 1000 W/m^2* [Eqn 2-5]. To calculate the expected electricity generation given the insolation in Whr/m^2 (from Appendix B), simply multiply the insolation, I, by the area and the efficiency [Eqn 2-6]. Therefore, to go directly to electrical energy generated, Whr/day, from the panel rating and the insolation, one must only divide the panel rating by 1000 and then multiply by the incoming radiation [Eqn 2-7].

$$P_{rated} = A * E * 1000 \qquad (2\text{-}5)$$

$$Whr/day = I * A * E \qquad (2\text{-}6)$$

$$Whr/day = I * P_{rated} / 1000 \qquad (2\text{-}7)$$

One further consideration is the angle at which the solar collectors are placed. If the panels are oriented at the same angle from horizontal as their latitude, then they will point directly at the sun during the equinoxes [Figure 2-14]. If possible they should be tilted toward horizontal slightly (up to 11 degrees more) during the summer and closer to perpendicular during the winter.

Example Problem: Suppose a solar powered farm in central Kansas has 3200 rated peak watts of solar panels. How many kilowatt hours should it be expected to generate per year? How many kilowatt hours should it be expected to generate per day in the winter?

To answer the first problem, take the annual average insolation value from Figure B-1. Central Kansas is right on the border between yellow and orange, say 5000 Whr/m^2. To find the average daily energy generated divide by 1000, multiply by the rated power capacity and then divide by 1000 again to convert to kilowatts [Eqn 2-8]. For the yearly total, multiply by 365 [Eqn 2-9]. If these 5840 kWh generated each year are sold back to the utility company at around $0.10/kWh, these panels will generate around $600/year. The calculation for payoff time on solar products is exactly the same as the calculation done above for wind products. During the winter, however, the average insolation is only around 4 kWh/day [Figure B-2b]. Therefore, instead of the average 16 kWh/day offered by these panels, one should only expect 12.8 kWh/day. If this system were independent of the grid or a separate generator, this minimum daily value should determine the size of the array.

$$\text{kWh/day} = 5000/1000 * 3200 / 1000 = 16 \tag{2-8}$$

$$\text{kWh/year} = 16 * 365 = 5840 \tag{2-9}$$

*Solar panels are rated (by international agreement) at 25C and 1000W per square meter of incoming solar radiation distributed with a carefully specified frequency distribution intended to reflect the natural environment.

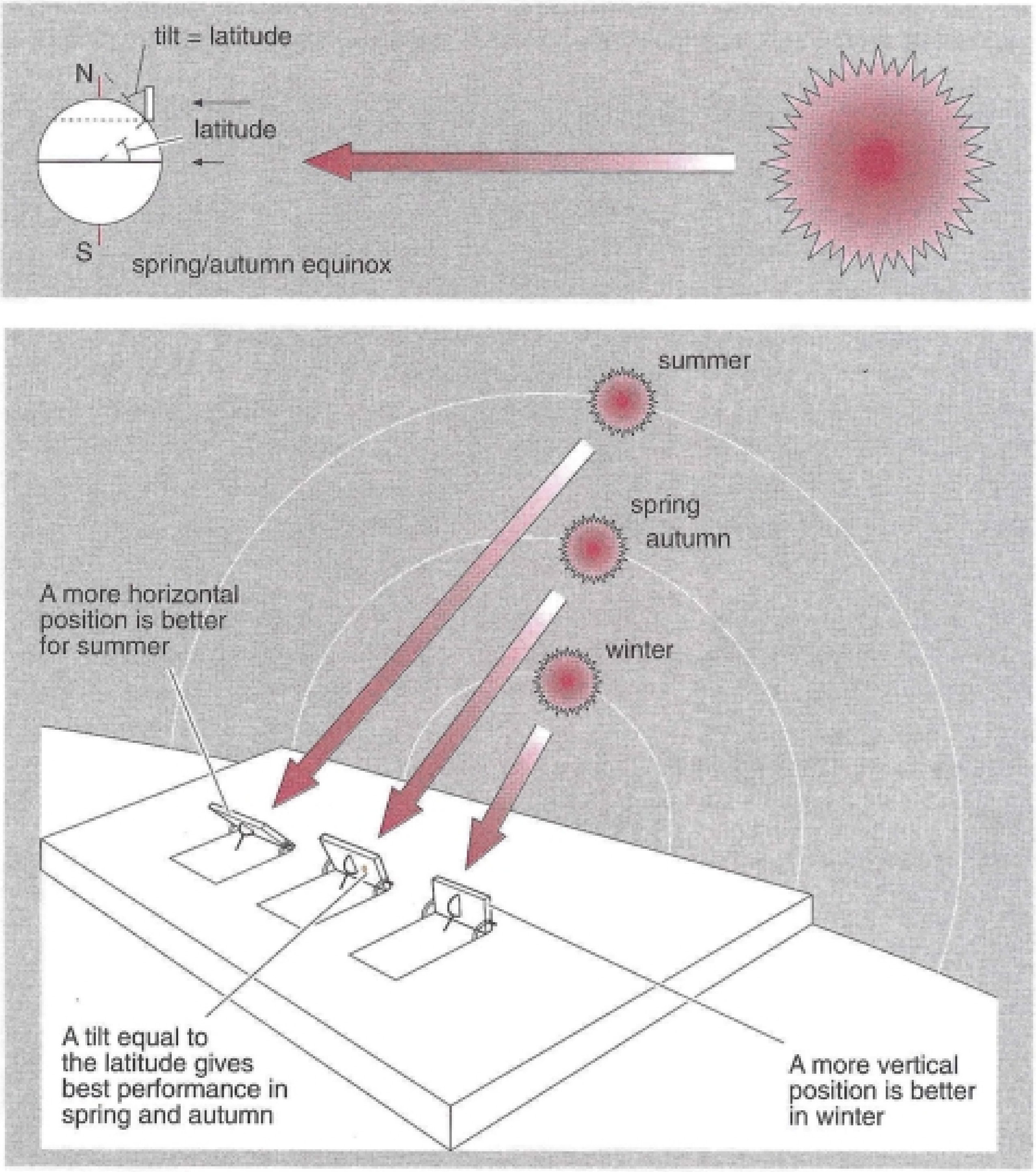


Figure 2-14: For maximum year round capture, align the solar panels such that the tilt equals the latitude. Slight variations during the summer and winter can improve performance.
From Boyle 1996

Economics

Unlike most other energy systems, PV cells require a only a modest operation cost. Apart from an occasional washing, maintenance requirements are very minimal and most solar systems come with a 20-25 year warranty. It is hard to find products that offer such long warranties! With no maintenance or fuel costs, solar panels can produce electricity for a long time with only capital cost expenditures.

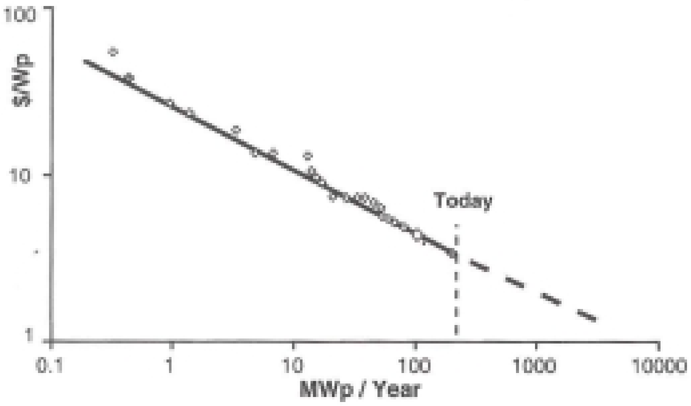


Figure 2-15: Log-log showing progressive decrease in module cost with increased production output over the past 20 years.

From Mason 2000

Unfortunately, the capital costs of a new solar cell system can sometimes be prohibitive. The good news is that these prices show a steady logarithmic decline with increased production [Figure 2-15]. Based on the survey conducted for this paper, the purchase of individual, small (few hundred watt) panels, seems to run around $\$5/W_{peak}$ [Figure 2-16]. However, larger packages can be purchased wholesale for between $3.25 and $3.75 per peak Watt. For a list of single solar products, see Appendix D1.

In some cases, PV systems can result in additional, often unexpected benefits. For example, a roof top solar panel will absorb a significant portion of incoming solar energy. This is energy that would otherwise go into heating the roof. Thus, during the summer a roof top PV system can decrease air conditioning

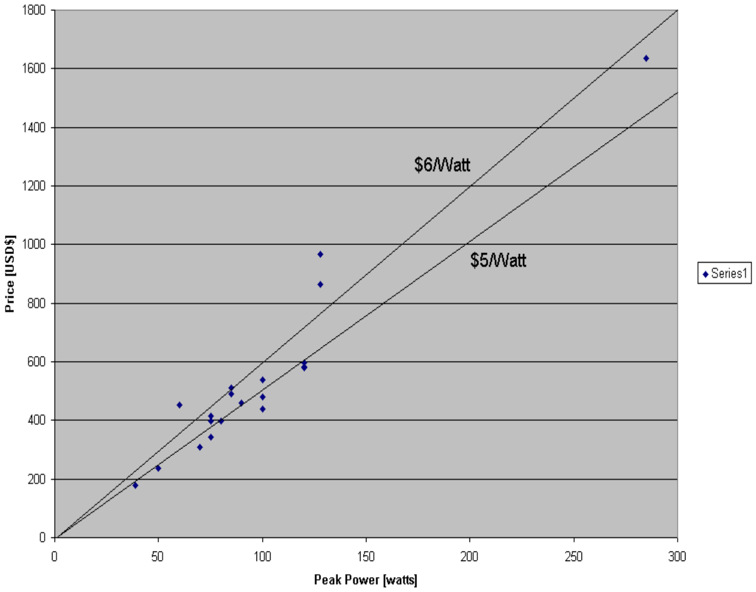


Figure 2-16: Distribution of price versus peak power for selected PV panels

load by decreasing the heat coming in through the roof.

Environmental Impacts

The utilization of PV cells can be one of the most environmentally benign energy sources available; however, the environmental impacts of PV cell manufacturing should not be ignored. Being passive devices, solar panels are not prone to high maintenance requirements and do not threaten surrounding wildlife or habitats. They do occupy some space; however, they are often suitably placed on the roof of a house and, unlike wind generators, they do not place requirements on surrounding habitat or structures.

Despite recent innovations, the PV manufacturing process leaves much to be desired [Figure 2-18]. Currently, the process is extremely energy intensive and since nearly all of the electrical energy available today comes from fossil fuels, this means emissions. It takes two to three years of use before solar panels generate more energy than it took to produce them. The introduction to this section suggested that only 10% of Kansas would have to be covered with PV to supply electricity for the entire U.S.; however, the energy required to make these PV cells would be many times the U.S. annual energy consumption! Furthermore, the process involves a significant usage of hazardous elements such as Arsenic and Cadmium.

Other options

Many other less well-publicized methods for generating electricity exist. It would be a shame to think that wind and solar were the only viable options. Unfortunately, these options will remain out of the scope of this paper. If the home acquiring a new energy system has a fast flowing stream nearby, for example, then the homeowner should sincerely look into the potential for hydroelectric power, which can be very clean, quiet, and inexpensive [Figure 2-17]. The internet is a great place to start for this and other options.

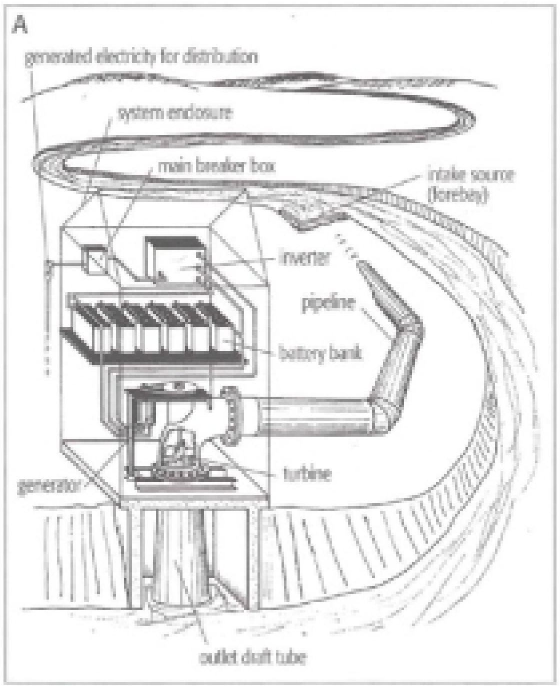


Figure 2-17: Low-head hydroelectric setup. *From Chiras 2000*

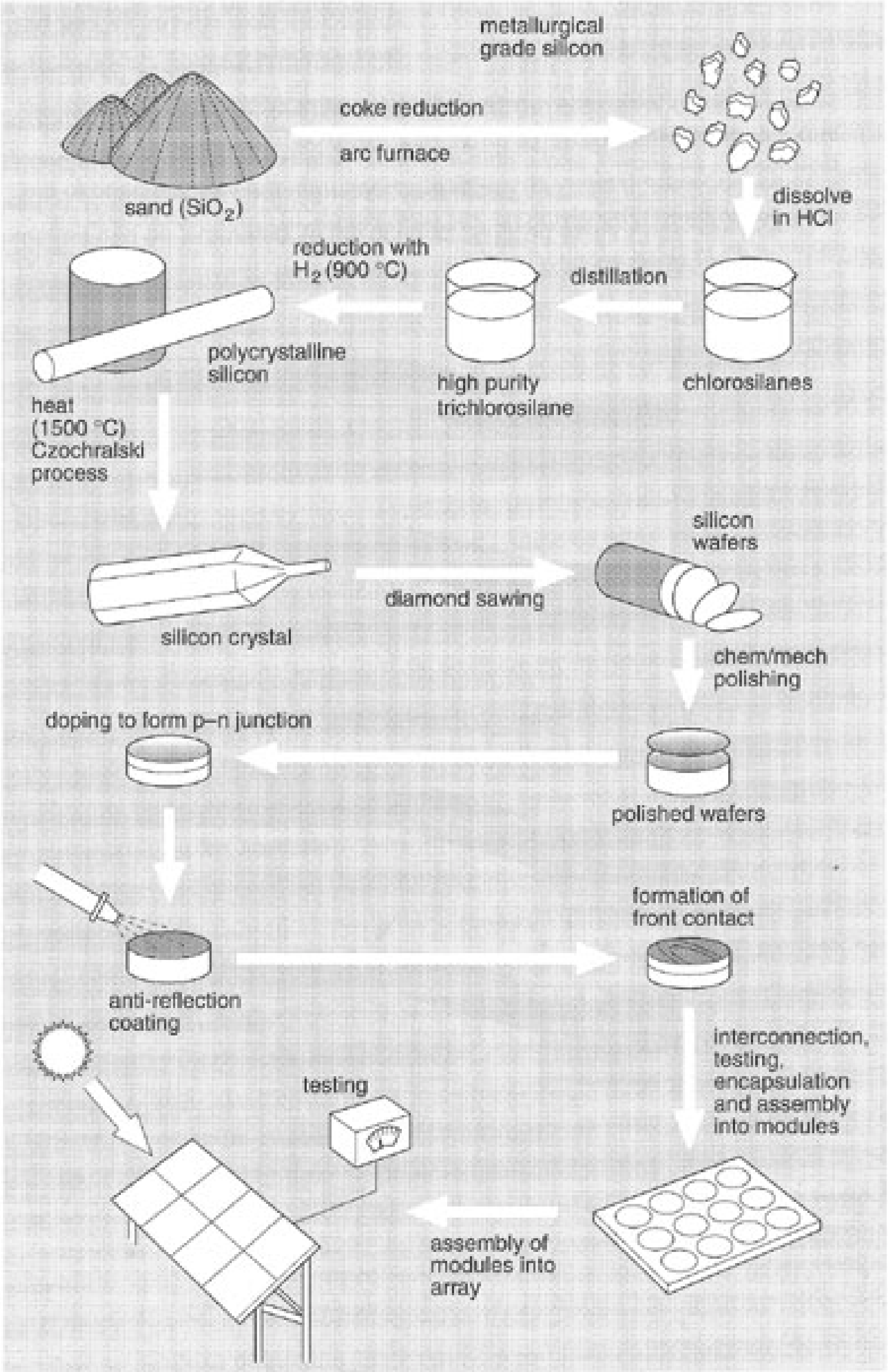


Figure 2-18: Stages in the photovoltaic manufacturing process

From Boyle 1996

III. Storage

The amount of power produced by renewable energy devices such as photovoltaic cells and wind turbines varies significantly on an hourly, daily and seasonal basis due to the natural variation in the availability of the sun, wind and other renewable resources. This variation means that sometimes power is not available when it is needed while on other occasions there is excess power. Electrical storage acts as a buffer to distribute power evenly over time.

For grid-connected systems, electrical storage systems are not strictly necessary, but sometimes included in the system to provide electricity during power line outages and boost the performance of inverters by stabilizing the supply line.

Batteries

The most common and widespread storage technology today is batteries. Batteries come in many types and sizes, but the basic principle revolves around a conversion from chemical energy to electrical energy and vice versa for these applications. Batteries often operate at between 65% and 75% round trip efficiency, meaning that less than three quarters of the electricity put into a battery can be recovered for useful loads.

Technologies

Although there are many types of batteries available for home electricity storage including Nickel-Cadmium (Ni-Cad) and Nickel-Iron (Edison), by far the most prominent battery type on the market is the Lead-Acid battery. Lead-Acid is actually a classification that includes several types of batteries: Lead-Calcium, Lead-Antimony, and pure-Lead. Before delving into the pros and cons of different batteries, several key battery terms should be defined:

Self-discharge rate- the rate at which a battery will discharge itself, not supplying useful current. This rate should be as low as possible.

Maximum charge rate- The maximum rate at which a battery will accept a recharge.

Cycle life – The number of charge-discharge cycles to a specified percent depth of discharge (DOD) before battery loses significant capacity.

Lead-Calcium batteries are most suitable for home energy systems. They require minimal maintenance and rarely need replacement of water. However, their maximum charge rate is low compared with other battery types and they do not cycle as deeply (only 10 to 20 percent per cycle). Lead-Antimony batteries are higher maintenance, but will cycle to 50 - 80% DOD. Pure-lead batteries should not often be cycled below 10% DOD. They are typically only used as backup systems.

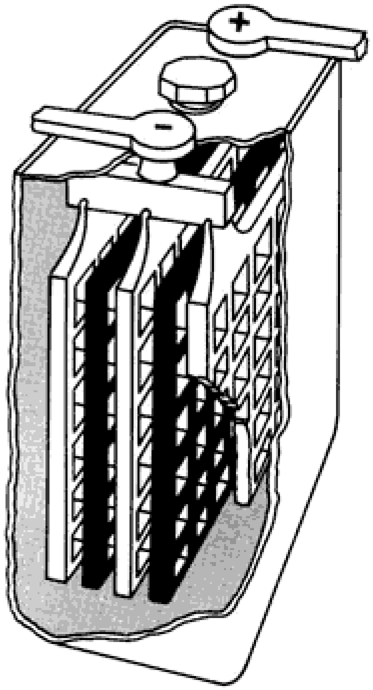


Figure 3-1 Anatomy of a Sealed Gel Cell

To avoid maintenance issues, some homeowners choose sealed gel cells [Figure 3-1]. Although they do not require equalizing and can not lose fluid, they cost two to three times as much as regular Lead-Acid batteries and don't last as long. In the long run, it makes more sense to buy standard Lead-Acid and put in the small amount of maintenance time. Maintaining the battery room temperature between 50 and 80°F is very important for battery life and performance. Also, batteries should not be placed on cement floors or against cement walls due to the unequal temperatures in the battery (colder on the bottom), which will cause them to operate less than optimally [Chiras 2000].

Economics

The required battery investment for a home energy system depends on the type of system installed. For grid connected systems, only a minimal battery set is recommended. People not connected with the grid, typically install batteries for a week's worth of power. At a rate of around $150/kWh, this can become a rather large investment. Some climates are more predictable and if you are willing to put up with an occasional power outage, fewer batteries can be used.

Environmental Impacts

Lead-Acid batteries constitute the majority of inorganic lead production in the world. 65% of the weight of a Lead-Acid battery is lead. A significant amount of energy is involved with the processing and manufacturing of this lead. If improperly handled or disposed of, this lead can pose a serious threat to the environment. The good news is that nearly all of the lead from a used lead-acid battery can be recycled.

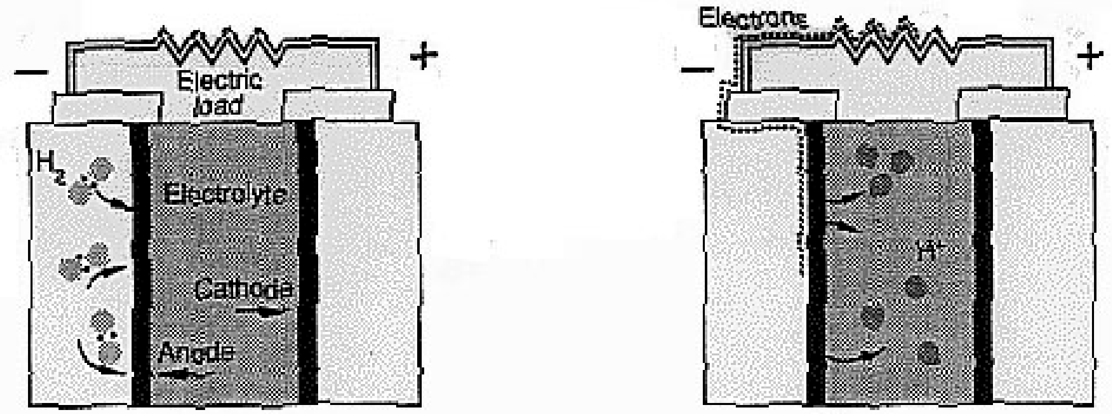
Permeable Electron Membrane Fuel Cells (PEMs)

PEM fuel cells recombine hydrogen and oxygen in such a way as to create electricity [Figure 3-2]. When used in combination with electrolysis (the process of electrically separating hydrogen and oxygen out of water), this can be a powerful storage technique with tanks of hydrogen containing the energy that might otherwise be stored in a battery. Hydrogen can be converted to electricity with around 80% efficiency.

The brilliance of fuel cells is that they are completely emission free. Water is created and water is destroyed. If the process is interrupted somewhere along the chain, only water leaks from the system.

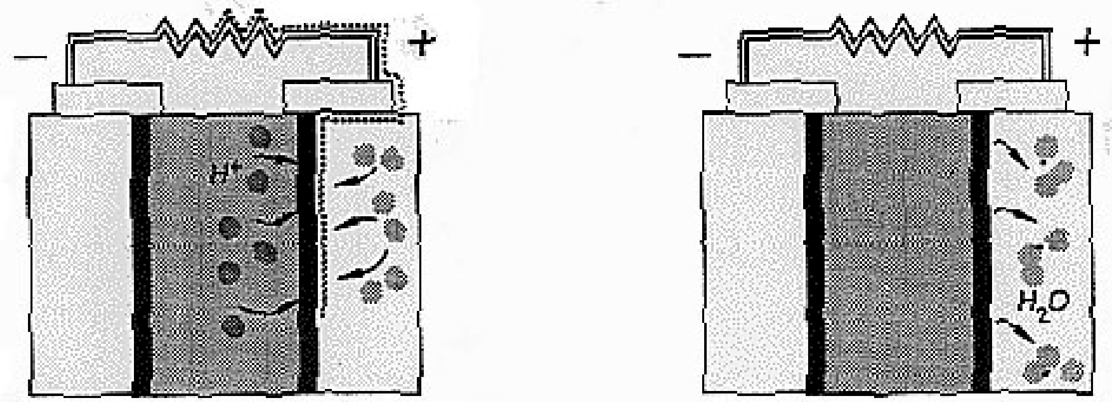
Fuel cell research began with the space program in the 1950's. Unfortunately however, fuel cell technology is still in its infancy. There are a few fuel cell products on the market. For example, Dais-Analytic makes a tiny PEM fuel cell (3x4x4 inches) for power discharges of up to 20W. It sells for $1000. Clearly, at this time it does not remotely make sense economically for the small home owner to invest in the few fuel cell products that are available. Some day, this will be a great technology, which will replace the Lead-Acid battery.

See http://www.iclei.org/efacts/fuelcell.htm for more information.



1. Hydrogen gas flows over the anode.

2. Electrons split away from hydrogen and flow through anode to external electric load.



3. Hydrogen ions move through electrolyte to cathode. Electrons stream into cathode from load. Cathode is bathed with oxygen.

4. Hydrogen, electrons, and oxygen combine to form water (steam).

Figure 3-2: Schematic Representation of fuel cell operation
From iclei.org

IV. Conversion

Inverters

Inverters are a key component to any home renewable energy system. In general, all renewable power sources generate DC power. Although it is possible to purchase DC appliances, this approach is only reasonable in a few isolated situations. Distributing high power DC electricity around a house is inefficient and sometimes dangerous. Therefore, people use inverters to convert their direct current electricity into alternating current electricity.

Technologies

When choosing an inverter there are typically two parameters that need to be calculated. The first parameter reflects the typical load of the house. This is the maximum continuous load to be expected in the home. The second is the peak power (or surge power). High frequency switching inverters such as Statpower, the Heart "Jazz" (formerly Whistler brand), Exeltech, Power to Go, and nearly all the inexpensive inverters in the 50 to 500 watt range are typically surge rated to 25% to 50% maximum overload. Transformer based, low-frequency switching inverters such as Trace and Heart can handle surges up to 300% of their rated capacity. Although the higher-frequency switching inverters don’t have the surge capacity of the others, they are typically lighter and cheaper than their low-frequency cousins.

Inverters come with sine wave, modified sine wave (quasi-sine), and square wave outputs. Many appliances (i.e. motors and microwaves) can only achieve full power with a good sine wave. Some appliances such as bread makers, light dimmers, and some battery chargers will only function with a sinusoidal power supply. Sine wave inverters are always more expensive sometimes by a factor of 2 to 3. Modified sine wave inverters generate a stepped output. They sometimes cause lowered efficiency and extra audible noise in appliances. Because of the increased electrical noise, they sometimes cause timers and clocks to run faster. Only the cheapest inverters produce square waves. They are not recommended.

As with all energy converters, inverters are not perfect. However, modern inverter technologies generate AC electricity from DC electricity at 90-95% efficiency.

Economics

A typical small American home will require at least a 2400-watt inverter. This, of course, depends on the calculated energy needs of the home. Naturally, homes with deep well pumps or other heavy equipment may need larger inverters.

Prices for inverters range significantly depending on size and quality [Figure 2-3]. They usually fall between $0.40 and $1.50 per watt. For specific products see Appendix E.

Connecting to the Grid

Where possible, connecting to the grid makes sense for a variety of reasons including security, convenience, and makes a comfortable transition to decreased dependence on utility power. Change from dirty power to clean power can happen incrementally. The cost savings for tying into the grid can be quite substantial. One can save $1000-$2000 on a generator and between $2000-$5,000 by avoiding the purchase of batteries. Most importantly a grid tie-in allows the environmentally conscious to shunt excess electricity to the grid to help make other people's power greener.

In 1978 the U.S. congress passed the Public Utility Regulatory Policy Act (PURPA), which requires the nation's power companies to purchase excess electricity from small electrical generators, including individual households. By law, utility companies are only required to pay you what it costs them to generate electricity (about a third of what the consumer pays); however, because this would require every home to have two electricity meters most electric utilities just install a single meter which runs forward when the house is drawing net energy and backward when the house is generating more electricity than it uses. In essence, the electric utilities are reimbursing home electricity producers at the same rate they charge customers! The Gods must be crazy! The term used for this arrangement of paying only for the difference between energy used and energy produced is called *net metering.*

Although utilities are required to buy the excess electricity, some may throw major road blocks in the way. They may, for instance, require the purchase of extra meters and then charge a monthly fee to read your meter. Because of this, some people choose to install their renewable energy systems without permission. For more information on this option, read in the Guerrilla Solar section at http://www.homepower.com/rogues.htm.

V. Conclusions

The final decision between solar and wind (or any other renewable energy source) should always revolve around the locally available resources. Trying to extract energy from a resource base that does not exist will only lead to frustration. Here is a brief outline for the recommended approach to making these important decisions:

1. Find ways to **reduce the demand** for electricity. Small reductions in energy requirements can save a lot of money when it comes time to size the system. Conservation should always be the first step in designing a home energy system. This includes finding ways to use solar thermal energy and other direct energy methods. Generating electricity and then converting the electricity back to heat is inherently more inefficient than directly using heat energy. http://www.rmi.org has many good suggestions.

2**. Evaluate demand:** Determine the expected baseline household load and peak power that may be desired**.** Baseline energy calculations should be averaged over at least a week [Figure 5-1]. Peak calculations should be charted versus time of day [Figure 5-2]. Many sources for appliance consumption information exist. Peak power calculations will help size the battery and the inverter, while baseline power numbers help determine the appropriate method of generation. http://www.city.ames.ia.us/electricweb/Energyguy/appliances.htm maintains a list of typical home appliance electricity consumptions.

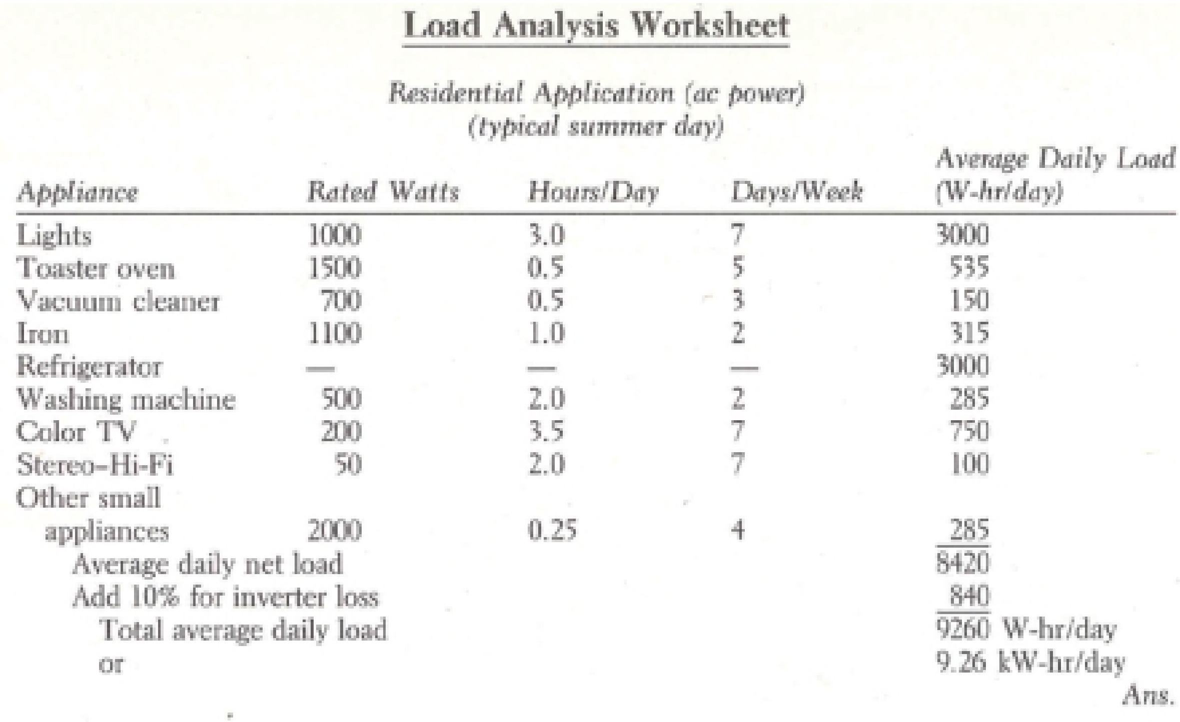
3. **Evaluate resource base**: This is the step that involves determining what energy technologies are appropriate for the specific location in question. Use the charts in the appendices to get a relative feeling for what might be good. Do some of the calculations as outlined in the text to determine how large a specific system would have to be to supply the needed energy. This also includes political resources. Take the time to evaluate potential economic incentives for green energy and selling back to the grid.

4. **Choose generation systems**: Based on the previous evaluation of the available resources decide which technologies make sense. Typically, it's best to diversify as much as is reasonable. The best systems have at least a mixture of wind and solar harvesting capabilities. This enhances the dependability of your resource availability.

5**. Choose accessories:** Choose the inverter and batteries necessary to accommodate the energy generation equipment.

6. **Throw a party**: Have friends over to celebrate your new renewable energy system.

Small changes do make a difference. Changing a home from dirty utility power to clean renewable energy is an important step toward decreasing the human impact on the Earth.



Load Analysis Worksheet

Residential Application (ac power)
(typical summer day)

Appliance	*Rated Watts*	*Hours/Day*	*Days/Week*	*Average Daily Load (W-hr/day)*
Lights	1000	3.0	7	3000
Toaster oven	1500	0.5	5	535
Vacuum cleaner	700	0.5	3	150
Iron	1100	1.0	2	315
Refrigerator	—	—	—	3000
Washing machine	500	2.0	2	285
Color TV	200	3.5	7	750
Stereo-Hi-Fi	50	2.0	7	100
Other small appliances	2000	0.25	4	285
Average daily net load				8420
Add 10% for inverter loss				840
Total average daily load				9260 W-hr/day
or				9.26 kW-hr/day *Ans.*

Figure 5-1: Example home load analysis worksheet.
From Park 1981

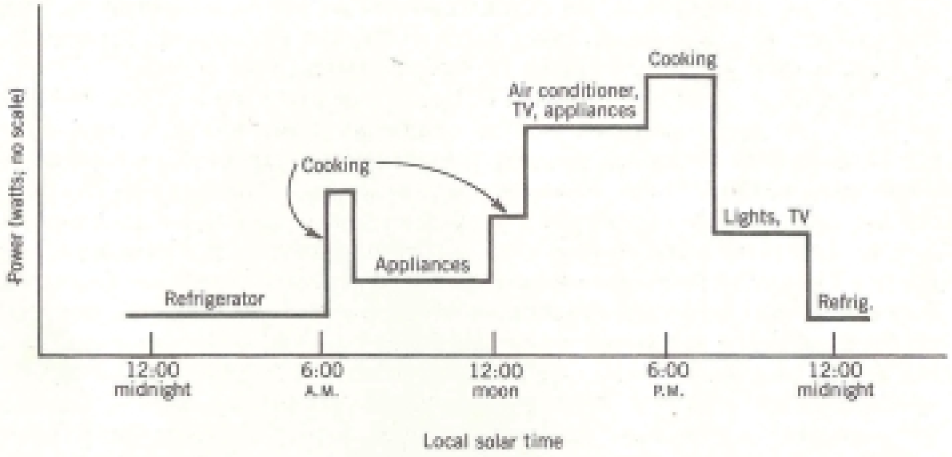


Figure 5-2: Peak load analysis graph.
From Park 1981

References

Boyle, Godfrey (1996) *Renewable Energy: Power for a Sustainable Future*, Oxford University Press, Oxford.

Chiras, Daniel D. (2000) *The Natural House: A Complete Guide to Healthy, Energy-Efficient Environmental Homes*, Chelsea Green Publishing Company, Vermont.

Dodge, Darrell M. (2001) *Illustrated History of Wind Power Development* http://telosnet.com/wind/index.html

ENS (2001) *Evidence of Rapid Global Warming Accepted by 99 Nations* Environmental News Service Jan 22.

Harris, Norman C. (1985) *Solar Energy Systems Design* John Wiley & Sons, New York.

Inglis, David R. (1978) *Wind Power and Other Energy Options*, University of Michigan Press, Ann Arbor.

Mason, N.B. (2000) “Prospects for Power Generation by Photovoltaics” in *Power Generation by Renewables*, Professional Engineering Publishing, London.

McGuigan, Dermot (1978) *Small Scale Wind Power*, Prism Press, Dorchester, Dorset.

Park, Jack (1981) *The Wind Power Book*, Cheshire Books, Palo Alto, CA.

Stitt, Fred A. (1999) *Ecological Design Handbook*, McGraw-Hill, New York.

Appendix A: Wind Energy Potential Charts

This appendix includes a couple of tables for calculating wind potential and a few charts for determining location-specific wind information. For more detailed listings of wind speed averages for every month for hundreds of US and Canadian cities see The Wind Power Book Appendix 2.3. [Park 1981]
Additional, superb wind maps for the US can be found at

http://www.homepower.com/windmap.htm.

	50	*100*	*200*	*300*	*400*	*500*	*600*	*700*	*800*
0.5	17	34	69	103	138	172	207	241	275
1.0	69	138	275	413	551	689	826	964	1102
1.5	155	310	620	929	1239	1549	1859	2169	2479
2.0	275	551	1102	1652	2203	2754	3305	3855	4406
2.5	430	861	1721	2582	3442	4303	5164	6024	6885
3.0	620	1239	2479	3718	4957	6196	7435	8675	9914
3.5	843	1687	3373	5060	6747	8434	10120	11807	13494
4.0	1102	2203	4406	6609	8812	11015	13218	15422	17625
4.5	1395	2788	5576	8365	11153	13941	16729	19518	22307
5.0	1721	3442	6885	10327	13769	17212	20654	24096	27538
6.0	2478	4957	9914	14871	19828	24785	29742	34698	39655
7.0	3373	6747	13494	20241	26988	33735	40482	47228	53975
8.0	4406	8812	17625	26437	35249	44062	52874	61686	70498
9.0	5577	11153	22306	33459	44612	55765	66918	78071	89225
10.0	6885	13769	27538	41308	55077	68846	82615	96385	110150

Table A-1: Kilowatt-hours per annum for rotors with efficiency 0.2.

	100	*500*	*1000*	*5000*	*10000*	*50000*
100	11	2	1			
300	54	63	0.6			
500		11	5	1		
1000		27	11	2	1	
3000			54	6	3	0.6
5000				11	5	1

Table A-2: Payback time [years] for given capital costs and yearly production rates (assumes 5% interest and $0.10/kWh earnings).

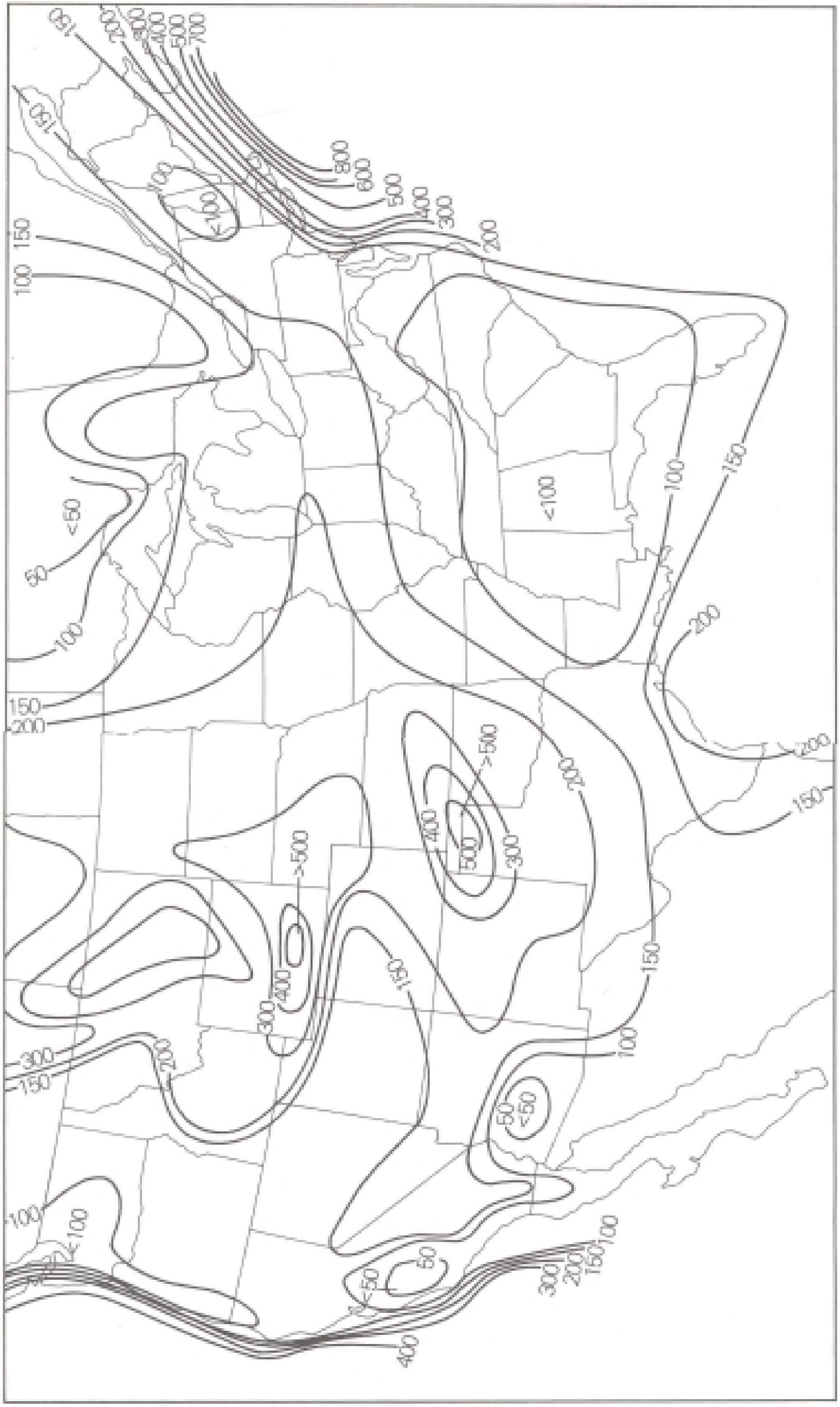


Figure A-1a: Spring Average Wind Power Available, in watts per square meter. *From Park 1981*

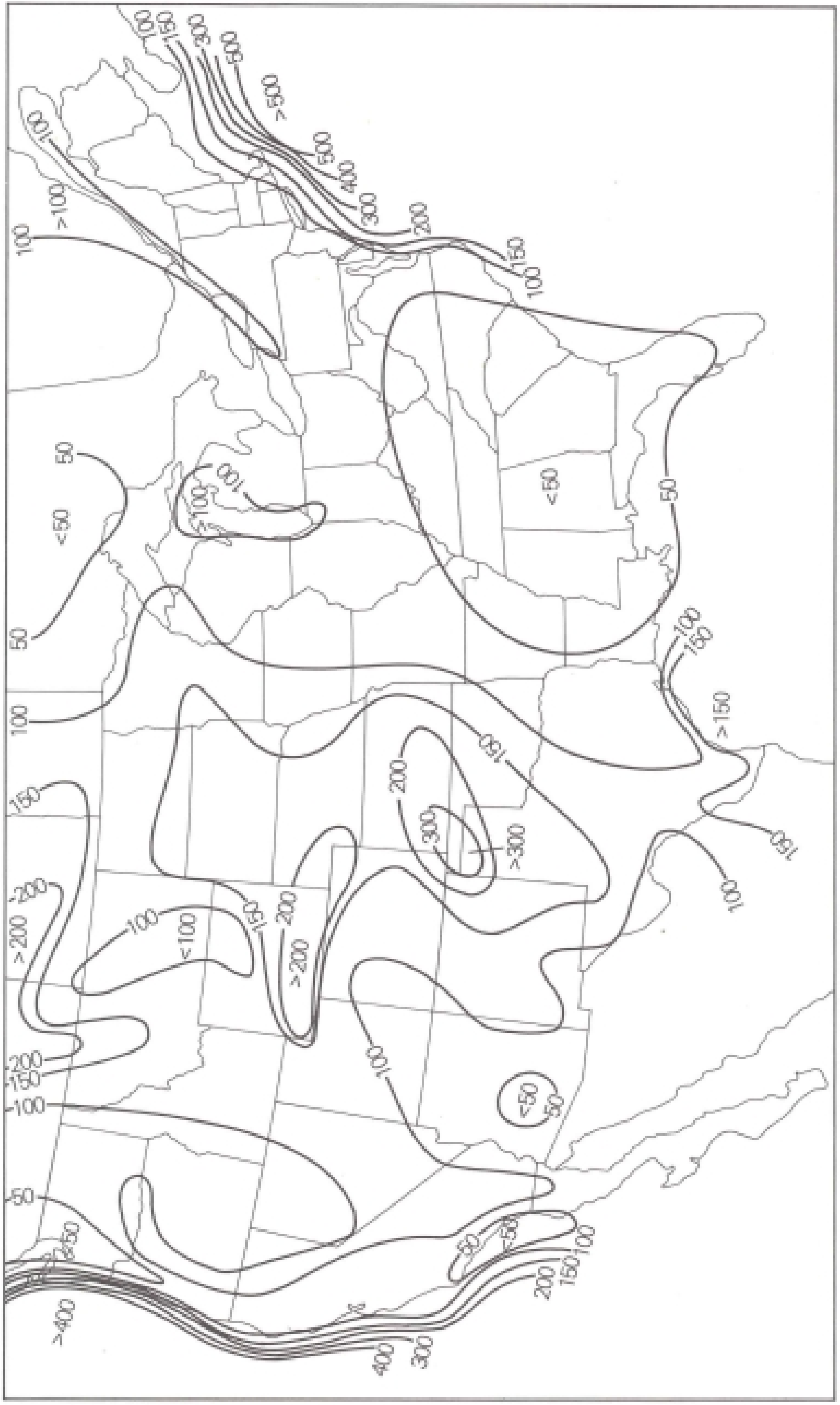


Figure A-1b: Summer Average Wind Power Available, in watts per square meter. *From Park 1981*

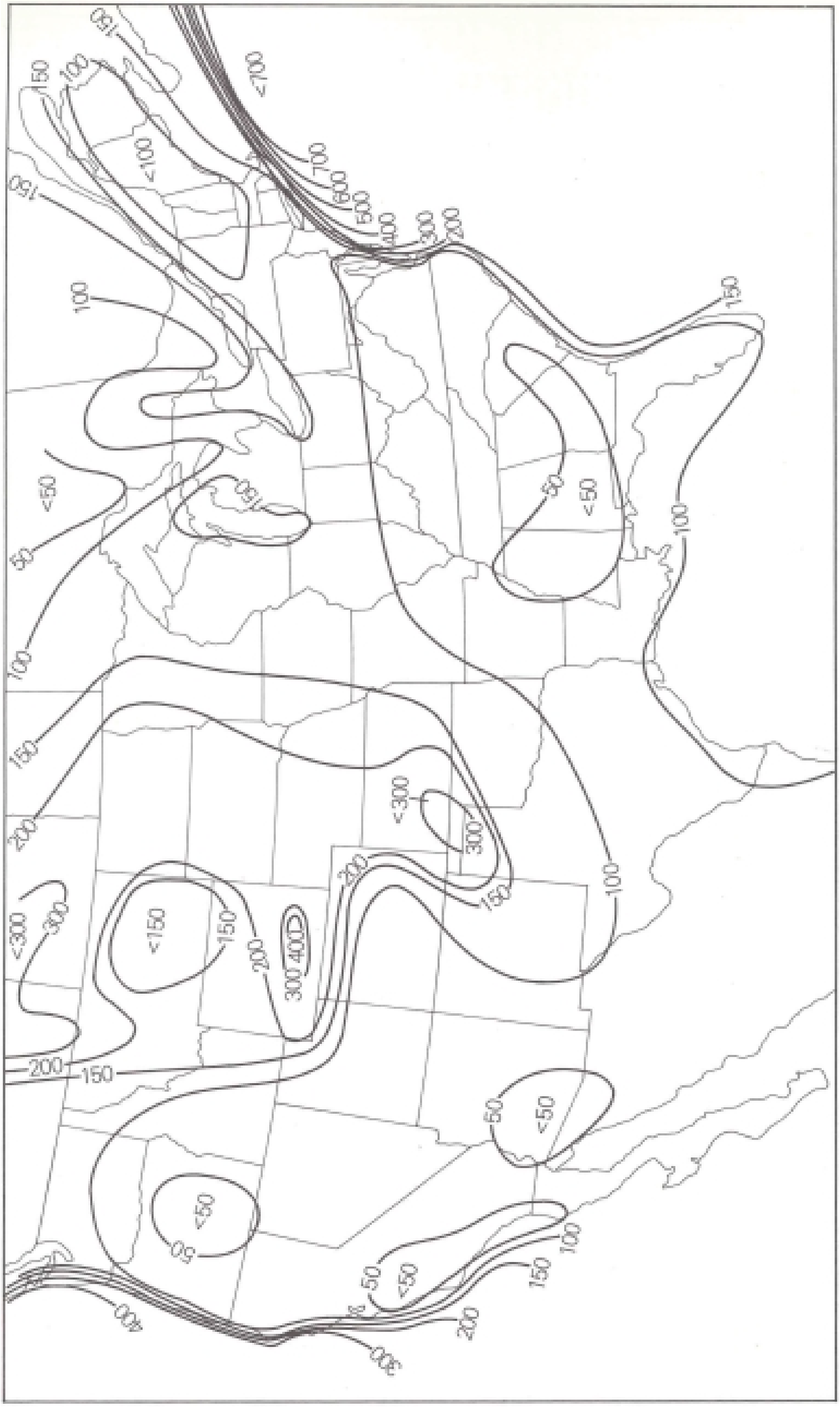


Figure A-1c: Autumn Average Wind Power Available, in watts per square meter. *From Park 1981*

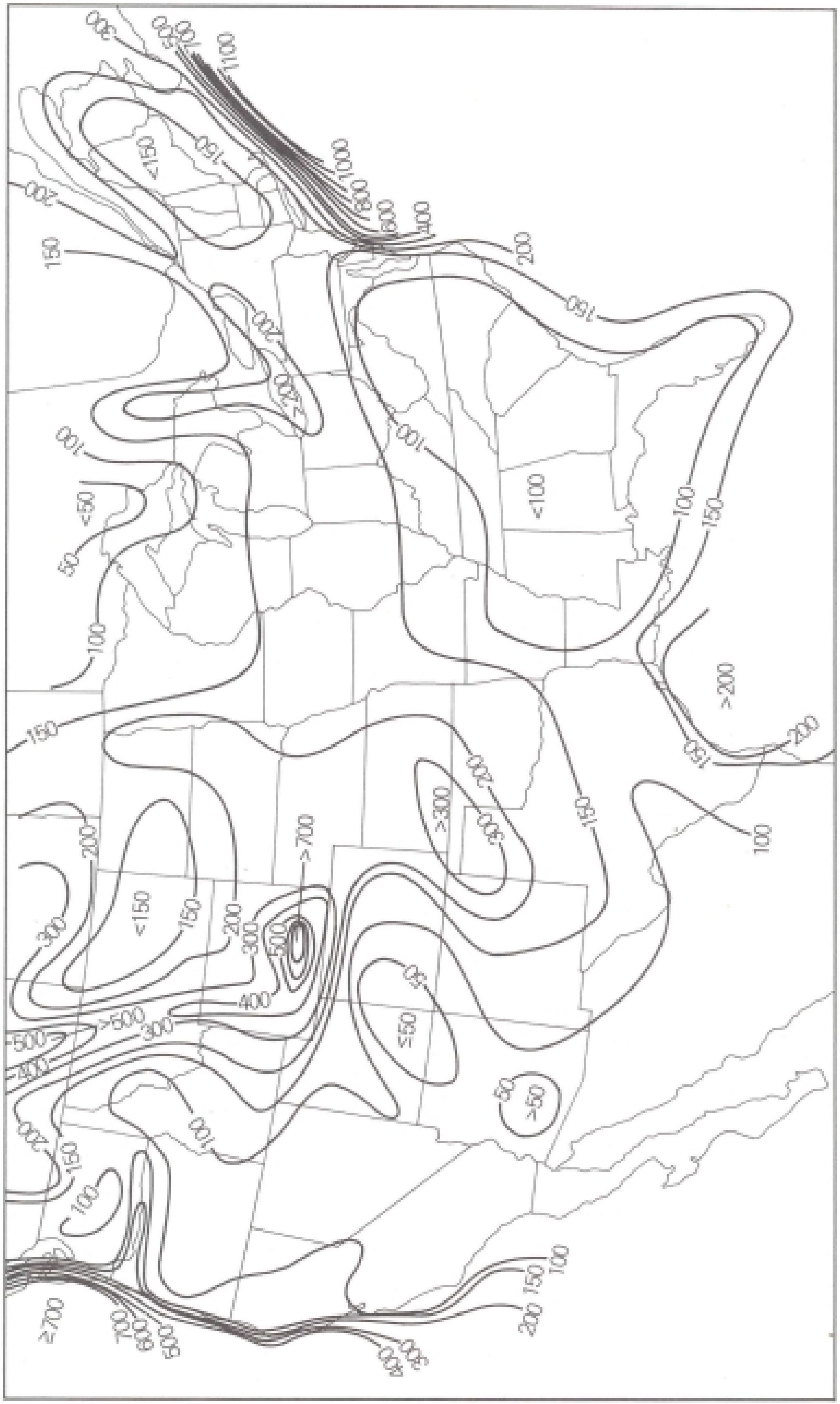


Figure A-1d: Winter Average Wind Power Available, in watts per square meter. *From Park 1981*

Appendix B: Solar Insolation Charts

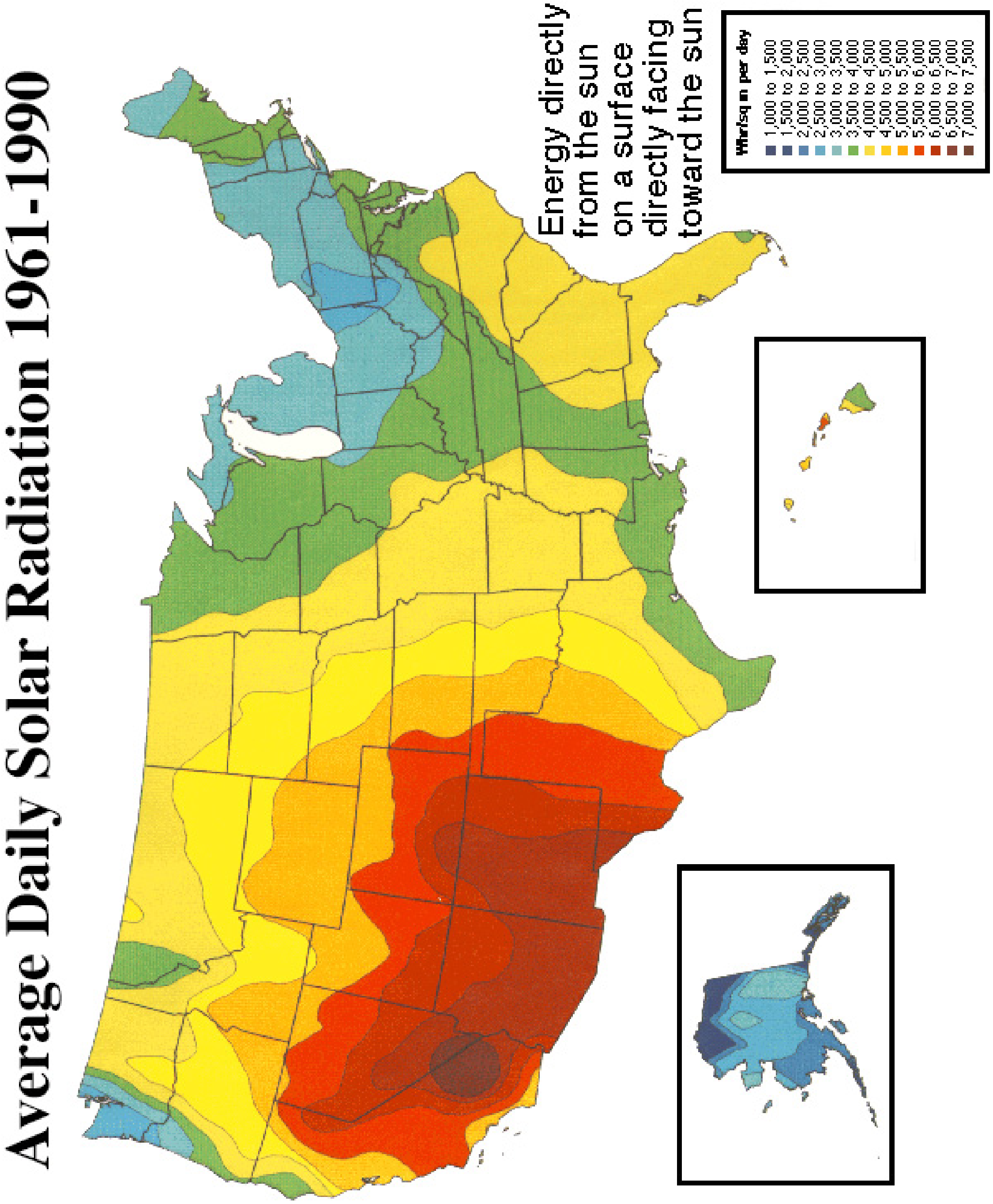


Figure B-1: Average Daily Solar Radiation for the United States
From www.NREL.gov

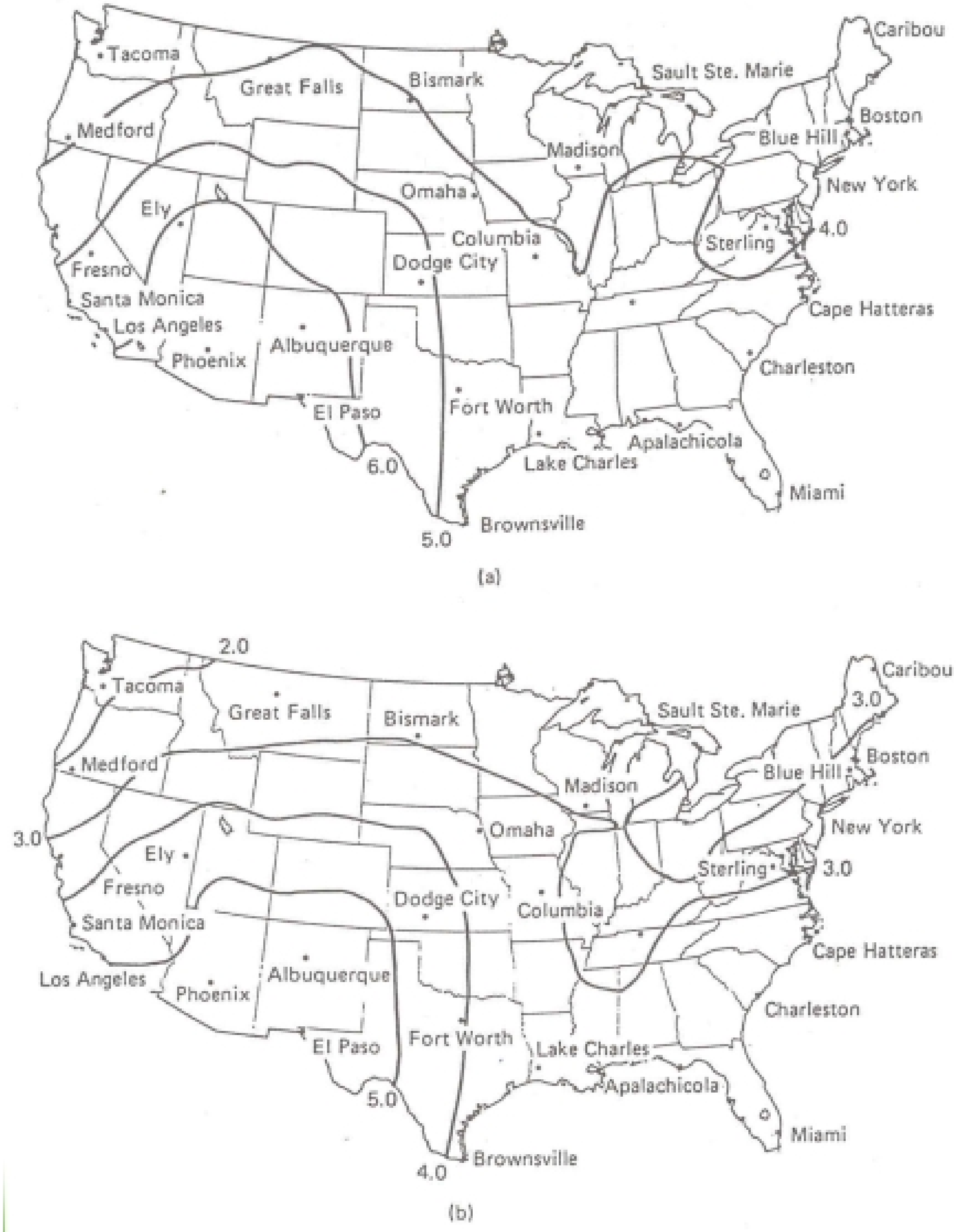


Figure B-2a(b): Average daily availability of total solar radiation on a south-facing 45° tilted surface for the United States in the fall (winter), in kWh/m^2
From Stitt 1999

Figure B-2c(d): Average daily availability of total solar radiation on a south-facing 45° tilted surface for the United States in the spring (summer), in kWh/m^2
From Stitt 1999

Appendix C: Wind Products

Product - AC output	Peak Output [W]	Wind Speed [mph]	$/Watt	Warranty [year]	Price	Source
World Power H500LV-12V	500	28	2.19	2	1095	www.nooutage.com
World Power H900LV-24V	900	28	1.67	2	1504	www.nooutage.com
World Power 80HVLV	1000	24	2.87	2	2867	www.nooutage.com
World Power 3000LV-48V	3200	27	1.49	2	4470	www.nooutage.com
Southwest Windpower AIR403	400	28	1.15	3	458	www.altenergystore.com
WHISPER H-80	1000	24	2.5		2496	Ferris Power Products
WHISPER H-40	1500	30	0.9		1352	www.solar-electric.com
WHISPER H-175	3000	27	1.33		3995	www.solar-electric.com
Air Marine 403	400	29	1.25	3	499	www.altenergystore.com
Windseeker 503	500		1.83		915	www.altenergystore.com
Rutland 503	44	30	11.93		525	www.e-marine-inc.com
Rutland 913	90	23	10.54		949	www.e-marine-inc.com
KISS	300	30	3.32		995	www.e-marine-inc.com
Bergey BWC 1500	1500		2.87	5	4299	www.altenergystore.com
Bergey BWC Excel	10000		1.7	5	17000	www.altenergystore.com

Appendix D: Solar Products

Solar panels can be purchased with standard direct current output (recommended for most systems), or with small inverters on each panel giving an AC output (only recommended for the smallest systems).

Product - DC output	Output [W]	$/Watt	Warranty	Price	Source
Photowatt PW390	39	4.62	25 year	180	www.clearsolar.com
Photowatt PW500	50	4.72	25 year	236	www.clearsolar.com
Photowatt PW750	75	4.59	25 year	344	www.clearsolar.com
Photowatt PW1000	100	4.4	25 year	440	www.altenergystore.com
ASE Americas ASE100ATF1734	100	5.38	10 year	538	www.nooutage.com
ASE Americas ASE285DG17	285	5.73	20 year	1634	www.nooutage.com
Siemens SP75	75	5.31	25 year	398	www.solar-electric.com
Siemens SR90	90	5.1	25 year	459	www.solar-electric.com
Siemens SR100	100	4.79	25 year	479	www.solar-electric.com
BPSolar BP270	70	4.43	20 year	310	www.altenergystore.com
BPSolar BP275	75	5.55	20 year	416	www.nooutage.com
BPSolar BP585	85	5.76	20 year	490	www.nooutage.com
Solarex MSX120	120	4.83	20 year	579	www.solar-electric.com
Solarex SX85U	85	6.01	20 year	511	www.nooutage.com
Kyocera KC-80	80	4.99	25 year	399	www.e-marine-inc.com
Kyocera KC-120	120	4.98	25 year	598	www.solar-electric.com
Unisolar ASR128	128	7.56		968	www.solardepot.com
Unisolar ASR60	60	7.57		454	www.solardepot.com
Unisolar PVL128	128	6.75		864	www.solardepot.com

AstroPower AP-120	120	4.86		583	www.clearsolar.com

Product - AC output	Output [W]	$/Watt	Warranty	Price	Source
ES112	112	10.02	20 solar; 5 year inverter	1012	www.nooutage.com
SUNSINE325	325	9.49	20 solar; 5 year inverter	2609	www.nooutage.com
INTERTIE1000	960	9.46	20 solar; 5 year inverter	8138	www.nooutage.com
INTERTIE2400	2400	7.37	20 solar; 5 year inverter	16224	www.nooutage.com

Appendix E: Inverter Products

Product	Power	Input Voltage	Price	Source
Advanced Energy GC-1000	1000	52-92	1450	www.altenergystore.com
Exeltech	250	12	418	www.altenergystore.com
Freedom Marine 30-12	3000	12	1225	www.altenergystore.com
Heart 458 10-12	1000	12	625	www.altenergystore.com
Heart 458 20-12	2000	12	755	www.altenergystore.com
Heart 458 30-12	3000	12	905	www.altenergystore.com
Statpower Prosine 1000	1000	12	860	www.altenergystore.com
Statpower Prosine 1800	1800	12	1235	www.altenergystore.com
Statpower Prosine 2500	2500	12	2400	www.altenergystore.com
Statpower Prosine 3000	3000	12	2800	www.altenergystore.com
Statpower Prowatt 1500	1500	12	540	www.altenergystore.com
Trace DR-1512	1500	12	995	PlanetarySystems.com
Trace DR-1524	1500	24	890	PlanetarySystems.com
Trace DR-2412	2400	12	1295	PlanetarySystems.com
Trace PS-2512	2500	12	1650	PlanetarySystems.com
Trace SW-2512	2500	12	2450	PlanetarySystems.com
Trace SW-4024	4000	24	2895	PlanetarySystems.com
Trace SW-5548	5500	48	3200	PlanetarySystems.com