4107

SOLAR CELL ELECTRICITY: PHOTOVOLTAICS

FACTSHEET

WASHINGTON ENERGY EXTENSION SERVICE

December 1987

INTRODUCTION

Converting sunlight directly into electricity, or photovoltaics, is a process that was discovered nearly a century ago, but found its first practical application in America's space program. In the last two decades the decreasing cost of manufacturing and the increased efficiency of solar cells have opened new applications. Remote communication equipment, navigational aids, railroad switching systems, and irrigation activity are just a few of the areas where photovoltaics are being used. In the residential sector, remote home locations are using photovoltaic (PV) systems as an alternative to the high cost of extending power lines. Some utilities have begun to experiment with PV's as a method for centralized generation of electricity.

While PV's today are not a practical alternative to readily available grid power, many predict that cost decreases and system efficiency increases might make PV's an increasingly more significant technology in the residential market. This factsheet, therefore, will describe a complete residential photovoltaic system, with observations on what the future of PV's may hold.

ELECTRICITY

The first step in understanding a photovoltaic system is to understand the end product. The following definitions of basic electrical terminology will help clarify the explanation of PV system design.

a. Electricity -- the movement of electrons through a circuit.
b. Current -- expressed in amperes (or amps), it's the number of electrons passing a given point per unit of time.
c. Voltage -- pressure forcing electrons through a circuit.
d. Power -- expressed in watts, it is the product of voltage multiplied by the current, P = Volts (V) X Amps (I).
e. Resistance -- load characterized by resistance to the flow of electrons, Ohm's Law: V = I X Resistance (R).
f. AC and DC -- two ways in which electricity flows. Direct current (DC) is produced by battery systems (such as in an auto) and by solar cells. Alternating current (AC) is usually of higher voltage and is typical of utility supplied power.

These basic terms will help you in understanding PV produced electricity, but are equally useful in monitoring electrical use for standard home appliances. For instance, a 60 watt light bulb in the home draws, when lit, a little over .5 amp (60 W/110 V = .55 amp). Most every major home appliance will carry a manufacturer's tag which lists the power requirements for operation. A few simple calculations and a watchful eye on the amount of "on time" for the appliance gives a good picture of where electricity is most intensively used.

WISE USE OF RESOURCES THROUGH EDUCATION

SEATTLE UNIVERSITY
SEATTLE, WA 98122
(206) 296-5640

747 MARKET STREET #744
TACOMA, WA 98902
(206) 591-5085

W. 808 SPOKANE FALLS BLVD., RM. 627
SPOKANE, WA 99201
(509) 624-4180

SOLAR CELLS

The interaction of sunlight with electrons is the basis for all photovoltaic devices. Different solar cells utilize different materials, but all work on the same basic principle. Light energy, in the form of photons, strike the surface of solar cell devices. The cell itself is made of a semiconductor material such as silicon, into which two additional elements, in very small quantity, have been added. These additional elements, such as boron and phosphorous, create two distinct "layers" within the solar cell. One layer will have a negative charge, the other a positive charge. The voltage differential that is created sets the stage for the photovoltaic effect. The photons of sunlight excite electrons in the solar cell. When these electrons are liberated and move across the cell, they are picked up by metallic contacts placed on the surface of the cell. These electrons, when hooked into an electrical circuit, do work. Thus, without any moving parts or any degeneration of material, the solar cell produces electricity (see Figure 1).

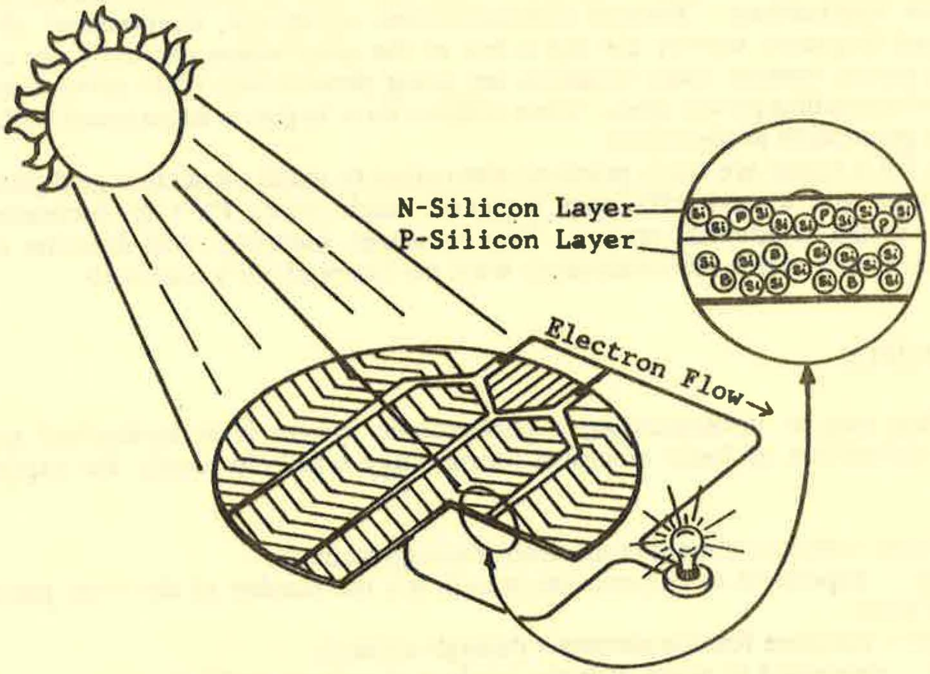


Figure 1. Single Crystal Silicon Solar Cell

There are a number of different semiconductor materials that can be used to create a solar cell. Silicon has been, almost exclusively however, the basic material for all commercially available solar cells. To produce a higher efficiency cell, silicon is refined to near purity before it is fabricated into a solar cell. This silicon, while abundant as a raw material, does require costly processing to purify. Single crystal silicon can be "grown" as a solid ingot as the first manufacturing step in creating a solar cell. Out of this round ingot, precision saws cut the ingots into very thin wafers. Additional processing of the wafers creates the photovoltaic potential. This wafer type of the manufacturing process has been predominant in the industry and still represents the process of choice for many cell manufacturers.

In the early 1980's an alternative manufacturing process was developed using the same basic material -- single crystal silicon. This new process called ribbon technology is designed to grow a continuous rectangular ribbon of pure silicon as opposed to a round ingot. By growing a continuous ribbon (indeed manufacturers can now grow nine ribbons simultaneously from one source) there is less cutting and therefore less waste. The final product differs little from the wafer process. The one obvious difference is the appearance. Wafer technology produces round cells and the ribbon method yields rectangular cells. Rectangular cells have a better packing density, or more cell area per square foot of panel than do round cells.

There are many other materials and manufacturing processes that are currently undergoing theoretical and applied research. Discussion of these solar cell developments is included in the final section of this factsheet.

SOLAR PANELS

Once individual cells have been fabricated, they are then connected in series and/or parallel to create a solar panel. Depending on the number of cells, their individual characteristics and how they are connected, a solar panel will have a particular voltage and current output rating. Cells that are wired in series increase voltage and cells wired in parallel increase current. All solar panels are rated by their peak watt output (voltage X current = watts) at one full sun. This is the panel's electrical production at noon on a clear day, or the equivalent of 1000 watts per square meter. Thus, a panel which has a peak rating of 16 volts at 2.2 amps will be a 35 watt panel. This rating system allows for comparison of different panels in spite of size and manufacturer. When panels are used together to form a solar array, it is best to match the voltage characteristics of each panel. In this way, panels from different manufacturers can be used in the same array.

Panel manufacturers use different methods and materials for fabricating solar panels. In most residential type panels, the cells are packed in an aluminum framed water tight case. The cells are covered by a polymer material with a tempered glass cover over the front. Cell connections should be strong and redundant, so that if a soldered connection were to break, the panel would continue to function. The case itself should be water tight to avoid corrosive activity from infiltration. Positive and negative terminal connectors on the back of the panel allow for wiring into a multi panel array (see Figure 2).

The panels described so far are called flat plate solar panels because they are designed to operate under normal solar insulation conditions. However, manufacturers also produce panels that operate by concentrating sunlight onto the cell surface. These are called concentrator panels. The effect of concentrating sunlight onto the cell surface is probably obvious -- more electrical output per given surface area. Concentrator panels use mirrors or special lenses to focus sunlight on the solar cell and increase the panel's efficiency by a typical range of 4 - 6 percent. The disadvantage of the concentrator panel is the high temperatures it creates which increases resistance and lowers output and its higher cost.

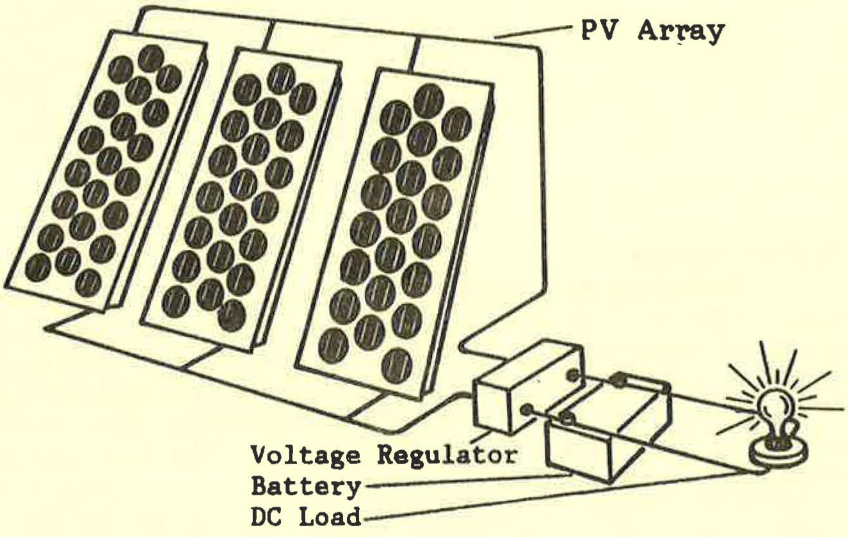


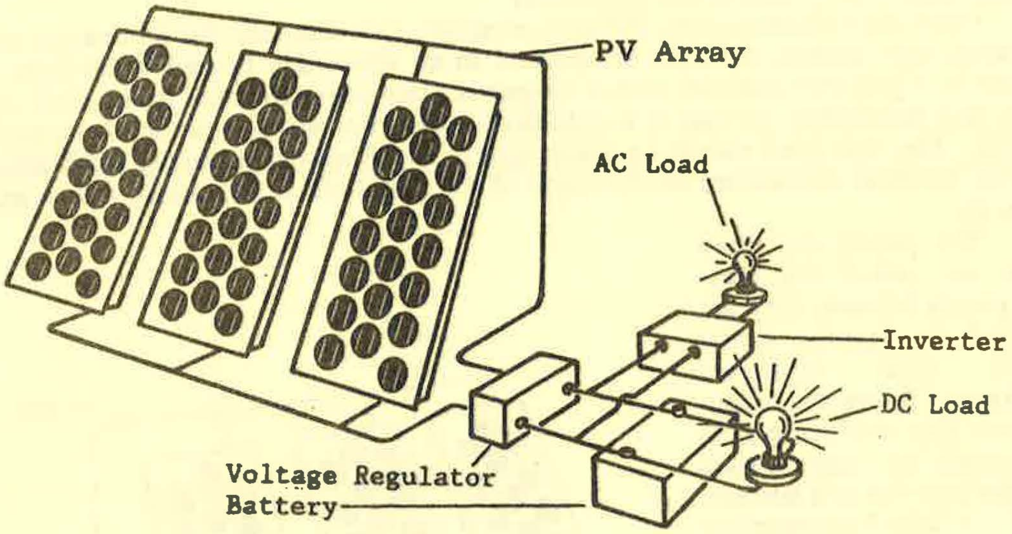
Figure 2. Array and Regulator for DC

Some manufacturers also produce a special panel for marine use. Popular with sailboat enthusiasts these panels feature a rigid plastic glazing (as opposed to tempered glass) and special water tight construction. The panels themselves are not much different from other flat plate panels. The panels are often smaller in size, but contain the same number of smaller cells as the standard residential unit. This type of construction (many smaller cells) allows the marine panel to maintain high voltage output with lower current characteristics. Thus, a small panel can trickle charge a 12 Volt marine battery.

RESIDENTIAL SYSTEM DESIGN

A complete photovoltaic power system does not end with the solar panel, but in fact requires a number of components for efficient operation. A PV system will typically include battery storage, a regulator to protect the batteries, and depending on the type of installation, an inverter and a backup electrical generator (see Figure 3). These components are necessary whether considering a PV installation for a "remote" residence (i.e. no utility power available), a vacation cabin, or a sailboat.

Figure 3. PV System for DC and AC



Battery Storage

Almost all photovoltaic applications require the use of batteries to store the electrical output of the solar panels. The use of electricity does not consistently track solar availability (after all, electricity is always needed after the sun goes down). A battery storage system provides the flexibility for variable time of day use and peak power use beyond the rated output of the solar array.

While there are a number of different battery types available, the lead acid battery is the most commonly used photovoltaic storage system. The lead acid battery (the type used in automobiles) contains plates of lead dioxide and sponge lead in an electrolyte solution. Batteries of this type come in a variety of voltages with the 2 volt cell being the basic building block. The 12 volt and 6 volt battery are the most common. By wiring batteries in series, system voltage can be increased beyond a single battery's voltage characteristics. Some batteries use antimony or calcium in the plates which provide a longer service to the battery and higher efficiencies.

Batteries are rated by their amp hour storage capability and their cycle life. The battery's amp hour (or watt hour) storage simply indicates the amount of current it can deliver over what period of time. A 100 amp hour battery, for instance, can provide 1 amp for 100 hours or 5 amps for 20 hours. (The more quickly you discharge the battery, the less the theoretical maximum amp hours are delivered. Each battery also has a maximum discharge and charge rate.

The cycle life of the battery indicates the number of times it can be significantly discharged and recharged and continue to function. Automobile batteries are designed to have shallow cycle characteristics, that is, they cannot be deeply discharged and recharged more than 20 - 25 times. Cars start with a quick discharge (starting the engine) and are quickly recharged. In a PV system, the battery will be drawn down by 50 - 60 percent of its capacity before it's recharged. Deep cycle batteries which can handle 300 - 1000 or more of these cycles work best. The addition of antimony to the battery plates will help provide this characteristic. Examples of batteries used for this purpose include marine trolling, golf cart, and fork lift batteries. The use of calcium in the battery plates will provide another important characteristic, that is, a slow self discharge rate. Lead calcium batteries are typically low maintenance, but do generally cost more than a lead antimony battery.

The temperature of the battery storage system is another important consideration. A battery at 80°F will deliver 100 percent of its rated capacity, but will fall to 65 percent when the temperature drops to 20°F. It is therefore best to keep battery temperatures between 50°F - 85°F. While it is not recommended to store batteries in proper living spaces, it is possible to locate them in buffered spaces or earth berm a storage container to shield the batteries from low temperatures.

A good battery maintenance program is also recommended to extend battery life. Clean battery terminals and keep temperatures below 85°F. Check electrolyte solution levels monthly. By checking the specific gravity of the electrolyte, the battery's relative state of charge can be determined and potential battery failure monitored. Even with the best maintenance program, however, expect to replace batteries periodically over the life of the PV system. Good quality 12V batteries can range in cost from $75 - $200.

Regulators

A photovoltaic power system must be regulated in some fashion to prevent the array from overcharging the batteries. Additionally, the system must be designed to prevent the batteries from discharging through the solar panels during night time hours. Depending on the size and complexity of the installation, this can be done in one of several ways.

At the very simplest, a small panel output connected to a fairly large battery storage capacity needs no regulation device at all. For instance, a 35 watt panel would not overcharge a 100 amp hour battery. The panel's current output represents only 2 percent of the storage capacity of the battery. Anything under 5 percent would probably be safe without a regulator. To prevent battery discharge through the solar panel, a blocking diode would be used. Like a plumbing check valve, this diode will allow current flow in only one direction. The diode does cause a small voltage drop when the panel is producing electricity, but does insure consistent efficient system operation (see Figure 4).

A second approach to regulation utilizes a special PV panel design to prevent overcharging. These so-called "self-regulating" panels are available from a number of manufacturers. The panels typically have some fewer solar cells than a standard solar panel (say 30 cells instead of 33). Under full sun conditions, however, they can produce electricity at voltages nearly equal to a larger panel that uses a regulator device. As the voltage increases to the point of near full charge on the batteries, current output drops precipitously to avoid overcharging. Thus, the panel is self-regulated. It would be wise to also use a blocking diode to prevent night time battery discharge. This type of self-regulated system works best with small to intermediate sized systems of 8 panels or less (35 W per each panel).

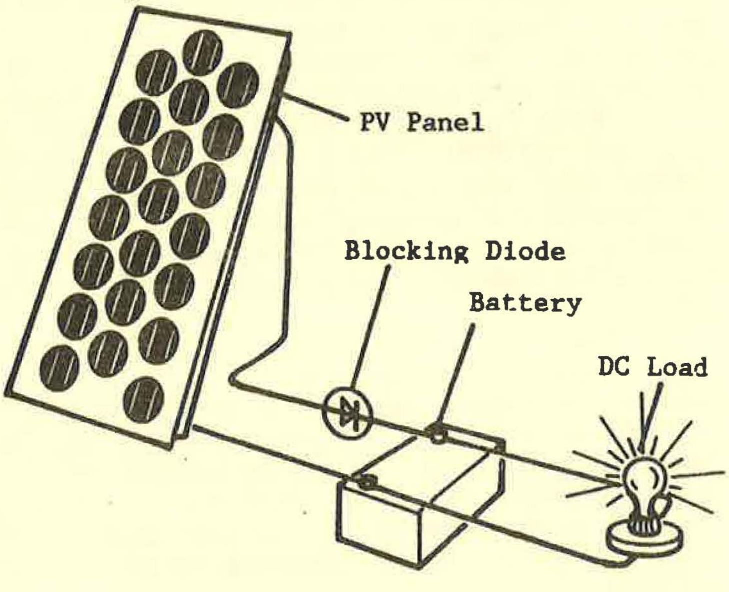


Figure 4. One Panel, One Battery System

Finally, one can use a regulator device, much like an automobile electrical system, to provide battery protection. Many regulators are available on the market ranging from the very basic at $50 - $75 to the more complex and sophisticated devices selling for $300 - $500. Regulator devices can protect the batteries by stopping the flow of electricity to the battery (referred to as a series regulator). Other devices shunt excess power to a ground or dissipate the energy as heat (shunt regulators). More sophisticated shunt regulators offer attractive options for using excess power. Instead of wasting this output, these regulators will switch output to power optional loads such as a water pump, fan, or water heater. A desirable feature of these regulators is the capability to maintain a trickle charge to the battery when they are at a full charge state. This will compensate for the self discharge rate of the battery.

At the very least, these series or shunt regulators should provide a warning of low battery charge state. Some models will actually automatically interrupt service loads when low charge conditions occur. Other regulators automatically activate standby generators during these conditions. Finally, more expensive regulators will provide gauges to read voltage and current on both the input and output sides. It is a good idea to add quality meters if the regulator does not have them.

Generators

In many remote home situations, owners have found the cost of a PV system sized to meet 100 percent of their demand to be excessively high in cost. Systems sized for "worst case" weather conditions are always oversized during the normal weather. To reduce the cost of this inefficiency, some homeowners have turned to a motor generator for back up to the PV system. Sometimes referred to as a "photogenset" system, the generator allows for sizing the PV system for normal weather conditions and significantly reduces the initial capital cost of the PV system. As mentioned above, regulator devices can provide for automatic operation of the generator when PV output falls behind demand.

ALTERNATING VS. DIRECT CURRENT

As mentioned earlier, electricity is simply the flow of electrons. Photovoltaic devices produce electricity as direct current (DC) which is characterized by the uniform direction of flow from positive to negative. Batteries also deliver direct current whether they are used to start a car or light a flashlight. However, most American homes use another form of electricity referred to as alternating current (AC). AC is characterized by the movement of electrons first in one direction, then back in the reverse direction. Though this cycling can occur at a variety of intervals, the United States standard is 60 cycles per second. Utility companies deliver AC power to homes, businesses, and industry to power refrigerators, table saws, lights, and the myriad of appliances that characterize modern life.

While both AC and DC power can do similar things, there are important differences. AC power is generally of higher voltage. For instance, the standard refrigerator will operate at 110 volts and the electric range may require 220 volts. Higher voltages are less susceptible to resistance losses and therefore are at an advantage in long distance transmitting because less current is required to deliver the same power. Additionally, this fact allows for use of smaller diameter wire in residential installations because the resistance loss is negligible. Finally, the commonly used induction motor requires AC electricity.

These points would all seem to encourage the use of AC electricity. However, the choice in a photovoltaic power system is not so simple. PVs produce direct current and, depending on the wiring scheme, can deliver electricity at voltages ranging from 12 volt to 24V, 36V, 48V, or larger. If precautions are taken to minimize resistance losses, low voltage DC current can power many essential home electrical needs. As any recreational vehicle owner will attest, there are DC appliances for lighting, refrigeration, stoves, television, and power tools. The use of DC will exclude the need to purchase an expensive electrical inverter ($500 - $1,000) that converts DC to AC. Beyond the capital cost of the inverter device, one avoids the efficiency loss of inverting power (sometimes as much as 20 percent).

The decision of AC vs. DC power will be made by the requirements of the end use of power. Many modern conveniences require AC power and may therefore require dedication of at least part of the photovoltaic output to be inverted. Using both AC and DC current requires dual wiring and coding of outlets.

INVERTERS

A static inverter is a device that is used in independent power systems to transform DC to AC. A synchronous inverter performs the same function, but is used exclusively with those systems tied into the utility grid. Static inverters are rated by their watt output capacity. The greatest efficiencies are achieved by matching size to the power requirements of the load to which it is dedicated. The inverter must also be matched to the input voltage from the battery bank, whether 12V, 24V, 48V, or larger.

There are both solid and state rotary inverters available on the market. Each inverter uses a small constant amount of current while not in operation. This loss of system efficiency is heightened when the device is operating, resulting in total inverter losses of 5 - 20 percent. The solid state devices typically operate at higher efficiencies than rotary inverters.

A final inverter problem rests with the characteristics of induction motors. Induction motors draw a surge of current when activated that is many times higher than the motor's standard running current. The inverter output is also a consideration. The ideal is an electrical output that is a perfect wave form. Realistically, inverters will produce current with some amount of "distortion". High levels of distortion can cause problems with induction motor operation and longevity.

SYSTEM SIZING

Sizing a photovoltaic system begins at the end. The power requirements of the individual household determines the number of panels needed. This simply means that if the use of electricity is high, the expense of the system will be equally great. Begin by calculating the daily amp hour requirement. By making a list of all needed lights, appliances, communications, entertainment, tools, and other items, one can calculate an average amp requirement for a typical day (see Table 1). It is easy to see that activities such as electric space heating, water heating, or cooking should not be used with a PV system (unless the budget can accommodate $75,000 - $100,000). Even if you are not planning a PV system immediately, it is very illuminating to compile an electrical requirements list. It not only indicates where the majority of electricity is used, but also shows the necessary energy reductions that are required for a moderately sized PV system. Designing a PV system for sailboat or vacation cabin requires the same amp hour calculation.

There are a number of cookbook formulas for estimating the required number of panels. Chart 1 provides one such way. This sizing method relies on the average peak daily sun hours for a particular location and is only an estimation, not a reliable guide for actual system installation. The average for each location is determined by the total amount of sunlight that occurs in a particular day converted to peak sun hours. One peak sun hour is the equivalent of 1000 watts per square meter. These values are then averaged for a year's time. Western Washington has an annual average of four peak daily sun hours. Eastern Washington has five.

Once the average daily electrical requirements and the number of panels are computed, the battery system can be sized. In a perfect world, the battery system would only need to hold one night's worth of storage for a residential system. Realistically, however, the battery system should be sized to hold from 5 to 25 times the average daily load. The use of a standby generator can significantly reduce the needed battery storage. Sizing battery storage for other PV applications like cabins or sailboats will be determined by the type and frequency of their use.

Table 1*

Major Appliances	AC (in Watts)	DC (12V) (in amps)
Hot Water Heater	4500	22 (wringer)
Washing Machine	375	2 (3 cu. ft.)
Refrigerator/Freezer (15 cu. ft.)	425	
Dishwasher	1190	
Range	12000	
Clothes Dryer	4350	
Space Heater	1300	
Color TV	115	4.1 (13")
Black & White TV	75	1.4 (12")
Microwave	650	
Household Appliances		
Blanket	170	
Blender	290	
Clock	2	
Coffee Maker	850	11
Crock Pot	70	
Fry Pan	1160	
Hair Blower	700	
Iron	1100	10 (traveling)
Lights (60 Watt bulb)	60	1.9 (30W fluorescent)
Lawn Mower	1000	
Radio	75	.5 (AM/FM car radio)
Record Player	160	.5
Sewing Machine	100	
Toaster	1100	20
Vacuum Cleaner	700	9

*Consumption varies by size and type of appliance as well as average usage.

Chart 1.

A. Amp hours/day X 1.22 = ________________ amp hour/day
(A)

B. Product from line A / average annual peak daily sun hours*
= ____________ amps per hour
(B)

C. Product from line B / peak amps per module**
= ___________ (# of panels)

* 4 in Western Washington or 5 in Eastern Washington
** e.g. .35-Wp panel (nominal 12V) produces approximately 2.2 amps

PV SYSTEM SITING

Obviously, like all solar devices, photovoltaic panels must be exposed to direct sunlight. Unlike solar thermal collectors, however, PV panels do not tolerate even minimal amounts of shade. When even one cell of a panel is shaded, while other cells are exposed to direct sun, the output drops dramatically. By performing a solar site survey, panel location can be optimized.

The tilt and orientation of the solar panels in much like that of a solar water heating system. Oriented towards true south, a high tilt angle (greater than 45°F) takes advantage of low winter sun, with a low tilt better for the summer sun. Panel mounting options include every possibility from a fixed orientation and tilt, to seasonal tilt adjustment capability, and even automatic daily tracking of the sun's path. Length of wiring runs, security, and wind loading are other siting considerations.

PVs IN THE NORTHWEST

While the amount of sunlight in the Northwest does not rival the American Southwest, photovoltaic panels will produce electricity year round in the diffuse light of a cloudy climate. Solar cells react differently in different light intensities, as one would expect. As light intensity decreases (read clouds), current output drops. Interestingly, however, cell output voltage is not so greatly affected by light intensity. Voltage remains high over a wide variety of intensities even to low sunlight conditions (read rain). This means that a solar panel will produce some current at appropriately high voltages even under gray and cloudy skies.

This attribute gives hope that photovoltaic power will continue to find an increasing number of practical uses in the Pacific Northwest. Anticipated future cost reductions are forecasted which could make photovoltaic use a more common sight in Washington.

PVs IN COMBINATION WITH UTILITY POWER

While the remote home, utility independent system is the most widespread residential PV application, there are other possibilities. First, it is possible to link the PV system with the utility grid. These systems are referred to as utility intertie systems. The PV array supplies power to the home, but also can "dump" excess production into the utility grid. By arrangement with the utility, the PV owner will be paid by the utility for this production. Conversely, when the PV system does not produce sufficient electricity, the utility can provide for this shortfall. It must be recognized that there are a number of significant questions pertaining to safety, power conditioning, liability, and costs that must be carefully considered in this arrangement. The utility should be consulted before any major decisions for an intertie system are made.

A new approach to PV systems in urban areas has been developed called a standby or uninteruptable power system (UPS). The UPS system uses both PV power and utility grid power to charge a battery storage system. PV production has priority in the system, that is, all available solar power is used first. Utility power is used when PV production is not available. The battery bank is there to supply power during blackout conditions to insure a continuous supply of electricity for critical loads. This type of system design has been touted to not have the regulatory requirements of the intertie approach.

FUTURE

There are presently a number of applied and theoretical research and development projects underway in the United States and around the world. Researchers are experimenting with new materials and new production techniques to lower cost and increase efficiency. Semiconductor materials such as gallium arsenide, copper indium diselenide, and amorphous silicon hold particular promise. Refinements in wafer and ribbon manufacturing and wholly new approaches such as thin film deposits represent potential cost breakthroughs.

More work is needed in areas that are "downline" from the cell. Batteries and inverters are two areas where much can and is being done. The future of photovoltaic technology is anyone's guess. Many anticipate reductions from present prices of $5 - $10 a peak watt to $2 - $3 per peak watt by the mid 1990's. Such a reduction would open many new and exciting uses for PV power.

Typical Costs for PV Components

Panels (35Wp)	$250 - $350 per panel
Battery (100 amp hr. lead antimony deep cycle)	85 - 100 per battery
Regulator (with meters)	150 - 200
Inverter (1000 W)	800 - 1000
Mounting hardware (fixed)	25 - 35
Wiring & Miscellaneous	50 - 250*

*Great variation by installation

SUGGESTED READING

How to Design an Independent Power System, Paul, Terrance, Best Energy Systems, P.O. Box 280, Necedah, WI, 1981.
Published by an inverter manufacturer. In depth discussion of the system components beyond the PV panel. Filled with practical information on batteries, power conditioners, and rule of thumb guides.

Photovoltaics: Sunlight to Electricity in One Step Maycock, Paul and Stirewalt, Edward, Brick House Publishing Co., 1981.
A well written book that covers the physics of cell function in terms the public understands. Covers the range of potential PV applications, their economics, and social impact.

The Solar Electric Home: A Photovoltaic How-to Handbook, Davidson, Joel and Komp, Richard, AATEC Publications, 1983.
Davidson and Komp are PV pioneers. Written for those who want practical how-to information now. Filled with diagrams and helpful appendices, including the 1984 National Electrical Code for photovoltaic installations.

Written by: Stan Price and Mike Nelson
Illustrations provided by: Steve Tracy

Washington Energy Extension Service, a Seattle University and Washington State Energy Office program, is funded by the Bonneville Power Administration and the U.S. Department of Energy.

You can obtain free copies of this and other fact sheets by contacting a WEES office listed on page one of this document, or:

Energy Librarian
Washington State Energy Office
809 Legion Way S.E., FA-11
Olympia, WA 98504-1211

FS-1603 (Revised EY0600, 12/87)