PHOTO-WHAT?

by Richard Gottlieb

Besides hard to pronounce, photovoltaics or "PV" presents a number of challenges to both contractor and consumer. Even so, it's often the best choice for electrical power on remote sites.

Nicely integrated PV installation in coastal Maine

In my work as an installer of and consultant on photovoltaic systems, I often work with electrical contractors assigned to wire a home using photovoltaic power. After the initial "Photo-*what*?" or better yet "Did you say 'photogalactics?'" most contractors settle down to a half-hour discussion, ending with "Oh, so we wire the same way, only with fatter wire." For the electrical contractor, it's usually as simple as that,

In essence, what we do is bring solar electricity to the house (not unlike when the utility brings in power), and the electrician, using conventional practices, feeds the house from the system we've put in place. What's not conventional about photovoltaics (PV)—the conversion of light to direct-current electricity—is that it does not provide the ac electricity they and their appliances are used to, and it's not available in the unlimited quantities and for the usual prices. In addition, the homeowner is both the electric-power plant owner and the consumer of the electricity produced. Some of the energy produced by the system is used directly and some is stored in batteries for later use. Perhaps the most important aspect of a photovoltaic system is that it requires a more conservative approach to energy use in the home.

Why PV?

The reason that PV has emerged at the top of the pile of choices for home electric systems is that it is simple to understand, has no moving parts to wear out or fail, requires no elaborate permit procedures to install, and has a simple predictable pattern of annual energy production. This' last quality allows one to reasonably size a system to power any given load. In addition, PV is modular in nature, with the basic building block typically being a 50-watt PV module. If the demand for electricity increases, additional capacity can easily be added. Finally, it makes no noise, is ecologically sound, and is readily available.

The Typical System

The typical PV system in the Northeastern United States is depicted in Figure A. (next page)

During sunlight hours, the PV array, through the controller, charges the battery bank and simultaneously powers the dc loads in the home. For ac loads, power is supplied through the inverter from the battery bank. At night the battery bank powers the dc loads directly and the ac loads through the inverter. If the battery bank can't meet the loads, the engine generator starts up and powers the ac loads directly. It also charges the battery bank through the inverter. (Modem solid-state inverters have the capacity to act as both inverters and battery chargers.)

Let's have a look at an entire system—that is, the panel array, mounting structure, transmission line, central control board, battery bank, inverter, engine generator, dc and ac loads.

The array. The array consists of PV modules mounted on a support structure that is either fixed or tracking (it follows the sun). It is wired to give a nominal 12 volts or 24 volts. Modules are typically single-crystal, semi-crystalline, or amorphous thin-film (see "What's in a Cell?" for more on this subject). The module consists of cells, each of which is a half-volt dc generator. Typically a module contains 33 or 36 cells connected in series to give an output voltage of 14 to 16 volts when attached to a load such as a 12-volt battery.

Single-crystal and semi-crystalline PV modules are now widely accepted in the remote home application, whereas thin-film modules are not. The lower efficiency of thin-film modules means that a larger panel is needed to do the same job as the single or semi-crystalline variety. The array area can become excessively large, and with it the cost of the support structure. Single and semi-crystalline modules generally carry a 10-year warranty for production of electricity, whereas amorphous thin-film, because of its degradation in full sunlight, generally carries only a one-year warranty.

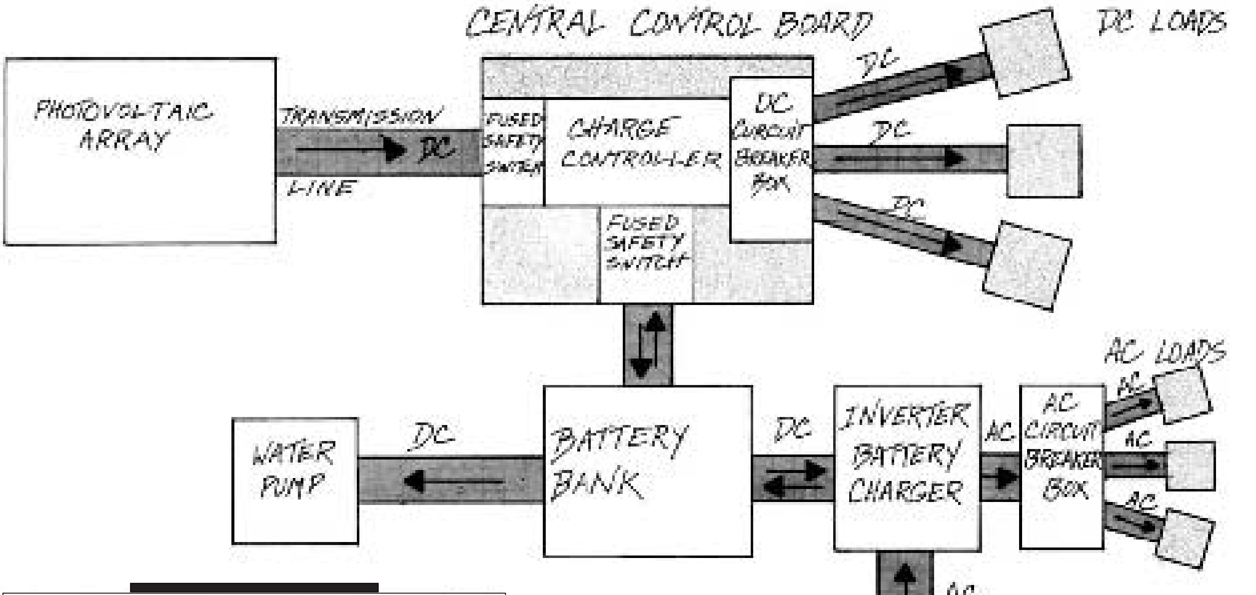
Although unable to make a serious dent in the PV home electric market, thin-film technology is widely used in consumer items, such as solar watches and calculators, where the electrical needs are miniscule and the major use is in ambient light rather than direct sunlight. Thin-film is less expensive to produce, however, so most large manufacturers are currently at work to make thin-film technology more efficient and more durable.

With PV, the homeowner is both the electric-power plant owner and the consumer of the electricity produced.

The mounting structure. Mounting structures are of more or less three varieties: fixed-roof mounts, variable-tilt ground mounts, and tracking pole-mounts (usually called "trackers"). In the fixed-roof mount, the modules are racked up on aluminum rails, interconnected electrically in parallel for 12-volt operation, and mounted clear of the roof by a few inches on aluminum feet and stand-offs. Ground mounts are similar to the roof mounts, but usually have a variable-tilt feature that allows the owner to raise the collectors toward vertical in the winter and lower them in summer to make the most of the available sunlight.

Trackers are generally pole-mounted devices with an adjustment to seasonally vary the tilt angle. They follow the sun from east to west either passively with a Freon driven system or electromechanically using two small PV panels and a dc gear motor. Trackers generally hold from two to twelve modules. They boost the output of the modules 10 to 15 percent in the winter and up to 50, percent in the summer. With systems of four or more modules, trackers are a worthwhile investment if they can be architecturally integrated into the home site. You can further enhance the power production with reflectors.

Transmission line. A two-wire transmission line connects the array to the central control board. The line is sized to minimize line losses and voltage drop. Typically an eight-module, 400-watt, 12-volt system will produce 28 amps in full sunlight. If these modules were located 50 feet from the control board, two runs of #2/0 wire (about the circumference of a fat Havana cigar) between the array and the board would be needed. If the system were 24-volt, *Schematic of typical PV system.*



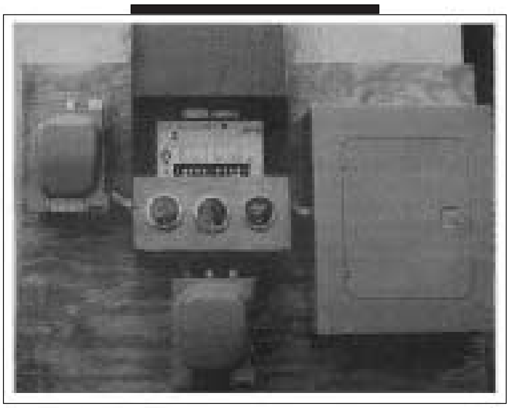


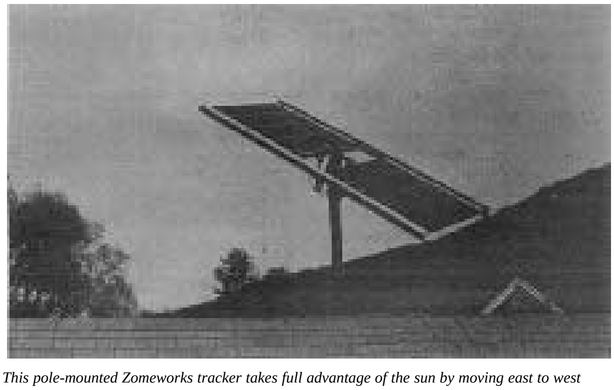
Photo Inset: Central control board houses fused safety switches to the array and battery bank, a charge controller, and a circuit-breaker box to the dc loads.

the current would be 14 amps and the transmission line could be reduced to #2.

Typically the transmission line begins at the array in a waterproof junction box where it connects to the wires from the modules. It enters the central control board through a 30-amp fused safety switch. (We use a Square D switch because it is reliable, commonly available, and one of the few popular brand items that have actually been certified for use in a PV system. It's rated up to 60 volts dc.)

Central control board. The function of the central control board is to provide a neat enclosure for the termination and connection of the wires from the array to the battery bank and the dc loads. Enclosed in a hinged metal cover box, the central control board houses a safety switch to the array, a safety switch to the battery bank, a charge controller, and a circuit-breaker box to the dc loads.

The *safety switches* contain 30-amp cartridge fuses and provide fused disconnects to the array and the battery bank. Their large screw lugs provide convenient terminations for the large wires that come from the array and the batteries. Wiring inside the central control board is generally black (for positive) and white (for negative) #10 THHN stranded wire.



This pole-mounted Zomeworks tracker takes full advantage of the sun by moving east to west with the day's light.

In a sense, the *charge controller* is the brain of the system. The SCI (Specialty Concepts, Inc.) charge controller is typical of the ones used. This device automatically connects the array to the battery bank and household loads at sunrise, and maintains the connection during the time that the PV modules are producing electricity. At night the controller disconnects the array in order to prevent back leakage of the current that would dissipate energy in the array.

The controller generally works in two stages. As the batteries near full charge on a sunny day, the controller tapers off the charge to the batteries. If the battery voltage rises further indicating full charge, the controller disconnects the array from the batteries to prevent overcharging.

If the batteries are completely drained, the controller senses this and disconnects the dc loads from the battery bank until it is recharged (either by the panels, a generator, or some other backup energy system). Many systems include a generator with an electric starter. When the contoller senses low voltage in the batteries, it will have the generator recharge the batteries to the electric supply so use will be interrupted.

A system ameter is often installed in the line from the circuit-breaker box to the dc loads. This allows the homeowner to gauge the power being used. The *circuit-breaker box* for the dc loads is usually an 8-breaker Square-D box with QO-type 15-amp circuit breakers. Branch circuits go out from this box to lighting circuits, receptacles, and to various dc appliances in the house. Exceptions to this include a dc water pump and the inverter, both of which draw more current than can be managed by the charge controller, so they come directly off the battery bank via their own breakers or fuses.

The battery bank. In the Northeast, deep-cycle batteries are required. For this region, we recommend one 140ah (T12-140) for each 50-watt PV panel.

The connection to the battery bank is generally made with #2 to #4 THHN wire depending on the distance from the central control board. It's important to have a large cartridge fuse (150-200 amp) at the positive terminal of the battery bank. In the event the transmission line to the batteries is short-circuited, the fuse will melt before the batteries explode.

The inverter and the engine generator. Since many household appliances are not readily adapted or changeable to dc, an inverter or engine generator (sometimes both) is often included in a system. Notice in Figure A that the flow of dc electricity goes in both directions between, the battery bank and the inverter.

The two major inverters available (Trace and Heart) have battery chargers as an integral option. If the system is permanently installed, the inverter is hard-wired to the battery bank with a 1/0 to 4/0 cable and appropriately fused. The output of the inverter (120 volts ac) can be hard-wired to a standard circuit-breaker box, and the branch circuits to the ac household receptacles go from there. The inverter/battery-charger unit can be plugged into the 120-volt ac plug of the generator while directly supplying the ac loads.

A word about mixing ac and dc in a house: The National Electrical Code is very clear about this. At no time shall ac and dc transmission lines be run in the same conduit or boxes, and the dc should have twist-lock caps and receptacles, and be incompatible with the ac plug and socket.

Getting the Most Out of PV

So much for production and storage. That is really only half the story. The most important aspect is how the current produced will be used. The trick in making the most of a PV system is to use the dc electricity it creates most efficiently. For some tasks (e.g. space heating), this means finding an alternative to electrical power entirely. In the case of some other tasks (e.g. an older typewriter, copier, or washing machine not easily convertible to dc) it makes sense to use ac, which is why the home should be wired for both. But in general the most efficient and reliable systems use dc whenever possible. And those dc uses should be highly efficient. In other words, in order to make a PV system work, it's essential that we strive to get the most lumens of light, gallons of water, cold food and beverage, hours of music, entertainment, or computer time, etc., for every watt-hour of energy. That means using the most efficient equipment available, in the most efficient way.

Battery banks are like Swiss bank accounts. You pay when you put money into the account and again when the money is taken out. Your battery bank extracts a 10 percent penalty for putting electricity into the battery for storage in the form of chemical energy. Another 10 percent is sacrificed when the chemical energy is changed back to electrical energy.

To avoid these losses, the homeowner should do as many tasks as possible during sunlight hours (drawing directly rather than from storage). For example, if you have a large pressure tank for the water supply system, pump and pressurize it during sunlight hours with a dc pump. This puts you watt hours ahead of pumping and pressurizing the water with an ac pump.

Best uses

Given the rule of thumb that dc electricity be used as efficiently as possible, lighting, water pumping, and refrigeration are tasks best suited for dc power. In each of these areas, there are ways to make the most of the dc current available.

Lighting. Regular incandescent lamps turn 5 percent of the electricity to light and 95 percent into heat. Halogen-cycle lamps are incandescent in nature, but are somewhat more efficient, turning about 8 percent of the electricity into light with the remainder going into heat.

Fluorescent lamps that run from electronic ballasts do a better job yet, as they turn 20 percent of the electricity into light and the remainder into heat. Longevity for the regular incandescent lamps is about 600 hours, and for the halogens 1500 hours. The fluorescents are rated at 10,000 hours. So even considering the higher initial costs of the lamp and ballast, fluorescents are way ahead on a life-cycle costing basis.

Fluorescent lighting has a bad connotation for many people. With PV electricity, however, most of the objections are overcome. Fluorescent lamps are traditionally run on a 60-cycle ac line. In PV systems, they are run on miniature electronic ballasts that operate at 20,000 cycles. As a result, the lamps don't flicker. The other objection to fluorescents has been the color. Fluorescents are now available in a wide variety of color renditions from cool white through warm white, from grow-light pink to full-spectrum Vita Lites.

Another feature of the electronic ballasts is that they rapid-start the fluorescent tubes. No starter or igniter is required. Also they are now available as compact and supercompact lamps, with screw bases and frosted globes, able to replace incandescent lamps in regular household fixtures.

The highly-efficient Sunfrost refrigerator is well-suited for use with photovoltaic home electric systems.

One last comment about lighting. Because there has been a revolution in low-voltage lighting, we who work with 12-volt dc systems can take advantage of all those wonderful lamps, fixtures, and track lighting formerly reserved only for fancy restaurants and museums. All of this specialty lighting works just as well with 12-volt dc systems as with 12-volt ac.

Water pumping. There are many ways to deliver and pressurize water for use in the PV home. Gravity-fed systems and shallow wells are easy to outfit. A drilled well with a 6-inch casing is a little more difficult. In the first case, a shallow well pump directly driven by a dc motor will do the job. The AY MacDonald (Dubuque, Ia) centrifugal pump or the Windlight Workshop (Santa Cruz, N.M.) rotary-vane pump work very well. For the drilled well, there are many variables. If the well is deep but has a static level near the surface and a good recovery rate, a dc submersible pump like Warns (Keyser, W.Va), Jacuzzi (Little Rock, Ark.), or Windlight Workshop's Flowlight can do the job. If the pump has to go down more than fifty feet, the wire size at 12-volt or 24-volt dc becomes excessive and it becomes necessary to drop a 120 volt or 240-volt ac multi-stage submersible pump into the well, powered either through the inverter or by the generator.

Refrigeration. The choices in electrical refrigeration are few. Sunfrost makes a high efficiency dc unit. Sunfrost has three inches of foam insulation, where the typical ac fridge has 1 to 1-1/2 inches of foam insulation. A new 16-cubic-foot ac refrigerator requires 125 Kwh per month to operate, compared to Sunfrost's requirement of 21 Kwh per month on dc. Powering the ac model doesn't make sense, since you'd need an enormous PV system to generate enough capacity to run it.

Another option for refrigeration is an absorption unit that runs on propane gas. If one is cooking and heating with gas already, this is a reasonable idea. One drawback is that the unit must be properly vented, as with any gas appliance, and with refrigerators, this is not always easy. Sibir, a Swiss company, makes a modern version of the old Servel gas refrigerators, with significantly increased efficiencies. One nice feature about gas refrigerators is that they, like PV, make no noise.

Price and Sizing

Finally there are the questions of price and sizing. Various design manuals (Steve Strong of Solar Design Associates, P.O. Box 143, Still River, MA 01467, has the best) propose different methods based on full sunlight hours.

Offered below are the results of monitoring our system in Guilford, Vermont. The first column shows actual month-by-month production of kilowatt hours by eight Arco Solar M73 modules (40 watts each) on a Zomeworks tracker with seasonal adjustments. The second column represents calculations for the newer Arco Solar modules M75 (47 watts each), and what we'd expect to get at our site from a 2-module system. You can use this column as a rough guide for determining how many Arco modules you would need to obtain a certain level of performance, given similar climate conditions.

Armed with this data, the task of the designer is to encourage the prospective customer to come up with a month-by-month account of how he or she intends to use the electricity. Balancing the consumption with the proven production from PV in your region will determine the size of the system. Coupled with a engine generator to aid in the worst-case months (November through February), you can reliably estimate system performance. The generator can be used for backup when needed. And, as stated above, the systems are modular, production equipment (PV modules) and storage capacity (batteries) can always be added if more power is needed.

Kwh of Energy Produced

Month	8 Arco M73 Modules 320 Watts	2 Arco M75 Modules 94 watts
Aug ('85)	34	10
Sept	37	11
Oct	32	9
Nov	11	3
Dec	14	4
Jan ('86)	15	5
Feb	21	7
Mar	37	11
April	42	12
May	43	12
June	50	15
July	46	13
Yearly total	382	112
Monthly ave.	32	9

One PV panel with a small controller and one battery can be had for under $500, and will typically produce less than 5 Kwh per month on average. Modest-sized systems of four to twelve panels range in price from $5000 to $15,000, depending, of course, on the size of the system and the additional components for auxiliary energy systems.

Final Considerations

PV is a viable option for the remote homeowner who is willing to do a little work to meet the various energy needs in the home. Homeowners faced with the high cost of importing power from the central grid often decide that the adjustments they must make in their load and lifestyle are well worth it. Currently, most installations require a "PV consultant." Although we and other consultants used to be totally responsible for installation (except for the eager-beaver do-it-yourselfer) more and more we will work with your electrical contractor, providing a quick lesson in PV wiring. Obviously, the best system starts with good planning—both in choosing power equipment and efficient ways to use the power it generates. ■

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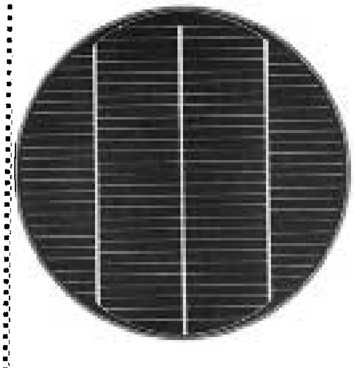
What's in a Cell?



The single factor that most affects the performance and cost of a photovoltaic cell is the material from which it is made. There are several materials currently used in making cells, each with its own advantages and disadvantages.

The *single-crystal* cell type is the "pioneer," first used in 1954 at Bell Telephone Laboratories. It's highly reliable, quite efficient, and the most expensive to produce. It is literally "grown" from a single-crystal seed and requires pure silicon for its manufacture. Hence the high cost.

The *semi-crystalline* cell type is less costly than the single-crystal variety because it can take advantage of less pure material and automated production. It is made from polycrystalline silicon, which is granular in nature. The larger the crystals, the more it will behave like single-crystal material.

Amorphous cell material does not have the structural uniformity of crystalline silicon, making it rather dense and disordered. But because it absorbs solar radiation 40 times as efficiently as single-crystal silicon, very thin cells of this material can be used, yielding much lower production costs. It does degrade in sunlight, however, and so far the decreased cost of production does not make up for that.