Home photovoltaic systems for physicists

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Installing a modest photovoltaic system and using it to run a suite of appliances can be educational and immensely satisfying. This brief how-to guide will help get you started.

feature article

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Physicists seldom allow students in their courses to escape without understanding and being able to perform calculations pertaining to energy. Outside of science circles, however, "energy" generally refers not to an overall conserved quantity but rather to the large-scale *conversion* of stored energy into electricity, locomotion, or manufacture. Physicists have much less contact with the conversion aspect of energy, though it is tremendously important to society.

Two hundred years ago, the ability to harness energy helped stimulate an industrial revolution that was accompanied by an explosion of agricultural productivity, human population, and economic growth. But human society has never before experienced energy availability at today's scales—each year some 4×10^{20} J is converted for human activity. About 85% of that energy derives from the use of fossil fuels. At some point in the near future, humankind must necessarily see a declining annual availability of fossil-fuel resources, given their finite nature and geological limitations to the rate of their extraction. That decline will be most sharply felt for petroleum, but it is also relevant for natural gas, less so for coal. The disappearance of global resources that are so important to our way of life is unprecedented. We have little choice but to adapt by reducing demand, migrating to alternative energy resources, or, very likely, employing a combination of both strategies.

It was with those concerns in mind that I decided to explore the practical side of photovoltaic energy: In 2007 I built a PV system to power my living room. Though reasonably well informed on the semiconductor physics of PV junctions, I felt unsuitably prepared to evaluate the practical realities of owning and operating a personal solar PV system. Because I believe physicists can play a role in our energy future that extends beyond the confines of advanced research, I want to share my experiences in the hope that others might develop home PV projects. What better way to motivate innovation in the alternative-energy sector than to get a talented pool of physicists engaged on a personal level?

PV for the TV

Residential PV systems range from very small arrangements that generate less than 100 W to those generating more than 5 kW. They can be integrated into the local electricity grid—in which case they're called grid-tie systems—or can be standalone battery-based systems. Hybrid systems are tied to the grid but have battery backup. In the US, most states allow net metering of grid-tie systems, in which consumers pay only for electricity not produced by their own PV systems. Policies vary by state, with 37 offering net metering on an an-

nual or monthly basis.[1] Overproduction is seldom rewarded with a check from the electric utility, however, as is done, for example, in Germany.

By offsetting electricity bills, properly sized grid-tie systems can recover the cost of installation in as little as 8 years in states with rebate programs—though 15 years is a more typical time frame. Small standalone PV systems will likely not recover installation costs at today's energy rates: Many components are necessary or desirable whether the system is large or small, but they cost similar amounts in either case. Still, few PV owners are motivated by purely economic reasons. That couldn't be more true for me. I opted to build a small standalone system to power my modest living room, which includes a TV, DVD/VCR, stereo, and lighting. My goal was to learn the ins and outs of a personal PV system, characterize performance, and experiment with various configurations. The sense of satisfaction I get when watching a movie or reading a book using stored solar energy is reward enough.

For the sake of learning, I implemented two parallel systems. One used a 64-W triple-junction thin-film flexible panel to power the lighting. The other used a 130-W polycrystalline silicon panel to run the entertainment system. Figure 1 shows what the solar panels look like. I have tried four different charge controllers (devices that regulate battery charging) and have evolved the system complexity over time. In developing my system, I found the *Real Goods Solar Living Sourcebook* (New Society, 2005) to be a particularly helpful reference.

This article describes a single standalone system that may serve as a template for individual exploration. Such a system will include at least one PV panel, a battery or battery bank, a charge controller, an inverter for converting DC current to AC, safety disconnects and current-limiting devices, a mounting surface, conduits, feedthroughs, and wire. For my system, I included an optional monitor. Figure 2 shows a typical circuit diagram, and figure 3 is a photograph of the power center for my dual system. A full-bore grid-tie system installation would require a contractor who can arrange the permits and inspections necessary to legally connect to the grid.

Sizing up

What might you want to power with a small-scale standalone PV system? Relevant factors include average daily energy used by the application, peak power demand, and sun exposure at the site. An additional consideration is ease of connection. Anything plugged into a wall outlet is easy to connect to an extension cord that runs to the PV system's inverter, but it's not easy to safely connect to the system integrated
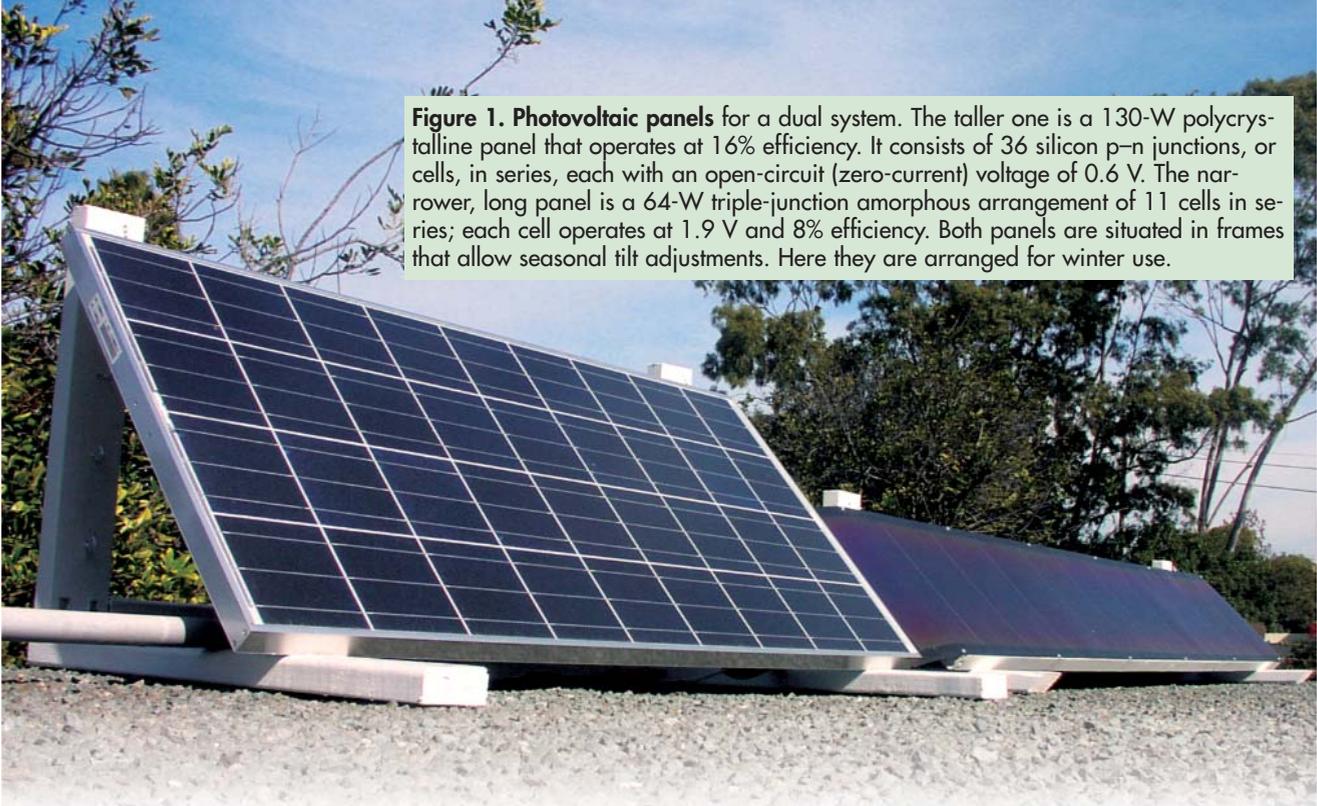
Figure 1. Photovoltaic panels for a dual system. The taller one is a 130-W polycrystalline panel that operates at 16% efficiency. It consists of 36 silicon p–n junctions, or cells, in series, each with an open-circuit (zero-current) voltage of 0.6 V. The narrower, long panel is a 64-W triple-junction amorphous arrangement of 11 cells in series; each cell operates at 1.9 V and 8% efficiency. Both panels are situated in frames that allow seasonal tilt adjustments. Here they are arranged for winter use.

household systems such as lighting. Handy devices on the market measure instantaneous power and also accumulate net energy usage so that as you explore possibilities, you can understand long-term usage demands for any plug-in device. Several sizing parameters—available solar energy, average energy demand, and peak power—affect the nature of the system.

A perfectly clear day with the Sun straight overhead may deliver as much as 1000 W/m² of solar flux across all wavelengths. A typical polycrystalline PV panel can convert about 16% of that to electrical power. Diurnal and seasonal effects, together with weather, diminish the average annual insolation by about a factor of five, typically to around 200 W/m², less at higher latitudes or in cloudier climates.

Another way to characterize the insolation is in terms of hours of peak-equivalent sunshine per day. San Diego, for example, averages 5.7 peak-equivalent hours per day, so a 100-W panel would deliver 0.57 kWh daily. The city's monthly average ranges from 4.6 to 6.5 hours. Seattle, on the other hand, averages 3.7 hours per day, and its monthly average spans 1.4–5.7 hours. Across the continental US, the annual average runs from about 3.5–6.5 hours.[2] Wintertime monthly averages range from about 1.5–2.5 hours in the Pacific Northwest, Upper Midwest, and New England to more than 5 hours in the Southwest. Summertime averages range from 5 hours in New England to almost 8 hours in the Southwest. These averages assume a flat panel oriented to the south and tilted from horizontal by the site latitude. Adjusting the tilt of the panel to follow the seasonal path of the Sun produces a gain of roughly 8%. Tracking the path of the Sun by rotating the panels about an axis parallel to Earth's axis can produce 20–40% gains averaged over the year—the impact being more substantial in summer and in sunny locations. Perfect tracking of the Sun, which requires rotation about two axes, offers an additional improvement of less than 4%.

PV panels do rather well even on cloudy days. A sunless day may often yield 20–50% of the energy delivered on a perfectly cloudless day. But solar thermal technology and any PV system relying on concentration are ineffective under indirect illumination.

The average energy demand for the selected application, together with available sun, establishes the size and number of PV panels that you'll need. That, in turn, sets the current in the system, which sets the size of the wiring and charge controller. It will also determine the required battery capacity. Average energy demand is thus the most important parameter in sizing the system. After characterizing the number of watt-hours per day the application will need on average, divide by the number of sun hours per day to determine the peak PV panel capacity needed. (Peak capacity is the power delivered in full, normal-incidence sun, with the solar panel at 25 °C.) If the application will run year-round, use the winter value for the number of sun hours in producing an estimate.

For instance, two hours of TV watching per day at 100 W plus 22 hours of 8-W off-state power consumption (2 W for the inverter, 6 W for the entertainment equipment) yields about 400 Wh per day. Note that the energy used when the appliances are off is about the same as when they are on! I got rid of a stereo that I found demanded 12 W just to stay off, dominating the total energy budget. Such discoveries are part of the unanticipated learning that happens when one experiences PV power firsthand. They make us far more efficiency-minded, something we'll need for our future. For my system in San Diego, with a winter average of 4.6 peak-equivalent hours per day, I can in principle power my entertainment system with a single 100-W panel.

It is wise to size panels for 25–50% more capacity than initially calculated. For one thing, PV panels are rated for 25 °C—far cooler than an actual panel in full sun. Increased carrier concentrations at higher temperatures result in greater losses from recombination and concomitant power reduction. Indeed, my 130-W panel seldom delivers more than 110 W in real conditions, and I can see an immediate 10% gain by spraying cool water on the panel. Also, the
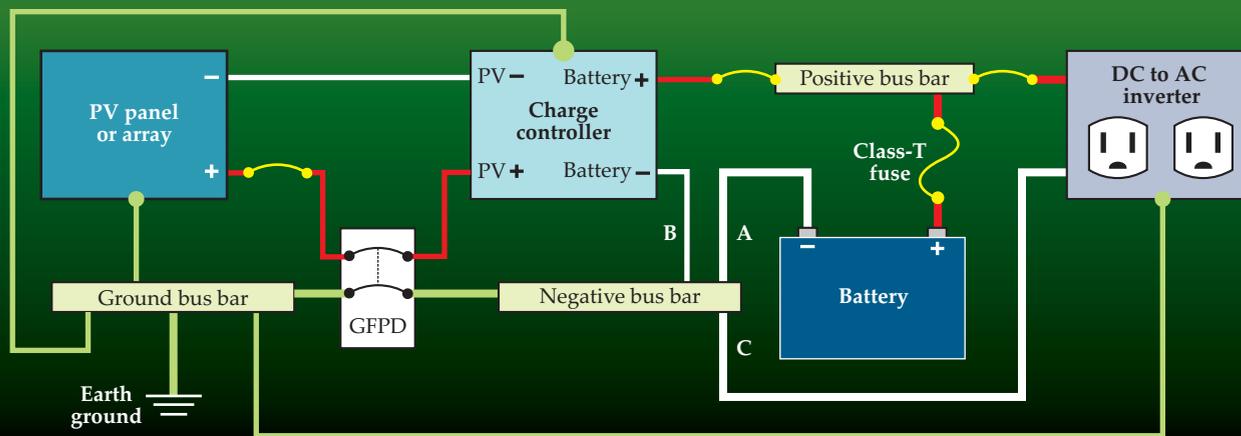
Figure 2. Circuit diagram for a standalone photovoltaic system. The breakers (yellow arcs) serve as overcurrent protection and disconnect simultaneously, but they can be implemented as fuses and disconnect switches. If the PV panels are not attached to a dwelling, the ground-fault protection device (GFPD) can be eliminated and the same bus bar, a metal strip that allows branch connections, can be used for negative and ground. All modules have grounded frames. In-line shunts can be placed at locations A, B, and C for measuring net battery current, solar input current, and load current, respectively—although, since those currents obey a sum rule, any two will suffice. Ground wires are green, negative white, and positive red.

charging system, which includes the battery, typically has an efficiency of 60–80%.

The average daily energy demand also sets the size of the battery or battery bank. Conventional wisdom dictates a capacity to run the system for at least three full days with no energy input. For my entertainment system, that means a battery capacity of 1200 Wh, or 100 Ah at 12 V. A larger battery will avoid having its capacity deeply depleted and will live longer. If you've ever wondered how big solar panels and battery banks would have to be to meet the nation's full electrical demands, see the box on page 45.

The peak power of the device run by the PV system does not affect the PV panel capacity, but it does determine the capacity of the inverter used and possibly the voltage of the battery system. For small systems, a cheap 400-W inverter running on 12 V will suffice. But if your system includes, for example, a microwave oven, which has a low average energy demand but a 1000-W peak demand, you will need a more capable inverter. You may also want a 24-, 36-, or 48-V battery system to reduce the current below the impressive 80 A that a 12-V battery would have to supply. Inverters must be matched to the voltage of the battery bank, so the battery–inverter arrangement is not easily reconfigured.

From photons to AC

Having established the size of the system, it's time to nail down some specifics. Your choices will depend on your overall goals. Is the system experimental? Will it likely be expanded over time? Does the system need to be fully reliable, or is household AC still available in case the batteries run down?

Photovoltaic panels come in several varieties. Typical efficiencies for silicon polycrystalline or single-crystal panels are around 13–18%. Thin-film products have efficiencies in the range of about 4–8%. Both are comparable in terms of cost per peak watt—about $4–5 per watt—though thin-film devices are beginning to come down in price. Thus a 100-W panel should cost roughly $450. Panels are typically guaranteed by the manufacturer to operate at better than 80% of initial performance for 25 years. Contrary to the persistent myth

that a PV panel never produces as much energy in its operational lifetime as went into producing it, the current energy-payback time is 3 or 4 years and improving.[3]

In the Northern Hemishpere, the panel should be placed in a south-facing orientation, tilted from horizontal by an angle comparable to the site latitude. Shade must not cover *any* part of the panel. The individual cells are arranged in series, so a shadow on one part of the panel can wipe out the panel output, essentially limiting the output current to that of the weakest cell. Bypass diodes are often built into a panel for partial shade mitigation. But even so, large groups of cells are often bypassed by a single diode, so that a shaded cell can still kill half the panel. Try to locate the panel as close to the charge controller and battery as possible to minimize wire length. For low-voltage systems, wires have to be surprisingly beefy.

Lead–acid batteries are the most cost-effective electrical storage medium. Golf-cart batteries are great for home PV systems. Unlike automotive batteries, which are a poor choice for PV systems, golf-cart batteries are deep-cycle batteries made to tolerate frequent depletion of as much as 80% of the battery capacity before recharging. A deep-cycle battery, though, will last longer if it is kept near the top of its capacity: My 12-V, 150-Ah battery generally uses 30 Ah, or 360 Wh, per charge cycle and seldom goes below 80% of full capacity. Lead–acid batteries require some periodic attention, such as equalization of the cells once per month (essentially, conditioning weak cells back to full performance; a good charge controller can manage an equalization cycle) and addition of distilled water on roughly the same schedule. If treated properly, golf-cart batteries can last about 4–6 years in a standalone PV system. More expensive batteries may last 15 years or more. Batteries or battery banks for PV systems are most commonly configured to 12 V, 24 V, or 48 V, although 36-V or 60-V configurations are sometimes used.

Charge controllers, also called regulators, put batteries on a carefully regulated voltage diet, generally consisting of a daily three-course meal. Such a regimen is necessary because too much voltage applied to the battery results in electrolysis and concomitant depletion of the electrolyte. For a
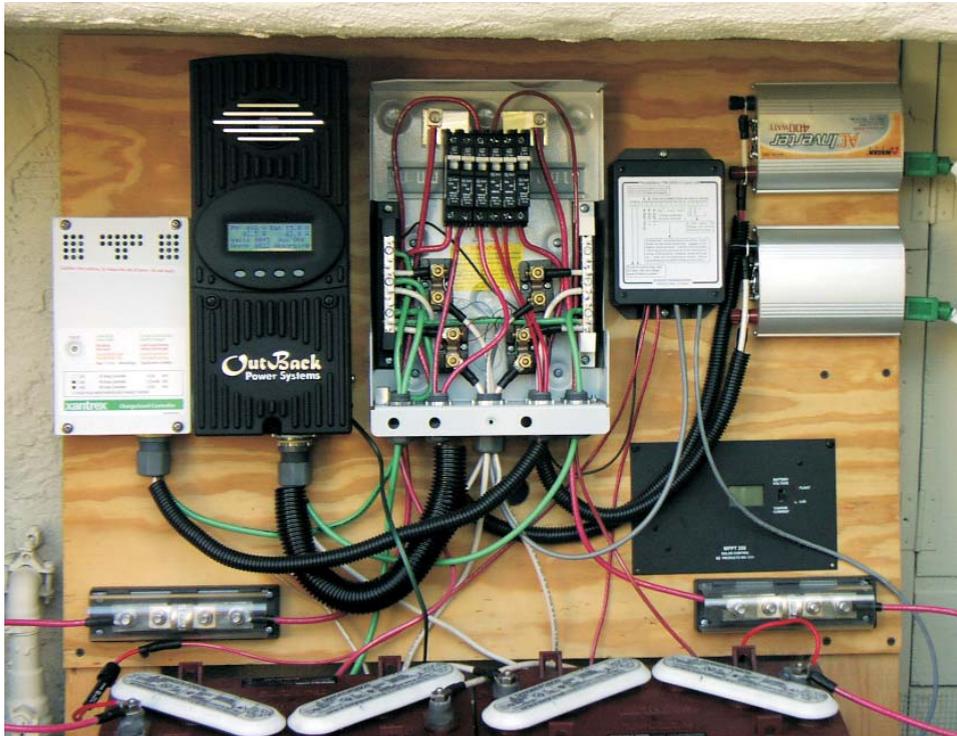
Figure 3. Power center for my dual PV system. Only half the parts are necessary for a more typical single system. Cut off at the bottom edge of the photo are two 12-V, 150-Ah batteries (one for each system), and immediately above them are 110-A class-T fuses. At left are two charge controllers. The black one is a maximum power-point tracking charge controller, as described in the text; it is certainly overkill for this small system. In the upper right are two 400-W inverters. Below them is an MPPT charge controller not currently used. To the left of the inverters is the monitoring system, capable of measuring two voltages and three currents. In the center is the exposed breaker box, showing three breakers per system, four shunts for current measurement (I use only three at a time), and for each panel, connected grounded bus bars, metal strips that allow branch connections. Ground wires are green, negative white, and positive red. The green extension cords on the right deliver AC power to appliances in the house. This particular system implementation does not require a ground-fault protection device.

12-V battery, for instance, the charge controller initially operates in the so-called bulk charge mode, during which it delivers the full PV current at a voltage—typically between 12 V and 14 V—matched to the charge state of the battery. Because of that matching, most charge controllers forfeit about 20% of the available PV power, as shown in figure 4. Bulk charging continues until the battery reaches the "absorption stage" voltage, usually around 14.6 V. That voltage is then held while the current to the battery is reduced, generally via pulse-width modulation, at whatever rate maintains the absorption stage voltage. After an hour or two, the battery will be fully charged and voltage will drop to the "float stage" voltage, usually around 13.3 V. The battery is held at that voltage until the input solar power is no longer capable of maintaining it because the Sun sets or an appliance is run. When a load is turned on, the battery may or may not receive net current, depending on the balance of PV power available and load demand. The charge controller does not care: It delivers

as much current as it must to maintain the appropriate voltage, and delivers all available current if it is falling behind.

It is in charge controllers that one finds the greatest variety of choices for a standalone system. Usually, charge controllers are rated by maximum current capability. Many can be configured to work with various battery-bank voltages, and most require a PV voltage input matched to the bank. For instance, a 24-V battery configuration will typically require two standard PV panels in series.

The exception is the maximum power-point tracking (MPPT) charge controller, which operates the PV panel or panels at the voltage that delivers maximum power. That voltage will generally be higher than the voltage required to charge the battery, so the excess voltage is converted into extra current at the voltage demanded by the battery. Therefore, MPPT controllers not only maximize power extraction from PV panels but also allow tremendous flexibility in PV configuration. For instance, four standard PV panels in series

PV for the nation

What would it take to get 100% of the US electrical demand from the Sun? A grid-tie system doesn't need a battery because it can exploit the flexibility of power plants to increase or decrease their power output. But if solar power systems become dominant, the nation's power plant infrastructure will no longer be able to accommodate the power swings; real storage will become necessary.

In the Southwest desert, the yearly average insolation is equivalent to six full-sun hours per day. Each square meter of a photovoltaic panel operating at 16% efficiency would deliver 1 kWh per day. The US produces about 10^{12} W of electricity,

or 24×10^9 kWh daily. An area approximately 160 km on a side would have to be reserved for PV production—not an impossibly large amount.

What about storage? Guaranteeing a week of capacity with no solar input would require about 2×10^{11} kWh of battery capacity. My 150-Ah, 12-V battery occupies about 0.01 m^3; scaling its dimension to meet the national need yields about 10^9 m^3 of lead–acid battery volume, or 1 km^3. It is not too hard to imagine that volume distributed around the country.

Whether the US has the materials, necessity, and will to proceed in the PV direction is a separate issue.
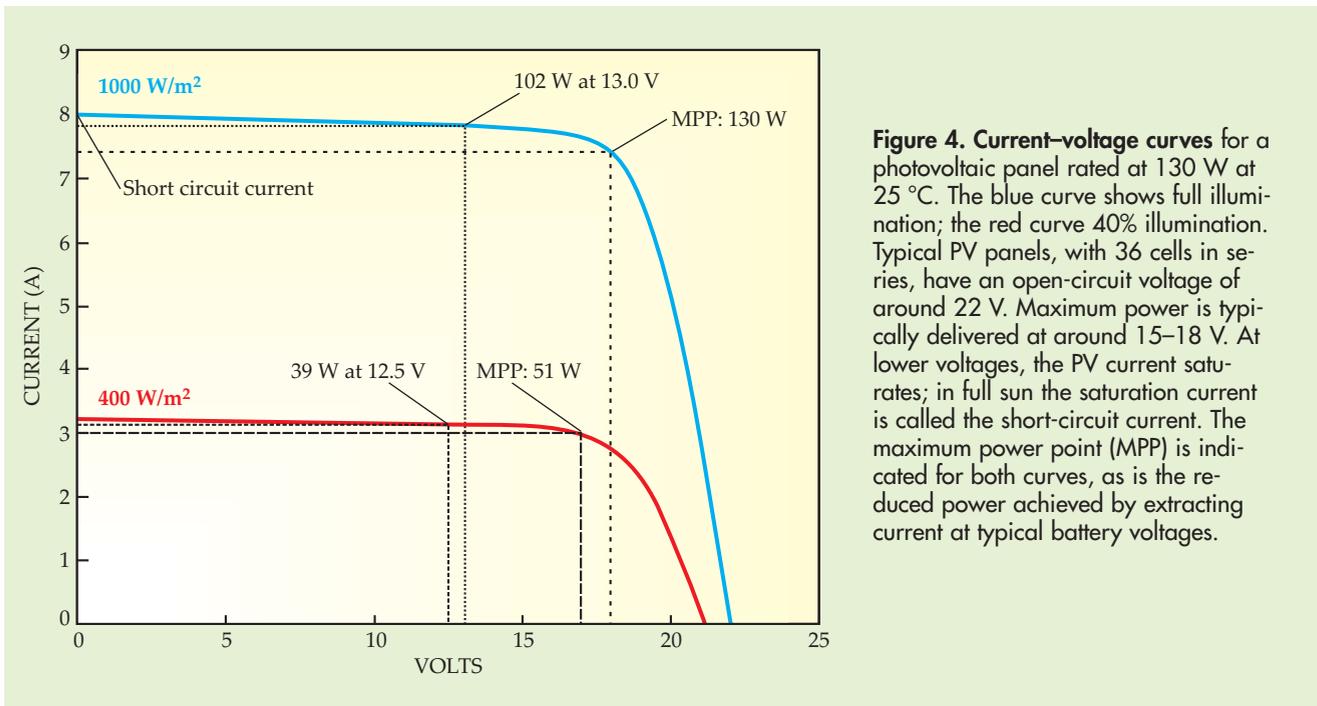
Figure 4. Current–voltage curves for a photovoltaic panel rated at 130 W at 25 °C. The blue curve shows full illumination; the red curve 40% illumination. Typical PV panels, with 36 cells in series, have an open-circuit voltage of around 22 V. Maximum power is typically delivered at around 15–18 V. At lower voltages, the PV current saturates; in full sun the saturation current is called the short-circuit current. The maximum power point (MPP) is indicated for both curves, as is the reduced power achieved by extracting current at typical battery voltages.

might operate at maximum power with a combined voltage of 64 V and a series current of 8 A, for a power of 512 W. An MPPT controller could apply 51.2 V to a 48-V battery bank at a current of 10 A, or it could present 12.8 V to a single 12-V battery at a current of 40 A. A standard controller would require a 48-V battery system and would operate the PV array at 51.2 V with a current of 8 A. It would thus extract only 410 W from the array.

Unless you are running DC appliances such as are common for marine or recreational vehicle applications, you'll need an inverter to convert the DC current supplied by the battery into AC. My dual system uses two cheap 400-W inverters. They are of the modified sine wave variety and synthesize the sine wave in steps. My TV, VCR/DVD, and fluorescent lights don't seem to care that the sine wave is less than pure. My stereo, however, emits a slight buzz whether off or on. More expensive inverters that produce cleaner sine waves do not produce a buzz.

Putting it all together

One aspect of my system that surprised me was how thick the wires had to be to accommodate the high currents at low voltages. The wire must be rated for the current it is to carry, but often more important is the need to guarantee a low voltage drop so that not much energy is wasted heating the wires. Given the resistivity of stranded copper wire, 1.73×10^{-5} Ω mm, the area of the conductor in square millimeters must be $0.035IL/fV$, where I is the current in amps, L is the one-way length in meters, f is the fractional power loss that can be tolerated, and V is the PV voltage delivered across the wires. For instance, my system uses a 12-V panel at 8 A with a one-way distance of 15 m. To keep losses below 5%, I need 7 mm² wire, which translates to AWG (American wire gauge) #8 wire. The above considerations imply that arranging multiple panels in series rather than parallel means big savings in wire size; the voltage is increased and the current decreased by the same factor. An MPPT charge controller thus becomes attractive because, for such a controller, the PV arrangement is independent of the battery configuration. Keeping the PV-to-controller run short is an obvious way to keep wire size down.

The battery and inverter will often require wire that is substantially thicker than the PV delivery wire, but this time to accommodate high current rather than voltage-drop power loss. Running a microwave from a 12-V battery, for example, will require 80 A and #2 wire with a diameter of 6.5 mm. Fortunately, such runs can be short, even if they are unwieldy. The grounding wire must not only be able to handle more current than any component in the system but also be able to handle the sum of all currents for dual or larger systems with multiple subarrays and controllers sharing the same ground.

In installing my system, I closely followed the National Electrical Code (NEC). Doing so led to a safe system, and the code also provided useful guidance. Photo documentation of a code-compliant installation can potentially assuage suspicious insurance adjusters who will come around in the event of a fire. You may find it worthwhile to get a specialist to confirm and document code compliance.

The many aspects of the NEC for PV systems are too numerous to specify in this article, but here are a few standouts:
▶ Use red for positive, white (not black) for negative, and green for ground wires.
▶ Ensure that wires accommodate the maximum possible current after derating for temperature conditions—PV panels can get hot and transfer heat to the connection wires.
▶ Ground the negative side at one point only, typically in a bus bar, as shown in figure 2.
▶ Use a ground-fault protection device on any system that attaches PV panels to a dwelling. Detached garages or carports do not require a GFPD.
▶ Make sure that every positive wire has overcurrent protection with an appropriate safety factor.
▶ Provide disconnects for the PV panel or array, the charge controller, the inverter, and any DC appliances.

Fuses and switches can serve as disconnects and provide overcurrent protection, but DC circuit breakers do both at once. Other NEC guidelines relate to electrical conduit, approved crimping practices, and so forth. A good summary of the NEC PV standards was compiled by John Wiles and was my primary source for information.[4]
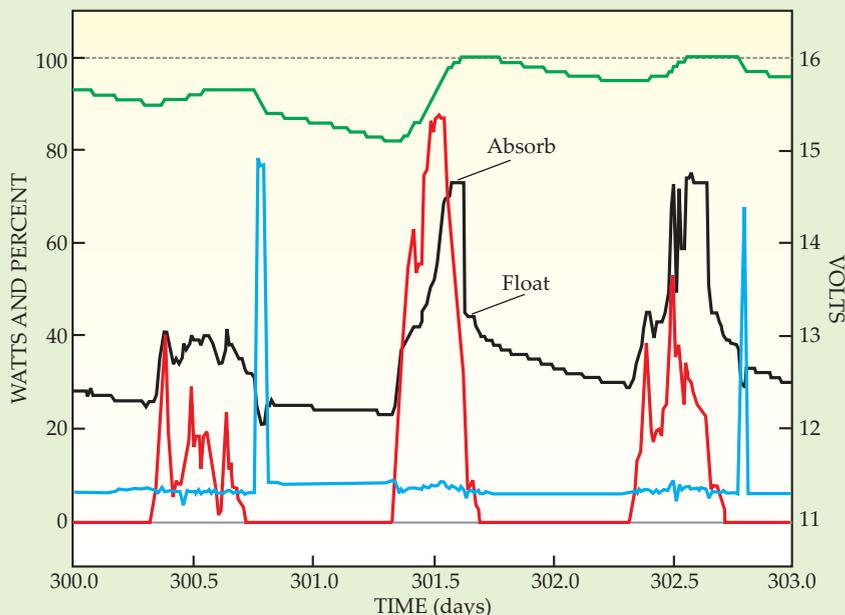
Figure 5. Sample data for a 130-W solar panel powering an entertainment system. Day 300 had a heavy but variable overcast; day 301 was mostly sunny; day 302 was cloudy. The red curve traces the solar power delivered by the panel to the charge controller, and the blue curve traces the load. Note the constant "off" load plus brief intervals of television usage. The black curve is battery voltage, as indicated on the right-hand scale. The battery reached absorption stage on days 301 and 302 and also showed intervals of float stage—indicating a fully charged battery—at the end of both days. The green curve indicates battery charge as a percent of capacity. The first day made only a small positive contribution to the battery charge, but the sunny day that followed made up for the deficit. Note that the falling edge of the solar power on the sunny day is not due to a decline in illumination, but reflects the diminishing current demand in maintaining absorption-stage voltage. Additional data samples are available at http://physics.ucsd.edu/~tmurphy/pv_for_pt.html.

For me—a data-crazed physicist—the experiment of setting up a small PV arrangement has been vastly more rewarding due to the monitoring system. For a while I routinely made trips outside with a clipboard and digital voltmeter to monitor voltages and currents. A system monitor never tires of the task of logging parameters at user-determined regular intervals. In-line shunts, essentially calibrated thick pieces of wire, allow currents to be measured in situ. For my system, I installed a comprehensive monitoring device that measures and logs up to three currents and two voltages, plus temperature. Besides logging, the meter keeps track of useful information regarding battery charge, how long it has been since the battery or batteries were last charged and equalized, cycle-by-cycle charge efficiency, and so forth. A computer interface permits monitoring, configuration changes, and transferring logged data. See figure 5 for a sample record.

Now go have fun

A small PV system will cost either a lot or a whole lot, depending on your preferences. The PV panel price is determined by its peak power capability, at approximately $4–5 per watt. A 12-V, 150-Ah battery may cost $200 or more—and the price of lead is climbing. Charge controllers range from $40 for the simplest to $500 for a deluxe MPPT unit with a capacity of several kilowatts. A decent configurable charge controller with equalization capability may be about $140. Low-power inverters can be as cheap as $40, but pure sine wave devices might be $200 or more. The fuses, breakers, and breaker box may total $250, while wiring can run $50–100, and miscellaneous hardware such as conduits, terminations, feedthroughs, and mounting can total $100. A system monitor and associated shunts can be as little as $150 or as much as $600. Thus a 100-W system may range from $1200 to $2500. Adding more PV panels does not significantly raise the cost of the system beyond the extra cost of the PV itself. The economic payback time on the cheaper system is 40 years if electricity prices remain at $0.15 per kWh over that period. Clearly, the motivation must be other than economic.

Indeed, having a solar-charged cell phone or laptop, watching a movie on a solar-powered TV, or entertaining guests late at night with stored-up sunlight have all been rewarding experiences. I now enjoy a feeling of energy independence—come what may in the future. I may not be personally turning the tide on fossil-fuel use and all its associated ills, but my home PV system is a small contribution in that direction. What is more, I can share the knowledge I have gained with students and peers. It is especially valuable to get physicists to participate in solar technology at a personal level. Many simple experiments concerning, for example, the monitoring, tilting, cleaning, cooling, and repositioning of the PV panels have given me a much firmer grasp of the real-world practical limitations and potential usefulness of solar technology. Additional experiments with tracking, concentration, heterogeneous combinations of panels, partial shading, and so forth also promise to be fruitful. The greater the number of physicists tinkering with PV technology, the more good ideas we'll generate. So get plugged into the Sun!

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The online version of this article features additional data and brief analyses.