PV SYSTEMS Simplified

by Justine Sanchez & Ian Woofenden

Photovoltaic (PV) modules make electricity from sunlight, and are marvelously simple, effective, and durable. They sit in the sun and, with no moving parts, can run your appliances, charge your batteries, or make energy for the utility grid. It's difficult to find a product that combines the longevity *and* productivity of PV modules. When you buy them, you're buying 40-plus years of electricity for a one-time cost.

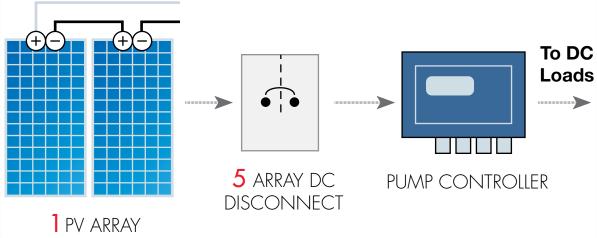
A PV array is the energy collector—the solar "generator." To use the energy from the array, you also need other components which make up a solar-electric *system*, and you need to design the whole system for the purpose desired. This article explains the basic components and configurations for the four most common system options in solar electricity:

- PV-DIRECT
- STAND-ALONE (OFF-GRID)
- GRID-TIED WITH BATTERY BACKUP
- BATTERYLESS GRID-TIED

Specific systems will vary—not all equipment is necessary for every system type. In the diagrams, the numbers in red correspond to the major components needed.

PV-DIRECT SYSTEMS

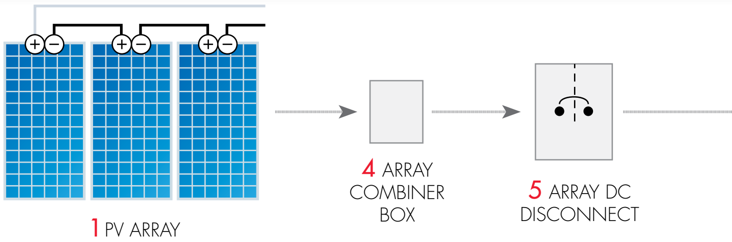
These are the simplest of solar-electric systems, with the fewest components. Because they don't have batteries and are not hooked up to the utility, they only power the loads when the sun is shining. This means that they are only appropriate for a few select applications, notably water pumping and ventilation—when the sun shines, the fan or pump runs. At night these systems do not provide energy. These systems require a match between the PV modules and the load, and may also have electronics between the array and load to facilitate start-up and maximize energy production.



OFF-GRID SYSTEMS

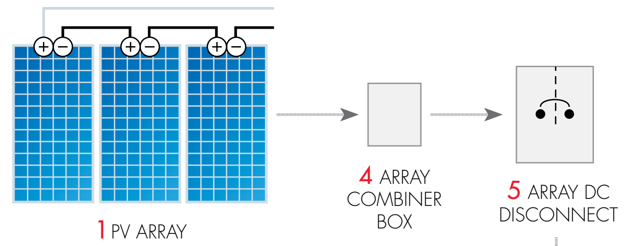
Although they are most common in remote locations without utility service, off-grid solar-electric systems can work anywhere. These systems operate independently from the grid to provide all of a household's electricity. That means no electric bills and no blackouts. People choose to live off-grid for a variety of reasons, including the prohibitive cost of bringing utility lines to remote home sites, the appeal of an independent lifestyle, or the general reliability a solar-electric system provides. Two key components are batteries to store energy and an engine-generator which can provide energy during periods of cloudy weather.

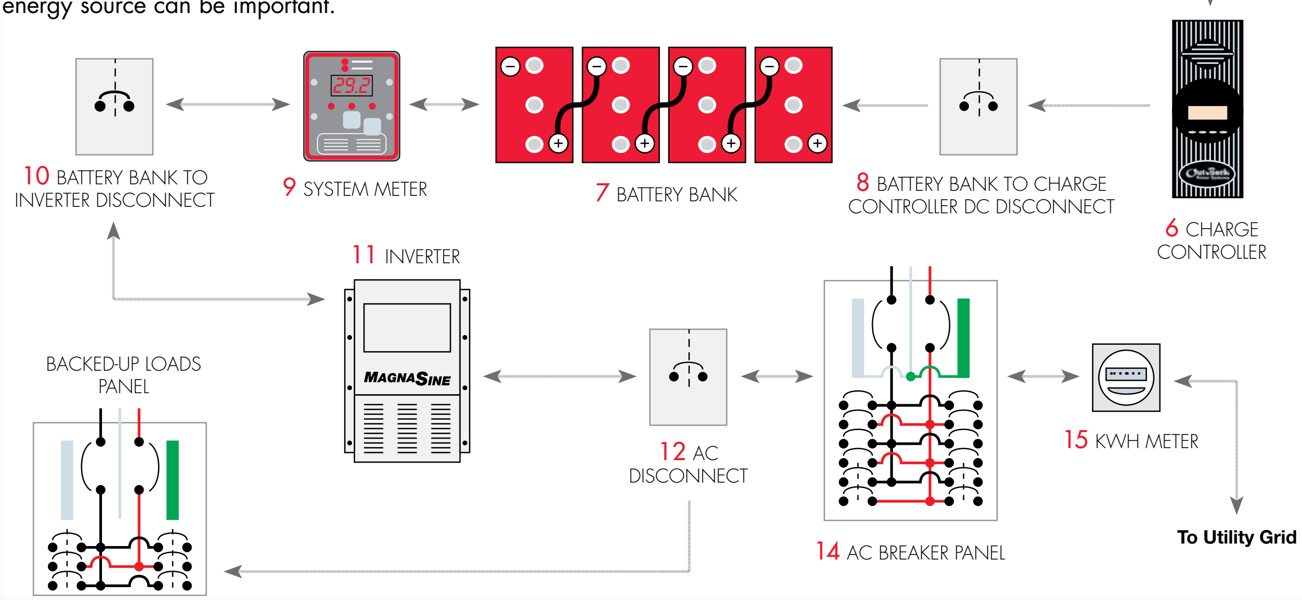
Those who live off-grid often make adjustments to when and how they use electricity, so they can live within the limitations of the energy available. This doesn't necessarily imply doing without, but rather is a shift to a more conscientious use of electricity.

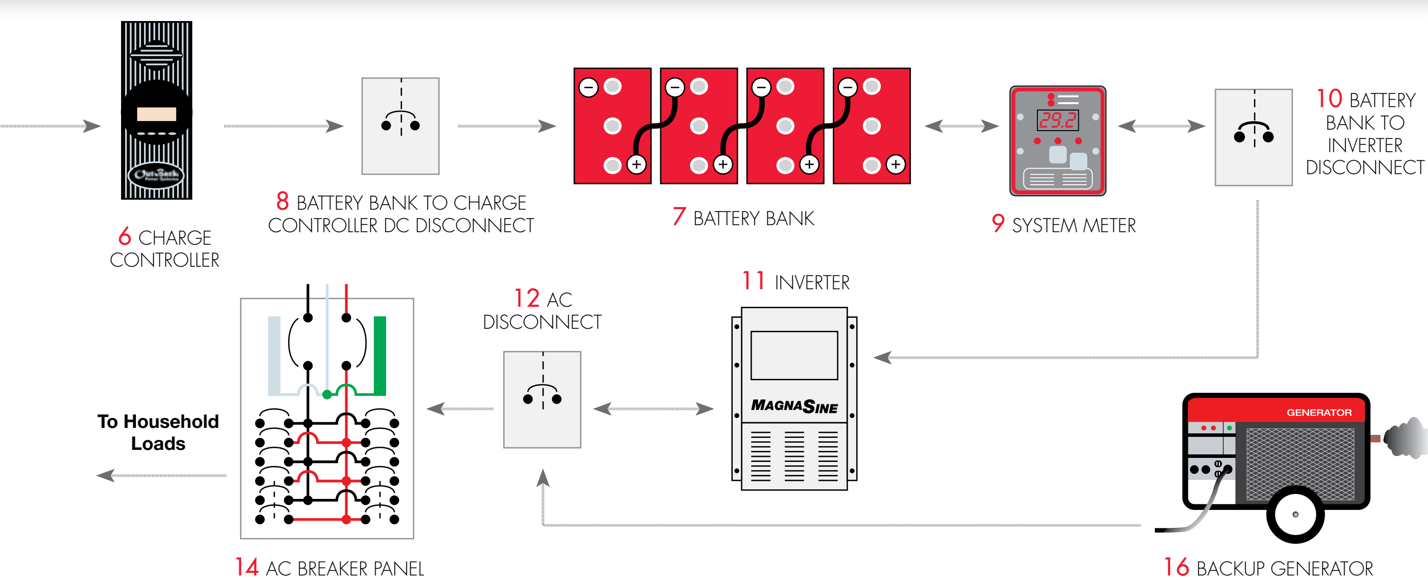


GRID-TIED SYSTEMS WITH BATTERY BACKUP

This type is very similar to an off-grid system in design and components, but adds the utility grid, which reduces the need for the system to provide all the energy all the time. The battery bank provides backup to some or all loads during utility outages. Battery backup can be provided for any household circuit, but common backup loads include refrigeration, a well pump, or a computer. Including batteries in a grid-tied system requires more components, is more expensive, and lowers the system's overall efficiency compared to a batteryless grid-tied system. But for homeowners who regularly experience utility outages or have critical electrical loads, having a backup energy source can be important.



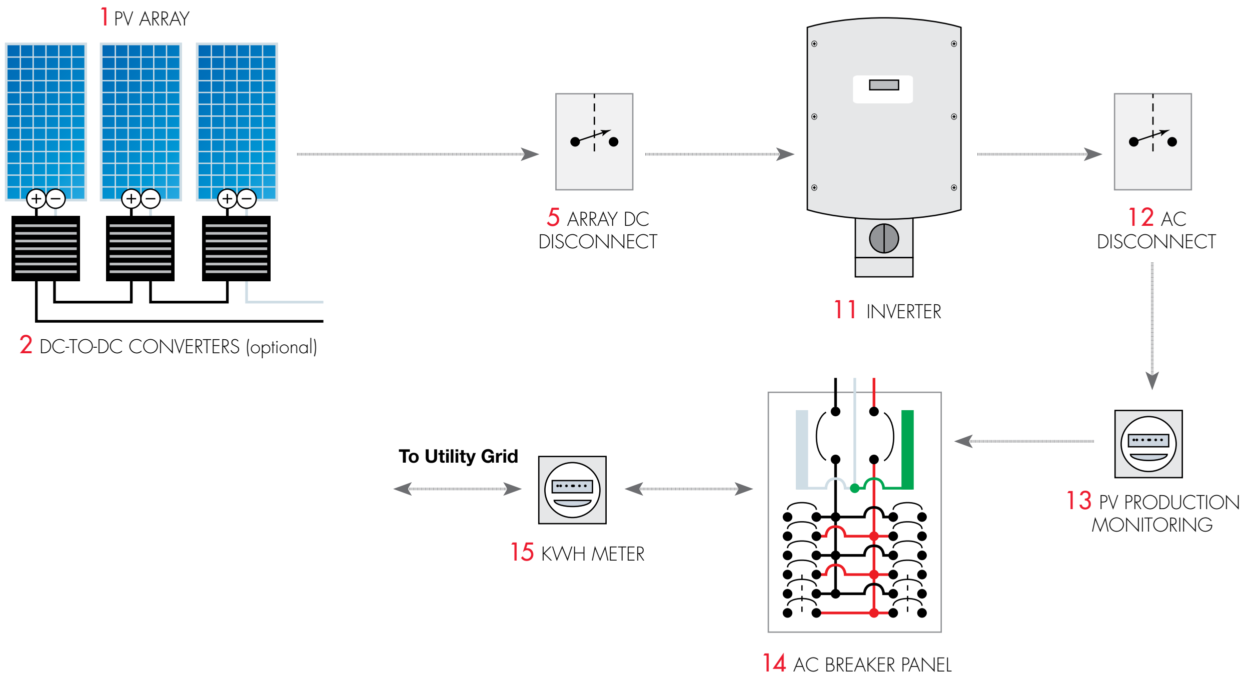




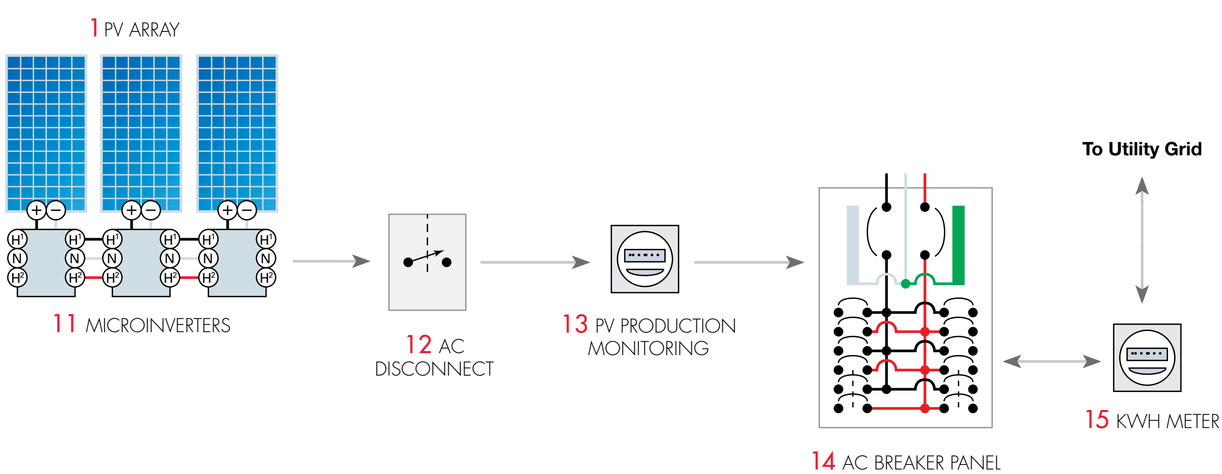
BATTERYLESS GRID-TIED SYSTEMS

These most common PV systems are also known as on-grid, grid-tied, utility-interactive, grid-intertied, or grid-direct. They generate solar electricity and route it to the loads and to the electric utility grid, offsetting a home's or business's electricity usage. Living with a grid-connected solar-electric system is no different than living with utility electricity, except that some or all of the electricity you use comes from the sun. The drawback of these batteryless systems is that they provide no outage protection—when the utility grid fails, these systems cannot operate.

In many states, the utility credits a grid-tied customer's account for solar electricity produced during each billing cycle, which is then applied to periods when the system produces less or electrical consumption is greater. This arrangement is called net-metering or net billing. The specific terms of net-metering laws and regulations vary from state to state and utility to utility. In some states, a production incentive may pay the system owner a premium for PV system production. (See www.dsireusa.org for states' incentives details.)



MICROINVERTER SYSTEMS



1 PV MODULES (AKA: solar-electric modules)

PV modules are a solar-electric system's defining component, where sunlight is used to make direct current (DC) electricity. Behind a PV module's shimmering face, semiconductor materials work their magic, using light (photons) to move electrons in a circuit—what's known as the photovoltaic effect.

PV modules are rated in watts, based on the maximum power they can produce under ideal sun and temperature conditions. You can use the rated output (along with a figure representing your local solar resource and an efficiency factor) to determine how many modules it will take to meet your electrical needs. Multiple modules combined together are called an array. Although framed modules are most common, PV technology also has been integrated into roofing shingles and tiles, and even peel-and-stick laminates for standing-seam metal roofs.

PV modules are very durable and long-lasting—most carry 25-year warranties. They can withstand severe weather, including extreme heat, cold, and hail.

Solar World

2 DC-TO-DC CONVERTERS (AKA: distributed power harvesters, power boxes, module maximizers)

A new component that's showing up on some batteryless grid-tied PV systems is DC-to-DC converters. These units can maximize the output of each module and reduce losses due to variances between modules' outputs. They are directly wired to each module and are bolted to either the module frame or the PV rack. The output of each power box is combined (either in series or parallel) to the other power boxes and the final output is wired to the PV disconnect.

SolarEdge

3 ARRAY MOUNTING SYSTEM (AKA: mounts, racks)

Sungevity

Mounts provide a secure platform on which to anchor your PV modules, keeping them in place and oriented correctly. Modules are generally mounted on a rooftop, atop a steel pole set in concrete, or at ground level. The specific pieces, parts, and materials of your mounting system will vary considerably depending on which method you choose.

Usually, arrays in urban or suburban areas are mounted on a south-facing roof (although east- and west-facing roofs can also be used), parallel to the roof's slope. This approach is sometimes considered most aesthetically pleasing, and may be a local requirement. In areas with a lot of space or if your roof is not ideal because of orientation or shading, pole- or ground-mounted arrays are options.

Pole-mounted PV arrays can incorporate tracking, automatically following the sun across the sky from east to west each day. Tracked PV arrays can increase the system's daily energy output by 25% to 40%, but come with more cost, complexity, maintenance, and potential failure than fixed arrays.

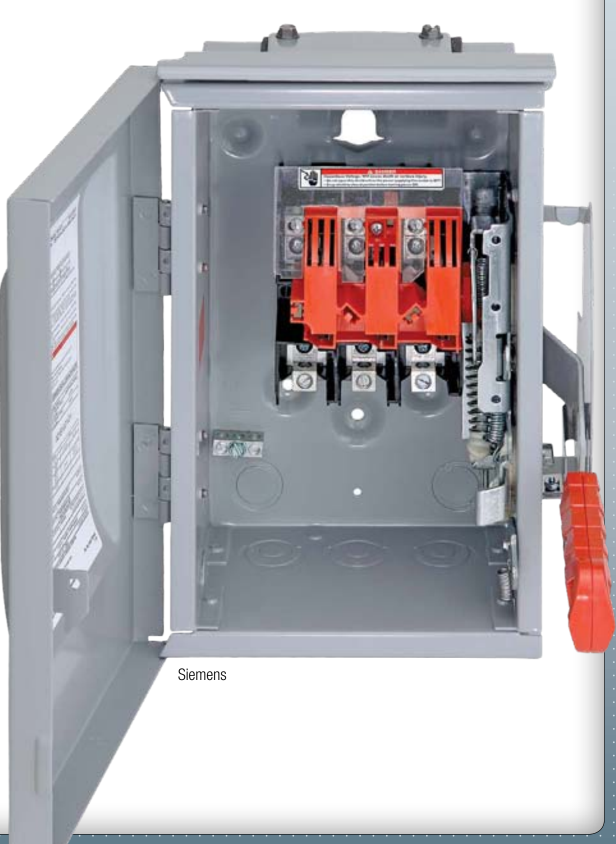
4 COMBINER BOX (AKA: series string combiner)

The array combiner box is used to wire and combine parallel strings of PV modules. These are most commonly found in off-grid systems, although larger on-grid systems will have combiner boxes as well. Coming into the input side of a combiner box will be the positive and negative wire for individual module strings, each with its own terminal. Each positive terminal is internally connected to a series circuit breaker (or fuse) for that string. The output of each breaker/fuse is connected together on a common bus bar to which a positive output wire is connected. The strings' negative wires are simply connected to a common bus bar along with the negative output wire. Some batteryless grid-tied inverters integrate a combiner box on the input side of the inverter, eliminating a separate combiner box. And some grid-tied systems only have a few PV module strings (3 or less), and do not need a combiner box at all.


MidNite Solar

5 DC DISCONNECT

The DC disconnect is used to safely interrupt the flow of electricity from the PV array. It's an essential component when system maintenance or troubleshooting is required, and may be mandated by local inspectors. The disconnect enclosure (sometimes a part of the inverter package), houses an electrical switch rated for use in DC circuits. It also may integrate either circuit breakers or fuses, if needed.


Siemens

6 CHARGE CONTROLLER (AKA: controller, regulator)

A charge controller's primary function is to protect the battery bank from over-charging. As a battery becomes charged, the controller moderates the flow of electricity from the PV modules. Batteries are expensive and need careful treatment. To maximize their life, avoid overcharging or undercharging them. Most modern charge controllers incorporate maximum power point tracking (MPPT), which optimizes the PV array's output to maximize energy production. Some battery-based charge controllers also include a low-voltage disconnect for the DC loads to help prevent over-discharging, which can permanently damage the battery bank.

OutBack Power Systems

7 BATTERY BANK (AKA: storage battery)

PV modules produce electricity only when the sun shines on them. If your system is designed to provide energy without the utility grid, you'll need a battery bank—a group of batteries wired together—to store energy so you can have electricity at night or on cloudy days. For off-grid systems, battery banks are typically sized to keep household electricity running for up to three cloudy days. Grid-tied systems also can include battery banks, which provide emergency backup power during grid outages to keep critical electric loads operating until grid power is restored.

Although similar to car batteries, the deep cycle batteries used in solar-electric systems are specialized for the type of charging and discharging they'll need to endure. Flooded lead-acid batteries are most commonly used in solar-electric systems, are the least expensive, but require adding distilled water occasionally to replenish water lost during the charging process. Sealed batteries, absorbed glass mat (AGM) and gel-cell, do not require adding water and often used for grid-tied systems where the battery bank is usually small (as compared to off-grid banks), and the batteries are typically kept at a full state of charge.

Surrette

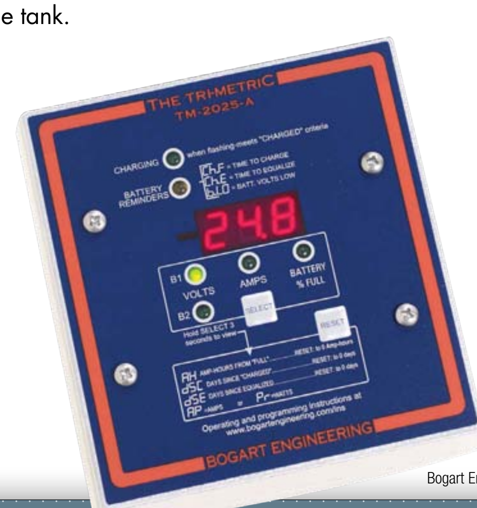
8 BATTERY BANK TO CHARGE CONTROLLER DISCONNECT

Because all electrical components may need to be serviced periodically, it is necessary, and required by the National Electric Code (NEC) to place disconnects between all sources of power and the other components. Because of this, a disconnect (usually a circuit breaker to also protect the wire) is placed between the battery bank and charge controller, which enables isolating the charge controller from the battery bank for servicing.

MidNite Solar

9 SYSTEM METER (AKA: battery monitor, amp-hour meter)

System meters measure and display several different aspects of a PV system's performance and status—tracking how full your battery bank is; how much electricity your solar-electric array is producing or has produced; and how much electricity is being used. Web-based monitoring is offered in some metering packages and is extremely handy to keep tabs and potentially troubleshoot the system. Operating your solar-electric system without metering is like running your car without any gauges—although it's possible to do, it's always better to know how much fuel is in the tank.



Bogart Engineering

10 BATTERY TO INVERTER DISCONNECT (AKA: main DC disconnect)

In battery-based systems, a disconnect between the batteries and inverter is typically a large, DC-rated breaker mounted in a sheet-metal enclosure. This breaker allows the inverter to be quickly disconnected from the batteries for service, and protects the inverter-to-battery wiring against too-high current.

Carling Technologies

Siemens

12 INVERTER AC DISCONNECT

Utilities usually require an AC disconnect between the inverter and the grid. Some grid-tied inverters have integrated AC disconnects, but these may or may not meet local requirements, calling for a separate PV system AC disconnect box, usually located near the utility kWh meter. In battery-based systems an AC disconnect is also required between the inverter, the AC breaker panel and any other AC power source. It is usually incorporated into an inverter bypass breaker assembly, allowing the AC loads to be fed by either the inverter, or if power from the inverter is unavailable, by another AC power source such as a backup generator.

11 INVERTER (AKA: DC-TO-AC CONVERTER)

Inverters transform the DC electricity produced by the PV modules or from the batteries into the alternating current (AC) electricity commonly used for lights, pumps, and other electrical appliances. Grid-tied inverters synchronize the electricity they produce with the grid's AC electricity, allowing the system to feed any unused solar-made electricity to the utility grid.

Most grid-tied inverters are designed to operate without batteries, either tying to one or more strings (series grouping) of modules, or using a "microinverter" for each module. Similar to systems using DC-to-DC converters, microinverters offer module-level monitoring and maximize array output with module-level MPPT, enabling each module to operate independently of the others.

Battery-based inverters for off-grid or grid-tied use often include a battery charger, which is capable of charging a battery bank from either the grid or a backup generator during cloudy weather. Most batteryless inverters can be installed outdoors, but most battery-based inverters are not weatherproof and should be mounted indoors, close to the battery bank.

SMA

Magnum

Enphase Energy

13 PV PRODUCTION MONITORING

An additional meter to measure solar production is useful for tracking system performance, and is needed for production-based (per kWh) incentives. This can be a dedicated kWh meter that counts the kWh coming out of the inverter, or can be a full revenue-grade or Web-based data monitoring package.

Power-One

Benjamin Root

15 KILOWATT-HOUR METER (AKA: kWh meter, utility meter)

Most homes with a grid-tied solar-electric system will have AC electricity coming from and going to the grid. A bidirectional kWh meter can cumulatively track the flow in both directions. The utility company often provides these special meters at no cost.

14 AC BREAKER PANEL (AKA: mains panel, AC load center, breaker box, fuse box)

The AC breaker panel is where a building's electrical wiring connects to the source of the electricity, whether that's the grid or a solar-electric system. This wall-mounted panel or box is usually installed in a utility room, basement, garage, or on the building's exterior. It contains a number of labeled circuit breakers that route electricity to the various rooms or household circuits. These breakers allow electricity to be disconnected for servicing, and also protect the building's wiring against overcurrent, which may cause electrical fires.

Just like other electrical circuits, an inverter's electrical output needs to be routed through an AC circuit breaker. This breaker is usually mounted inside the building's mains panel, which enables the inverter to be turned off and isolated if servicing is necessary, and also safeguards the circuit's electrical wiring.

Benjamin Root

16 BACKUP GENERATOR (AKA: gas guzzler, the racket)

Honda Power Equipment

Off-grid PV systems can be sized to provide electricity during cloudy periods when the sun doesn't shine. But sizing a system to cover a worst-case scenario, like several cloudy weeks during the winter, can result in a very large, expensive system that will rarely get used to its capacity. To spare your pocketbook, size the system moderately, but include a backup generator to get through those occasional sunless stretches. Generators are also used to provide battery equalizing charging—occasional, high-voltage, prolonged charging that brings the weaker battery cells up to the charge level of the stronger cells.

Engine generators can be fueled with biodiesel, petroleum diesel, gasoline, or propane. These generators produce AC electricity that a battery charger (either stand-alone or incorporated into an inverter) converts to direct current, which is stored in batteries. Like most internal combustion engines, generators tend to be loud and polluting, and require maintenance. A well-designed PV system will require running a generator only 50 to 200 hours a year.

SOLAR-ELECTRIC SYSTEMS DEMYSTIFIED

As you can see, the anatomy of a solar-electric system isn't that complicated. All of the parts have a purpose, and once you understand the individual tasks that each part performs, the whole system makes more sense. Now you're ready to look at the system articles and schematics in *Home Power* without your eyes glazing over, and you'll have a clearer understanding of what is going on. To solidify your understanding, your next task could be to examine a solar-electric system in person, going on a local solar tour, or getting on the solar grapevine to visit folks ahead of you on the solar curve.

ACCESS

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Home Power Senior Editor **Ian Woofenden** (ian.woofenden@homepower.com) has been living with solar-electric systems since the early 1980s. His systems include a wide range of applications, including solar flashlights, vent fans, hybrid wind-PV systems for home and shop, a PV-powered waterslide, electric fence chargers, an iPhone backup charger, and more.