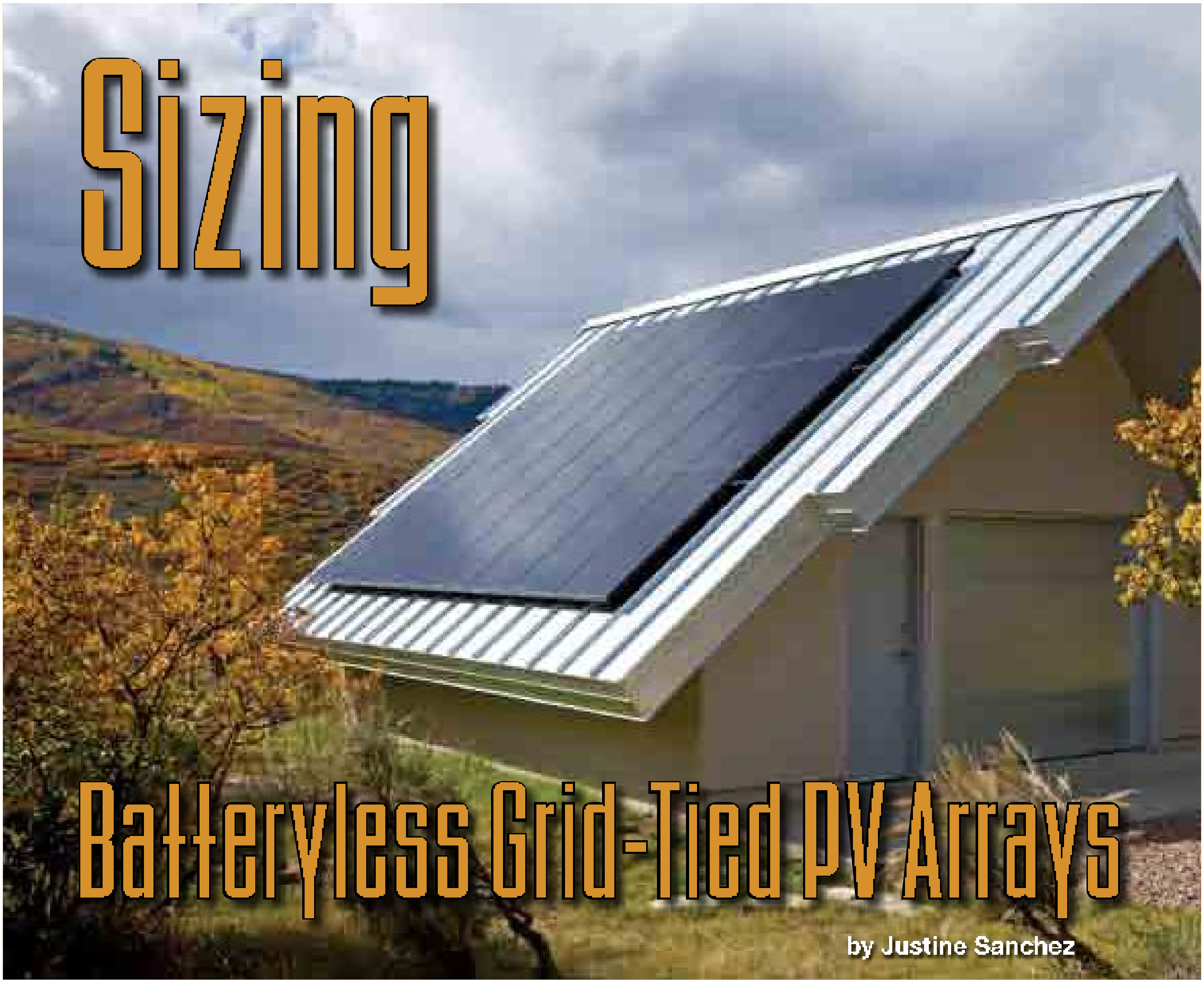
Sizing Batteryless Grid-Tied PV Arrays



by Justine Sanchez

[illegible]

Interested in clean power? Check.

Already on the grid? Check.

Are utility blackouts infrequent? Check.

Have a sunny location to mount PV modules? Check.

If this describes your situation, then a batteryless grid-tied PV system could be the perfect fit. Here's how to design your system to maximize production and your return on investment.

Compared to their off-grid counterparts, batteryless grid-tied systems are simple to understand and design, with only two primary components: PV modules and an inverter that feeds AC electricity back into the electrical system to offset some or all of the energy otherwise purchased from the utility. These systems are cheaper, easier to install and maintain, and operate more efficiently than battery-based systems of comparable size. Their main drawback is that when the grid goes down, they cannot provide any energy for you to use.

If the grid is mostly reliable, and outages are infrequent, these systems can offer the best payback for the least price.

Sizing for kWh

The primary goal of a grid-tied PV system is to offset all or some of your electricity usage. Yet the first step in going solar is not sizing the PV system, but reducing electricity usage through conservation and efficiency measures. "Negawatt-hours" are the watt-hours you save by conserving energy—not using it in the first place. The cost of reducing energy use is about 1/3 to 1/5 the cost of producing those same kilowatt-hours with a PV system. Plus, the resulting smaller system means fewer modules, which consume raw materials and energy in their manufacture and shipping.

web extra

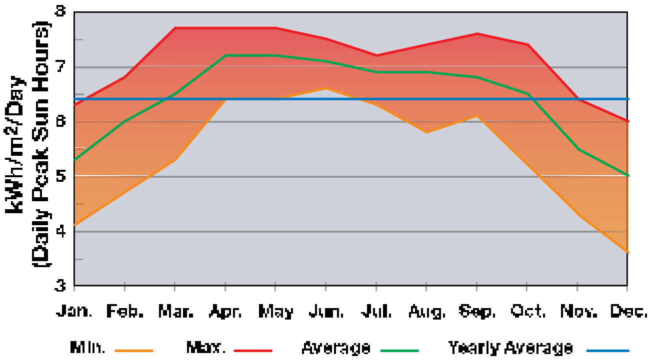
For appliance efficiency tips and strategies, see our Web Extras page: **www.homepower.com/webextras.**

Solar Hot Water & Passive Solar Design

There are many ways to implement solar strategies to reduce a home's energy consumption (both electric and gas). Using a solar hot water (SHW) system to heat the household water is one example. See "Solar Hot Water Simplified" in *HP107* for an overview of SHW systems and components.

If you are building your own home, or considering a remodel, there are many passive solar design strategies that can heat (and cool) your home without any mechanical systems. For example, you can heat or ventilate/cool rooms by simply putting in windows and overhangs in the appropriate places. See "Passive Solar Retrofit" in this issue for more information.

Solar Insolation for Albuquerque, NM



Data: NREL; based on flat-plate collector facing south at a fixed tilt of 35.05° (corresponding to the location's latitude), uncertainty ±9%.

Once energy-efficiency and conservation measures have been implemented, you're ready to size a PV system to offset the remaining energy usage. Annual energy use figures can be requested from your utility, and these values can be used to determine the PV array size. If you've adopted energy-efficiency measures, waiting a full year after their implementation can help you size your PV system more closely to your usage. But you can guesstimate the new annual energy use if you know your consumption patterns and the approximate energy savings for your new energy-efficient appliances. (For example, say you upgrade to a more energy-efficient washing machine—you can calculate the kWh savings per load and multiply that by how many loads of laundry are washed per year to figure out its annual consumption reduction, and then repeat this calculation for all of your upgraded appliances.)

To determine the PV array size needed, you'll also need to know the peak sun-hour figure for your location. Once we have these two values, along with an overall system efficiency factor, a simple calculation can be used to figure the PV array size needed to offset your utility usage.

As an example, let's say we have a home located in Albuquerque, New Mexico. After implementing energy-efficiency strategies, this home consumes 4,000 kWh per year. Using solar data for Albuquerque, supplied by the National Renewable Energy Laboratory (http://rredc.nrel.gov/solar/pubs/redbook/), you'll find the average peak sun-hours per day for a south-facing array, mounted with tilt angle equal to latitude (in this case, 35°) is 6.4. We also estimate an overall average system efficiency factor of 66% (see "PV System Derating").

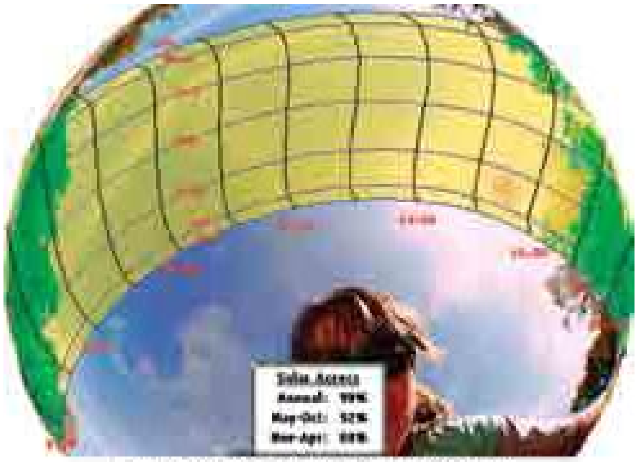
To calculate the array size needed to offset annual energy consumption, divide the annual kWh consumption by 365. This gives an average daily consumption in kWh. Divide this amount by average daily peak sun-hours to get the approximate array size in kW. That value is then divided by the system's efficiency derate factor:

4,000 kWh/yr. ÷ 365 days/yr. = 10.96 kWh/day

10.96 kWh/day ÷ 6.4 sun-hours/day = 1.71 kW

1.71 kW ÷ 0.66 efficiency factor = 2.59 kW array

Several tools, including smartphone apps, are available to help determine your site's solar window.



Data by Solmetric SunEye™ – www.solmetric.com

Array Orientation & Tilt

Generally speaking, nontracking PV arrays in the northern hemisphere will experience the most solar exposure by facing true south at a tilt angle equal to within 5° of the latitude. However, region-specific factors can alter when your array receives the most sunlight. For example, in areas with extremely cloudy winters (like Seattle, WA), a tilt angle of latitude minus 15° can yield the highest annual production for a grid-tied system—summer energy gains at the more shallow tilt far exceed the winter gains at the steeper tilt. Another situation that favors a different array orientation is if your site regularly gets early morning fog. In this case, you will want to shift your array orientation toward the west. See "Optimizing a PV Array" in *HP130*.

To offset 100% of this home's annual electricity consumption, a 2.59 kW system is needed.

However, a benefit of a grid-tied system (as opposed to an off-grid system) is that the system size can be determined by your budget or preference—it doesn't have to be designed to meet 100% of your electrical needs. For example, you could decide to offset 75% of your electricity with a PV array, which would decrease the required system size to 2 kW (2.59 kW × 0.75 = 1.94 kW).

While our example system is located in New Mexico, if our house was in a less sunny climate, such as Eugene, Oregon, which has an average peak sun hour value of 4.1, we would need a 4 kW array:

4,000 kWh/yr. ÷ 365 days/yr. = 10.96 kWh/day

10.96 kWh/day ÷ 4.1 sun-hours/day = 2.67 kW

2.67 kW ÷ 0.66 efficiency factor = 4.05 kW array

PV System Derating

There are many environmental factors that can affect how much power a system can produce. These factors are combined for an estimated efficiency/derate value used in array sizing. (For more detail on these individual factors, see "Pump Up the Power—Getting More from your Grid-Tied PV System" in *HP127*.)

An overall average system efficiency of 66% is used in the example calculations to account for the following:

88% derate for energy lost due to module heating (12% loss)

95% for inverter efficiency (5% loss)

97% for DC and AC wiring inefficiencies (3% loss)

95% for module production tolerance and mismatch (5% loss)

95% for module power loss due to dust and dirt (5% loss)

90% shade factor to account for array shading before 8 a.m. and after 4 p.m. (10% loss)

To arrive at 0.66 (66%), multiply all the efficiency factors together:

0.88 × 0.95 × 0.97 × 0.95 × 0.95 × 0.90 = 0.66

While this 0.66 is a general value used for estimating a batteryless PV grid-tied array's size, a derate factor can be adjusted to match each system and site specifics. For the next example, let's say the array will consist of microinverters, which will eliminate losses due to module mismatch, and will use modules that have a positive-only production tolerance. In this case, the module production tolerance and mismatch loss will be zero (or will have an efficiency of 100% for a factor of 1.0), increasing the overall efficiency factor to 69%.

0.88 × 0.95 × 0.97 × 1.00 × 0.95 × 0.90 = 0.69

Conversely, let's go back to the original string inverter and after performing a shade analysis on the roof, we find that the solar window is really from 8:30 a.m. to 3:30 p.m. and the shading factor is 0.85. This will decrease the efficiency factor to 62%.

0.88 × 0.95 × 0.97 × 0.95 × 0.95 × 0.85 = 0.62

PVWatts Results for Albuquerque, NM

	Solar Radiation (kWh/m²/day)	AC Energy (kWh)	Energy Value ($)
January	5.33	303	$26.36
February	6.06	304	26.45
March	6.44	357	31.06
April	7.16	367	31.93
May	7.40	380	33.06
June	7.10	344	29.93
July	7.13	355	30.89
August	7.02	353	30.71
September	6.71	330	28.71
October	6.55	348	30.28
November	5.73	305	26.54
December	5.14	293	25.49
Annual	6.48	4,039	$351.39

Assumptions: 2.59 kW array, 0.716 derate factor, 35° tilt, south facing, 9.7¢ per kWh

Using PVWatts to Size a System

A common approach to array sizing is to use NREL's PVWatts program (www.nrel.gov/rredc/pvwatts/version1.html), an online PV system production estimator. By plugging in various PV array size values (and a few other system specifics), you can find what size array matches your annual energy production goal.

You can also use PVWatts to double-check your manual calculations. Note that you will need to work with the program's "DC to AC Derate Factor" calculator to match your system specifics, such as incorporating the shading factor. You will also see that they have more conservative default values, such as inverter efficiency. Their default value puts inverter efficiency at 92%, but the actual CEC weighted inverter efficiency values for many grid-tied inverters are closer to 95% (see Access).

Although PVWatts' "DC to AC Derate Factor" does not show a specific designation for losses due to module heating, the program automatically incorporates this efficiency loss using regional temperature data and a general PV power loss figure (0.5% per °C rise) in their kWh production estimates (see the PVWatts help files for more info).

Another handy feature of the PVWatts program is the ability to test the effects of various PV array tilt angles and orientations on energy output. In our example above, the array is sited to face true south and set at a tilt angle equal to the location's latitude. However, there are situations where an array cannot be "ideally" sited or tilted—these parameters can be entered into the PVWatts system specifics to see what the impacts on system production might be. For example, if the example array had been oriented at 225° and at a pitch of 20°, PVWatts would estimate output to be about 8% less than an optimally oriented array. Conversely, PVWatts can be used to find the optimal array tilt angle by entering various angles and noting which one gives the most kWh per year.

Sometimes, squeezing the maximum number of modules on the roof takes thinking outside the box.

Sizing within Space Constraints

In residential areas especially, a primary constraint to PV array sizing can be the size of the available shade-free mounting area. PV modules can be mounted on a roof, the ground, or a pole (which includes trackers). Roof-mounting generally takes advantage of underutilized space, but the installation may require penetrations through the roof, and can cause wear and tear on the roofing material while the work is being done. Ground-mounted systems take up yard space that might be preferred for other purposes (garden, etc.) and usually requires constructing substantial concrete footings. But the work can be done on the ground (easier and safer), and eliminates firefighters' concerns about electrical equipment being located on the roof. Plus, ground-mounted systems allow more airflow around the modules for less power loss from module heating. Pole mounting has the same basic pros and cons as the ground mounted approach, but offers the advantage of raising the array off the ground, mitigating shade issues from snow buildup or nearby bushes. Site specifics will dictate which mounting method makes the most sense for each installation.

Regardless of which mounting method is used, the shade-free area, minus clearance needed for maintenance or roof setbacks required by local fire department guidelines, will limit how large the array can be (see Access). In the case of roof-mounted systems, typically 50% to 80% of a roof plane will be available for mounting PV modules.

When space is a consideration, PV array size can be calculated using module power density (watts per square foot, W/ft.^{2}). Crystalline PV module output averages about 12 W per ft.^{2} and amorphous modules about 6 W per ft.^{2}. Let's say we have 250 square feet of roof space that is appropriate for mounting PV modules.

Crystalline modules: 250 ft.^{2} x 12 W/ft.^{2} = 3,000 W
Amorphous modules: 250 ft.^{2} x 6 W/ft.^{2} = 1,500 W

With crystalline modules, the roof space is more than adequate to fit the proposed array size (2.59 kW). (If amorphous silicon modules are used, the array will offset about 58% of the electricity usage.) Where feed-in tariff (FIT) programs are available—which pay a premium rate for solar-generated electricity—some homeowners will opt to maximize use of their roof space, which in some cases will oversize the array and produce a surplus. Even without access to a FIT program, life changes (such as a new baby and increasing loads of laundry per week) often provide opportunities for using those extra solar produced kWh.

Sizing by Budget

Often the most confining consideration is budget. Currently, the cost per *installed* watt of residential PV systems typically ranges from $7 to $9, which includes everything from modules, inverter, disconnects, racking, wire, and conduit to taxes, shipping, installation labor, and permitting.

At some sites, ground-mounted arrays can take advantage of larger areas and better solar access than roof-mounted arrays.

Pole-mounted arrays and trackers get the modules up off the ground, away from shading obstructions like bushes and snow.

Using the same location, let's say there's $10,000 available. Without any federal, state, or local incentives, the array size will be limited to between 1.1 kW and 1.4 kW:

$10,000 ÷ $7/W = 1,429 W
$10,000 ÷ $9/W = 1,111 W

Anyone with a federal tax liability can take advantage of the uncapped 30% federal tax credit, allowing you to increase the budget to $14,286 ($14,286 × 0.30 = $4,286 tax credit) and the system size from 1.59 kW to 2.04 kW—and still be within the $10,000. You'd need to pay the full cost up-front—and have enough tax liability to take the full credit that tax year or enough liability each year to spread the tax credit over several years.

Additionally, many individual states, municipalities, and utilities offer rebates that can further offset a PV system's cost. The Database of State Incentives for Renewables & Efficiency (DSIRE, www.dsireusa.org) organizes incentive programs by state and program type, making incentives easy to research. In New Mexico, for instance, PV incentives include a utility renewable energy credit (REC) of $0.13 per kWh, a personal state tax credit (10% of the cost, capped at $9,000); and a property tax exemption for solar systems. While none of these incentives reduce the up-front cost of the PV system, see the "Impact of PV Incentives" sidebar for how you can recoup your up-front investment and even make money over the system's lifetime.

Impact of PV Incentives

Scenario 1: System sized to meet 100% of electricity needs

At $7 to $9 per rated watt, a 2.59 kW PV system will cost between $18,130 and $23,310. The system is estimated to produce about 4,000 kWh per year.

30% federal tax credit ranges from $5,439 to $6,993

10% personal tax credit ranges from $1,813 to $2,331

Estimated REC payment: 4,000 kWh/yr. × $0.13/kWh × 12 yrs. = $ 6,240 total PNM REC payments

Estimated range of total incentives = $ 13,492 – $15,564

Estimated system cost, after incentives = $ 4,638 – $7,746

We can also consider the savings of the kWh offset at $0.09/kWh over 25 years (common module warranty period):

4,000 kWh/yr. × $0.09/kWh × 25 yrs. = $9,000 additional savings*

Scenario 2: Maximizes roof space; provides a surplus of electricity

A 3.0 kW system is estimated to cost between $21,000 and $27,000. This system may produce about 4,600 kWh per year.

30% federal tax credit ranges from $6,300 to $8,100

10% personal tax credit ranges from $2,100 to $2,700

Estimated REC payment: 4,600 kWh/yr. × $0.13/kWh × 12 yrs. = $7,176 total PNM REC payments

Estimated range of total incentives = $15,576 – $17,976

Estimated system cost, after incentives = $5,424 – $9,024

We can also consider the savings of the kWh offset at $0.09/kWh over 25 years (common module warranty period):

4,600 kWh/yr. × $0.09/kWh × 25 yrs. = $10,350 additional savings*

Scenario 3: Budget system

At $7 to $9 per watt, $10,000 will buy a 1.1 to 1.4 kW system, which may produce about 1,700 kWh to 2,160 kWh per year.

30% federal tax credit will be $3,000

10% personal tax credit will be $1,000

Estimated REC payment: 1,700 kWh/yr. × $0.13/kWh × 12 yrs. = $2,652 total PNM REC payments; or 2,160 kWh/yr. × $0.13/kWh × 12 yrs. = $3,370 total PNM REC payments

Estimated range of total incentives = $6,652 - $7,370

Estimated system cost, after incentives = $2,630 – $3,348

We can also consider the savings of the kWh offset at $0.09/kWh over 25 years (common module warranty period):

1,700 kWh/yr. × $0.09/kWh × 25 yrs. = $3,825 additional savings*

2,160 kWh/yr. × $0.09/kWh × 25 yrs. = $4,860 additional savings*

*Note the kWh offset values are conservative savings estimates that use New Mexico's current average electricity rate of $0.09 over 25 years. Electricity rates are likely to continue their upward climb over this period.

System Scenario Costs

	Meets 100% of Electricity Needs	Maximizes Roof Space (250 ft²)	Budget System
System size (kW)	2.59	3.00	1.1 – 1.4
Annual energy output (kWh)	4,000	4,600	1,700 – 2,160
System cost ($7 – 9 per W)	$18,130 – 23,310	$21,000 – 27,000	$10,000
Federal tax credit (30%)	$5,439 – 6,993	$6,300 to 8,100	$3,000
Personal tax credit (10%)	$1,813 – 2,331	$2,100 to 2,700	$1,000
Renewable energy credit (13¢ per kWh for 12 yrs.)	$6,240	$7,176	$2,652 – 3,370
Total incentives	$ 13,492 – 15,564	$15,576 – 17,976	$6,652 – 7,370
Net system cost	$ 4,638 – 7,746	$5,424 – 9,024	$2,630 – 3,348
Utility savings (9¢ per kWh for 25 yrs.)	$9,000	$10,350	$3,825 – 4,860