Designing

A STAND-ALONE PV SYSTEM

by Khanti Munro

Khanti Munro

The Ackerman-Leist pole-mounted array stands at the garden's edge, an integrated part of the family's homestead.

Living off the grid is a romantic ambition for some, a practical necessity for others. But whatever your motivation for off-grid living, cutting the electrical umbilical cord from the utility shouldn't be taken lightly. Before you pull out the calculator, size up the realities and challenges of living off the grid. Then, once you're convinced it's the way for you, use this guide to design a successful stand-alone system.

Design Considerations

Designing a stand-alone PV system differs substantially from designing a batteryless grid-direct system. Instead of meeting the home's annual demand, a stand-alone system must be able to meet energy requirements every day of the year. The PV system must be able to keep the battery bank charged—or include a generator for backup—because once the last amp-hour is drawn, the lights go out (see "Backup Generators" sidebar).

Efficiency first! This long-standing mantra for PV system design still holds true and is especially important for off-grid systems. Using energy efficiently should always be a prerequisite to energy design and production. Every $1 spent on energy efficiency is estimated to save between $3 and $5 on PV system costs. As a system designer, it's virtually impossible to mandate *wise* energy use by the end user, but we can specify efficient appliances, such as Energy Star refrigerators and clothes washers, and strategies, such as shifting loads to non-electric sources during times of low solar insolation. For more on efficiency and load-shifting, see "Toast, Pancakes & Waffles: Planning Wisely for Off-Grid Living" in *HP133*.

Energy Consumption and the Solar Resource. Carefully comparing the home's daily and seasonal energy usage with the daily and seasonal availability of the sun will help prevent energy production shortages. This important step involves a careful analysis of the home's changing seasonal load profile and the corresponding solar resource throughout the year. Paramount to this analysis is the presence or absence of a backup charging source, such as a generator. If a backup charging source is not incorporated, the designer should choose as the design target the time of year when energy consumption is expected to be highest and the solar resource at its lowest—usually during the depths of winter.

Without a backup generator, a PV system must produce every watt-hour required, at all times of the year. This is often a tall task during the winter months and typically results in a costly system that is oversized for the rest of the year. For this reason, stand-alone systems without a backup charging source are often limited to smaller, nonresidence applications, such as seasonal cabins.

For systems with a backup charging source, more design flexibility means designers can use average consumption numbers and peak sun-hour values. For example, they can choose to size the system at a time of year when energy consumption is not at its highest or lowest, but in the middle—say, a typical day in the fall or spring. In addition, they might use the specific location's average solar resource. Using the average for both consumption and sun-hours will strike a good balance between an affordable array size and generator run time. If minimal generator run time is desired, the array and battery bank may need to be upsized based on more conservative consumption and sun-hour values.

Size it Up: A Case Study

Let's explore an example sizing scenario, component by component, with a method Solar Energy International (SEI, see Access) uses in its classes to size stand-alone systems using an maximum power point tracking (MPPT) controller:

Who: The Ackerman-Leist family
Where: Pawlet, Vermont, approximately 3/4 mile from utility service
Solar window: 8 a.m. to 4 p.m.
Average daily solar resource: 4.6 peak sun-hours*
System backup: 4 kW backup engine generator
System voltage: 24 VDC
Projected energy use (AC and DC): 2.2 kWh per day
Expected avg. ambient temperature for batteries: 60°F
Record low temperature: -35°F
Desired days of autonomy: 3
Desired battery depth of discharge: 50%
Battery: 6 V nominal, 225 Ah, deep-cycle flooded lead-acid
PV modules: 12 V nominal, 80 W STC , array tilt equal to the latitude (43°)
Charge controller: MPPT, 60 A
Array mounting: Pole-mount
*Peak sun-hours are based on Concord, New Hampshire, values, which more accurately reflect the site's latitude and weather patterns.

Step 1: Estimate Electric Load

Determine the amount of energy (kWh or Wh) that will be consumed on a daily basis. If it is for a home not yet built, this can be a very involved and time-consuming step. A designer will need to work closely with the homeowner/builder to realistically estimate the daily and seasonal energy requirements.

Shawn Schreiner

A watt-hour meter gives precise figures on consumption for appliances already owned. Without that information, the values in the "Loads" table must be estimated.

The power (W) of individual loads and their estimated energy consumption (Wh) can be tallied to calculate the household's average daily load. This step will help identify opportunities for efficiency improvements and pave the way for sizing the system components. The table below lists the electrical loads found in the Ackerman-Leist household. The family heats their home with wood, cooks with wood and propane, uses a propane refrigerator, and heats their water with a solar thermal system and a backup propane boiler, so those are not factors in the load analysis.

According to the table, daily household loads average 1.8 AC kWh and 0.36 DC kWh (from the chest freezer), totaling almost 2.2 kWh a day.

Ackerman-Leist Load Analysis

AC Loads	V	x	A	=	W	x	Qty.	=	Total W	x	Hours Each Day	x	Days Each Week	÷	Days In a Week	=	Avg. Wh/ Day
CF lights	120		0.17		20.4		10		204.0		4.00		7		7		816.0
Laptop computer	120		0.50		60.0		1		60.0		2.00		5		7		85.7
Staber clothes washer	120		4.00		480.0		1		480.0		0.42		3		7		86.4
Satellite internet modem	120		0.30		36.0		1		36.0		2.00		5		7		51.4
Well pump	120		13.00		1,560.0		1		1,560.0		0.25		7		7		390.0
Composting toilet fan	120		0.13		15.6		1		15.6		24.00		7		7		374.4
							Total AC W for Inverter Sizing		2,355.6				Total Avg. Daily AC Wh				1,803.9

DC Loads	V	x	A	=	W	x	Qty.	=	Total W	x	Hours Each Day	x	Days Each Week	÷	Days In a Week	=	Avg. Wh/ Day
SunDanzer freezer	24		2.5		60		1		60		6.00		7		7		360
													Total Avg. Daily DC Wh				360.0

Contained in this simple battery box, three parallel strings of four 225 Ah Trojan T-105 batteries make a 24 V, 675 Ah battery bank.

Backup Generators

Employing a backup generator in a stand-alone PV system is a prudent addition. Trying to produce every last watt-hour needed can cost a pretty penny in added PV array and battery bank capacity—much more than the cost of a generator. That's why using a backup generator in a stand-alone PV system can make financial sense. A reliable backup source allows greater design flexibility and, most often, a smaller and more cost-effective system. The size of the PV array can be reduced to a more affordable size, while a backup generator can make up the difference when the solar resource is inadequate. In addition, equalization, an important aspect of battery maintenance, can be difficult to achieve with a PV array alone. As long as there is fuel in the generator, you aren't dependent on the weather to keep the lights on and the beer cold. (For more information on backup generators, see "Engine Generator Basics" in *HP131*.)

Step 2: Battery Bank Sizing

The average daily load is then used to calculate the battery requirements. The batteries must be able to store the total daily load, in addition to the extra energy lost by inverting from direct current (DC) to alternating current (AC). Dividing the AC average daily load by the inverter efficiency (90% standard), inflates the average daily load that the batteries must store to account for efficiency losses from the inverter. While inverter manufacturers will commonly list "peak efficiency" (generally ranging from about 92% to 95%), we use a more conservative 90% to account for the fact that the actual operating efficiency depends on the AC load, which is constantly fluctuating. Hence, an inverter will rarely operate at the load level which results in peak efficiency.

The battery bank's ambient operating temperature is also taken into consideration, since temperature affects a flooded lead-acid battery's internal resistance and ability to hold a charge. As temperatures fall below 80°F, battery capacity is reduced. A battery temperature multiplier table can be used—check with the battery manufacturer for their specific correction factors.

Days of autonomy is also an important design criterion, as it dictates how many days the battery bank will need to sustain the average daily load when there is little or no sunshine to recharge it. It's a compromise between having energy during overcast spells, how much time the generator will run, and the added cost of a larger battery bank. The more days of autonomy desired, the larger the battery bank. Generally three to five days of autonomy provides a good balance. Keep in mind that the larger the battery bank, the larger the PV array will need to be to recharge the bank sufficiently on a regular basis—or the more the generator will be needed to pick up the slack.

The last major design criterion for sizing batteries is the depth of discharge (DOD). While deep-cycle lead-acid batteries are designed to discharge 80% of their capacity, the deeper they are discharged on a regular basis, the fewer charge/discharge cycles they can provide over their lifetime. When choosing a DOD, strike a balance between longevity, cost, and the significant hassle of replacement. Many system designers will specify a 50% DOD to be used in the worksheet. Because several days of autonomy are accounted for, which increases the battery bank size, the actual depth of discharge during sunny weather will often be less than 20%. The DOD design value can greatly affect the cost of the battery bank. (For simplicity, the numbers from the load table have been rounded in the following equations.)

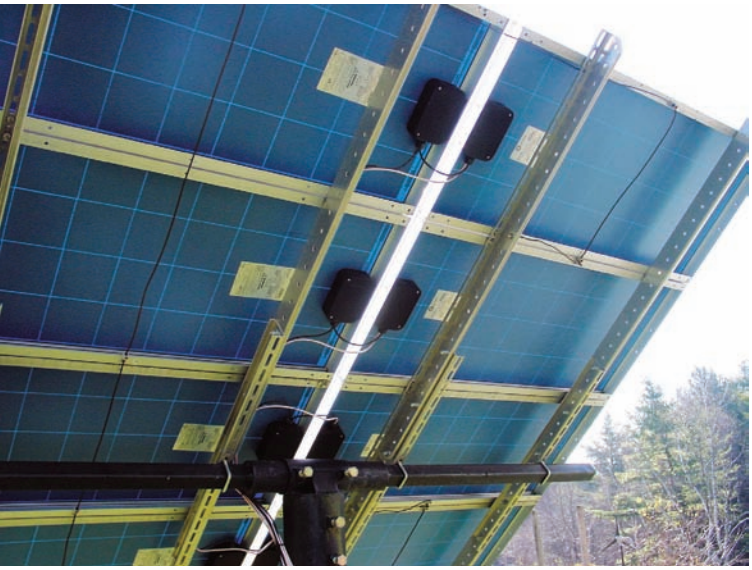
(1,800 AC Wh Avg. Daily Load ÷ 0.9 Inv. Eff.) + 360 DC Wh Avg. Daily Load = 2,360 Wh/day

2,360 Wh/day ÷ 24 DC System Volts = 98.3 Avg. Ah per day

98.3 x 1.11 battery temperature multiplier x 3 days autonomy ÷ 0.5 DOD = 654.7 total system Ah

Battery Temperature Multiplier

Ambient Temperature (°F)	Multiplier
80	1.00
70	1.04
60	1.11
50	1.19
40	1.30
30	1.40
20	1.59



This pole-mounted array offers unimpeded solar access at the site from 8 a.m. until 4 p.m.

654.7 ÷ 225 Ah individual battery capacity = 3 parallel battery strings (rounded up from 2.9)

24 V system voltage ÷ 6 V battery voltage = 4 batteries in series

3 parallel strings x 4 batteries in series = 12 total batteries

The battery calculations indicate that a battery bank made up of 12 of the chosen 6 V, 225 Ah, flooded lead-acid batteries will provide adequate storage to meet daily energy requirements, inverter efficiency losses, operating temperature effects, days of autonomy, and the desired average depth of discharge. The number of batteries or series-strings of batteries connected in parallel should be kept to a minimum, preferably three or less. This minimizes the chance of unequal charging from one battery or string to the next. While using higher-capacity batteries would have resulted in fewer parallel strings, the Ackerman-Leists chose lower-capacity batteries for budgetary reasons.

Batteries are rated by their capacity in amp-hours and at the rate that they are charged/discharged. In most PV systems, the appropriate Ah rating to use is based on a discharge over 20 hours. Unlike shallow-cycle vehicle batteries, deep-cycle batteries in PV systems are charged and discharged over 24 hours, and the weather, level of solar irradiance, and energy usage patterns all influence the charge/discharge scheme. In this system example, the battery could provide 225 Ah of stored energy—if discharged 100% over 20 hours. If it were discharged faster, the capacity would be less, and vice versa. Be sure to check with the battery manufacturer, as they provide battery-specific Ah capacity values based on different charge/discharge rates. Choose the 20-hour rate when sizing and selecting batteries, unless a specific load profile dictates otherwise.

Step 3: Array Sizing

Now that we have calculated loads and storage, next calculate the array size in watts, and the number of PV modules needed. The array calculations must include Wh per day (calculated from the average daily load), the location's solar resource, expressed in daily peak sun-hours, battery efficiency losses (about 20%), module temperature losses (about 12%), possible array shading, and a conservative derate multiplier to account for things like wire losses, module soiling, and production tolerance.

Peak sun-hours are the equivalent number of hours per day when solar irradiance (intensity) averages 1,000 watts per square meter, as derived from the National Solar Radiation Database (http://rredc.nrel.gov/solar/pubs/redbook/). Dividing the Wh required by the location's peak sun-hours leaves us with the initial PV array watts needed. For this sizing example, the solar data for Concord, New Hampshire (at 43.2°N) provides the closest estimate of the solar resource for Pawlet, Vermont (at 43.3°N) at an array tilt angle equal to latitude. Since this system is using a backup generator, the average daily peak

web extra

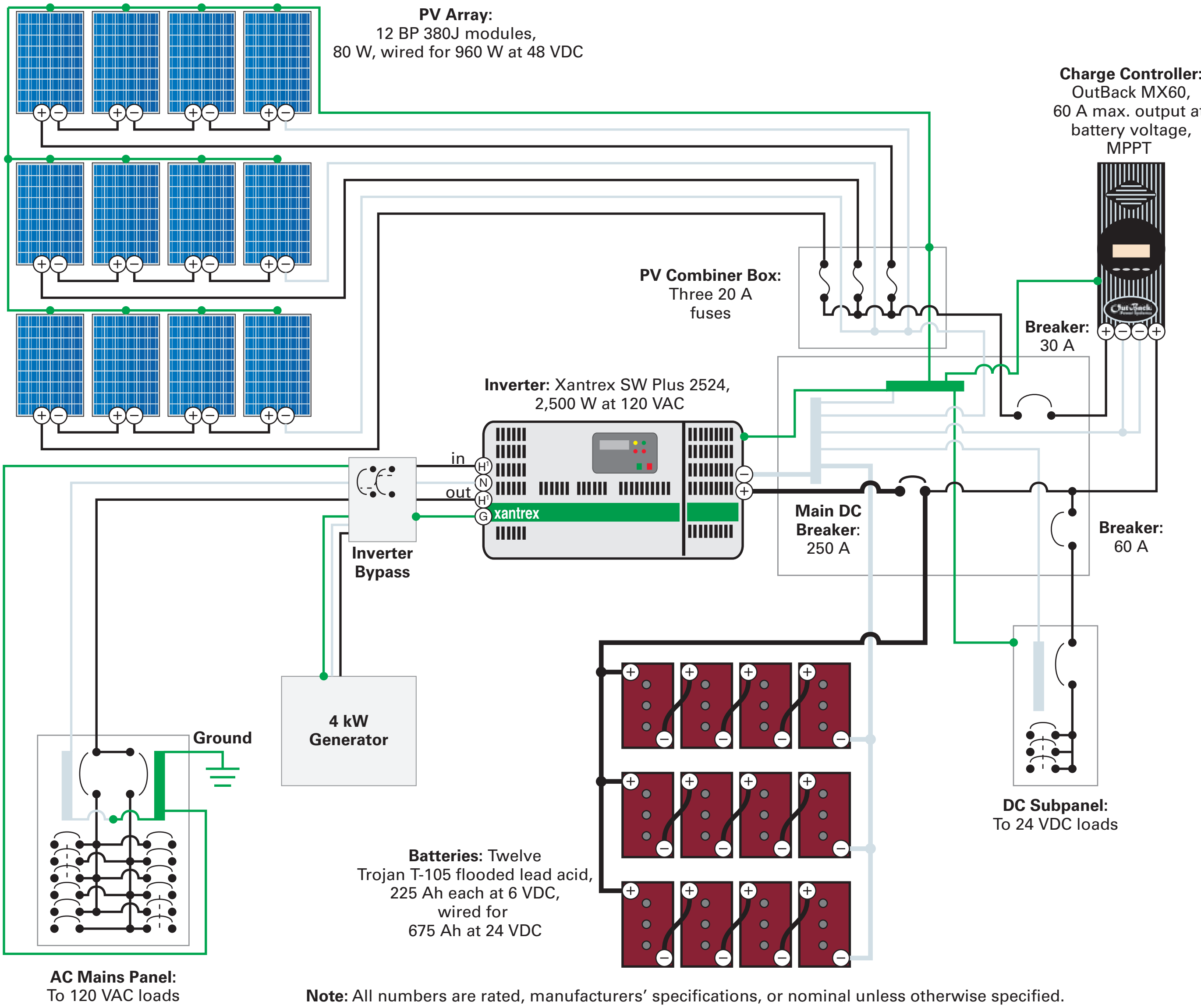
Off-Grid or On: Getting Real

Living without the utility (off-grid) means managing your own power plant, and the costs and responsibilities should be examined carefully. For a detailed analysis of the advantages and disadvantages, see "Off or On Grid? Getting Real" on the Web Extras page at www.homepower.com.

Estimating Generator Run Time

So how much will you need to rely on your generator? You can start by estimating the system's expected energy production at the location's average daily sun-hours, and then look at the times of year when you'll be short, due to higher consumption and less sun. Once you have an idea of how much energy you'll need to make up, you can estimate the generator run time. Changing weather and consumption patterns make estimating this a moving target, but this process will give the designer an idea of when during the year the generator will run and for how long—and may prompt the designer to suggest additional load-shifting and efficiency measures for these times.

Ackerman-Leist Off-Grid PV System



Note: All numbers are rated, manufacturers' specifications, or nominal unless otherwise specified.

sun-hours can be used (4.6), as the generator can cover energy shortages during periods of low insolation or high energy consumption—or both. If less generator run time is desired, the array size must be increased or daily energy consumption must be reduced appropriately (or both).

Battery efficiency: Since batteries are not 100% efficient in converting electrical energy into chemical energy and back again, the array size must be increased to account for energy lost in the storage process. A common battery efficiency is 80%.

PV temperature losses: Module standard test conditions (STC) ratings, which are based upon a cell temperature of 77°F (25°C), don't reflect real-world operating conditions. To account for losses due to higher cell temperatures, a derating value of 0.88 can be used. This assumes an average daytime ambient temperature of 68°F and an estimated cell

PVWatts System Derate Computation

Component Derate Factor	Derate Value	Acceptable Value Range
PV module nameplate DC rating	0.950	0.800 – 1.050
Mismatch modules	0.980	0.970 – 0.995
Diodes & connections	0.995	0.990 – 0.997
DC wiring	0.980	0.970 – 0.990
AC wiring	0.990	0.980 – 0.993
Soiling	0.950	0.300 – 0.995
Age	1.000	0.700 – 1.000
Derate Factor*	0.85	

*Computed by multiplying all derate values together

Step-down MPPT controllers can help decrease wiring costs by allowing PV array voltage to be higher than the battery bank voltage.

temperature of 122°F. (Another way to calculate temperature losses would be to use the specific module's maximum power temperature coefficient, in conjunction with a cell temperature based on the record high daytime local temperature.)

Shading coefficient: Although 9 a.m. to 3 p.m. is often considered the ideal solar window, site-specific shading should always be evaluated for the whole day. Even moderate shading can have a substantial impact on array output. In the case of this sizing example, with a shade-free solar window of 8 a.m. to 4 p.m., an average shading coefficient of 0.90 was determined with a Solar Pathfinder array siting tool.

Derate factor: A 0.85 derate factor (from NREL's PVWatts online performance calculator) accounts for other system losses, including module production tolerances, module mismatch, wiring losses, dust/soiling losses, etc. An experienced designer can adjust this value to reflect conditions for your specific site. See the table for a summary of these values.

2,360 Wh daily load ÷ 4.6 peak sun hours ÷ 0.8 battery efficiency ÷ 0.88 temp. losses ÷ 0.9 shading coefficient ÷ 0.85 system derate = 953 W peak array

953 ÷ 80 W STC individual module = 12 modules needed

48 V nominal array voltage ÷ 12 V nominal module voltage = 4 modules per string, 3 strings total

The resulting 12-module array will have a capacity of 960 W STC, rounded up slightly from the 953 W specified in the calculations. Although the DC system voltage and the battery bank are 24 VDC, this array can be wired at a higher voltage of 48 VDC, because of the "step-down" feature of the charge controller being used. Since the modules are nominally rated at 12 V, they will have to be wired into three series-strings of four modules each.

If these calculations seem conservative, it is because they are. It is imperative to design a system that will operate reliably and efficiently—and that will produce, on average, the expected amount of energy required. In other words, it is the designer's job to give the system manager/homeowner a *realistic* idea of what to expect.

Step 4: Controller Sizing

With an array size specified, a charge controller is next—sized to safely handle and regulate the array's incoming power to prevent overcharging the batteries. A charge controller needs to be selected based on the maximum array watts, nominal battery voltage, and desired features. A MPPT controller allows the array to maximize the energy put into the batteries, particularly under cold conditions (high array voltage) and low battery voltage. These controllers also have the ability to step down a higher array voltage to a lower battery bank voltage which, in turn, helps keep wire size and costs down for long wire runs. It can also reduce the number of series fuses and the size of the combiner box. To prevent damaging the controller and potentially voiding its warranty, the maximum open-circuit voltage (Voc) of the array must never exceed the charge controller's maximum voltage rating at the lowest expected ambient temperature.

12 modules x 80 W each = 960 W (max. W controller must handle)

960 W ÷ 1,500 W max. controller W rating at nominal battery voltage (24 V) = 1 charge controller required (rounded up from 0.64)

22.1 V module Voc x 4 modules in series x 1.25 temp. multiplier (per *NEC Table 690.7* for record low temp. of -35°F) = 110.5 VDC maximum PV array Voc

110.5 max. Voc < 150 VDC, the controller's maximum Voc rating

***Max. system voltage was calculated using the module's Voc temp. coefficient**

Although charge controllers are most commonly rated by the amount of current (amps) they can deliver to the battery bank, it is often simpler to compare the calculated array watts with the controller manufacturer's recommendation for

Select an inverter to handle the maximum loads that will be on at once in the home. Choosing the next larger size will help ensure your system can meet the demands of future loads.

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maximum array watts (STC) at the applicable battery bank voltage. More often than not, the maximum array watts for different battery bank voltages are listed on the controller's spec sheet, allowing the designer to simply divide the system's array size (in watts) by the controller's maximum allowable watts, to determine how many controllers will be needed.

Another option, especially when a controller spec sheet does not list the maximum allowable watts, is to use the manufacturer's controller string-sizing tool on its Web site to determine allowable array configurations. If no string-sizing tool is available, make sure that the calculated array size meets the given controller specifications, mainly "maximum input current." In the example here, the controller spec sheet does specify an STC nameplate rating of 1,500 W for a 24 VDC battery bank. Lastly, the above calculations also verify that at the coldest expected low temperature, the maximum array voltage will not exceed the controller's maximum open-circuit voltage rating.

Step 5: Inverter Sizing

A battery-based inverter must handle all the household AC electrical loads that could be on simultaneously (AC total watts). An inverter must also be able to handle the expected surge or in-rush of current that some large loads draw upon startup. While a conservative method for estimating surge requirements is simply to multiply the total AC watts by three, realistically, many household loads do not surge. In this sizing example, likely only the clothes washer and well pump will surge significantly, although we also include the base load of the other appliances that may also be consuming power. Always be sure to compare the surge rating of an inverter with the expected surge requirements of the system.

Other design criteria include matching the inverter's input voltage with the nominal battery voltage, choosing the desired AC output voltage (120 or 240 VAC), considering environmental conditions (indoor or outdoor, mountainous or coastal, etc.), and weighing different optional features, such as an internal battery charger.

2,356 W total AC loads = minimum inverter continuous watt rating (round up to 2,500 W typical inverter size)

[(1,560 W pump + 480 W washer) x 3] + 316 W base load = 6,436 W minimum surge rating

Desired AC output: 120 VAC

Desired features: Integrated AC-DC battery charger, digital display

An inverter with a continuous rating of 2,500 W and a minimum surge rating of 6,436 W will meet the household's instantaneous power and surge requirements. The inverter model chosen must have an input voltage of 24 VDC to match the nominal voltage of the battery bank, and have an AC output voltage of 120 VAC to meet the needs of household loads. There are no 240 VAC loads in the Ackerman-Leist home, but if there were, the following options would be available: specify an inverter with 120/240 VAC output; stack two 120 V inverters in series; or use a step-up transformer for the loads that require 240 VAC. Inverter features are also important to consider, such as an inverter-integrated AC-DC battery charger. This feature is convenient for use with a backup generator when the batteries need supplemental charging. A digital interface can also be a helpful feature.

System Recap

This system was sized appropriately given the design parameters and, along with the backup generator, should provide the family with a reliable and long-lasting PV system. The daily and annual energy production of any PV system is largely dependent on how much available sunlight there is and weather patterns, which vary from year to year.

It is interesting to examine how the system design would change if a backup generator was not incorporated. Using the month with the lowest peak sun-hours (December, 2.8 daily sun-hours) and increasing the days of autonomy from three to five would require 20 batteries and 20 modules—a 66% increase! Of course, higher-capacity batteries and larger modules could be used, but the increase in cost would still be substantial.

Since it was installed in May 2004, the Ackerman-Leist system has performed well and has provided the family with almost all of their electrical needs—minus about 30 hours per year of generator run time to equalize the batteries and make up for occasional shortages during the winter months. Although the system was sized for 12 modules, they started out with 10 for budgetary reasons. But with the addition of two children to the family (making them a family of five) and a few new loads, they will be adding the other two PV modules soon. In addition to the use of efficient appliances, the family is also in-tune with the weather and their energy usage patterns; they only do laundry on sunny days and only use a clothesline to dry their clothes. The system powered the entire construction of their three-level home and has since served as an educational model for them, their community, and students at Green Mountain College, where Philip Ackerman-Leist teaches.

It's inspiring to see a family of five use so little energy and yet live so comfortably—a system of this scale would be vastly undersized for almost any other full-time residence, at least here in the United States. A testament to energy conservation, efficiency, and awareness, the Ackerman-Leist family lives *with* their system, paying close attention to the ebb and flow of energy.

Access

Khanti Munro (khanti@solarenergy.org) is a Green Mountain College alum, an ISPQ-certified PV instructor, and SEI's PV online coordinator and instructor trainer. Tied to the grid since childhood, Khanti lives vicariously through his off-grid friends and clients, with ambitions to someday unplug.