Off-Grid Batteries

30 Years of Lessons Learned

by Allan Sindelar

Thirty years ago, an off-grid PV system was likely to consist of a couple of solar-electric modules and a pair of automotive or truck starting batteries. The system had no inverter, as reliability was still nearly a decade away, and the 12-volt system was likely to power little more than a few DC car-type tailights, a car stereo, and maybe a few RV appliances.

In those days without adequate how-to information, off-gridders were likely to use car batteries. The PV modules charged the batteries, but not being the right "tool" for the job, they often failed to hold their charge after only a year or two.

Home Power published its first issue in 1987, primarily to spread how-to and homebrew information for early solar pioneers. In the premier issue, *Home Power* founder Richard Perez writes, "After many battery failures and much time in the dark, we finally tried a real deep-cycle battery. These batteries were hard to find; we had to have them shipped in, as they were not available locally. In fact, the local battery shops didn't seem to know they existed."

The first deep-cycle batteries were not developed for remote home systems, but were adapted from other uses—golf carts, supermarket floor scrubbers, and mining cars. A few pioneers could afford to order industrial-grade "traction batteries" directly from battery manufacturers. Some off-grid pioneers reused batteries that were routinely replaced by railroads and telephone companies long before their life was up; these were once commonly available for a fraction of a new battery's cost.

Our understanding of what works and lasts has improved considerably. Some of this information remains unchanged over the decades and some is newly emerging. This article will focus on batteries in off-grid residential applications, and their selection and sizing.

Selection

For off-grid applications, flooded lead-acid batteries are the most common, although sealed batteries are sometimes used (see "Basic Battery Concepts" sidebar).

Golf-cart batteries are mass-produced by the millions. Even with price increases in recent years, they remain the best low-cost choice for small systems. Seldom does a set last more than seven years; typically they last 4 to 5 years. However,

A classic golf-cart battery: 6 V, 225 Ah at a 20-hour rate; 10 3/8 in. wide by 7 1/8 in. deep x 10 7/8 in. tall; 62 pounds.

they will stand up to remarkable abuse, including chronic undercharging and lack of equalization, still providing adequate service. For some systems, frequent replacement of a set is a reasonable, low-cost approach, and their size and weight (62 lbs., about the same as a large car battery) make them easy for a homeowner to handle.

At 225 Ah at 6 V, a 24 V set of four provides about 4 kWh of usable energy, so these batteries are only for small systems. Given their short life expectancy, I have seen the three-string limit (see "string sizing section") exceeded without the shorter-life penalties of more expensive batteries, but even four strings yields only about 16 kWh. At 48 V, two strings offer the same kWh capacity; designing a relatively small off-grid system at high nominal voltage could be a good approach.

L16 batteries and similar "commercial" batteries were originally designed for use in supermarket floor scrubbers, where they were run all night and charged from the grid the next day. Their combination of size, deep-cycle performance, and relatively low cost makes them an acceptable choice for some RE systems. With three cells (6 V) and 350 to 400 Ah, these batteries are well-suited for small-to-medium systems. However, they are more expensive per Ah than golf-cart batteries without supplying substantially more cycle life; 5 to 8 years is typical. At 120 pounds, they can be moved by two people fairly easily.

Several manufacturers are now offering 2 V batteries using the same overall case dimensions as the 6 V models. Using a lower-voltage, higher-capacity battery means fewer strings in parallel for the same kWh storage (see "Battery String Sizing" section). Some are simply three cells connected internally in parallel rather than series; others are true 2 V cells with thicker plates and a longer cycle life.

Industrial batteries are available in a wide variety of configurations, up to about 2,500 Ah per cell. Industrial batteries no longer fit a dimensional standard, as they are not adapted from another industry. Rather, the number and size of lead plates determines both the capacity and physical size of each cell. A battery bank is sized to the desired capacity, and cells ordered in cases holding one, two, three, or six cells. Some cells can be removed from the cases for ease of installation, others use welded interconnects between adjacent cells. Installation must be carefully planned to manage a weight that can easily exceed 300 pounds.

A typical L-16-type battery: 6 V, 370 Ah at a 20-hour rate; 11 3/4 in. wide by 7 in. deep x 16 1/2 in. tall; 113 pounds.

Courtesy Deka Solar

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Twelve 2 V IBE batteries in individual steel cases, wired as a single string for 24 V.

Industrial cells are substantially more expensive: $2,000 to $10,000 for a set is not uncommon, depending on capacity. Their substantially greater cycle life—15 to 20 years of good performance is typical—has been shown to be the best bargain on a lifetime basis. This is especially so if replacement labor is amortized into the life-cycle cost, as they are replaced less frequently. Some long-time installers will only sell industrial cells, preferring to maintain a positive relationship with their customers over the long haul.

With newcomers to off-grid living, however, installers may advise a set of L16s or even golf-cart batteries as a training set, rather than suggesting more expensive batteries. Some homeowners are simply better than others at maintenance duties, and a ruined bank of industrial cells is a bitter pill to swallow. An inexpensive first set is a smaller investment, and allows for several years of adjustment to an off-grid lifestyle and load-watching. Plus, because of change in family size and lifestyle, the replacement industrial bank may end up larger or smaller than the load analysis determined in the initial design.

Sealed batteries offer some benefits over flooded batteries. They require no maintenance beyond proper charging. As the

Warranties

The warranties on batteries vary tremendously by brand and battery type. At the most basic, warranties may be for a year or two; some of the best written warranties are for as much as 10 years. Warranties will usually include a free replacement period, followed by a prorated term during which a replacement will be supplied at a reduced price. The key to warranties, however, is that they are designed to cover manufacturing defects, not perceived overall premature failure due to poor maintenance and loss of capacity from sulfation. That is, if a single cell fails during the warranty period, the cell (or battery case with that cell) may be replaced under warranty. However, if the entire bank fails prematurely, it won't be covered.

Basic Battery Concepts

Cell: The basic building block of any battery is the cell, the unit in which the chemical reactions of charging and discharging occur. All lead-acid cells nominally produce 2 V; a 12 V battery has six cells connected in series.

Battery: A battery is a generic term for a collection of one or more cells in a single case. This can be confusing, as we are used to thinking of a car battery (12 V with six cells) or a golf-cart battery (6 V with three cells, but as large and heavy as a large car battery). In most PV applications, batteries have one to six cells. The cells may be of any size, but the term remains the same. In fact, the larger the capacity of each cell, the fewer the cells in the battery case.

Flooded: The most common batteries in off-grid residential systems are flooded lead-acid. Flooded refers to an internal structure that uses a liquid sulfuric acid and water electrolyte to submerge suspended lead plates.

Sealed: Sealed batteries, better known as valve-regulated lead-acid (VRLA) batteries, surround the lead plates with an electrolyte that is either gelled (gel batteries) or absorbed within a fiberglass mat (absorbed glass mat or AGM batteries). Opinions vary in the industry as to which sealed type performs better in off-grid use.

Shallow: A car battery is the perfect example of a shallow-cycle battery. It has to supply high current to start a stiff engine in below-zero weather, so it has multiple thin plates to maximize surface area for more starting current. This is why automotive batteries are rated in "cold-cranking amps." Even a cold start, however, only discharges a few percent of the battery's capacity; it then is immediately recharged by the car's alternator.

Deep: A deep-cycle battery has fewer but much heavier plates, as it is designed to be deeply discharged and recharged multiple times without damage. Deep-cycle batteries are rated in amp-hours (Ah), a measure of the battery's ability to deliver current over an extended time.

Series: A series connection adds voltage by connecting individual cells positive-to-negative. Six 2 V cells in a battery are connected in series to make 12 V. Either four 6 V batteries or twelve 2 V batteries connected in series makes a 24 V battery string.

Parallel: Parallel connects strings of the same voltage together, positive-to-positive and negative-to-negative, to increase the battery bank's capacity. For example, wiring two 12 V, 220 Ah batteries in parallel will make a 12 V, 440 Ah bank.

Bank: Multiple batteries connected together, in series and/or parallel, are referred to as a "bank" instead of individual batteries.

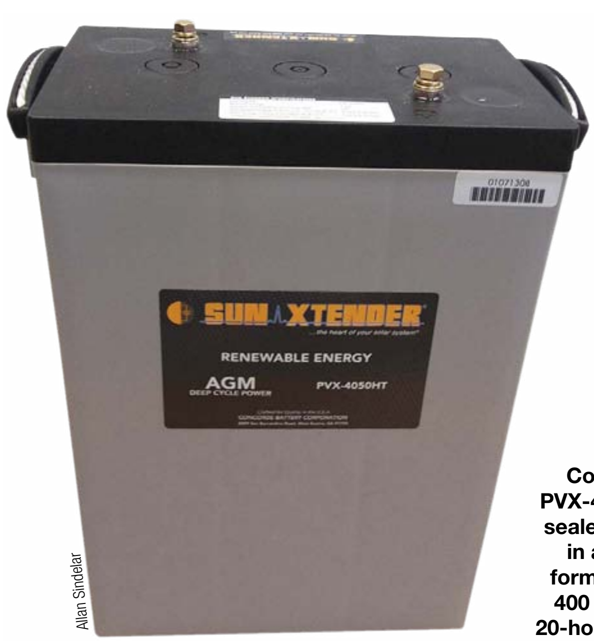
Amp-Hour: Any cell or battery has a specified capacity, described as the amp-hour capacity (Ah) of the battery. This is a common term for comparing types and sizes of batteries.

Kilowatt-Hour: A more useful term is the kilowatt-hour capacity (kWh) of a battery bank: this is the amp-hour capacity multiplied by the bank's nominal voltage.

State of Charge (SOC) and Depth of Discharge (DOD): These are the terms for how charged or discharged a cell or battery is, usually expressed in percent. The two always add up to 100%: a cell that has a 70% SOC has a 30% DOD.

Days of Autonomy: An off-grid RE system is sized so that the total amount of daily charging energy from all sources—PV, wind, hydro or generator—exceeds the home's total average daily load. The major role of the battery bank is to store energy between charging periods. Days of autonomy refers to the theoretical number of days that a battery could supply the total average daily load without recharging, usually down to a minimum threshold of about 80% DOD (20% SOC).

C/Rate: This ratio is used to quantify charge and discharge rates. It refers to the rated capacity of a cell or battery divided by the number of hours to either fully discharge or charge it. For example, a common golf cart battery has a capacity of 220 Ah. If a 22 A load is placed on the battery, it is being discharged at a C/10 rate (220 ÷ 22 = 10). If the battery is then recharged by a PV array producing 11A, it's being charged at a C/20 rate. A 1,000 Ah battery would need to be charged at 50 A to achieve the same C/20 rate.



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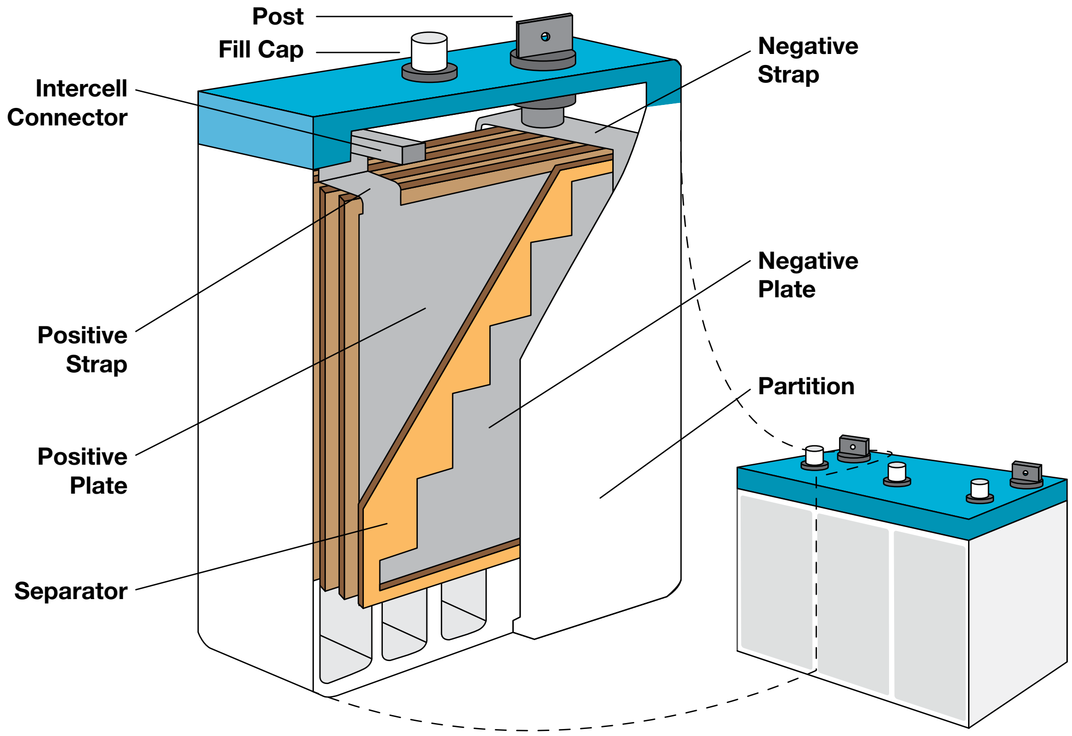
Concorde PVX-4050HT sealed AGM in an L-16 format; 6 V, 400 Ah at a 20-hour rate.

electrolyte is either gelled or absorbed, they don't gas during normal charging. Lacking liquid electrolyte, they are charged to lower voltages and can tolerate small arrays and lower charge rates, as long as they regularly reach and maintain full charge. They don't require adding water or equalizing, plus they don't leak and won't foul battery storage areas or attract corrosion on terminals. Absorbed glass mat (AGM) batteries are non-spillable and non-hazardous, so can be shipped via common ground and air freight with no hazardous material costs. Since access to the cell tops to add water is not necessary, they can be mounted in any orientation without harm. Their stackability means they may occupy less floor space than flooded batteries.

But sealed batteries are not without their drawbacks. AGM batteries may last longer than inexpensive flooded batteries, but not as long as industrial flooded batteries. For example, Concorde estimates seven to 10 years of service in

Anatomy of a Flooded Lead-Acid Cell



off-grid use. They are substantially more expensive: typically double the cost of industrial cells of similar capacity. They are more susceptible to damage from overcharging.

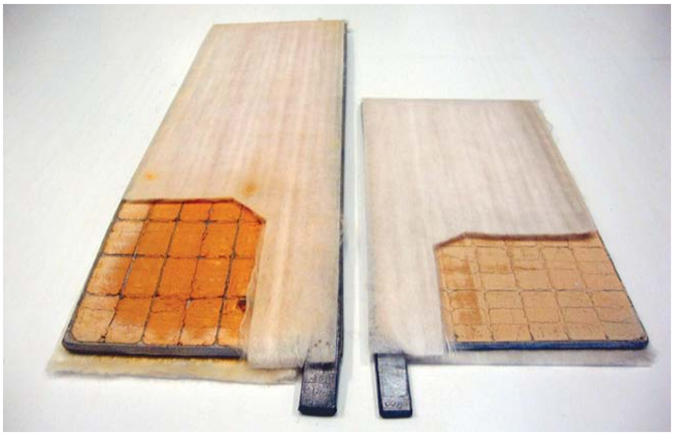
These batteries are well-suited to homeowners who don't want to perform their own battery maintenance. This includes many newcomers to off-grid living, who want (and can afford) a professionally designed and installed system, and can live well within its limitations, but prefer not to be involved with battery maintenance. Sealed batteries are also well-suited to cabins and homes with seasonal use and little maintenance, and for weekend cabins in which small arrays and larger banks provide energy for weekend use.

PV-to-Battery Sizing

Originally, deep cycle batteries were meant to be cycled during a work shift and then be immediately and fully charged daily with utility power: a predictable and well-managed charging regimen. In an off-grid home system, both loads and RE resources vary from day to day and season to season. Some days, batteries will be full by mid-morning; at other times, batteries may not be full for days. Opportunity charging is the term given to the treatment of batteries in RE systems: the charging system takes maximum advantage of any RE source when it's available. In practical terms, this means that charge voltage settings are often set higher, and absorption times are often set to the maximum available—often 4 hours (with the 2% current threshold as an override, to minimize daily gassing when a system is left unused)—see "The Charging Process" sidebar on page 87.

To accomplish proper charging of flooded cells, the charge rate has to be high enough to overcome the cells' internal resistance. A PV charge rate of C/20 or better is generally considered the minimum needed. For a 1,000 Ah battery at 24 V, this would be 50 A (plus enough to meet the household loads)—or a PV array rated at more than 1,500 watts. While a C/20 rate is the minimum, the preferred rate is between C/12 and C/6, so for each 100 Ah of flooded battery capacity, the combined DC charge rate should be at least 8 A, or C/12, and

The active material on the plates is comprised of lead oxide, acid, water, and fiber. The plate grid metal is lead with 4.25% antimony. The white material is the glass matting used to assist in improving cycle life. Left: A 0.260-inch-thick positive plate from a Surrette industrial cell. Right: A smaller plate from an L-16 cell.



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A Surrette series 5000 industrial battery: 4 V, 546 Ah at a 20-hour rate.

not more than 16 A, or C/6. This is the combined amperage of all charging sources, including a PV array, wind or hydro generator, or an engine generator.

In the early years, PV modules were far more expensive than today, and batteries were less expensive. Early practice was to size for 4 to 8 days of autonomy, but that led to small arrays and large battery banks, resulting in chronically inadequate charging. Some old-timers will remember "one module per battery"—modules were 35 W to 50 W, or 6 A per pair of golf-cart batteries. At 220 Ah and 6 A of charge, this resulted in a C/36 rate: too low for good battery care.

Modern systems now call for only 2 to 3 days of autonomy, as long as the system includes a backup generator to make up for extended cloudiness. If the budget allows, array capacity is expanded, rather than increasing battery capacity.

Battery String Sizing

Fewer parallel battery strings in a bank means better performance over the batteries' life. Slight imbalances between strings within a battery bank can cause increasingly uneven performance, leading to premature failure of part of a bank and early replacement of the entire bank. Larger individual cells allow for fewer strings, as does higher nominal system voltage. A single series string is a wise choice, and two strings in parallel are considered acceptable. Three is the maximum number of parallel strings, but should be avoided if possible.

Battery-based systems are generally wired at 12 V, 24 V, or 48 V. Systems have progressively moved toward inverter-based AC loads, so 12 V system advantages have largely disappeared, and the strong disadvantages of high current and large wire sizes discourage the use of 12 V for all but RV and portable applications and the smallest cabins with minimal loads.

For a 48 V system, a single string of batteries of the proper Ah capacity is recommended. If a single cell fails, it can usually be temporarily bypassed until a replacement cell is installed, and the system can remain in use. Even with the temporary bypass of three cells (an entire battery), as would be the case with a string of eight 6 V batteries, set points can often be adjusted to allow the 48 V system to operate at 42 V.

Twenty-four volt systems are often designed with two strings, as the failure of either a cell or a 6 V battery requires only that one of two strings be temporarily disconnected from the system.

Temperature Effects

All lead-acid batteries lose their effective capacity as they get cold. The loss varies slightly for different batteries and is almost in direct proportion to their temperature. For example, at 0°F, a battery can supply about 55% of its 77°F capacity. Low-temperature capacity loss isn't permanent; raise the temperature and the capacity returns. But most off-grid systems are most stressed in winter, when days

Two paralleled 24 V strings of 6 V Deka L-16 batteries in an enclosure sized for three strings, interconnected and arranged to allow easy access to the electrolyte caps for maintenance.

A single 24 V string of 2 V flooded cells has about the same size and capacity as the three strings of L-16s, but with fewer cells to water and fewer interconnects.

The Charging Process

Early charge controllers were crude: generally little more than voltage-actuated on/off relays. Modern charge controllers have substantially improved battery charging and longevity.

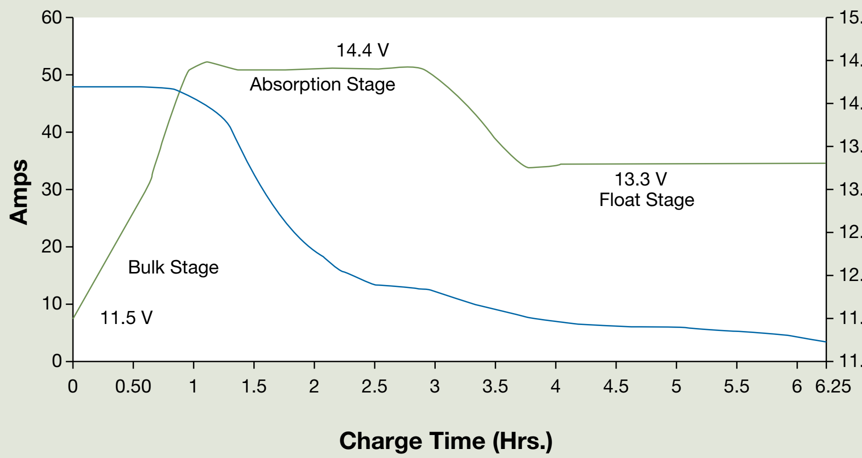
The charging process for flooded cells involves four steps: bulk, absorption, float, and equalization. During the bulk phase, which generally fills the cell to around 85% of its capacity, the charge controller (from a PV, wind, or hydro source) or the inverter (from a generator or AC source) allows all available charge current to flow into the cells. As the current is absorbed by the plates in the cell, the cells' voltage steadily increases. When the voltage reaches the bulk voltage set point (typically about 2.45 V per cell), the controller moves into the absorption stage. During absorption, the voltage is held at the bulk set point, and the charge is regulated to the current necessary to maintain that voltage (plus power any loads that are on).

When any flooded lead-acid battery approaches full-charge voltage, the cells begin to "gas." The cells are no longer able to absorb all of the energy, and the excess energy separates water in the cells into hydrogen and oxygen gases. Gassing is an important part of the charging process: the process brings weaker cells closer to the charge level of stronger cells, and the bubbling action destratifies the electrolyte.

As the cell approaches 100% SOC, the amount of current necessary to maintain this voltage steadily drops. When either a preset time duration (typically 2 to 4 hours) is reached, or the charge current drops below a set threshold (typically a C/50 rate, or about 2% of a healthy cell's capacity), the cell is considered fully charged, and the controller moves into float stage. During float, a tiny amount of current holds the cell slightly above its resting voltage, and the charging process is finished until the next charging cycle.

Equalization is the periodic, deliberate overcharge of a full battery. It stirs up the electrolyte, breaks up light sulfation (which is what eventually wears out a battery), and evens out the chemical state of charge in each cell. It generally requires taking the full cell up to about 2.6 V and holding it at or above this threshold for several hours.

Example Three-Stage Charge Curve (12 V, 221 Ah battery)



This graph is from Surrette for their 12 V, 221Ah battery. Often, manufacturers provide a range of bulk and float voltage values. While this graph displays values toward the middle of that range, PV charge controllers will usually be set to the higher end of that range.

How *not* to do it: Four parallel strings, with cables attached at one end and interconnects interfering with access to the caps for watering. Extensive acid corrosion around several terminals prevents good electrical conductivity.

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are shortest and loads are typically greatest. Adding the reduced capacity of frigid batteries only exacerbates this seasonal weakness.

Batteries thrive in a thermally tempered space, with a temperature that seldom drops below 50°F. This can often be achieved by housing them in a space that is well-insulated, has south glazing with overhangs, and adequate thermal mass (the batteries themselves contribute substantially). Batteries don't need to remain in a heated indoor space, although this too can be done safely and effectively. They do need to be protected from uneven temperatures from radiant heat sources, including exposure to direct sunlight, as identical cells at different temperatures will not perform equally.

A second consequence of temperature's effect on battery performance is that a cold battery must be charged to a higher voltage than a warm battery to achieve the same SOC. All modern, quality charge controllers have temperature compensation to adjust the charge voltage according to the battery's temperature. In most cases, the sensor is attached to the battery terminal or case. Unless a battery's temperature remains constant, a temperature sensor is an important component of an RE system. Without temperature compensation, cells will not reach 100% SOC in winter. In summer, they can be overcharged, reducing battery life.

Battery Advances

While there are tremendous advances taking place in battery development, most are based around increasing a battery's performance and capacity per pound—that is, lightweight, high-capacity batteries for electric vehicles and portable applications of all kinds. In the RE industry, weight isn't a key factor; a more relevant figure has been energy density per dollar, and conventional flooded lead-acid batteries have filled this bill the best.

Battery choices have been slow to evolve, due to a unique quandary: their longevity. Since deep-cycle batteries can last 15 to 20 years, learning by experience what works best can take decades. Plus, there's only a handful of long-time off-grid installers who have been selecting, installing, and maintaining batteries for long enough to actually compare and learn from entire battery life cycles. In the absence of long-term data, we tend to use what has worked previously, rather than trying new and possibly expensive approaches.

A relatively new shift is the use of high-quality sealed batteries in some off-grid applications, but there isn't yet a large body of experience from which to draw conclusions and predict performance. The expectations of some old-timers are that high-quality, maintenance-free AGM batteries may last about seven to 10 years in full-time off-grid use, with good care.

Access

Allan Sindelar (allan@positiveenergysolar.com) installed his first off-grid PV system in 1988. In 1997, he founded Positive Energy of Santa Fe, New Mexico. He has lived off-grid since 1999. Allan is a licensed commercial electrician and a NABCEP-certified PV installer.

Further Reading:

"Top Ten Battery Blunders: And How To Avoid Them" by Windy Dankoff in *HP114*

"Flooded Lead-Acid Battery Maintenance" by Richard Perez in *HP98*

"Designing a Stand-Alone PV System" by Khanti Munro in *HP136*

"Toast, Pancakes, and Waffles: Planning Wisely for Off-Grid Living" by Allan Sindelar in *HP133*

For a listing of battery manufacturers and their products, see "Choosing the Best Batteries" in *HP127*