Making the Switch

Converting an Off-Grid System to Lithium Batteries

Roth and Ramberg Photography

There is considerable mystery, myth and confusion with respect to retrofitting Lithium batteries into existing off-grid systems. There are five major areas of concern:

- Safety
- Application compatibility
- Charge/discharge management
- Low temperature performance
- High cost

None of these areas of concern pose real-world obstacles for off-gridders that want to upgrade to Lithium batteries, none the less, they each should be addressed in system design or operational strategy.

Safety

There are many types of Lithium batteries utilized in a variety of applications around the world. Some of these applications require such a high degree of energy density that the battery design results in something more volatile than would be appropriate for off-grid application. Examples include Nickel Cobalt Oxide (NCO) and Nickel Manganese Cobalt (NMC). Both of these chemistries are used in automobiles and some grid-tied energy storage applications.

Likewise there are many Lithium applications that have safety and durability as their highest priorities. These include industrial, telecommunications and off-grid habitation. Typically for these types of applications designers turn to $LiFePO_4$ batteries. This chemistry is the safest and most stable.

$LiFePO_4$ batteries are actually safer than lead acid batteries because they do not give off corrosive and explosive gasses. It is safe to install $LiFePO_4$ batteries inside living spaces. Many $LiFePO_4$ batteries that are intended for off-grid application carry agency listings such as UL 1973, which addresses standards for stationary and light rail batteries. UL 9540 covers safety of energy storage systems (ESS). Additionally a UN38.3 listing indicates that the battery meets UN and DoT standards for shipping.

Application Compatibility

Off-grid applications present a unique set of demands and challenges to any battery. The battery must be able to:

- Deliver very large amounts of current instantly
- Recharge quickly
- Have tolerance for partial undercharge
- Support deep discharge without damage

That is a tall order for any battery type and, for decades, large format lead acid batteries, both sealed and flooded, have been the best choice for off-grid application. While the technology doesn't score an unequivocal yes on any of the requirements, it has come closer to meeting those needs than any other type of battery that was available until the advent of $LiFePO_4$ chemistry and battery packs designed and configured for off-grid type applications.

A glance at the specifications of a $LiFePO_4$ battery intended for off-grid use shows a product that does score an unequivocal yes on all of the requirements. For this example, a Discover Battery AES 42-48-6650 was used.

Battery Capacity	130	Amp Hours
Max Current – Charge and Discharge	130	Amps
Max Allowable Depth of Discharge (DOD)	100	%
Max Recommended Design DOD	80	%
Operating Temperature Minimum	-20	0°C
Operating Temperature Maximum	50	0°C
Charging Temperature Minimum	0	0°C

$LiFePO_4$ batteries operate well at a partial state of charge, and they attain 80% of full charge quickly (maximum at the C1 rate). They suffer no penalty operating for long periods of time at partial charge (between 20% and 80% DoD) and are warrantied to support 100% DoD.

This means that a single 48V $LiFePO_4$ battery rated at 130 Amp hours (6.8 kWh) will happily accept 130 Amps, which at nominal 48V equates to a 6kW charge rate. It will deliver at least 80% of its capacity as useful storage. The C1 rate of recharge translates into real world savings, $LiFePO_4$ batteries recharge about four times faster than lead acid batteries do. Reducing charging time by a factor of four makes for huge annual fuel savings if charging from a generator.

Another important requirement for retrofitting a new battery chemistry into an existing off-grid system is power electronic compatibility. The new batteries must work with the installed inverter, charger controller(s) and monitoring system. Almost all commonly used off-grid power electronic equipment works with $LiFePO_4$ batteries. At the simplest level, a $LiFePO_4$ battery that has no communications with the power electronics can be safely installed with only a few minor adjustments to inverter and charge controller settings (more details below). More advanced batteries and off-grid power electronics can be networked together to operate as an integrated unit.

Charge/Discharge Management

Virtually all $LiFePO_4$ batteries have some form of Battery Management System (BMS). The most basic BMS are designed to protect the batteries from high or low voltage thresholds. They are often very simple switches that require manual resetting when they trip. This can be more than inconvenient, especially with an unattended system so it is critical to set all the power electronic equipment low and high voltage disconnect points to occur before the battery can engage its own protection circuitry. This way the batteries will stay on line and the system will recover when the over or under voltage condition has been cleared.

More sophisticated BMS monitor individual cell voltages and current and balance the charge between cells as necessary to stay within desired target voltage and current. This BMS allow batteries to attain a higher SOC because they are designed to taper current as the battery attains full charge.

The BMS also communicates with other equipment in the system, and under some charge management scenarios can act as the system master and control inverter and charge controller operation to maximize charging efficiency. This is called a "closed loop" communications system because the batteries close the loop with respect to providing accurate and timely information and directions to the external power electronics that they are connected to. The batteries "drive" the charge process which speeds the final charge considerably. Direct communication with the BMS also allows for very accurate SOC measurement and reporting.

Many inverters that are currently fielded are capable of closed loop communications with $LiFePO_4$ batteries including those from SMA, Victron, Schneider Electric and others. Similarly, many charge controller manufacturers also offer closed loop communications with $LiFePO_4$ batteries. In closed loop retrofit installations, the settings for compatible power electronics are supplied by the battery. This is the most desirable way to operate $LiFePO_4$ batteries, as the internal BMS is able to charge more aggressively and, as such, attain a full SOC earlier in the solar day. This equates to more available solar energy each and every day.

Brendon Sauer, Discover AES Product Manager, says "in a closed loop system, our BMS will taper its current request to the charging source (PV controller and/or inverter/charger). This gives us the ability to have a thorough balancing phase at the end of charge. It's almost magical to watch a closed loop charger balance a battery."

When retrofitting a $LiFePO_4$ battery that does not have closed loop communications capabilities into an existing off-grid system, some settings in PV charge controllers and inverter/chargers will need to be changed. They are simple and a growing number of manufacturers are including $LiFePO_4$ pre-sets along with those for flooded lead, AGM and Gel.

The table below shows settings that can generally be used to program controllers and inverters for nominal 48 Vdc $LiFePO_4$ batteries. It is always prudent to confirm any battery charge settings with the battery manufacturer. The example settings below are for a Discover AES.

Discover AES Open Loop Charge Settings

Battery Capacity	Amp Hours
Bulk Voltage	54.4 Vdc
Absorption Time	2 hours per 100 Amp hour of battery capacity
Float Voltage	53.6Vdc

Low Temperature Performance

$LiFePO_4$ batteries have different performance characteristics than lead batteries. On the plus side of the equation, they do not lose capacity as temperatures decline. Their operating range for discharge of these batteries - 20°C to 50°C - is excellent. Virtually existing off-grid installations have their batteries installed so that they are within the operating range temperatures.

The temperature range for charging $LiFePO_4$ batteries is not as broad. Charging should only begin when $LiFePO_4$ batteries are at or above 0°C. This limitation can cause some significant problems for system operators, particularly on cold winter mornings – the time that always seems to be when the batteries need recharging most. Fortunately, there are very simple and quite effective solutions that address this issue.

1. Move the batteries inside the building envelope. They don't off gas and take up far less space than the batteries that they are replacing.
2. For PV systems, choose a charge controller that reduces or stops charge current when temperatures are below certain thresholds.
3. Build a tight enclosure for the batteries that can be heated with a very small external electric heating device. Keep in mind that the internal battery temperature is what matters, not the air temperature. A 15 Watt flat mat heater intended to warm soil trays placed under the batteries should be sufficient to keep them above 0°C in a well-insulated enclosure.
4. If a larger enclosure is used for batteries and power electronics, an external space heater with a thermostat can be used. This approach is appropriate where the charge will be provided by a generator. The generator can be utilized to raise ambient temperatures to sufficient levels to initiate battery charging. In this application, the inverter/charger can be programmed to allow the generator to run until desired temperature (or time) is reached before starting the charger function.
5. Sometimes a large load is sufficient to bring the battery internal temperature to the recharging threshold. In essence, the "work" that the battery must do to support the load causes it to warm up. For example: a battery that is 95% efficient still gives off 5% of the energy being used as heat. At this level of efficiency, a 1500 Watt coffee maker will generate 75 Watts of heat inside the battery. If the inverter is in the same enclosure as the battery it will add another seven to ten percent to the heat being generated. Using the same coffee maker and a 92% efficient inverter, another 120 Watts of heat would be generated in the battery enclosure. The simple act of making coffee can add 185 watts of heat to the battery enclosure, helping the battery warm up and begin its charging day.

One or more of these approaches is going to address any concerns about operating in low temperatures. The degree of response is going to be based entirely on geography and the constraints of the existing installation. For new installations, installing the batteries inside a heated building is the most desirable situation – but even there, consideration must be made for safe system operation if the building is vacant and unheated during the winter. It is also important to remember that any well designed system, lead acid or lithium, should have a sufficiently well heated enclosure to keep the batteries reasonably warm. No matter what the technology, a good design will keep batteries above 0°C. It's just easier to accomplish the goal with lithium because it doesn't need venting.

[1] In very cold locations, where the heaters are expected to operate a significant amount of time, extra capacity should be added to the system design.

High Cost

This is another myth that is not supported by careful examination. To begin to compare costs between Lithium and lead acid technologies, one must select a "target" in the lead acid spectrum. Comparing a Lithium battery to a generic low-cost lead battery does not yield realistic results because the life cycle and maintenance characteristics of the two batteries are so different.

It is more appropriate to compare Lithium to the best sealed batteries that lead acid has to offer. While no lead battery can approach lithium for internal communications or networking, AGM or Gel batteries designed for solar applications have been proven reliable and easy to operate (no watering required). For this comparison three highly regarded manufacturers were selected: Surrette Rolls for their top-of-the-line 2 Vdc AGM; Trojan for their 6 Vdc workhorse Solar AGM; and Discover AES for their $LiFePO_4$ battery with integrated BMS.

The basic specifications for all three are below:

CHEMISTRY	LiFePO4 Discover AES	Lead Acid AGM Rolls	Lead Acid/AGM Trojan
Mfg.	DISCOVER AES	Rolls	Trojan
Model	12-48-6650	S2-590AGM	Solar SAGM 06 375
VDC Nominal	48	2	6
Discharge Rate (hours)	NA	20	20
SPECIFICATIONS:			
Unit weight (lb)	192	81.5	114
A/hr Rating	130	550	375
DoD Rating for Cycle Life Count	100%	50%	50%
Rated Capacity at Specified DoD	6.66	13.20	9.00
Avg. Lifetime Round Trip Efficiency (RTE)	95%	65%	65%
Useful Capacity per string @ RTE	6.32	8.58	5.85
Cycle Life*	10,000	1,400	1,750

For the purposes of this comparison, a 6 kWh daily load with three days autonomy was the design target. This means that the batteries needed to store as close to a useable 18 kWh as possible. There was no correction for capacity at temperatures below 25°C. The table below shows the system sizing to meet the desired load for each of the batteries.

CHEMISTRY	LiFePO4 Discover AES	Lead Acid AGM Rolls	Lead Acid/AGM Trojan
Mfg.	DISCOVER AES	Rolls	Trojan
Model	12-48-6650	S2-590AGM	Solar SAGM 06 375
VDC Nominal	48	2	6
Useful Capacity per string @ RTE	6.32	8.58	5.85
Desired Useful Capacity	18.00	18.00	18.00
Number of Strings	3.00	2.00	3.00
Battery Bank Capacity (kWh)	18.97	17.16	17.55
Number of Batteries	3	48	24
Weight per Battery	192	82	114
Weight of Battery Bank (lbs.)	576	3912	2736

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It would take only three of the Discover AES batteries to equal the capacity of two strings of the Rolls and three strings of the Trojans. The difference in battery bank weight represents considerable difference to the type of structure required for the installation as well as the cost of inter-battery cabling and incoming freight.

While shipping, handling and installation costs of the AES would be considerably less than the comparable lead batteries. The "elephant in the room" question is the initial capital cost of the Lithium vs Lead. The results below show some myth-busting numbers. All costs shown are retail pricing current mid 2018. They were found at a popular and well regarded website operated by a company that supplies installers and DYI customers with renewable energy products and systems.

CHEMISTRY	LiFePO4 Discover AES	Lead Acid AGM Rolls	Lead Acid/AGM Trojan
Mfg.	DISCOVER AES	Rolls	Trojan
Model	12-48-6650	S2-590AGM	Solar SAGM 06 375
Cost per Battery (Retail Website)	$6,600.00	$502.00	$480.00
Number of Batteries	3	48	24
Initial Capital Cost	$19,800.00	$24,096.00	$11,520.00
Warranty (years)	10	7	3
Warranty terms	37 MWh of measured energy throughput	2 Year Replacement Prorated for Defects	Replacement for Defects
Cycle Life	10,000	1,400	1,750

The initial cost of the AES battery costs less than the Rolls and considerably more than the Trojans. If initial cost was the only consideration then the Trojans would be the clear winner, except upon closer examination the Trojans have the shortest warranty. They are also 30% lighter than the similarly sized Rolls – the only thing that can be missing is lead. The more expensive Rolls batteries have more material – which, in lead batteries, often translates into greater durability. In short, the least expensive batteries might well represent a "penny wise and pound foolish" choice when the expected battery life is factored into the equation. The Trojans, like most batteries of that size and form, have an expected service life of 8 years. The heavier plated Rolls have a maximum expected service life of 12 years. The AES have an expected service life of at least fifteen years with very reasonable expectations of more .

Over the term of the first ten years of system operation, the Trojans will likely have had to be replaced once which brings their total capital cost for the first ten years to $23,040 – more than the AES and only slightly less than the Rolls. At the ten year mark, both the Rolls and Trojan will be on the tail end of their service life with a replacement for both expected within a couple of years. The AES will still be going strong on the initial capital investment. The cost myth does not hold up. The battery with the lowest initial capital cost becomes the second most expensive within the first eight years when it needs replacing.

The battery investment in relation to cycle life provides a useful way to assess value as well as cost. Dividing the initial cost by the rated cycles shows the cost per cycle. This evaluation shows a clear advantage to the lithium – 10,000 instead of 1400 for Rolls and 1750 for Trojan.

CHEMISTRY	LiFePO4 Discover AES	Lead Acid AGM Rolls	Lead Acid/AGM Trojan
Mfg.	DISCOVER AES	Rolls	Trojan
Model	12-48-6650	S2-590AGM	Solar SAGM 06 375
Initial Capital Cost	$19,800.00	$24,096.00	$11,520.00
Cycle Life*	10,000	1,400	1,750
Cost per Cycle	$1.98	$17.21	$6.58

Another factor beyond capital cost and cycle life that is important to consider when making financial comparisons between the technologies is total energy yield. This equation looks at the available energy input, generally a PV array or other known source of charging such as a hydro or wind generator, and calculates how much of the energy will be available for delivery to load(s). As the efficiency of the energy storage chemistry increases so does the energy yield. The table below shows the yield from one kW of PV with six hours of solar radiation.

CHEMISTRY	**LiFePO4 Discover AES**	**Lead Acid AGM Rolls**	**Lead Acid/AGM Trojan**
Mfg.	DISCOVER AES	Rolls	Trojan
Model	12-48-6650	S2-590AGM	Solar SAGM 06 375
Avg. Lifetime Round Trip Efficiency (RTE)	95%	65%	65%
PV Array Nominal Capacity (Watts)	1000	1000	1000
Solar Radiation (Hours)	6	6	6
PV Yield (kWh)	5700	3900	3900

The lower two-way efficiency of lead batteries means that nearly 50% more PV is required to yield the same kWh of energy when compared to the lithium yield. The higher efficiency of the lithium battery also comes to play when considering operating costs when charging from non-renewable resources such as generators.

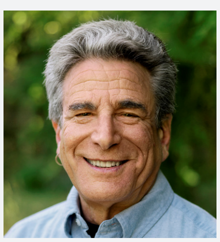
Operating cost with the lithium battery is far lower. They accept charge at more than twice the rate of the comparable AGM. The rate of charge plus the efficiency advantage of the lithium battery equates to much faster charging times and far better generator utilization. Unlike lead batteries that require a tapering charge as part of their cycle, lithium batteries charge at full current until it is time to terminate the charge. This allows an optimal match of generator capacity and load which in turn maximizes fuel efficiency and generator life expectancy. In short, this means that $LiFePO_4$ batteries can utilize a much smaller PV array to meet a given load and that charging them with a generator will take less fuel.

Summary – It is very simple and easy to retrofit $LiFePO_4$ batteries into an existing off grid system but there are a few "rules" to observe:

- Choose a $LiFePO_4$ battery that is intended for off grid. It should have a charge/discharge rate equal to its rated capacity (C/1) and an ability to handle peak load demands (2-4C peak current output). It should also be warrantied for off grid application.
- Choose a $LiFePO_4$ battery that has communication capability – much of the benefit of converting to the new technology is lost with "dumb" batteries.
- Change charger and charge controller settings to reflect desired charging voltages, absorption time, high and low disconnect points for the $LiFePO_4$ battery.
- Ensure that batteries will be within temperature thresholds for winter charging.
- Find more things that use power during the sunny months of the year, changing to $LiFePO_4$ will increase the available energy from the array to be at least 25%.
- $LiFePO_4$ batteries are not more costly than high quality lead acid maintenance free (AGM) batteries on initial purchase and far less costly over the cycle life of the battery bank.

The benefits gained from making the switch to $LiFePO_4$ batteries far outweigh the very small amount of effort it takes to change a few settings. In real terms for most existing installations the changeover is no more difficult than it would be if changing from flooded lead acid to AGM. The results, especially to experienced users of lead acid batteries, will be dramatic. The increase in energy yield coupled with the ease of operation and stability of voltage become apparent very quickly.

ABOUT THE AUTHOR



Ezra Auerbach has been living off grid since 1968. and co-founded his first solar business, Energy Alternatives in 1986. Since selling the company in 1996 he has remained active in the industry as a consultant in a variety of roles including: sales, marketing, product management, policy development, and engineering. His writing or interviews have appeared in many journals and videos. Ezra continues to completely enjoy living and working off grid and especially treasures the opportunities to test and evaluate new products and technologies as they enter the mainstream market.

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