Lithium-Ion Batteries for Off-Grid Systems

Is lithium-ion technology a good match for off-grid RE systems?

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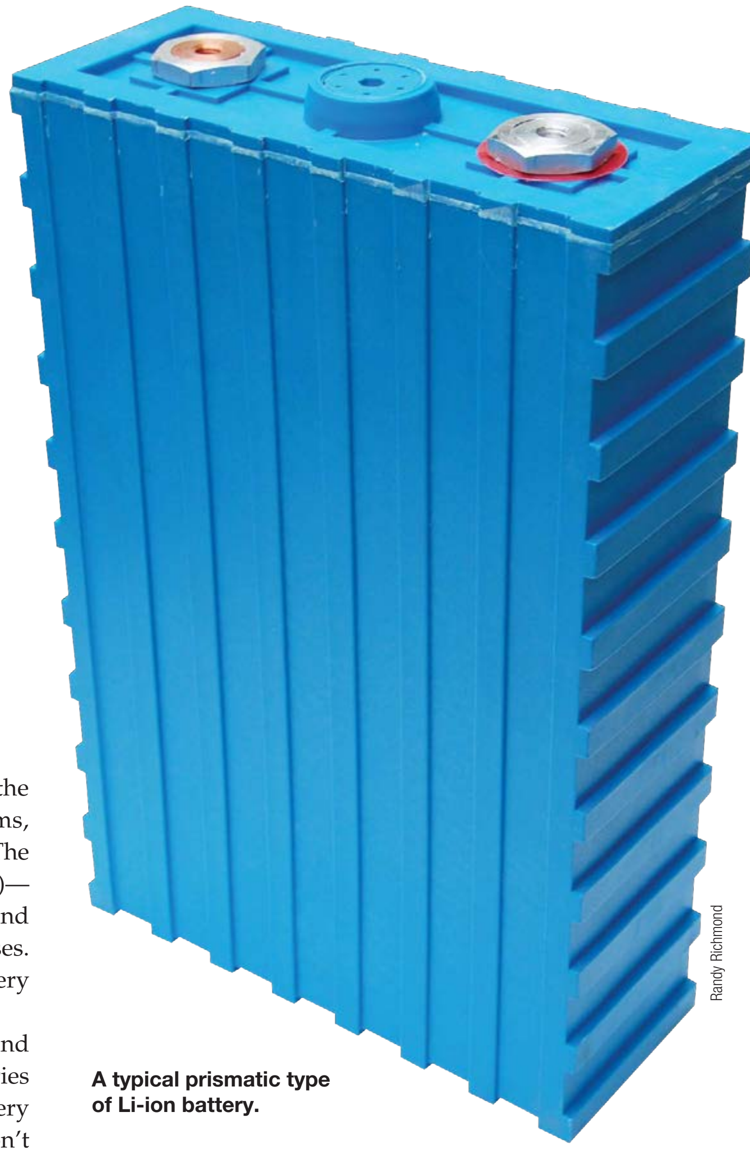
by Randy Richmond



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A typical prismatic type of Li-ion battery.

For decades, lead-acid battery technology has been the mainstay of battery-based renewable energy systems, providing reliable storage and ample energy capacity. The most common battery used—flooded lead-acid (FLA)—requires regular watering to maintain electrolyte levels and venting to avoid the buildup of hydrogen and sulfuric gases. Additionally, FLAs are large and heavy, making battery replacement a challenging task for some systems.

With all of the recent action in the electric vehicle and personal electronics industries, lithium-ion (Li-ion) batteries have gained much attention. Here, we examine Li-ion battery pros and cons, and discover why most system owners won't be swapping out their FLA batteries anytime soon.

What's Behind Li-Ion?

"Lithium-ion" refers to a variety of lithium-based battery chemistries. Each chemistry has its strong and weak points, which means certain types of chemistries are better-suited for particular applications. There continues to be new lithium-based chemistries being developed (such as lithium-air), but it is too early to tell which will become commercially viable. See the "Lithium Battery Technologies" table for details on a few of the more common types of Li-ion chemistries.

Lithium Battery Technologies

Chemical Name	Material	Abbreviation	Applications
Lithium cobalt oxide	$LiCoO_2$	LCO	Cell phones, laptops, cameras
Lithium manganese oxide	$LiMn_2O_4$	LMO	Power tools, EVs, medical, hobbyist
Lithium iron phosphate	$LiFePO_4$	LFP	Power tools, EVs, medical, hobbyist
Lithium nickel manganese cobalt oxide	$LiNiMnCo0_2$	NMC	Power tools, EVs, medical, hobbyist
Lithium nickel cobalt aluminum oxide	$LiNiCoAlO_2$	NCA	EVs, grid storage
Lithium titanate	$Li_4Ti_5O_{12}$	LTO	EVs, grid storage

Source: batteryuniversity.com

Cylindrical Li-ion batteries are often ganged into voltages appropriate for cordless tools.

Courtesy Wikipedia

You'll find these pouch types of Li-ion batteries in radio-controlled hobbyist cars and other places where weight is a concern.

Li-ion batteries typically come in one of three formats: pouch, cylindrical, and prismatic (rectangular-cubic). Pouch types tend to be used in small portable devices, such as smart phones and tablet PCs, or in devices where low weight is important, such as hobbyist remote control vehicles. Cylindrical forms lend themselves to powering medium-sized portable devices, such as power tools. Prismatic are generally the largest, and are typically used in electric vehicles. Prismatic types are also favored in applications that were previously powered by lead-acid batteries, such as backup or off-grid telecommunication systems. Prismatic types usually have hard corrugated sides, which creates air gaps between adjacent cells—an aid to cooling.

Suitable for Renewables?

If Li-ion has an application for residential RE storage, the best candidate is the large-format prismatic lithium iron phosphate ($LiFePO_4$; LFP) battery. But how do they compare with lead-acid technologies?

Weight. Comparing weight versus available energy storage, an LFP is about one-third the weight of a lead-acid (LA) battery. This is a great advantage for mobile applications, such as boats/RVs, but for stationary RE applications, weight is usually a consideration only during battery change-out.

Space. At about half the volume of an LA battery with equivalent energy storage, LFPs take up far less space. This may be an advantage for mobile applications, but for stationary RE applications, size or volume is typically not a deciding factor.

Low-Temperature Capacity. The storage capacity of LAs drops by 50% at -4°F, compared to 8% with LFP. Keeping lead-acid batteries warm so that they maintain reasonable capacity in cold climates can be challenging, giving LFPs an advantage. However, LFP batteries generally should be charged at a slower rate when cold—usually no more than a C/10 at ambient temperatures below 32°F. (For example, if you have a 200 Ah battery, a C/10 charge rate will be 20 A.)

Discharge Voltage & Impedance. LA batteries' discharge voltage tapers significantly as state-of-charge decreases, whereas LFP batteries' voltage remains fairly steady until they are close to being fully discharged. LFPs have about one-quarter the internal resistance (impedance) of LA batteries, which reduces battery energy lost to heat. These both combine to improve system efficiency and prevent DC voltage sags that can affect voltage-sensitive equipment.

Charge & Discharge Current. LFPs can be safely charged and discharged at a higher current than LA batteries. But the relatively low current in RE applications (compared to EV applications) makes this aspect not very useful.

Self-Discharge. At room temperature, idle (stored or disconnected) LA batteries lose 5% to 15% of their electrical capacity per month, compared to 1% to 3% for LFPs. In RE applications where energy is used only occasionally (such as pleasure boats, RVs, or vacation cabins), or during periods of low RE source, this can be a useful attribute.

Maintenance. Wet LA batteries, if not watered when needed, will have a greatly shortened life. LFPs require no additional liquid to maintain their electrolyte levels. Sealed LA batteries, which have a much lower up-front cost than LFP batteries,

Lithium Timeline

Although Li-ion research started in the late 1970s, commercialization of Li-ion batteries didn't begin until the 1990s (it took about a dozen years to figure out how to manufacture usable, stable Li-ion batteries).

1991
Sony commercializes the first Li-ion battery, used in cell phones and laptop computers.

1996
Lithium polymer batteries become commercialized.

1999
Lithium-phosphate batteries become commercialized.

2006
Lessons learned from laptop computer fires: battery chemistry and manufacturing quality control are important.

2007
Large-format lithium iron phosphate batteries become widely available (for EV conversion).

Battery Technology Comparison

Specifications	Lead-Acid	NiCd	NiMH	Li-Ion: Cobalt	Li-Ion: Manganese	Li-Ion: Phosphate
Specific energy density (Wh/kg)	30 – 50	45 – 80	60 – 120	150 – 190	100 – 135	90 – 120
Internal resistance (mΩ/V)	<8.3	17 – 33	33 – 50	21 – 42	6.6 – 20	7.6 – 15.0
Cycle life (80% discharge)	200 – 300	1,000	300 – 500	500 – 1,000	500 – 1,000	1,000 – 2,000
Fast-charge time (hrs.)	8 – 16	1 typical	2 – 4	2 – 4	1 or less	1 or less
Overcharge tolerance	High	Moderate	Low	Low	Low	Low
Self-discharge/month (room temp.)	5 – 15%	20%	30%	<5%	<5%	<5%
Cell voltage	2.0	1.2	1.2	3.6	3.8	3.3
Charge cutoff voltage (V/cell)	2.40 (2.25 float)	Full charge indicated by voltage signature	Full charge indicated by voltage signature	4.2	4.2	3.6
Discharge cutoff volts (V/cell, 1C*)	1.75	1	1	2.5 – 3.0	2.5 – 3.0	2.8
Peak load current**	5C	20C	5C	> 3C	> 30C	> 30C
Peak load current* (best result)	0.2C	1C	0.5C	<1C	< 10C	< 10C
Charge temperature	-20 – 50°C	0 – 45°C	0 – 45°C	0 – 45°C	0 – 45°C	0 – 45°C
Discharge temperature	-20 – 50°C	-20 – 65°C	-20 – 65°C	-20 – 60°C	-20 – 60°C	-20 – 60°C
Maintenance requirement	3 – 6 months (equalization)	30 – 60 days (discharge)	60 – 90 days (discharge)	None	None	None
Safety requirements	Thermally stable	Thermally stable, fuses common		Protection circuit mandatory		
Time durability				>10 years	>10 years	>10 years
In use since	1881	1950	1990	1991	1996	1999
Toxicity	High	High	Low	Low	Low	Low

Source: batteryuniversity.com. The table values are generic, specific batteries may differ.

*"C" refers to battery capacity, and this unit is used when specifying charge or discharge rates. For example: 0.5C for a 100 Ah battery = 50 A.

**Peak load current = maximum possible momentary discharge current, which could permanently damage a battery.

compare better than FLA but their lifetime cost per kWh is greater than either LFP or wet LA batteries.

Lifetime. While longevity can vary widely depending on factors such as daily depth of discharge and LA battery type (marine, golf cart, AGM, industrial, etc.), regularly used and properly maintained common deep-cycle LA batteries have an average lifespan of about five years; LFP batteries have an estimated longevity of 10 years—half the frequency of LA battery replacement. In both cases, natural aging of the battery chemicals can impair batteries before their cycle life is used if they are cycled infrequently. When used up, both types of batteries can and should be recycled by returning them to a dealer, although due to the long history of LAs, there are presently more recyclers for LAs than LFPs.

Cost. Although LA batteries are cheaper up-front than LFPs, their lifetime price per kWh can be higher. This assumes that you can use most of the lifetime capacity (usable capacity multiplied by cycle life) prior to the battery failing due to age. With a 3,000-cycle or 10-year life (whichever comes first), one would need to cycle LFP batteries nearly daily to optimize the payback. (Note: End-of-battery life is generally considered to be when the battery can maintain only 70% to 80% of its original capacity.)

Lithium Safety

Any energy storage technology can be dangerous if the energy gets in or out too quickly. For example, if charged too quickly, LA batteries can heat up and be damaged and even explode. Similarly, an LA battery that's discharged too quickly (such as a short circuit), can spark and ignite lingering hydrogen gas. Lithium technologies, relying on a chemical reaction to store energy, are no exception. Two incidents were widely publicized—impurities combined with oxide-based lithium batteries fostered thermal runaway, causing laptop computers to overheat and catch fire; and the 2011 Chevy Volt fire, in which the coolant from the battery system dripped onto the ruptured batteries in a junkyard Volt and caused a fire. (General Motors has redesigned the battery system to reduce the likelihood of another incident.)

Of all of the Li-ion chemistries, lithium iron phosphate ($LiFePO_4$ or LFP) offers the most stable chemistry and is considered very safe. For this reason, LFP is used for most large-capacity Li-ion batteries, and is the most common type used in EVs and telecom power systems.

Lithium Iron Phosphate Two-Part Reaction

$$LiFePO_4 \longleftrightarrow FePO_4 + Li^+ + e^- \qquad Li^+ + e^- + C \longleftrightarrow LiC_6$$

Positive Electrode (Cathode): Lithium iron phosphate on aluminum terminal

Electrolyte: $LiPF_6$ in ethylene carbonate (EC)/ dimethylcarbonate (DMC)

Negative Electrode (Anode): Graphite on copper terminal

Left to Right = Charging **Right to Left = Discharging**

The Need for Management

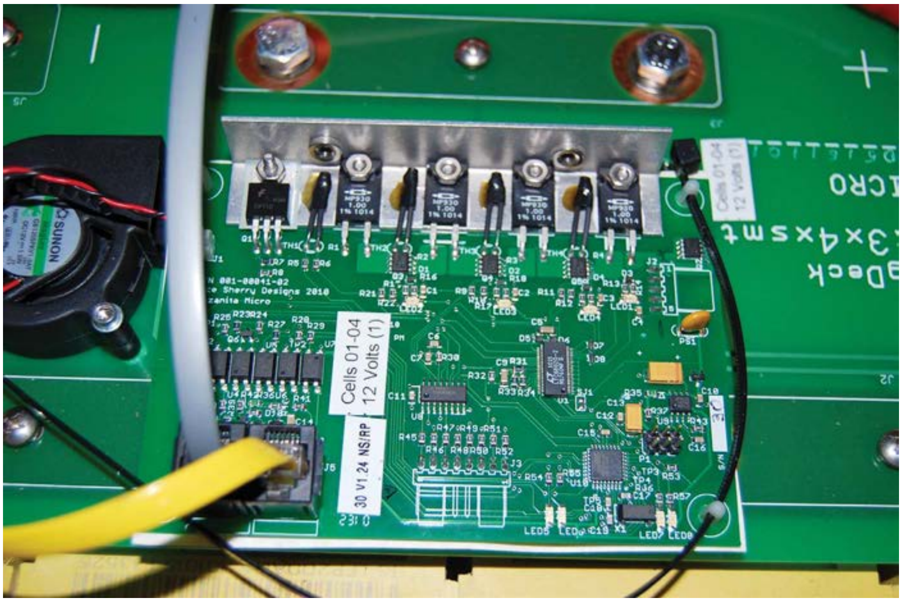
The biggest disadvantage of any Li-ion battery is needing a battery management system (BMS). The job of a BMS is to monitor the voltage and temperature of each individual cell and protect from excessive charging and discharging. While any battery system, whether it be LA or LFP, can be improved with a BMS, a BMS is not typically required of LA cells. As long as all the batteries in a pack are of the same model and age (ideally from the same manufactured batch) and have been treated equally, the individual cells tend to behave the same while being charged. However, LFP battery cells, even in the same manufactured batch, can have variations in capacity. When charging, cells with lower capacity can become full much sooner than cells with higher capacity, which can lead to dangerously elevated voltages on the full cells as the others continue charging.

While LA cells tolerate brief periods of overvoltage (in fact, periodically elevating charge voltage to perform an equalization charge is recommended), even a fraction of an hour at elevated voltage can damage an LFP cell. A BMS protects individual cells from overvoltage by shunting current around the full cells when they reach their recommended "full" voltage. This allows the remaining cells to continue charging. A good BMS can detect when a cell is beginning to overheat (another sign of pending danger to cells) and shut off charging to the pack to protect all cells.

A BMS can also help during discharge by signaling for load disconnection when individual cells drop below their minimum voltage. Cells discharged too deeply can be permanently damaged or, at minimum, have their capacity or cycle life permanently reduced.

Li-Ion in RE Systems

There are no known Li-ion BMS power conversion products (inverters with chargers, and charge controllers) for the residential RE industry (although Clean Power Auto does have a solution for RVs and boats). The missing feature in standard power conversion is BMS cell monitoring and the available RE equipment can't modify charging characteristics to handle when some cells have reached full capacity and other cells have not. Reading the voltage of the entire pack of cells is not helpful, since there's no means of knowing whether or not some cells have already reached their capacity. Available charge controllers can't adjust



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This BMS cell-balancer board is mounted to a set of four LFP cells. It is typical of a BMS for EVs.

LFP Precautions

Expect the precautions for using LFP battery cells to be refined as more experience is gained. In considering whether or not to use LFP instead of LA batteries, take the following precautions:

- Never overcharge LFP batteries—even a fraction of an hour of overcharging can permanently damage the cells. A battery management system (BMS) is essential to preventing overcharging.
- Never short LFP batteries! LFP batteries can put out even more instantaneous current than LA. When working around any batteries, always use insulated tools.
- Don't place LFP batteries upside-down (any other orientation is OK). If upside down, electrolyte can leak out of their safety vents if the batteries become overheated.
- When creating a series pack, use cells from the same manufacturer, and the same model and age, so they are as closely matched as possible. This is the same for LA batteries. You won't be able to get LFP cells perfectly matched, and that is another reason why a BMS is needed.
- To increase capacity, it is preferable to use a single string of larger cells rather than paralleling smaller cells. The weaker of the paralleled cells will reduce the overall efficiency of the pack. For this same reason, LA batteries also have better performance when not in parallel. If paralleling is unavoidable, then only well-matched cells (make, model, age, capacity, impedance) should be paralleled.
- Reduce the charging current for LFPs to a C/10 or less when the cell temperature is below 32°F. Otherwise, permanent damage to the cell may result. Check with the manufacturer for specific temperature and current limits.
- Long-term trickle or float charging is not LFPs' optimum use. LFPs have the best price/lifetime energy payback when cycled often. If floating is unavoidable, then caution must be used to select a safe yet effective float voltage.
- Store LFP battery cells at a 40% to 60% SOC to optimize their shelf life. Storing them at 0% SOC is likely to permanently damage them, and storing them at 100% SOC may reduce their cycle life.
- With only 12 years of history, the battery industry is still learning the optimum way to treat LFP batteries (e.g., some say charging to 80% rather than 100% will greatly increase cycle life).

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An overcharged LFP cell can rupture, leaking caustic electrolyte.

current on the fly to match the BMS's ability to shunt current as cells start to reach 100% SOC.

If power conversion equipment with provisions for BMS become available, then LFP batteries can be useful in RE systems if:

- The depth of cycle is often more than 30% of capacity. Otherwise, LA batteries are a more cost-effective option.
- The space available for batteries is at a premium. LFPs can save about 50% of the space compared to LA for the same usable capacity. (These factors can be very important for RV and boat applications.)
- The application requires low maintenance (such as hard-to-reach sites, or a user who won't or can't do the work). With twice the longevity of LAs, this also means halving the battery replacement frequency.
- The application calls for frequent cycling of the batteries—with LFPs having several times the cycle life of LAs and at a deeper depth of discharge. Off-grid applications generally fit this profile.

LFPs can definitely help solve some residential RE storage problems. But perhaps a better question is, "Is the residential RE industry ready for LFPs?" At present, the lack of BMS integration in residential RE power conversion equipment is the biggest hurdle. Once LFP-compatible products become available, then LFP batteries will find a home in many RE applications, especially off-grid and mobile.

Access

After earning his electrical engineering degree, Randy Richmond (randy@RightHandEng.com) worked for the telecom industry. In 1999, he founded his own company, RightHand Engineering LLC, which makes products for monitoring RE systems. Since then, Randy has earned his professional engineer license and also offers design, test, educational, and consulting services for Li-ion-based power systems.