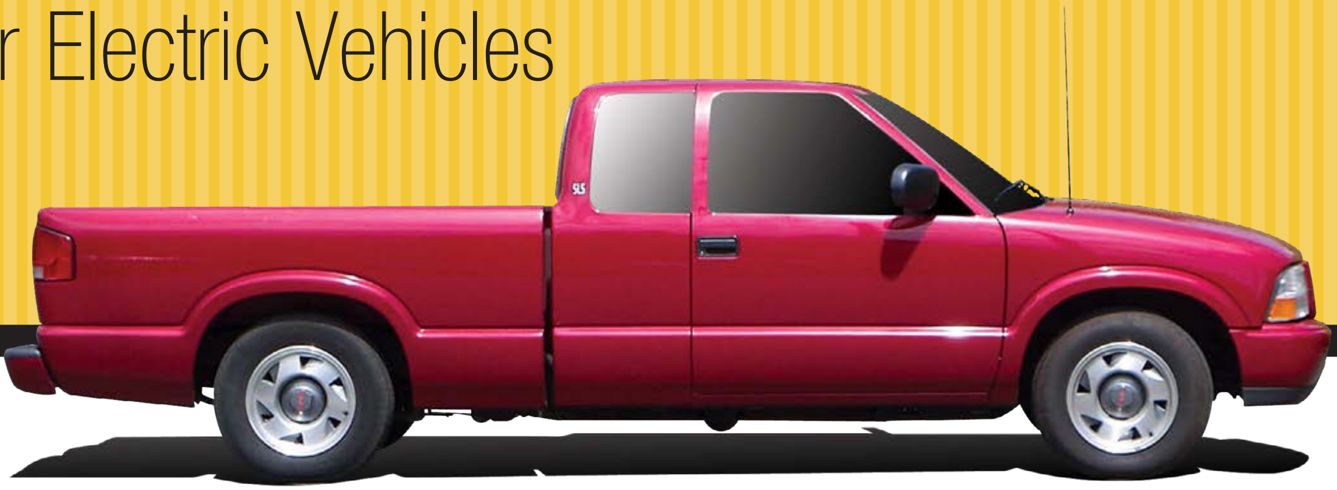
Lithium-Ion Batteries

for Electric Vehicles



Story & photos by Randy Richmond

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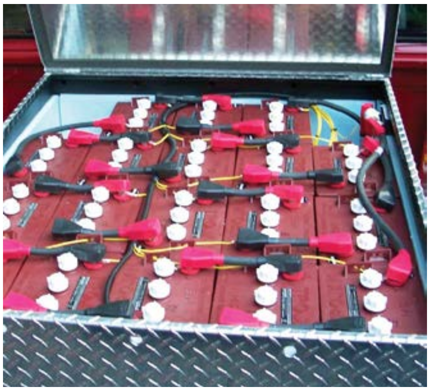
In 2007, I converted a GMC Sonoma from its original gasoline propulsion to pure electric, using flooded lead-acid (FLA) batteries (see "Born to be Wired" in *HP122*). The type of FLA batteries most commonly used for EV conversions, golf cart batteries, have three 2 V cells and a capacity ranging from about 200 to 260 amp-hours (Ah). Moving the truck's 3,200 pounds required a higher voltage than the 96 or 120 volts commonly used for lighter-weight vehicles, so I used 24 batteries for 144 V and an energy capacity (at 100% discharge) of about 37 kilowatt-hours (kWh).

However, the battery weight (approximately 1,800 pounds) brought the vehicle very close to its maximum gross weight of 5,000 pounds. I expected my batteries to have a five-year life, but in the third year, they started to show signs of failure.



Eighteen of the original FLA batteries in a custom-built box in the truck bed. The six other batteries were housed under the truck's hood.

The short life boiled down to maintenance. I knew that the best practice for FLA batteries is to re-water them monthly if they are being cycled frequently (as they usually are in an EV). The charging process causes evaporation through electrolysis. I was usually good at watering the batteries, but on a few occasions, I postponed it, only to find that enough of the electrolyte had evaporated to expose the top of the lead plates to air. Exposed lead oxidizes, making it harder for the plates to interact with electrolyte and, thus, reduces their capacity.

This undoubtedly contributed to a shorter life, but the nail in their coffin occurred when I was unexpectedly called away for several weeks during the summer. In my original design, a daily timer was set on the battery charger to ensure the batteries were fully charged before I left on my morning commute. Without daily driving, the charger was excessively charging the batteries. This boiled off a significant portion of the electrolyte and overheated the batteries, causing them to swell.

I didn't realize this until I tried to drive my vehicle and heard a "bang" in the battery box, and the vehicle lost power. Several of the batteries in the middle of the pack (those that got the hottest) had swollen—one had swollen enough to cause an internal short circuit, which ignited the gasses at the top of the battery. I replaced the worst of the batteries, hoping that the remaining ones still had some life. But after testing, I found that all of the remaining batteries had a significant reduction in capacity—the only solution was to replace them all.

Battery Shopping

Because I wanted my next battery pack to give me better service, I started investigating lithium iron phosphate (LFP) batteries, which had dropped in price significantly—from $75,000 for a 31 kWh pack in 2006 to $12,000 in 2010 (since then, prices have remained fairly constant). A comparable FLA bank was more affordable (about $5,000), but I was convinced that Li-ion batteries would improve vehicle performance (power, acceleration, range, and energy economy) and render a long-term payoff.

Switching to LFPs shaved almost 1,000 pounds from the vehicle, more than doubled the vehicle's range, gained back the vehicle's original acceleration, and nearly halved its energy use per mile. To see why I experienced such a dramatic improvement, we need to compare the batteries themselves.

The FLA reference battery is a standard 225 Ah, 6-volt golf cart battery (e.g., Trojan T105). The LFP reference batteries are high-capacity (180 to 200 Ah), 3.2 volt prismatic batteries. There are a variety of manufacturers and distributors for this type of battery, the most popular and available being the CALB SE180AHA, the Sinopoly LPF200AHA, and the FluxPower BATVXLFP200AH. In comparing, keep in mind that a golf-cart battery has three cells for about 6 V, whereas the LFP prismatics come as single cells (packs of 4 cells for 12 V are also available). The comparison table values based on watt-hours (Wh) provide an apples-to-apples comparison because they relate to stored energy. Except where noted, the table characteristics come from manufacturers' specification sheets. The LFP column is the average of the specifications for the three popular LFP models, whose values differ by 10% or less.

Electrical, Physical & Environmental Comparison

	Flooded Lead-Acid (FLA)	LFP (LiFePO4) Lithium-Ion
Reference battery	Trojan Golf Cart	180–200 Ah Prismatics
Nominal cell volts	2.0	3.2
Cell capacity (Ah at 20 hr. rate)	225	190
Cell volume (in.^{3})	268	265
Cell weight (lbs.)	20.7	13.1
Cell energy capacity (Wh)	450	608
Volume per Wh (in.^{3})	0.596	0.402
Weight per Wh (lbs.)	0.046	0.021
Recommended discharge amps	45	57
Max. continuous discharge amps	500*	570
Peak discharge amps	not specified	950 (10 sec. max.)
Recommended charge amps	23	57
Max. charge amps	Not specified	570
Max. float volts per cell (77°F)	2.20	Check with manufacturer
Max. charge volts per cell (77°F)	2.45	3.6 – 3.9
Max. equalize volts per cell (77°F)	2.58	Not applicable
Max. volts per cell (77°F)	2.70	3.6 – 3.9
Min. discharge voltage per cell	1.75	2.5 – 2.8
Impedance (mOhm) per 3.2 V	2.2*	0.6*
Usable charge temperature range	24.8°F – 125.6°F	32°F – 113°F
Usable discharge temperature range	-4°F – 113°F	-4°F – 131°F
Temperature effect (capacity @ temp)	50% @ -0.4°F 100% @ 80.6°F	92% @ -4°F 100% @ 77°F
Self discharge (per month @ 77°F)	4%	1 – 3%*

*Obtained from actual measurements or discussions with manufacturer—not from the product specification sheets

Of the many advantages of LFP over FLA, the most important may be the difference between their cycle life versus depth of discharge. The LFPs can be discharged more deeply, which means more usable energy. A typical FLA golf-cart battery has a life of about 1,000 cycles when discharged to 50% of its capacity each cycle. An FLA's life cycle drops rapidly when the depth of discharge is increased above 50%. LFP batteries have a life of about 3,000 cycles when discharged by 70% each cycle (about 2,000 cycles when discharged by 80%). This factor plays significantly into the total payback of these batteries.

Compared to flooded lead-acid batteries, lithium iron phosphate batteries pack in more energy per physical size and weight.

Usable Energy Comparison

	Flooded Lead-Acid (FLA)	LFP (LiFePO4) Lithium-Ion
Reference battery	Trojan Golf Cart	180–200 Ah Prismatic
Recommended maximum depth of discharge	50%	70%
Cycle life	1,000	3,000 (2,000 @ 80%)
Usable energy capacity (Wh)	675 (3 cells)	426 (1 cell)
Volume (in.^{3} per usable Wh)	1.19	0.570
Weight (lbs. per usable Wh)	0.092	0.030

The Sinopoly batteries, with the battery management boards, newly installed in the truck.

Other LFPs vs. FLA Advantages

Lighter weight. For about the same usable energy capacity, LFPs are about one-third the weight. The reduction of weight contributed significantly to my vehicle's increased acceleration and range, and decreased the amount of energy used per mile.

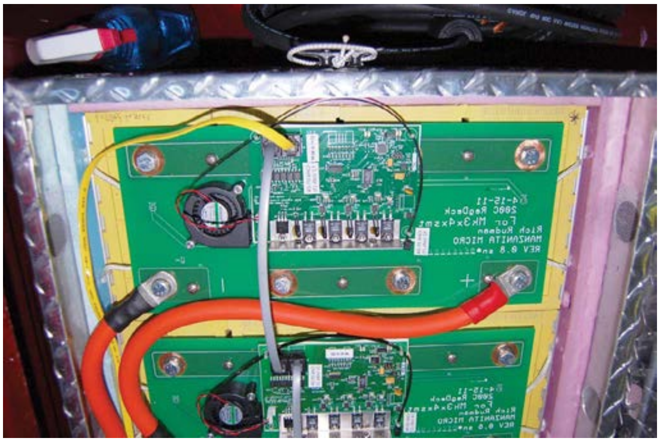
Less space. LFPs are about half of the volume of FLAs—I was able to consolidate all of my batteries in the bed of the pickup (instead of putting some under the hood), while retaining the pre-upgrade cargo space. This left more room under the hood for future enhancements, such as regenerative braking.

Improved capacity at low-temperatures. In cold (say, -4°F), the capacity of FLAs drops to about 50%. LFP capacity only drops by about 8% at that temperature. Although winters where I live aren't that cold, I still had to reduce my winter driving range expectations by about 25% with FLAs—with LFPs my range reduction is less than 10%.

Steady discharge voltage & low impedance. An FLA's discharge voltage tapers significantly as its state-of-charge decreases, whereas an LFP's remains fairly constant until the battery is close to empty. Also, with one-quarter of the internal resistance (impedance) of FLAs, LFPs supply more power to the motor and lose less to heat. The steady discharge voltage and the lower impedance, along with the weight reduction, also improved the vehicle's acceleration and range.

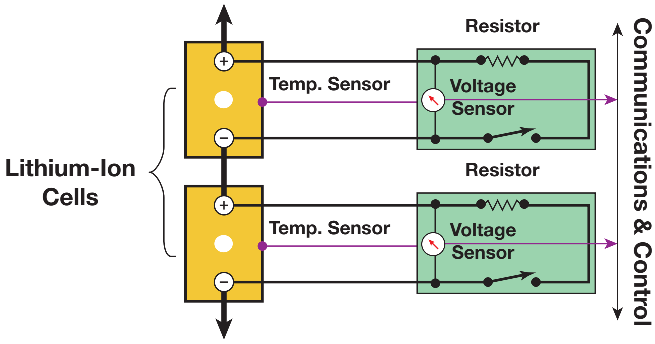
Higher charge & discharge current. LFPs can be safely charged and discharged at a much higher current than FLAs. A suitably large charger is capable of charging a nearly empty pack within about one-third of an hour (based on a 3C charge rate). To keep costs down, I kept my 30 A Manzanita Micro PFC-30 charger.

The on-board 30-amp charger.



A battery management system protects its cell by shunting current around it when it is full.

Battery Management System (BMS)



The higher discharge capability allowed me to increase the battery amp setting on my Zilla controller, adding a few more horsepower to improve acceleration.

Less self-discharge. When not being charged, FLAs can lose 4% to 15% of their energy per month (depending on temperature), compared to 1% to 3% for LFPs. I can now let my EV sit for long periods without having to worry about recharging the batteries.

In addition to these measurable ones, there are some less tangible advantages that also make a big difference:

No idle memory. Although a phenomenon that is not well-documented, experienced EVers know that FLAs temporarily lose capacity when left idle. Prior to the battery upgrade, if the EV was idle for several days, the apparent capacity on the first drive/charge cycle was reduced by up to 25%. LFPs don't experience this.

No maintenance. LFP batteries need no regular maintenance, eliminating the risk of damage that can result to FLAs if they are not watered—the reason that I got only 60% of the useful life out of my original batteries. There are "zero-maintenance" sealed lead-acid batteries, but these have a lower cycle life and a higher cost than vented FLAs, and they can still lose capacity if left in even a partially discharged state.

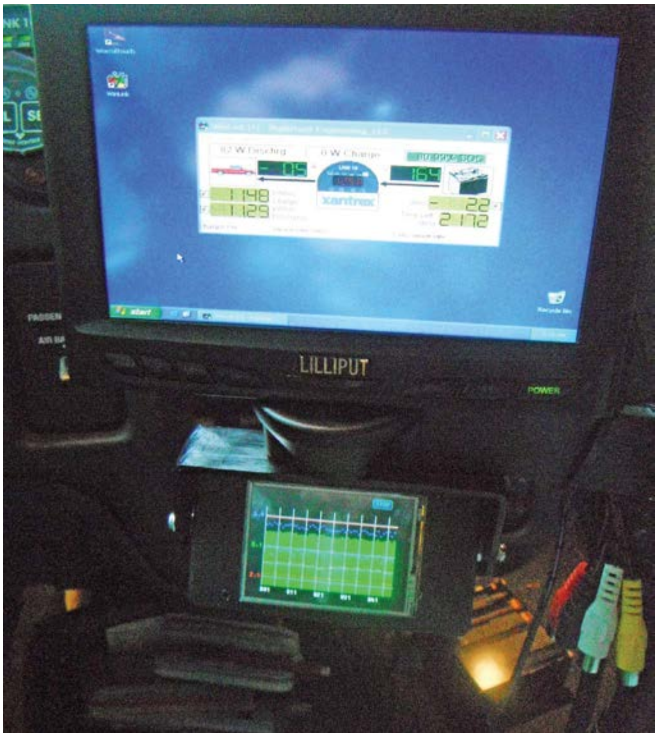
The AC input for the battery charger is accessed through the old fuel filler door.

Longer life. While this 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 EV-type FLAs have a typical life of about five years; LFP batteries have a typical life of 10 years. With only 12 years of data on LFP technology, their true longevity is uncertain.

The Main Disadvantage

While Li-ion batteries offer many benefits for EV applications, the main disadvantage (other than cost) compared to FLAs is the need for a battery management system (BMS), particularly while being charged. The job of a BMS is to monitor the voltage and temperature of each cell to protect them from excessive charging and discharging. While any battery system, whether it be FLA or Li-ion, can be improved with a BMS, they are not typically used with FLA cells because, as long as all the batteries in a pack are of the same manufacturer, 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 cells, even of the same manufactured batch, can vary in capacity, leading to dangerously elevated voltages on the full cells as the others are still being charged.

FLA cells tend to be fairly tolerant of brief periods of high charge voltage (it is recommended to periodically elevate charge voltage, known as an equalization charge, which gasses the electrolyte vigorously in an effort to remove water/acid stratification and bring weaker cells up to full). With Li-ion batteries, even a fraction of an hour at elevated voltage can cause damage. Highly overcharged cells will swell and create internal gas pockets that prevent electrolyte contact with the electrodes. This usually permanently damages the cell (cells can be damaged and not show swelling). In extreme cases, the swelling can cause a cell case to rupture, releasing volatile organic solvent gases, which can be caustic and flammable. It should be noted that LA batteries have their share of dangers, including explosions, and a very hazardous electrolyte.



The truck's in-cab battery monitors show battery state-of charge (top), and BMS cell voltage and temperature (bottom).

A BMS protects individual cells from over-voltage by shunting current around the full cells when they reach their "full" voltage, which allows the other cells to continue to charge. A good BMS can also 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 of the cells.

Battery Lifetime Price Comparison

Characteristic	Flooded Lead-Acid (FLA)	LFP (LiFePO4) Lithium-Ion*
Reference battery	Trojan Golf Cart	180–200 Ah Prismatic
Average price	$160	$270
Average price per Ah	$0.64	$1.40
Average price per Wh	$0.12	$0.44

	Flooded Lead-Acid (FLA)	LFP (LiFePO4) Lithium-Ion	
Recommended Discharge Depth	50%	70%	80%
Cycle life*	1,000	3,000	2,000
Usable energy capacity (kWh)	0.675	0.426	0.486
Lifetime kWh (cycles × usable capacity)	675	1,278	972
Average BMS price per cell	None	$35	$35
Lifetime price per kWh	$0.24	$0.24	$0.31

*190 Ah rating. **The long cycle life of LFPs potentially prevents using their full mileage capability within their lifetime.

A BMS can also help during discharge by signaling for disconnection of the load 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.

All factory EVs, such as the Leaf and the Volt, have a BMS that performs these functions. Some also manage air or liquid cooling of cells, both during charge and discharge, to prevent thermal runaway (a condition where one overheated cell causes its neighbors to begin generating heat), and to help maintain peak battery efficiency. Typical EV conversions using prismatic, hard-cased LFP cells usually don't need active cooling for the cells because the cases have separators and air gaps built into them. This helps spread out the heat, and LFP chemistry (unlike some lithium-oxide-based chemistries) does not contain much internal oxygen, which can be a catalyst to thermal runaway.

The bottom line is that the risk of damage or danger is far too high to use Li-ion batteries without a battery management system. My upgraded conversion uses a relatively high-end BMS manufactured by Manzanita Micro (about $35 per cell). An optional display shows the state of each cell—both its voltage and temperature—in real time. Being a data-geek, I like to keep an eye on the whole system.

Is the Investment Worth It?

When I decided to go with LFP batteries, I dug into EV discussion forum (evdl.org) archives, and researched large-format Li-ion vendors. I settled on a set of 48, 200 Ah, 3.2 V cells manufactured by Winston (formerly Thundersky, now Sinopoly) of China, and sold by Manzanita Micro, for $15,000 (with BMS).

The price comparison table compares the cost of a properly maintained FLA system and an LFP system using two reference batteries that are the most economical options available in both categories. It shows the lifetime price per kWh for the two battery types. Note that the up-front price per unit of storage (Wh) of LFPs is nearly four times higher than FLAs. But the LFP lifetime energy capacity (usable energy multiplied by cycle life) is much higher than the FLA. Thus, even with the additional cost of a BMS (ranging from $15 to $50 per cell) the total lifetime price per kWh for LFPs is very close when using a 70% depth of discharge, and somewhat worse than FLA when using an 80% depth of discharge.

The long cycle life of LFPs potentially prevents the ability to use the full mileage capability of those batteries within the 10-year expected battery longevity. With my vehicle's 400 Wh per mile, this can yield 153,000 miles. With an average annual driving distance of 7,500 miles, that's about 20 years. However, the true longevity of LFPs is unknown since this type of battery was first put into use only 12 years ago.

The real comparison comes by looking at your particular vehicle's performance, local energy costs, and the distances you intend to travel. The good lifetime price per kWh of LFPs, combined with the reduced energy cost per mile, is where the rubber meets the road. The cost comparisons table shows the projected total cost of my two battery systems (pre- and post-upgrade), plus the electrical energy used to charge them over a 10-year period, with my particular EV, using my electrical rate of $0.09 per kWh, an average commute of 25 miles, and my average annual driving distance of 7,500 miles. Even without using the full kWh lifetime capacity of my LFP batteries, the 10-year total cost is nearly $3,800 less, or 82% of the cost of FLAs.

I've been driving my LFP-upgraded GMC Sonoma EV conversion for about a year and have put about 7,500 miles and 200 cycles on the LFP batteries. Compared to using FLAs, LFPs give about twice the range (with very little range reduction in cold weather), much better acceleration, and zero maintenance. Compared to FLAs, they only use about half the energy per mile, and this is with LFPs that have 77% of my original FLAs' energy storage capacity (200 Ah vs. 260 Ah). The advantages gained were well worth the higher up front cost. What next? The new batteries are now capable of supplying more power than my 9-inch DC motor can consistently take, so I am preparing my EV for a higher-power AC motor, which will be more efficient and provide regenerative braking, promising to extend the EV's range even farther.

Randy shows off his Li-ion-powered truck.

Vehicle Performance

Number of batteries	24	48
Battery voltage	6.0	3.2
Capacity (Ah)	260	200
Cost	$3,300 (in 2006) $5,500 (2011 price)	$15,000 (w/BMS; in 2011)
Usable energy storage (kWh)	19 (50% of 37 kWh)	25 (80% of 31 kWh)
Battery weight (lbs.)	1,730	775
Vehicle weight (with batteries)	5,000 lbs.	4,045 lbs.
Typical driving range (miles)	25	60
Max. driving range (miles)	40	75
Acceleration, 0–60 mph (sec.)	35	21
Energy per mile (approx. kWh)	0.75	0.40

10-Year Projected Costs

Characteristics	Pre- Upgrade	Post- Upgrade
Battery Type	FLA[a]	LFP
Energy use per mile (kWh)	0.75	0.40
Energy price (per kWh)	$0.09	$0.09
Price per mile	$0.07	$0.04
Avg. miles per charge cycle	25	25[c]
Battery life cycles	1,000[b]	3,000[c]
Battery lifetime mileage	25,000	75,000
Avg. annual miles driven	7,500[d]	7,500[d]
Battery longevity (Yrs.)	3.3[e]	10.0
Battery system price	$5,500	$15,000
Battery cost per year	$1,650	$1,500
Energy cost per year	$506	$270
Total cost over 10 years	$21,560	$17,700

"Notes: a) The author's pre-upgrade FLA batteries were Trojan T-145s, slightly larger and more expensive than the T-105s commonly used in EVs and shown in the other comparison tables. b) Had the original FLA batteries been properly maintained, this is the cycle life that could have been expected. c) 25 miles represents about 36% of the LFP battery capacity, which will probably yield a battery cycle life much greater than 3,000. d) 7,500 miles per year is significantly less than the national U.S. average, but EVs are used for commuting, not long-distance driving. Thus, they typically experience much lower annual driving distances. Due to circumstances, I was driving considerably less than 7,500 miles per year before the battery upgrade. e) Although a well-maintained FLA battery should be capable of lasting five years, in this case, the battery's 1,000-cycle life is reached within 3.3 years. The author's FLA batteries died at three years, but that was due to neglect, not because the cycle life had been reached.

Access

After earning his electrical engineering degree, **Randy Richmond** (Randy@RightHandEng.com) went to work for the telecom industry. In 1999, Randy founded RightHand Engineering LLC, which makes products for monitoring RE systems. He is a professional engineer and offers design, test, educational, and consulting services for Li-ion-based power systems.

Large-Format LFP Manufacturers:
CALB • calibpower.com
FluxPower • fluxpwr.com
GBS • gbsystem.com
Headway • headwaybatteryandcable.com
RealForce • en.realforce.com.cn
Sinopoly • sinopolybattery.com

BMS Manufacturers:
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