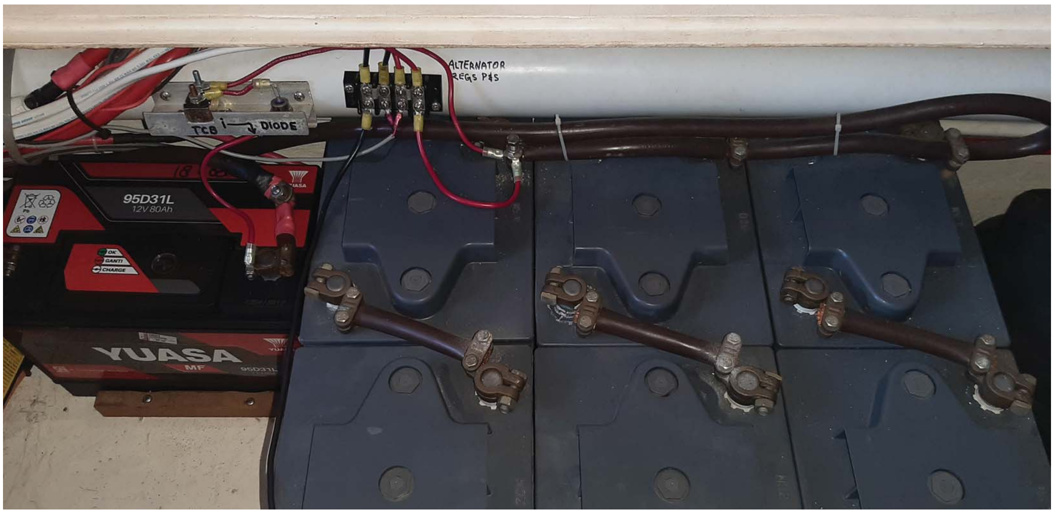
MARINE LITHIUM / LIFEPO4 BATTERY UPGRADE
Dave McCampbell

(This article contains general information and advice for a Best Practices lithium battery installation on a cruising yacht. Many more details on what we learned, what equipment we used and how we did our installation are available from our website, www.svsoggypaws.com/electricalsystems.htm.
All photos by the author except where credited.)

When we purchased *Soggy Paws*, our 2004-built St Francis 44 catamaran seven years ago, the house bank consisted of six very high-quality German 6-volt gel batteries, for a rated total of 600 amp hours (Ahrs). In early 2020, locked down by Covid in the Philippines and with our gel battery bank then 13 years old, we decided it was a good opportunity to install new lithium technology. According to gel literature, and with our quality charging equipment, the gels might have lasted several more years, but given our location in SE Asia and the time we had available, this was a good opportunity to upgrade.

Our installation is optimised for a catamaran cruising full time overseas and we have little tolerance for jury rigs, marginally safe practices and unnecessarily high-cost equipment. We believe that, if installing lithium on a cruising boat, it is worth developing the skills to install and make repairs ourselves with adequate spares and proper tools onboard. Had we not had the time to study the technology, place the orders and make the necessary electrical system changes, we would not have taken this on. It is not a project for those unwilling or unable to spend time learning how to do the installation properly.

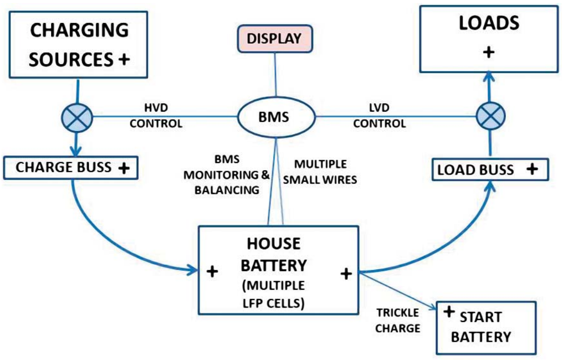
Our sealed lead acid start battery on the left and the original 390 lbs/175 kilos of gel batteries on the right. 'TCB' and 'Diode' on the aluminium heat sink are for trickle-charging the start battery off the gels



Basics

LiFePO4 (LFP) batteries suitable for cruising boats consist of an appropriate number of individual prismatic 3.2-volt cells that operate safely within a narrow voltage range. Straying beyond this range can cause permanent cell damage. For a Best Practices LFP battery system, a boat's electrical system should have separate charging and load busses (connection points) wired to a single house bank through appropriate shunts and fuses. Each of the charging sources (solar, alternator, shore, etc) should have a relay that allows a battery management system (BMS), monitoring individual cells, to shut the charging device down, not just disconnect it from the battery. This should happen automatically if there is a problem beyond what the charging device does with its own onboard charge termination. In normal operation the charging sources, reading total battery voltage, will control the charging and charge termination using mainly the bulk phase with no or only minimal absorption. The BMS will act as a backup to terminate the charge if a single cell's voltage gets too high (HVD) and the charging source fails to terminate the charge in time. There should also be a relay or relays on the load buss for the BMS to disconnect loads (LVD) if the battery reaches too low a state of charge.

After significant research and having lived with the new technology for over two years, we would like to share our thoughts on how to choose equipment and complete a DIY LiFePO4 lithium cell installation on a cruising yacht. But first some cautions:



Basic LiFePO4 battery wiring diagram with BMS and separate charging and load busses. Fuses, shunts, relays, etc not shown

- The technology and supporting equipment are still evolving, with a multitude of choices available, some much better than others. Quality of equipment is an important issue, not only with lithium batteries but with all equipment on a boat.
- No serious cruiser should change from lead acid (LA) to LFP batteries unless they are willing to spend a substantial amount of time in research, effort and money to do a proper installation.
- There are many opinions regarding how best to do this and even the experts' opinions differ. There are also substantial differences in off-grid home, electric vehicle (EV) and marine installation Best Practices.
- If a marine installation is done by an installer but the owner may have to perform adjustments or repairs after he has left, it is crucial that the owner has detailed knowledge of the installation.
- Competition among sellers of lithium equipment is stiff, especially among cell and BMS producers. US and European distributors can be significantly more expensive than purchasing cells direct from the manufacturer, usually in China.

- Not everything you read on seller websites is true, and some important things that are true are not there. Taking a close look at specifications and warranties is time well spent, especially if you later have a problem.
- Communication with the seller is important – some are much better than others. See lithium forums for the experiences of those who have made recent purchases.
- In order to create a successful installation it is necessary to have an open mind and be curious about what has worked or not worked for others.

Replacing our lead acid gels with blue LiFePO4 lithium prismatic cells. Only one of eight LFP cells is shown

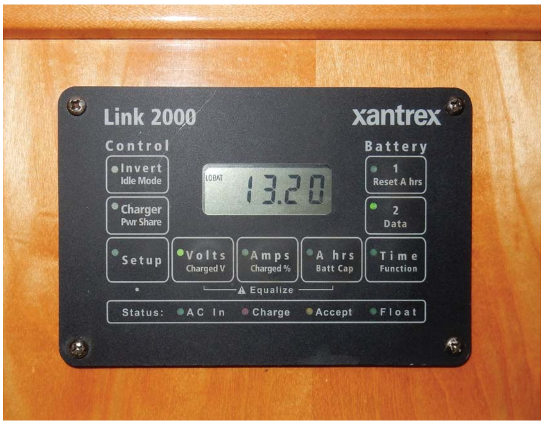
Lead Acid (LA) versus LiFePO4 (LFP)

Because of the vast differences between these two types of battery technologies, great care must be taken not to make any mistakes during planning and installation. A number of different lithium ion type cells are available now, but LiFePO4 is the best choice for cruiser batteries. It has significant advantages over the others, including being reasonably stable and safe in a marine environment. Even some of the electric vehicle companies are now changing to LFP.

Some differences between LFP and LA technologies:

- LFP cells do not require a full charge on a daily basis – in fact, charging to 90% or even less is perfectly acceptable and may give a slightly longer service life. This is a huge advantage.
- With LFP, no absorption or float charging is needed, only bulk. This means that once the bulk is completed the charger can be turned off, but not all LA chargers can do this.
- LFP cells typically have 50% more usable capacity for the same overall rated capacity. 80–90% of LFP rated capacity is useable on a regular basis versus a maximum of 50% for LA under ideal conditions.
- LFP service life is typically 3000–5000 full cycles versus 500–1000 cycles with LA.
- Cell level monitoring, balancing and disconnect control are required with LFP, whereas only those for the total battery are typically needed during charging with LA.

- Some significant electrical system modifications are usually required for a proper lithium installation. These include purchase of a quality and reliable BMS, installing separate charge and load busses and using separate inverters and chargers.
- Charging with an alternator requires some modifications or you risk overheating your alternator internals. You must either make sure the alternator is externally controlled by a smart alternator regulator with temperature and reduced output control or use battery-to-battery controlled charging, possibly with a lead acid battery also connected to the alternator. The externally-regulated alternator is much preferred.
- Batteries made of LFP cells are about one third the weight and take up two thirds the space of LA batteries. They can be charged significantly faster and have little voltage drop when placed under a heavy load.



Our older Xantrex Link 2000 lead acid battery monitor which displays only total battery parameters

Do It Yourself (DIY) LiFePO4 Cells

After a great deal of research, we settled on prismatic-style aluminium-cased individual LFP cells, purchased directly from RJ Lithium in China [https://www.rj-lithium.com/]. There are a number of other well-regarded Chinese companies from which we could have bought the same thing, but cruising friends had researched the subject and were buying from RJ. Their reputation was good, they offered documented Grade-A cells, the sales representatives were responsive, the website was informative and they offered a 5-year warranty.

Four of our eight 3.2-volts per cell prismatic cells connected in parallel during top balancing. Grade A testing stickers are intact and show, among other things, capacity, voltage, serial number and date of manufacture

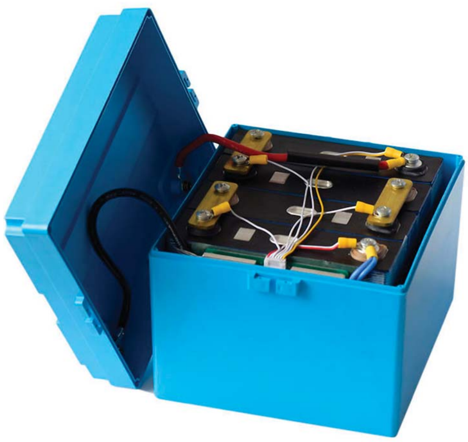
We purchased eight 3.2-volt 271 Ahr LFP cells. In order to get a single bank of 542 Ahrs at 12.8 volts, we arranged them in four sets of two cells in parallel (542 Ahrs at 3.2 volts for each set of cells) with the four sets arranged in series to make a 12.8 volt battery. Of that 542 Ahrs, more than 450 Ahrs are useable, so we increased our capacity by about 50% over our gel battery bank's useable capacity, plus we were able to remove 390lbs (177kg) of gels and replace them with only 100lbs (45kg) of lithium cells.

The LFP cells cost about US $150 plus about $35 shipping each, making a total cost of close to US $1500 for all eight. (The shipping cost was excessively high at the time due to the peculiarities of shipping into the Philippines via Hong Kong during Covid). We later discovered that, sourced locally here in the Philippines, we could have bought similar well-regarded but probably Grade B, EVE or Lishen cells without the longer warranty for about US $100 each plus a very modest shipping cost, totalling around US $900 including shipping. The LFP cell market is constantly changing and competition is fierce, so this pricing from China is no longer current. On the forums we often see these Grade A cells being shipped to the US and Europe at very reasonable prices. A cruising friend in our marina in the Philippines has recently purchased 240 Ahr Grade A EVE cells with a 2-year warranty and minimal shipping cost for about $100 US each.

Drop-In LiFePO4 Batteries

We do not recommend installing what are commonly referred to as 'preassembled' or 'drop in' lithium batteries on a serious cruising boat. They are better suited to coastal power boats and outboards for the following reasons:

- The cells and BMS are often secured inside a sealed battery box and may be inaccessible if there is a problem.
- Typically, the BMS provided uses small internal MOSFET (metal-oxide-semiconductor field-effect transistor) relay components that must control the high currents usually found on cruising boats. If anything goes wrong the owner may have to replace the entire battery and BMS.
- There may be little adjustment available to the charging and other control parameters which you may want to customise for your installation and longer service life.
- External communications with wifi or Bluetooth for monitoring and control may be limited. This is a critical component of the system and must be rock solid.
- If bought through a dealer, they can be extremely expensive compared to a



Four 3.2v LiFePO4 cells with MOSFET BMS, wired in series inside a 12-volt pre-assembled/drop-in battery case. Image courtesy RJ Energy, China

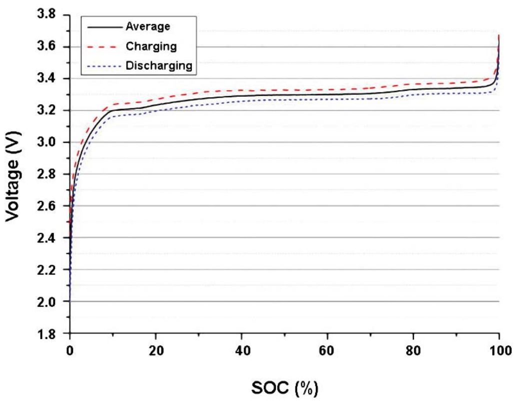
similar DIY installation using individual cells and separate quality BMS. Typically, quality units are two to three times the cost of a DIY installation.

- You will still need to do many of the same modifications to your electrical system as with a DIY system, in particular the separation of charging sources and loads into two busses.

If you can't take the time to do a proper DIY installation yourself, or with help from a knowledgeable friend who will teach you the system, we recommend buying quality gel batteries to install into your existing LA electrical system.

Charging and Discharging

The LFP cell charging curve is very flat in the middle between 3.2 and 3.4 volts per cell (VPC). It then goes nearly vertical (the knee) as the cell approaches full state of charge (SOC) at about 3.45 VPC and above. Because charging through the upper knee takes only a couple of minutes it represents very few Ahrs and may not be really necessary. Likewise, as the battery is discharging, the voltage stays very flat until dropping off rapidly below about 3.15 VPC as the battery reaches 10% SOC. The relatively high stable voltage and flat discharge curve are a big help when using high amp draw equipment like an inverter or windlass. This charging and discharging graph is provided by Energie Panda [www.energiepanda.com], a supplier of high quality LiFePO4 cells for DIY LiFePO4 batteries.



LiFePO4 cell charge and discharge curve comparison. Image courtesy Energie Panda

Cell Matching and Balance

Factory matching of LFP cell capacity and internal resistance are important for being able to maintain cell voltage balance. But it is a labour-intensive, and therefore expensive, process, so few companies selling cells at competitive prices are able to do a perfect job. Several, such as Winston and a few others, do better than average matching work, but this is reflected in their significantly higher prices. This is where a good balancer in the BMS (at least 200 milliamps) or a separately-purchased quality balancer earns its keep.

If the cells are not perfectly matched in capacity and internal resistance when charging, one cell can get to 3.65 VPC well before the others. This is an over-voltage situation which can destroy that cell before the total battery voltage reaches an alarm condition. Likewise, when discharging, if one cell is slightly more depleted than the others, its voltage can drop rapidly to below 2.5 VPC, a destructive under-voltage situation, again while the overall battery voltage is still at a safe level. A quality BMS which can monitor cell voltages can control these situations through external relays and prevent cell damage.

Finally, cells that are not well-matched for internal resistance will have slightly different charge curves, which might cause an automatic balancer to balance the wrong cells during charging. Our cells are not perfectly matched, so their charge curves intertwine voltage levels as they are being charged. Sometimes the low voltage cell at the start of charging becomes the high voltage cell at charge termination. A good cell-balancer can handle this and keep individual cell voltage balance levels within a reasonable difference.

Cell Grading

Well-regarded lithium factories produce thousands of individual cells a week. During initial testing, those that match advertised specifications and have no physical damage are graded as A cells. Those that do not become grade B cells and could have a range of problems. Both are sold on the open market. Grade A cells are usually more expensive, have QR and testing stickers intact and usually have warranties of a year or more. Grade B cells are often sold to off-grid applications that use hundreds of cells so can afford to have a few with problems. Serious cruisers would do well always to buy Grade A cells from a well-regarded supplier, as it helps ensure full useable bank capacity and makes balancing much easier.

Configuration

Banks of lithium cells are typically connected in sets of four 3.2-volt cells in series for a nominal 12-volt battery system. For a 24-volt electrical system, connect eight cells in series. For more capacity than four or eight single cells will allow, first connect cells in equal parallel sets, then wire those sets in series. The parallel sets can include cells of varying capacity, but the series sets must all be of equally-rated capacity and voltage.

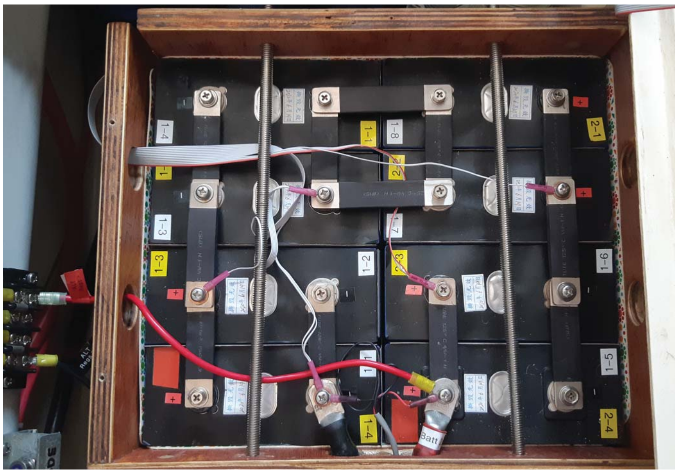
We originally planned to configure our eight cells into two four-cell 12-volt nominal 'batteries', with a 1-2-both selector switch so we could change batteries if we ran into a problem with one. However, once we started wiring up our two ElectroDacus BMSs, we found that trying to control the separate loads, charging sources, two busses and multiple external relays with our two BMSs became too difficult. Some internal relay BMSs are able to do this, but with somewhat degraded reliability and battery balance problems. We also realised that if we ever ran into an (extremely rare) sudden cell problem, rearranging the cells with our spares to make repairs was a pretty simple temporary solution. We ended up with four sets of two cells in parallel to make four 'supercells', then those four supercells in series for a 542 Ahr at 13.2-volt bank. This also had the advantage of requiring only one BMS instead of two. Since we had ordered two ElectroDacus SBMS0 BMSs we now had a spare.

Whether our configuration is called a 2P4S or 4S2P configuration depends on who you ask. It is written both ways in the lithium literature and on the internet. Be mindful of this when asking questions on lithium forums – sometimes it is preferable to describe your configuration rather than using one of these abbreviations.

Cell Compression

Most literature and experts on LFP cells recommend using a 'compression box' to contain the cells. On a boat this is also a 'limitation box' which provides cushioning, prevents the cells from chafing against each other and shorting, prevents terminals

Our eight LiFePO4 cells in their compression box in a 2P4S configuration, with two of the four threaded compression rods visible in place. Flexible connecting straps are made of multiple layers of copper carefully cleaned and firmly fastened to the terminals. The thin grey ribbon cable wiring is for the BMS monitoring and balancing functions



being damaged by connector tension as a result of expansion during charging and stops any sliding around as a bank in rough weather. According to EVE Energy, one of the largest lithium cell manufacturers in China, their aluminium case cells require compression in order to reach their full service life. Many others agree.

With this in mind we built a compression box to store the cells, using epoxy-coated ¾" (19mm) marine plywood and 3/8" (9·5mm) SS threaded rod. Between the cells we used 1 mm soft placemat material to prevent the cell sides from shorting together and provide somewhat of a cushion. The box has a polycarbonate cover and is strongly secured under our main cabin settee in the middle of the boat. It is only about 3ft (90cm) from the BMS, busses, regulators, relays and other major wiring.

Battery Management System

A good BMS is a critical component of a LiFePO4 system. Unlike most lead acid battery monitors that display only overall battery voltages, a good BMS must monitor individual cell voltages. In order to prevent cell damage a BMS must watch the voltage and SOC of each cell and make appropriate decisions regarding when to disconnect charge sources in case of a cell over-voltage event or disconnect loads in case of a cell under voltage-event.

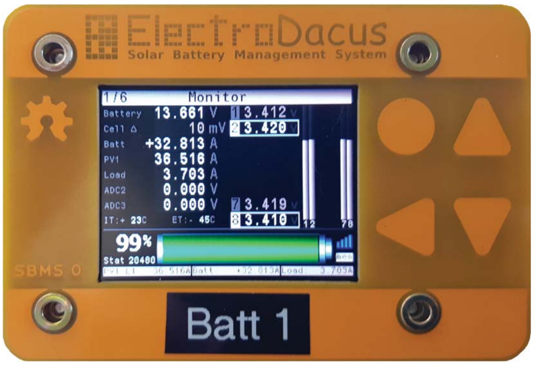
There are two types of BMS. One uses small internal MOSFET relays to turn on and off charging and loads when required. The other type of BMS controls more capable external relays. Since loads like inverters and windlasses and charging sources like alternators and generators might involve relatively high currents, cruising boat systems are better done with a BMS that can control high capacity external relays.

An important BMS feature is its ability to display externally what it is doing and important battery details such as voltage, current and SOC. Options include hard wiring to a display device such as a computer, wireless wifi and wireless Bluetooth using an application. We use wifi so that we can custom configure the display and see what is happening with our system when on or off the boat.

A good BMS will also have some sort of cell-balancing capability. 200 milliamps are usually sufficient to keep most reasonably matched and balanced marine house bank cells in line. Although most BMSs use some form of low current passive balancing, and that is usually sufficient over time, larger active balancers are available. They work with large cell deltas more quickly, removing excess amp hours from high voltage cells and placing them in lower cells.

BMSs range in price from cheap/dumb US $15 small open boards with no user interface, to high-quality programmable BMSs that will integrate seamlessly with existing proprietary equipment, such as quality Victron components, for about US $600. High price doesn't always give you all the equipment features you may need, but better quality BMSs are usually priced over US $100. Before purchasing a BMS you should look at the several internet sources for comparing BMSs, including user forums and YouTube videos. Just remember – serious cruisers cannot afford unreliable gear, so paying for reasonable quality and reliability is worthwhile, but there's no need to go overboard for capabilities you won't use.

We chose a very smart programmable BMS, an ElectroDacus SBMS0, made in Canada by a small, well-regarded company [https://electrodacus.com]. This one is targeted at the DIY solar community and can control multiple external relays with many adjustable parameters. It has an included detailed monitor screen, a 200 milliamp balancer, excellent HVD/LVD protection capability and an optional wifi interface. Just about every parameter for charging, discharging, balancing and HVD/LVD control is adjustable by the user. The HVD and LVD controls have six ways to set the control function and it has a very sophisticated logging capability. Finally, the developer and others provide significant help to users as needed via a forum and several beginners' guides.



Our ElectroDacus SBMS0 and its main monitoring screen, one of about two dozen screens available for monitoring and parameter adjustment. This screen shows, among other things, cell and total voltages, charging and load amps, maximum cell delta and SOC

LiFePO4 Installations and the Insurance Issue

- I suspect that most underwriters are suspicious of Chinese lithium batteries (where almost all are made) and BMSs. However, even most 'US' branded 'drop-in' lithium batteries use Chinese cells and BMSs.
- LiFePO4 technology is different from, and safer than, lithium-ion batteries used in electronic devices like cell/mobile phones, computers and most electric vehicles.
- A year after installation, the danger from a cell problem is minimal but danger from a poor installation or equipment continues. A cruiser must be very familiar with his or her installation.
- There are several ways to do a lithium installation, including for off-grid homes and

electric vehicles where a failure is not such a big problem. Not all are suitable for a cruising boat, especially one travelling overseas, where failed equipment or poor installation techniques can spell disaster.

- Not all installers, though 'certified', will be as familiar as you might like with your marine installation. Even if using an installer, you must be familiar with your boat's electrical system and what will be required for a 'Best Practices' installation. Make sure the installer is also, and that you both agree the installation details. Be aware that the installer's choice of equipment may be best for his profit margin but not necessarily best for your installation.
- A lithium battery installation is not for everyone. If lithium installation challenges are insurmountable, our experience with high quality gel batteries has convinced us that they are the best LA technology for cruisers.
- Watch the installation very closely and double-check the installer's mounting, wiring and termination techniques. This will further familiarise you with the system and hopefully allow you to spot and effectively troubleshoot a problem in the future.
- If you have done the research, know what you are doing and are willing to do the installation yourself, you can ensure a proper installation and save a considerable amount of money. It is not rocket science and there's a lot of help available on the internet.

LiFePO4 Reference Sources

A good way to start an LFP project is to read this article in full, together with other detailed information about our installation, on our website at www.svsoggypaws.com/electricalsystems.htm.

Next join the Facebook group Lithium Batteries on a Boat, then watch some of Will Prouse's Mobile-solarpower.com YouTube videos. Graduate to some of those on Andy's Off-Grid-Garage.com. Finally, read the detailed LFP articles at MarineHowTo.com and NordkynDesign.com. Once finished, and if you can remember most of it, you should be ready to start your own DIY LFP project. Links to these and other resources will be found on our website above.

Enjoy learning about this new technology, but remember that the experienced experts don't all agree. The forums, especially, are full of conflicting opinions, but there are also many good options. Study carefully and subscribe, as we did, to the preponderance of evidence from trusted sources. In the end the effort will be well worth it, enabling you to spend more time cruising and less time working on your boat.

Sunset in the Indonesian tropics