# Sunlight to Socket: A Beginner's Guide to Off-Grid Solar

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**Powering a cabin, RV, boat or homestead from the sun, explained from the ground up.**

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Based on my *DIY Off-Grid Guide to Solar* (v4), rewritten and updated for current equipment. Last updated October 2026.

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*Electricity can hurt you, and batteries store a lot of it. This guide teaches principles, not code compliance. Check your local electrical code, follow the manufacturer's instructions for every component, and hire a licensed electrician for anything tied to a building's wiring if you are unsure.*

## 1. Why off-grid solar, and why it starts with your loads

The cheapest watt is the one you never use. Every watt-hour you cut from your daily use is a watt-hour you don't have to buy panels and batteries for, so an off-grid system is designed from the loads backwards, not from the panels forward.

Living off-grid means knowing what everything you own consumes, and for how long. A small load left on all day often uses more energy than a big load used briefly. A 10-watt router running 24 hours uses 240 watt-hours. A 1,000-watt microwave running 10 minutes uses about 167.

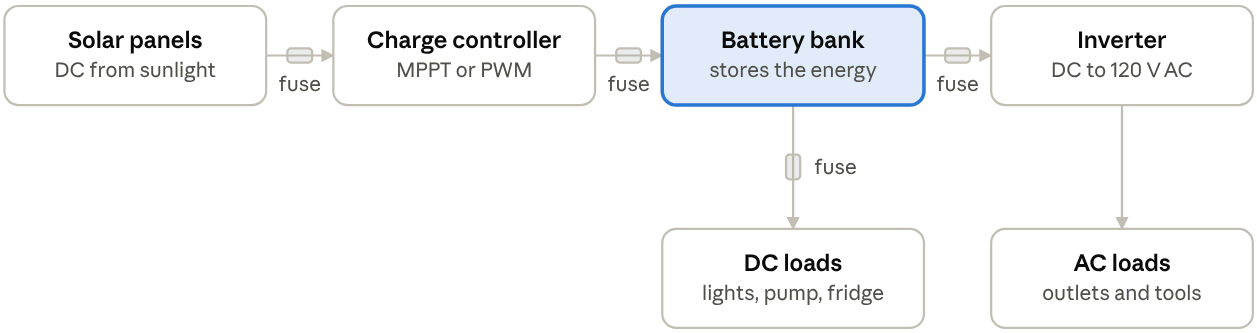
A good solar system costs real money up front, but after that the sun is free. Compared with running a generator, there is no fuel to haul, no oil to change every 50 hours, no noise and no smell. Keep a generator for the worst weather, and let the sun do the daily work.

My family and I lived off-grid for over six years on systems like the ones in this guide. We heated with wood from our own land, composted our food scraps in worm bins, and grew much of our food in raised beds. None of that required a huge solar array. It required paying attention.

## 2. The parts of a system

An off-grid solar system has four main parts: panels that make electricity, a charge controller that feeds it safely to the batteries, a battery bank that stores it, and usually an inverter that turns battery DC into household AC.

**Every DC connection between parts gets a fuse**




a basic off-grid solar system · 4 main parts, 2 kinds of load

The battery is the hub. Everything charges it or draws from it, and every wire leaving it gets a fuse or breaker sized to protect that wire.

- **Solar panels (PV)** turn sunlight into DC electricity. Photovoltaic cells release electrons when light hits them, and those electrons flow as direct current.
- **Charge controller** sits between the panels and the battery. It charges the battery at the right voltage and current, and stops when it's full.
- **Battery bank** stores energy for night and cloudy days. Its voltage (12, 24 or 48 V) sets the voltage of the whole system.
- **Inverter** converts low-voltage DC from the battery into 120 V AC for ordinary appliances.
- **Balance of system** is everything else: wire, fuses, breakers, disconnects, a battery monitor, and mounting hardware. Beginners underbudget this. Plan on 10 to 20 percent of the system cost.

## 3. The five formulas you need

You can size a whole off-grid system with five relationships. Learn these and the rest of this guide is arithmetic.

$$\text{Watts} = \text{Volts} \times \text{Amps}$$

$$\text{Watt-hours} = \text{Watts} \times \text{Hours}$$

$$\text{Amp-hours} = \text{Amps} \times \text{Hours} = \frac{\text{Watt-hours}}{\text{Volts}}$$

- **Series** connections add voltage. Two 12 V batteries in series make 24 V at the same amp-hours.
- **Parallel** connections add current and amp-hours. Two 12 V 100 Ah batteries in parallel make 12 V 200 Ah.

**Worked example.** A 200 W panel on a 12 V system delivers about 200 W ÷ 12 V = 16.7 A. In 3 full-sun hours that's 16.7 A × 3 h = 50 Ah, or 50 Ah × 12 V = 600 Wh. That 600 Wh would run a 100 W bulb for 6 hours, or a 9 W LED bulb for over 60.

**Think in watt-hours.** Amp-hours only make sense at a known voltage. A 100 Ah battery at 12 V holds about 1,280 Wh; at 48 V it holds about 5,120 Wh. Watt-hours let you compare batteries, panels and loads at any voltage.

## 4. Step 1: The load audit

List everything you plan to power, its wattage, and how many hours a day it runs. Multiply, then add it up. That daily total in watt-hours drives every other decision.

Get wattage from the nameplate, or better, measure it. A plug-in meter like the Kill A Watt reads watts and accumulated watt-hours on 120 V AC appliances, and inline DC meters do the same for 12 V loads. Nameplates show the maximum, and many appliances run well below it.

**Example: a small cabin**

| Load | Watts | Hours/day | Wh/day |
|---|---|---|---|
| 12 V compressor fridge (cycles on and off) | 50 | 8 | 400 |
| LED lights, 6 bulbs at 9 W | 54 | 5 | 270 |
| Microwave | 1,000 | 0.25 | 250 |
| Internet router | 10 | 24 | 240 |

| Load | Watts | Hours/day | Wh/day |
|---|---|---|---|
| Laptop | 45 | 4 | 180 |
| LED TV | 50 | 3 | 150 |
| Phone and tablet charging | 20 | 2 | 40 |
| Water pump | 60 | 0.5 | 30 |
| **Total** | | | **1,560** |

Add about 10 percent for inverter and wiring losses, and this cabin needs roughly **1,700 Wh per day**. We'll use that number through the rest of the guide.

**Watch the always-on loads.** The router uses almost as much as the microwave, because it never turns off. Inverters draw power just by being on, often 10 to 40 W at idle. A 25 W idle draw left on all day is 600 Wh, a third of this cabin's budget for nothing. Switch the inverter off when you don't need AC, or buy one with a low-power search mode.

**Then cut.** Swap any remaining incandescent or CFL bulbs for LEDs (9 W gives the light of an old 60 W bulb). Move heat jobs, like cooking, water heating, space heating and clothes drying, to wood, propane or the sun. Put phantom loads on switched power strips. Each 100 Wh/day you cut saves you roughly 30 to 40 W of panel and 110 to 170 Wh of battery.

## 5. Step 2: Sizing the battery bank

Size the battery to carry your daily load for one to two days without sun, using only the portion of its capacity you can safely draw. For most new systems today, that battery should be lithium iron phosphate (LiFePO4).

```
\text{Battery Wh} = \frac{\text{Daily Wh} \times \text{Days of autonomy}}
{\text{Usable depth of discharge}}
```

**Example.** Our cabin uses 1,700 Wh a day. For 1.5 days on LiFePO4 at 90 percent usable: 1,700 × 1.5 ÷ 0.9 = about 2,830 Wh. Three 12 V 100 Ah LiFePO4 batteries in parallel (3,840 Wh) cover it with margin. The same autonomy on lead acid at 50 percent usable needs 5,100 Wh, about four golf-cart batteries weighing close to 250 lb.

## Battery chemistries compared

| | LiFePO4 | Flooded lead acid | AGM / gel lead acid |
|---|---|---|---|
| Usable capacity | 80–100% | 50% | 50% |
| Cycle life (typical) | 3,000–6,000+ | 500–1,200 | 300–800 |
| Weight per kWh | about 20–25 lb | about 45–60 lb | about 55–65 lb |
| Max charge rate | about 0.5C | about 0.1–0.2C | about 0.2C |
| Maintenance | none | add distilled water, equalize | none |
| Venting | not needed | required (hydrogen gas) | not normally needed |
| Charging below 32°F | not allowed unless self-heating | yes | yes |
| Up-front cost per usable kWh | lowest today | low | moderate |

LiFePO4 prices have fallen far enough that it now wins on cost per usable kWh, before you even count its five to ten times longer life. Lead acid still makes sense for a bank that sits in an unheated shed through hard freezes, or where the budget is near zero and a used set is free.

## What "C-rate" means

C is the battery's amp-hour rating used as a current. On a 100 Ah battery, 1C is 100 A, 0.5C is 50 A, and C/20 is 5 A.

- **Lead acid** is rated at C/20. A 100 Ah battery gives 5 A for 20 hours, and only half of that is usable without shortening its life. Pull current faster and you get fewer amp-hours (look up Peukert's exponent). A full recharge takes many hours and a long absorption stage.
- **LiFePO4** is usually rated for 1C continuous discharge (limited by its BMS) and about 0.5C charge. A 100 Ah battery can deliver 100 A for close to an hour, and recharge from empty in about 2 hours at 50 A. Capacity barely changes with discharge rate.

## The BMS

Every LiFePO4 battery needs a battery management system (BMS). It balances the cells and disconnects the battery on overcharge, over-discharge, overcurrent, or charging when too cold. Most drop-in 12 V batteries have one built in. Buy batteries whose BMS current rating covers your inverter's full draw.

## Choosing a system voltage

Higher voltage means lower current for the same power, so smaller wire, smaller fuses and less loss.

| Inverter or peak load | Suggested battery voltage |
|---|---|
| Up to about 1,500 W | 12 V |
| About 1,500–3,000 W | 24 V |
| Over 3,000 W | 48 V |

Our cabin's 1,000 W microwave plus other loads puts it at the 12/24 V line. A 24 V bank would halve every current in the system.

## Wiring battery banks

- Series adds voltage; parallel adds amp-hours. Two 6 V batteries in series make 12 V. Four in series make 24 V.
- Use identical batteries of the same age in a bank. Don't mix old with new or lead acid with lithium.
- Keep parallel strings to four or fewer, and take the main positive and negative from opposite corners of the bank so every battery shares the load evenly.
- Check the manufacturer's limits before putting LiFePO4 batteries in series; many allow up to four.

## Safety

LiFePO4 is the most thermally stable lithium chemistry and far less prone to fire than the lithium-ion cells in phones and power tools. It is not risk-free. Any battery bank can dump thousands of amps into a short circuit, enough to vaporize a wrench and start a fire. Fuse

the main battery positive within a few inches of the terminal, and cover terminals. Flooded lead acid batteries vent explosive hydrogen while charging, so give them a vented enclosure and keep sparks away.

## 6. Step 3: Sizing the solar array

Divide your daily watt-hours by your peak sun hours, then by 0.75 to cover real-world losses. The answer is the panel wattage you need.

$$\text{Array watts} = \frac{\text{Daily Wh}}{\text{Peak sun hours} \times 0.75}$$

**Peak sun hours** are not daylight hours. One peak sun hour is the energy of one hour of full, 1,000 W/m² sunlight. A long, hazy summer day might deliver 5 peak sun hours; a short December day in the Northeast might deliver 1.5. Rough annual averages:

| Region (US) | Annual average | December |
|---|---|---|
| Desert Southwest | 6–7 | 4–5 |
| Southeast, Tennessee | 4.5–5 | 2.5–3 |
| Midwest | 4–4.5 | 2–2.5 |
| Northeast, northern New York | 3.5–4 | 1.5–2 |

These are approximate. For your exact location, use NREL's free PVWatts calculator, which gives month-by-month output for a given array size and tilt.

**The 0.75 factor** covers panel heat losses (panels lose output as they get hot), dust, wiring and controller losses, and battery charge efficiency. Lead acid batteries waste more energy in charging, so use 0.65 for them.

**Example.** Our cabin at 1,700 Wh/day in Tennessee, averaging 4 peak sun hours: 1,700 ÷ (4 × 0.75) = 567 W. Round up to 600 W. To stay solar-only in December at 2.5 peak sun hours you'd need about 900 W. The usual answer is to size for spring and fall, add a little margin, and let a generator cover the darkest few weeks.

Panels are cheap now, often cheaper than the battery capacity they replace. Oversizing the array 25 to 50 percent beyond your average need is the easiest way to make a system dependable in bad weather.

### Mounting and aiming

- **Face true south** (solar south, not magnetic) in the northern hemisphere. Up to 20° east or west costs only a few percent.
- **Tilt** equal to your latitude for year-round output. Add 15° for winter, subtract 15° for summer. Adjusting twice a year gains about 5 percent; for an off-grid system, a fixed winter-biased tilt is often best because winter is when you're short.
- **Avoid shade.** Shade on even a small part of one panel can cut that panel's output sharply, and in a series string it drags down the whole string. Check the site at the winter solstice, when the sun is lowest and shadows are longest.
- **Roof mounts** are secure, out of the way, and shade the roof in summer, but they're a pain to clear of snow or re-aim.
- **Ground and pole mounts** are easy to clean, adjust and clear of snow, and they keep holes out of your roof. Pole-mounted trackers gain 25 to 35 percent but add moving parts.
- **Size and weight.** A modern 400 W panel is roughly 68 × 45 inches and weighs about 45 to 50 lb. Plan mounts for wind load, and plan on two people for installation.

## 7. Step 4: The charge controller

Buy an MPPT controller unless the system is tiny. Size it so its current rating covers your array's output at battery voltage, and so your coldest-morning panel voltage stays under its input limit.

### PWM or MPPT?

A **PWM** (pulse width modulation) controller is essentially a fast switch that connects the panels straight to the battery. The panels are dragged down to battery voltage, so a panel that could make 18 V delivers its current at 13 V and the difference is lost. PWM needs 12 V panels on a 12 V battery.

An **MPPT** (maximum power point tracking) controller is a DC-to-DC converter. It runs the panels at the voltage where they make the most power, then converts that down to battery voltage at higher current. That typically harvests 10 to 30 percent more energy, more in cold weather, and lets you wire panels in series at higher voltage with thinner wire.

| | PWM | MPPT |
|---|---|---|
| Typical cost | $20–$60 | $100 and up |
| Energy harvest | baseline | 10–30% more |
| Panel wiring | panel voltage must match battery | series strings at higher voltage |
| Best for | under about 200 W, simple 12 V setups | everything else |
| Complexity | very simple | more electronics, still very reliable |

## Sizing the current rating

The controller's amp rating is its **output** to the battery.

```
\text{Controller amps} \approx \frac{\text{Array watts}}{\text{Battery charging voltage}}
```

Our cabin's 600 W array on a 12 V battery charging at about 14 V needs 600 ÷ 14 = 43 A, so a 50 A controller. On 24 V it needs about 22 A, so a 30 A controller. Many MPPT controllers safely clip an oversized array, but check the manufacturer's maximum before you rely on it.

## Staying under the voltage limit

This is the mistake that kills controllers. Every MPPT controller has a maximum PV input voltage, commonly 100, 150 or 250 V. Panel voltage **rises** as temperature falls, and the open-circuit voltage (Voc) on the label is measured at 77°F (25°C).

```
\text{Cold string Voc} = \text{Panel Voc} \times \text{Panels in series} \times \text{Cold factor}
```

| Coldest expected temperature | Cold factor |
|---|---|
| 32°F (0°C) | 1.10 |
| 14°F (−10°C) | 1.14 |

| Coldest expected temperature | Cold factor |
|---|---|
| −4°F (−20°C) | 1.18 |
| −40°F (−40°C) | 1.25 |

These factors follow the US electrical code's table; your panel's datasheet gives an exact temperature coefficient for a closer figure.

**Example from my own bench:** four 100 W panels wired two in series, two strings in parallel (2S2P). Each panel's Voc is about 22.5 V, so a string is 45 V. At −40°F that's 45 × 1.25 = 56 V, comfortably under a 100 V controller. Three in series would be 84 V, still under. Five would hit 141 V and destroy it.

At the other end, an MPPT controller needs the panels' operating voltage to sit a few volts above the battery's charging voltage, even on a hot day when panel voltage sags. For a 12 V battery, two panels in series is a good starting point.

### Setting it up

- Choose the correct battery profile. For 12 V LiFePO4, absorption is typically 14.2–14.4 V and float 13.4–13.6 V (or float off), with equalization and temperature compensation disabled. Use the battery maker's numbers if they differ.
- For lead acid, use the battery maker's charging voltages and fit the controller's temperature sensor to a battery.
- If your LiFePO4 battery isn't self-heating and could freeze, set the controller's low-temperature charge cutoff, or make sure the BMS has one.
- Connect the battery to the controller **before** the panels, and disconnect the panels first. Most controllers set themselves up from battery voltage at power-on.

## 8. Step 5: The inverter

Buy a pure sine wave inverter, sized for the largest set of loads you'll run at the same time, with surge capacity for anything with a motor or compressor.

An inverter turns battery DC into 120 V AC. Small ones plug straight into an appliance or have outlets on the case. Larger inverter/chargers wire into a breaker panel, charge the batteries from a generator or grid, and switch over automatically when the generator starts. All-in-one units now combine the inverter, charger, transfer switch and MPPT controller in one box.

## Pure sine or modified sine?

"Modified sine wave" (MSW) is a misnomer: it's a stepped square wave that only approximates a sine wave.

| | Modified sine wave | Pure sine wave |
|---|---|---|
| Waveform | stepped square wave | smooth sine, same as utility power |
| Works well with | heaters, incandescent bulbs, simple tools | everything |
| Problems with | motors run hot, buzz and wear early; some chargers, LED dimmers, audio gear, medical devices, newer TVs and microwaves misbehave or fail | none |
| Radio noise | often bad (a real issue for hams) | low on good units |
| Cost | cheapest | moderate; price gap is now small |

The price difference has shrunk to the point where MSW isn't worth the trouble. Many loads run less efficiently on it, wasting the energy you worked to collect.

## Sizing

- **Continuous rating:** add up everything that might run at once. In our cabin, the microwave (about 1,000 to 1,500 W from the outlet), TV, laptop and lights could coincide, so about 1,500 W.
- **Surge rating:** motors draw 3 to 7 times their running watts for a fraction of a second when they start. Pumps, fridges, freezers, compressors and power tools need a good surge rating. Low-frequency inverters with heavy transformers handle surges best.
- **Headroom:** run an inverter at 80 percent of its rating or less. Our cabin gets a 2,000 W pure sine inverter.

## The current on the DC side is large

$$\text{Battery amps} = \frac{\text{AC watts}}{\text{Battery volts} \times 0.9}$$

A 2,000 W load on a 12 V battery draws about 2,000 ÷ (12 × 0.9) = 185 A. On 24 V it's about 93 A; on 48 V about 46 A. This is the main reason to choose a higher battery voltage as systems grow, and the reason inverter cables are so thick.

### Features worth paying for

- **Low idle draw or search mode,** which sleeps the inverter until a load turns on.
- **Low-voltage cutoff** that matches your battery (adjustable on good units).
- **Built-in charger and transfer switch,** so a generator plugs into one inlet and everything else is automatic.
- **Generator auto-start** on larger units, which starts a generator when the battery runs low.

Wiring an inverter into a building's breaker panel involves neutral-ground bonding rules and code requirements. If you haven't done that work before, have an electrician check it.

## 9. Wire, fuses, breakers and disconnects: maximum vs. safe

The fuse protects the wire, not the equipment. Size the wire for the current and the distance first, then pick a fuse that will blow before that wire overheats.

Every spec sheet gives you a **maximum**: the most current a wire can carry before its insulation is damaged, the highest voltage a controller survives. Designing to the maximum works until a hot day, a loose lug or a cold morning pushes you past it. Designing to **safe** leaves margin. That margin is cheap insurance against fire.

### The four rules

1. **Wire ampacity must exceed the circuit's continuous current by at least 25 percent.**
2. **The fuse rating must be at or below the wire's ampacity** and at least 1.25 times the continuous current.
3. **Voltage drop should stay at or below 3 percent** (1 to 2 percent for battery-to-inverter cables).
4. **Every positive conductor leaving the battery gets a fuse or breaker** within about 7 inches of the battery terminal.

## Copper wire reference

| Size (AWG) | Conservative ampacity (A) | Resistance (Ω per 1,000 ft) |
|---|---|---|
| 14 | 15 | 2.53 |
| 12 | 20 | 1.59 |
| 10 | 30 | 1.00 |
| 8 | 50 | 0.628 |
| 6 | 65 | 0.395 |
| 4 | 85 | 0.249 |
| 2 | 115 | 0.156 |
| 1/0 | 150 | 0.098 |
| 2/0 | 175 | 0.078 |
| 4/0 | 230 | 0.049 |

Ampacity figures follow the US code's 75°C column for wire in conduit or a bundle, which is conservative for short open runs of high-temperature battery cable. Smaller AWG numbers are bigger wire.

## Voltage drop

$$\text{Volts dropped} = 2 \times \text{One-way length (ft)} \times \text{Amps} \times \frac{\Omega}{\text{ft}}$$

The 2 accounts for the trip out and back. Divide the result by system voltage for the percentage.

**Example: controller to battery.** 30 A at 12 V, 10 feet away. The 3 percent budget is 0.36 V. With 8 AWG: 2 × 10 × 30 × 0.000628 = 0.38 V, or 3.1 percent, just over. Step up to 6 AWG: 0.24 V, or 2.0 percent. Use 6 AWG, and a 40 A fuse.

**Example: array to controller.** Two strings of two panels, about 11 A at 36 V, 40 feet away. With 10 AWG: 2 × 40 × 11 × 0.001 = 0.88 V, or 2.4 percent. 10 AWG works. This is why higher string voltage is worth having: the same power at 12 V would need 4 AWG.

**Example: battery to inverter.** 2,000 W at 12 V draws about 185 A continuous. A 1.25 safety margin puts the fuse at about 250 A, which needs wire rated above 250 A. Many manufacturers allow 2/0 cable for this on a short run. I use 4/0 with a 250 A fuse and keep the cables under 6 feet. That's the difference between maximum and safe. On a 24 V system the same inverter needs only about 93 A, a 125 A fuse and 1/0 cable.

### Where the protection goes

- **Main battery fuse.** On LiFePO4 banks, use a Class T fuse at the battery positive. Lithium batteries can deliver very high short-circuit current, and a Class T fuse is built to interrupt it safely. MRBF terminal fuses suit smaller 12 V systems.
- **Battery to charge controller:** fuse or DC breaker sized to that wire.
- **Battery to inverter:** fuse or breaker sized to the inverter cable (often the main fuse does this job).
- **Array to controller:** a DC-rated disconnect, so you can isolate the panels for maintenance. Panels make power whenever light hits them, and you can't turn the sun off.
- **Parallel PV strings:** with three or more strings in parallel, each string needs its own fuse, per the panel's series fuse rating.
- **DC loads:** a fused DC distribution block or small DC breaker panel, one circuit per load.

### Workmanship

- Use only **DC-rated** breakers and switches. An AC breaker can't reliably break a DC arc.
- Use fine-stranded copper cable, tinned for damp locations, with proper lugs crimped by a hydraulic or ratchet crimper, then sealed with adhesive heat shrink. A loose or poorly crimped lug is the most common cause of heat and fire in DC systems.
- Torque terminals to the manufacturer's spec and recheck them after a month.
- Keep positive and negative cables the same length and run them together.
- Bond panel frames, racking and equipment cases to a ground rod. A ground-mounted array is a lightning target.

## 10. Battery monitoring

Install a shunt-based battery monitor. Running a system without one is like using a bank account without a check register: you don't know how much you have until it's gone.

**Why voltage lies.** A voltmeter on the battery tells you surprisingly little. Voltage rises while charging and sags under load, so the same battery can read 13.6 V or 12.4 V within a minute. LiFePO4 makes it worse: its voltage stays almost flat from 90 percent down to 20 percent, then falls off a cliff.

**How a shunt monitor works.** A shunt is a precision low-value resistor in the battery's main negative cable. Every amp in or out of the battery passes through it, and the monitor counts amp-hours deposited and withdrawn, like a fuel gauge. It shows state of charge as a percentage, current in amps (with sign), voltage and time remaining. Common units include the Victron SmartShunt and BMV series and the Bogart TriMetric. Many LiFePO4 batteries with Bluetooth BMS report state of charge as well.

**Set it up correctly.**

- All loads and charge sources must connect to the battery negative **through** the shunt, on its load side. Anything wired straight to the battery negative is invisible to the monitor.
- Enter the bank's real capacity and battery type.
- Let it synchronize at a full charge. Most monitors reset to 100 percent when they see the charged voltage and low current.

**Watch the trend, not just the number.** Note your state of charge every morning for the first few weeks. If it trends down over a stretch of good weather, your loads are larger than your harvest.

A basic multimeter is still essential for checking voltage, polarity and continuity during installation and troubleshooting. It's a tool, not a monitor.

## 11. Putting it together: build order

Build from the battery outward, with every fuse pulled and every disconnect open, and connect the panels last. The order matters because the battery is always live and the panels are live whenever there's daylight.

**Before you start:** take off rings and watches, use insulated tools, wear safety glasses, and keep a Class C fire extinguisher nearby. Never let a wrench bridge battery terminals. Red is positive, black is negative, and you check polarity with a meter before every connection.

1. **Mount everything.** Panels on their racking, and indoors (or in a weatherproof box) the controller, inverter, fuses and bus bars on a non-combustible backboard. Keep the battery close to the inverter and controller to keep heavy cables short.

2. **Wire the battery bank.** Series or parallel as designed, with the main fuse on the positive terminal and the shunt in the main negative. Leave the main fuse out.
3. **Run the DC bus.** Positive and negative bus bars, with the shunt between the battery negative and the negative bus.
4. **Connect the charge controller to the battery,** positive to positive, negative to negative, through its fuse or breaker, still open.
5. **Connect the inverter to the battery** through its fuse or breaker, still open, with the inverter switched off.
6. **Install the main fuse and close the battery breakers.** The controller should power up and detect the battery voltage. Set its battery profile now.
7. **Wire the panels.** Cover them with a tarp or wire them at dusk. Connect panels in series for voltage and strings in parallel for current, as designed and checked against the controller's voltage limit. Run the array wires to the PV disconnect, open.
8. **Measure before you close.** Check array open-circuit voltage and polarity at the disconnect with a meter. Confirm it's what you calculated and under the controller limit.
9. **Close the PV disconnect.** The controller should start charging.
10. **Turn on the inverter** and test with a small load first, then your largest.
11. **Set up the battery monitor** and let it synchronize at full charge.
12. **Label everything,** and recheck every terminal's torque after a week and a month. Copper cable settles under the lug.

Shutdown is the reverse: switch off the inverter, open the PV disconnect, then open the battery breakers.

## 12. Three example systems

A useful starter system now costs around $1,000, a comfortable cabin system $2,000 to $4,000, and a whole-homestead system $7,000 to $13,000 if you install it yourself. Prices have fallen sharply, especially for LiFePO4 batteries.

| | Starter: RV, boat, shed | Cabin (our worked example) | Homestead |
|---|---|---|---|
| Battery voltage | 12 V | 24 V | 48 V |

| | Starter: RV, boat, shed | Cabin (our worked example) | Homestead |
|---|---|---|---|
| Array | 400 W (four 100 W, 2S2P) | 800 W | 4–6 kW |
| Battery | 100 Ah LiFePO4 (1.3 kWh) | 3–5 kWh LiFePO4 | 15 kWh LiFePO4 rack |
| Charge controller | 30 A MPPT, 100 V | 35 A MPPT, 150 V | built into inverter, or 2 large MPPTs |
| Inverter | 1,000 W pure sine | 2,000–3,000 W inverter/charger | 6 kW all-in-one inverter/charger |
| Average daily harvest | about 1.2 kWh | about 2.4 kWh | about 12–18 kWh |
| Runs | LED lights, laptop, phones, router, fan, RV water pump | adds a 12 V or efficient AC fridge, TV, microwave, small tools | full fridge and freezer, well pump, washer, shop tools, mini-split in mild weather |
| Approximate cost, DIY | $900–$1,400 | $2,000–$3,700 | $7,000–$13,000 |

Costs are approximate late-2026 street prices for new equipment and include roughly 15 percent for wire, fuses, breakers, mounting and a battery monitor. Check current prices before you buy.

**The starter system** is the one I use as a teaching and test bench: four 100 W panels, a 30 A MPPT, and a 12 V 100 Ah LiFePO4. It also makes a good backbone for a rainwater pump, a ham station, or a portable power box.

**The cabin system** is where 24 V starts to pay. Panels in series reach higher string voltages, so pick a 150 V controller for headroom on cold mornings.

**The homestead system** at 48 V usually centers on an all-in-one inverter/charger with built-in MPPT, server-rack batteries, and a generator input. At this scale, it's worth having an electrician review the AC side and any connection to a building.

## 13. Generators as backup

A small inverter generator that runs a few hours a week in the darkest month is cheaper than doubling your array and battery bank. Plan for one.

If you live where it's 100°F and you want air conditioning, or somewhere with weeks of winter overcast, you have three choices: an outlandishly large solar system, a grid connection, or a generator. For most people, the generator is the practical answer.

- **Choose an inverter generator.** Models like the Honda EU2200i and Yamaha EF2200iS are quiet, sip fuel at light load, and produce clean power that won't upset inverter/chargers. Two can be paralleled for heavy loads and run singly for light ones.
- **Charge through an inverter/charger.** The generator plugs into one inlet. The inverter/charger passes generator power to your loads, charges the batteries with the rest, and switches back to battery automatically when the generator stops.
- **Run it hard, not long.** Charging a battery bank uses the generator efficiently because it loads it near its rating. Running a big generator for a single light bulb wastes fuel and wears the engine.
- **Consider auto-start.** Larger inverter/chargers can start a generator with a remote-start input when the battery drops to a set level, and stop it when charged.
- **Fuel options.** Many inverter generators can be converted to run on propane or natural gas as well as gasoline. Propane stores indefinitely and doesn't gum up carburetors.
- **Never run a generator indoors,** in a garage, or near windows. Carbon monoxide kills. Put a CO alarm in every sleeping area.

A generator is only as dependable as its maintenance. Change the oil on schedule, keep fresh stabilized fuel in it (or run it dry for storage), and exercise it monthly. The companion booklet, *Keep It Running: Small Engine Maintenance and Tune-Up*, covers exactly how.

## 14. Appropriate energy use: living within your harvest

Electricity is the most expensive energy you'll make off-grid, so save it for jobs only electricity can do: lights, electronics, motors and pumps. Do heat jobs with other fuels.

| Job | Avoid on solar | Better off-grid choice |
|---|---|---|
| Space heating | electric heaters | wood stove from your own woodlot; passive solar design |

| Job | Avoid on solar | Better off-grid choice |
|---|---|---|
| Water heating | electric tank | solar thermal, a wood-stove water jacket, or tankless propane |
| Cooking | electric range | wood cookstove, propane, solar oven; induction plate for quick jobs on a large system |
| Clothes drying | electric dryer | clothesline indoors and out |
| Water supply | deep-well pump running all day | rainwater catchment to a cistern with a small 12 or 24 V pump |
| Sanitation | flush toilet and septic pumping | composting toilet |
| Refrigeration | old full-size fridge | efficient 12/24 V compressor fridge or a new Energy Star unit |

Propane appliances are common off-grid, and propane stores indefinitely, but it trades the power grid for the propane delivery truck. Wood, sun and rain are the fuels you can produce yourself.

**Run big loads when the sun shines.** Do laundry, pump water, charge tool batteries and run the shop in late morning and early afternoon, when the panels are making more than you need and the battery is full. That surplus is otherwise wasted.

For us, appropriate energy use meant heating entirely with wood cut from our own land, a propane tankless water heater, worm bins for food scraps and raised beds for much of our food. The solar system only had to handle lights, electronics, pumps and the refrigerator, and that kept it affordable.

## 15. Maintenance and troubleshooting

A well-built solar system needs about an hour of attention a month. Most failures trace back to loose connections, dirty panels, shade that crept in, or a setting that's wrong.

## Maintenance schedule

| When | Task |
|---|---|
| Daily (first weeks), then weekly | Glance at state of charge and the day's harvest |
| Monthly | Look for corrosion, discoloured lugs or melted insulation; feel cables under load for warm spots |
| Monthly (flooded lead acid) | Check electrolyte; top up with distilled water only |
| After storms, snow, pollen season | Clear and rinse panels with plain water and a soft brush |
| Twice a year | Retorque terminals; check racking bolts; trim trees that now shade the array |
| Twice a year | Adjust tilt if you use seasonal angles |
| Yearly | Check grounding connections; test the generator and transfer; update controller firmware |

## Troubleshooting

| Symptom | Likely causes | Check |
|---|---|---|
| No charging on a sunny day | PV disconnect open, blown fuse, wiring fault, or panel voltage over the controller limit (controller faulted) | Measure array voltage at the disconnect, then at the controller input |
| Low harvest | Shade, dirty panels, wrong tilt, a failed panel or loose connector in one string | Compare string voltages and currents; walk the array at midday |
| Battery never reaches full | Loads larger than harvest, wrong charge profile, undersized array | Battery monitor history; recheck the load audit |
| Inverter shuts off under load | Low battery voltage, undersized cables, loose lug, surge beyond rating, BMS tripping | Measure battery voltage at the inverter terminals while loaded; check BMS current rating |

| Symptom | Likely causes | Check |
|---|---|---|
| Warm or hot cable or lug | Loose or poor crimp, undersized wire | Shut down, remake the connection, recheck torque |
| LiFePO4 won't charge in winter | BMS low-temperature cutoff below 32°F | Warm the battery space, add a heating pad, or use self-heating batteries |
| Battery state of charge drifts from reality | Monitor not synchronized, or loads bypassing the shunt | Full-charge sync; verify every negative goes through the shunt |
| Radio or TV interference | Inverter or controller noise | Pure sine inverter, ferrite chokes, twisted cable pairs, keep DC runs away from antennas |

# 16. Glossary and resources

## Glossary

| Term | Meaning |
|---|---|
| AC | Alternating current; household power, 120 V in North America |
| Ah (amp-hour) | One amp flowing for one hour; battery capacity at a stated voltage |
| Ampacity | The current a wire can carry continuously without overheating |
| AWG | American Wire Gauge; smaller numbers are thicker wire |
| BMS | Battery management system; protects and balances lithium cells |
| C-rate | Charge or discharge current as a fraction of amp-hour capacity |
| DC | Direct current; what panels and batteries produce |

| Term | Meaning |
|---|---|
| Depth of discharge (DoD) | How much of a battery's capacity has been used |
| Inverter/charger | An inverter that also charges batteries from a generator or grid and switches automatically |
| LiFePO4 | Lithium iron phosphate, the preferred off-grid battery chemistry |
| MPPT | Maximum power point tracking; a charge controller that converts panel voltage efficiently |
| Peak sun hour | The energy of one hour of 1,000 W/m² sunlight |
| PWM | Pulse width modulation; a simple switching charge controller |
| Shunt | A precision resistor that lets a monitor measure battery current |
| State of charge (SoC) | How full a battery is, as a percentage |
| Voc | A panel's open-circuit voltage, its highest voltage, with nothing connected |
| Vmp | A panel's voltage at maximum power output |
| Wh (watt-hour) | One watt for one hour; the unit for comparing energy |

## Resources

- NREL PVWatts calculator: month-by-month solar output for your exact location.
- Global Solar Atlas: solar resource maps for anywhere in the world.
- PowerStream wire size calculator: voltage drop and wire gauge for DC runs.
- *Wiring Unlimited*, a free book from Victron Energy on DC wiring, fusing and system layout.
- NEC Article 690 (solar PV systems) and Article 706 (energy storage), for code requirements in the US.
- A plug-in watt-hour meter (such as the Kill A Watt) and a DC inline power meter, for your load audit.

## About the author

Steve Spence, KK4HFJ, is a Navy veteran, engineer and homesteader who has lived off-grid on solar, wind and wood for years and designs off-grid power systems for his Tennessee homestead. More free guides, including *Resilience Gardens* and *Keep It Running*, are at kk4hfj.com.