

FINAL REPORT: SKY RANCH 540 WATT PHOTOVOLTAIC SYSTEM



Battery Box Cover

Table of Contents

INTRODUCTION

DESIGN

WHICH WAY IS SOUTH?

BUILDING THE MOUNT, PART ONE: THE FOUNDATION

BUILDING THE MOUNT, PART TWO: FRAMING CHANNEL

ATTACHING THE MODULES TO THE MOUNT

MODULE WIRING

CONNECTING THE ARRAY TO THE DC BREAKER PANEL

GROUNDING

BALANCE OF SYSTEM: THE "POWER WALL"

THE BATTERY BOX

BATTERIES

POWER UP

THE INVERTER

TEMPERATURE COMPENSATION

THE TRIMETRIC BATTERY MONITOR (AMP-HOUR METER)

PRECISION HYDROMETER

AC CIRCUIT

HOW DOES IT WORK?

List of Photos

1. Battery Box Cover
2. Kill-a-Watt Meter
3. Poles for True South
4. Auger Hole for Cement Pad
5. Square Forms with Anchor Bolts
6. Four Cement pads for Mount
7. Framing Channel Mount for Solar Panels
8. Solar Panels on Mount
9. Solar Panel Wiring & Combiner Box
10. Conduit From Combiner Box to DC breaker panel
11. Grounding from Combiner Box to Irrigation Pipe
12. The "Power Wall"
13. Battery Box
14. Batteries
15. Complete Power Wall
16. Power Inverter
17. Temperature Compensation Attachment
18. Trimetric Battery Meter
19. Thermometer Display Unit
20. Precision Hydrometer
21. Transfer Switch: DC/AC
22. Outback Charge Controller

INTRODUCTION

One day, the Alpha Institute (www.alphai.org) supreme council issued a directive: "We want solar."

The engineering department replied, "We can do it. We'll dust off our feasibility study from last year, scale everything to new requirements, order the components, and put it together. We need to get the financial department in here to see what kind of money we have to work with."

Said the financial department, "You've got \$5000."

The engineers answered, "That'll be tight for a full working system. Just running through the major components, it looks more like \$6000."

"Sorry to hear it. \$5000. Shop around."

DESIGN

First step was a re-examination of our earlier design studies. A while back, we worked through sizing calculations for a PV system to power the computers in the Sky Ranch office. Now, we turned it around: What could we build for \$5000, and what size load would it support? We ran new 7-day load tests on two full-time computers. Instantaneous power draw was 240-260 Watts, depending on what applications were open.



We recorded cumulative KW-H with our **Kill-a-Watt** meter. Average daily energy use for two computers was between 1250 and 1500 W-H (1.25 – 1.5 KW-H / day).

Field measurements on real working systems place overall efficiency for battery-based PV systems between 55 % and 65 %. This figure describes the ratio of energy delivered to the load to the energy generated by the PV array at its specified maximum power output. To calculate PV array energy, you multiply the array's rated power under

Standard Test Conditions by the annual average sun-hours per day for your location. (Note: STC = 1000 W / m² irradiance; 1.5 atmospheres air mass; 25 degrees C module temperature.) Major factors that limit overall efficiency include module temperature, dirt and dust, mismatch and wiring losses, battery charge efficiency, and inverter efficiency. (For a good explanation of efficiency factors, see **California Energy Commission Report, "A Guide to Photovoltaic System Design and Installation"**, also the **NABCEP Study Guide**.)

With a 1.25 – 1.50 KW-H / day energy requirement, and overall system efficiency of 55 – 65%, we would need an array with a power rating between 401 and 568 Watts. We specified a 540 Watt array, consisting of 4 ea. 135 Watt / 12 Volt modules, wired in series. Maximum power output is realized at 70.8 Volts / 7.63 Amps.

To get the most out of our modules, we decided to use an MPPT (maximum power-point tracking) charge controller, which continuously adjusts PV operating point for maximum power

output, rather than simply clamping PV output to the required battery charging voltage. Because MPPT controllers have a wide input voltage window, we could wire the array for 48 Volts, to reduce wiring losses, and still charge a 24 Volt battery. MPPT yields an added improvement in cold weather, since PV output voltage increases as module temperature decreases. In technical terms, PV modules exhibit a negative temperature coefficient, which means the voltage increases as temperature decreases. For our modules (multi-crystalline type) the coefficient is $-0.08 \text{ V / degree C}$.

We somewhat over-sized the charge controller, mainly because MPPT controllers are generally designed for larger systems. We selected an **Outback** MX60, which has a maximum PV open-circuit voltage of 150 Volts, and maximum output of 60 Amps continuous. It works with batteries from 12 to 60 Volts. It also features temperature compensation and comprehensive logging capabilities. Temperature compensation is recommended when batteries are subjected to temperature variations (like ours). Lead-acid batteries exhibit a negative temperature coefficient, $-5 \text{ mv / degree C / 2V cell}$, which means they want a higher charging voltage at lower temperatures.

Figuring 3 days of battery autonomy at 50% depth of discharge, we would need a battery bank of 412.5 A-H for a 1.25 KW-H / day load. This is slightly more than the A-H capacity of widely available L-16 class batteries. We tentatively selected 4 ea. **Deka** 8L16 batteries (6 V / 370 A-H), wired in series, for a 24V / 370 A-H battery bank. This falls a bit short of the design target, giving 2.7 days at 50 % depth of discharge. We can live with this limitation, since we have the grid. If the batteries get low, we can switch the load to utility power, and temporarily direct all available PV power to battery charging.

We initially planned to use a 600 W / 24 Volt Inverter, based on maximum steady-state load of 260 W. However, the 1100 W model was only \$80 more, so we decided to get the bigger unit, giving us some headroom for load surge and for future expansion.

We will not elaborate further on the sizing exercise, except to say there are many sizing calculator programs around, which generally yield similar results. One good example is the one published in the **Real Goods “Solar Living Sourcebook”** (<http://www.realgoods.com/>).

We shopped around, looked at catalogs, surfed vendor web sites, and ultimately selected a supplier who had all the PV components we needed: **Northern Arizona Wind and Sun** (<http://www.solar-electric.com/>), in Flagstaff, AZ.

Our shopping list included the following:

- 4 ea. Kyocera KD-135GX-LP solar panels, 135 Watt (17.7 V / 7.63 A at rated output), connected in series for a nominal 48 V array
- 1 Outback PSPV, PV array combiner, with 2 ea. 15A breakers
- 1 Outback MX60 MPPT charge controller, 60 A, for 12-60 V battery
- 1 Outback RTS remote temperature sensor
- 1 Outback FW 500-DC, DC breaker enclosure, with breakers (30 A PV disconnect, 30 A charging disconnect, 100 A inverter disconnect)
- 1 Exeltech XP-1100-24 Inverter, 1100 Watt / 120 VAC output, 24 Volt input
- 1 Bogart TM2020, Tri-Metric battery system monitor, with cable

We got a few extra integration doo-dads, such as **Water Miser** flip-top battery caps, lay-in ground lugs for the panels, and cable clips to secure the module wiring to the frames. We also

got a 30 ft. **MC4, Solarline 2**, extender cable to connect the modules to the combiner panel. All this cost \$4400.

We held off on purchasing batteries, because we wanted to wait until we had everything else ready. That way, we could start charging right away.

We built anything we could: items like the array mount, battery box, and electrical wiring. All the generic integration material came from **Home Depot** (www.homedepot.com/), our new favorite retail destination. We purchased bags of concrete mix, framing channel and hardware for our home-made array mount, wood; fasteners, and DWV vent pipe for our home-made battery box; wire, conduit, lugs, fittings, wire-cutters, pipe glue, candy bars, etc.

WHICH WAY IS SOUTH?

Prior to building anything, we had to find true South. Our homemade ground mount would have provision for seasonal elevation (tilt) adjustment, but we wanted to point the panels directly south to maximize solar collection. We found some handy survey software tools in the “Site Survey” section of the **BuildIt Solar** web site (www.builditsolar.com). We used the **Solar Noon method**, which is based on the fact that the sun always casts a true North-South shadow at solar noon. The link to the **NOAA Sunrise/Sunset Calculator** (<http://www.srrb.noaa.gov/highlights/sunrise/sunrise.html>) provides exact solar noon, to the second, for any specific date and location. (For exact latitude/longitude for a location, use the program – **Google Earth** from www.google.com)



To perform the survey, you set up a plumb bob, or an exactly vertical stake, and mark the shadow at solar noon. Get ready beforehand, and work fast, because the sun doesn't wait around. We set up 2 stakes with a string, planted one stake, and moved the second stake until the string lined up over the shadows. Then we planted the second stake. The two stakes served as our true North-South reference for the foundation.

Note: The orange and yellow poles are off set in the photo so that you can see them but they do show true south at solar noon.

Before building, it is also important to know the path of the sun throughout the year, so you know beforehand if or when the array will be shaded. Unless you are out in the wide-open, shading angles can be difficult to visualize. There are instruments available to perform this task. If you did it every day, you would probably want one. We did the next best thing: we ran the **University of Oregon Sun Radiation Monitoring Lab's Sun Path Chart Program** for our location. This very useful program (free, via the **BuildIt Solar** site) generates a sun path graph, in azimuth and elevation co-ordinates, from sunrise to sunset for any day or period of days up to 6 months. You enter your location (in lat/long or by ZIP code) and time zone offset from GMT, and the program does the rest. We made 4 graphs: Dec – June and June – Dec, for both MDT and MST.

We mapped the building with a compass and inclinometer, after first calibrating our compass against our solar noon reference line. The difference between true north and compass (magnetic) north is called magnetic declination. Declination varies with location; it also changes over time. To calculate declination for our site, we used the **NOAA / National Geophysical Data Center magnetic declination calculator** (another link on **BuildIt Solar**). We confirmed that declination (mid-2008) was just over 9 degrees East.

We mapped the roofline azimuth and elevation from the center of the array location, using the compass and a metal sighting rod with an inclinometer attached. We superimposed the building corners onto our sun chart printout, and connected the dots. It turns out the array is shaded by the building after 4 pm (MST) in early spring and late fall. In summer, we have sun until early evening (6 pm MDT between May and August). In winter, the sun is always south of the building corner, even at sunset. This result easily satisfies the rule-of-thumb site selection test, which dictates that you should have unobstructed exposure year-round between 9 am and 3 pm.

The other factor that influenced array location was wiring distance. It is desirable to minimize distance between the array and batteries to reduce voltage drop in the conductors (lost forever at \$5 / Watt). Our optimum location was 70 ft. (wiring distance) from the PV combiner box on the mount to the charge controller inside the building. Voltage drop would be 1.1% at full array power, using 6 AWG wire. Our goal was to stay under 2%. Even if we double the array size, we will still be pretty close, at 2.2%. Ampacity rating would not be an issue, since our calculated maximum continuous current, with safety factor and conditions of use reductions applied, was only 13.1 Amps (see NEC Tables 310.16 and 310.17 Conductor Ampacities).

BUILDING THE MOUNT, PART ONE: THE FOUNDATION

We designed our mount as a tilt-adjustable structure, raised 24 inches above grade on a fixed rectangular platform. We wanted to elevate the array at least 2 ft. above grade, to clear snowdrifts and weeds. We anchored the platform to the ground at the four corners, with the platform "footprint" of 96 inches across by 88 inches front-to-back. Each corner has its own below-grade concrete footing with a cast-in anchor bolt protruding from the top. For anchor bolts, we used 24-inch sections of ½ inch threaded rod, with metal cross-members nutted on, to sink into the concrete.

Now the real fun starts. We needed to dig 4 holes, 20 inches deep, for the anchor bolts. We started with a heavy pinch-point bar, suitable for busting up concrete sidewalks.

We drove the bar into the packed dirt, using our fence-post driver. The first 4-6 inches went easy, since it consisted of rocks, gravel, and loose dirt. Then we hit clay--hard clay. Progress slowed. After several hours we almost had one hole dug. The Communications Dept. truck rolled by, the driver chuckling at our folly. Minutes later, he returned with a motorized hand-held auger.



Running the auger was still hard work, even with eight hands on it, but we dug all four holes in one day and knocked off early.



We built some 20-inch square forms out of old 2x4's to finish off the tops of the holes. Then we made an anchor bolt template out of

plywood strips, to keep the four bolts in correct alignment during the pour. We fitted the template over the holes and dropped the anchor bolts through the template. We loosely nutted the bolts to the template, jiggled the whole thing around to get the bolts exactly vertical, centered in the holes, and square, then tacked the template to the forms. We threaded the bolts down to the bottom of the holes and tightened the nuts against the template. Finally, we baling-wired some re-bar sections to the anchor bolts to brace it in 3 directions against the sides of the holes. We taped the above-form sections of the anchor bolts to keep the threads clean.



We mixed the 80 lb. bags of pre-mix one at a time in a wheelbarrow, using a garden hoe and a hose. We had to keep going until it was all done, so there would be no faults in the concrete, but eventually we poured the 4 footings, one for each anchor bolt. Each hole took 3 to 4 bags, so we have around 1100 lbs. of concrete in the ground. We kept the concrete covered for several days while it cured, wetting it occasionally. After it cured,

we had a strong foundation, with 4 anchor bolts sticking up vertical out of the footings, in the right place, with clean threads. (Note the two alignment poles in middle of figure.)

BUILDING THE MOUNT, PART TWO: FRAMING CHANNEL



We fabricated a custom mount out of framing channel, using both 1 5/8 inch deep and 13/16 inch deep members, bolted together with 1/2 inch hardware, channel nuts, square washers and angle brackets. The bottom of the tilt-frame top structure pivots off the front of the platform, the lower edge 26 inches above grade. Adjustable telescoping legs tie the top of the tilt frame to the lower rear corners of the platform. These legs permit +/- 15 degree seasonal adjustment. We had originally planned to attach the legs to the top rear of the platform, but we couldn't get enough adjustment range

from there. Our design called for 30 degrees total elevation adjustment, between 55 degrees tilt (35 degrees elevation) in winter and 25 degrees tilt (65 degrees elevation) in summer, with a median spring/fall position at 40 degrees tilt (35 degrees elevation). The spring/fall tilt angle equals site latitude (within 0.5 degree). We fabricated the telescoping legs out of nested 1 1/4 and 1 1/2 inch EMT thin-wall conduit. We drilled 3/8-inch holes through inner and outer members, so we could pin the legs into desired position with bolts and nuts. We will spare you the trigonometry that went into these legs, except to say that the adjusted lengths are 57, 79, and 99 inches, center-center. In each position, the legs are pinned with two bolts to ensure strength and stability. Also the three positions (Fall/Spring, Summer and Winter) are color coded (green, red, blue) at the different bolt holes and mast for easy changing.

ATTACHING THE MODULES TO THE MOUNT



The top-layer rails on the tilt-frame run up and down, in two pairs. Side-to-side spacing is infinitely adjustable, since the rails are attached to lateral channels underneath with channel nuts. We spaced the top rails to match the mounting holes in the module

frames. The four **Kyocera** 135 W modules sit in “landscape” orientation, two across and two high. The tilt frame, actually the whole mount, is designed to carry eight modules, two across and four high. We can double PV capacity without disturbing the four existing modules. We bolted the modules to the frame with stainless ¼ inch hardware, channel nuts, and some custom 1/8-inch thick aluminum plates between the aluminum module frames and the galvanized steel mount.

MODULE WIRING



The **Kyocera KD-135** modules use industry-standard **MC4 “Solarline 2”** latching connectors, which are weather-tight once mated. Each module has a male and female connector, so you can connect the modules in series by simply plugging the cables together. To connect the series string to the PV combiner box, we used an extender cable, which has male and female ends. We cut this in the middle, and connected the free ends inside the combiner box. We got two breakers (for expansion), but we only wired to one, since we only have one string. The PV output circuit is protected by

a 15 Amp circuit breaker.

Before we plugged the four modules together, we tested them individually. On a hot summer day, with mostly clear sky, at 1130 MDT, we measured open-circuit voltages between 19.81 V and 20.01 V. Short-circuit current was between 8.50 A and 8.60 A. This was encouraging: Short-circuit current exceeded **Kyocera’s** published spec for I_{sc} at STC. Voc was a bit below the specified 22.1 V, but module temperatures were way above 25 degrees C (ambient temperature was 95 F, or 35 C). If module temperature was 51 C (reasonable in the hot sun), the 0.08 V / degree C coefficient would put us at 20.0 Voc, right on target.

We measured the full array 3 hours later, still under strong sun. Voc was 81.7 V, and I_{sc} was 8.45 A. We felt confident that the modules were in good working order.



CONNECTING THE ARRAY TO THE DC BREAKER PANEL

We needed a 1-inch conduit with three 6 ga. conductors to run from the combiner box on the mount to the DC breaker panel inside the building, a total distance of 70 ft. We didn’t want to penetrate the brick wall if we could help it, nor did we feel like trenching all the way to the building, so we devised a “low-impact” alternative: We ran the conduit underground from the array straight back to the chain link fence. From there, it comes up aboveground and follows the top bar of the fence over to the building corner, suspended by some homemade galvanized strap hangers. At the wall, we converted to non-metallic 1-inch flex conduit for the rest of the run: up the wall, through the soffit,

over the top of the brick wall, across the open attic, and down into the breaker panel. We fished some pulling twine into the conduit as we went along, then pulled the conductors through, using a lot of wire-pulling lube.

GROUNDING



We bonded the mount and all the array frames together with a single continuous 6 AWG solid bare wire and tin plated, direct burial lay-in lugs. The module-grounding conductor terminates at the ground lug in the combiner panel. We ran another bare ground wire from the same lug straight down into the ground, and East a short distance to a copper pipe that is part of an abandoned buried irrigation system. From the combiner ground lug, we ran another ground wire through the conduit to the ground bus in the indoor DC breaker panel. From there, we ran yet another grounding conductor outside to the utility grounding electrode, a copper stake driven into the earth. The PV grounded conductor (negative) terminates inside at the DC negative bus bar. The negative bus is connected to the ground bus in one place only, via a short jumper wire in the DC breaker panel.

BALANCE OF SYSTEM: THE “POWER WALL”

All the electronic components, wiring, and DC circuit breakers are grouped together on a plywood sheet mounted to an inside wall with carriage bolts and wing nuts. The whole equipment plate can be removed as a unit, once the array, battery, and AC output circuit are disconnected.



The equipment plate roughly mimics the layout of a pre-wired **Outback Power Center**, since we are using two **Outback** components. The **DC breaker panel** is in the center, with the **charge controller** directly to the right, and the **Exeltech Inverter** on the left. There is room for a larger inverter. We marked and drilled holes beforehand for “T-Nuts”. These grab the plywood on the back surface, so the equipment can be mounted to the front with machine screws. We mounted the

Bogart Trimetric battery monitor to the far right, on its own bracket. The meter can be installed remotely (we got 50 ft of 3-twisted pair cable for that purpose), but we elected to mount the meter on the plate with everything else. This worked out OK; we have found that we get the best picture of system operation from reading both the **Trimetric** meter and the charge controller data.

We included appropriate DC-rated circuit breakers to provide over-current protection for each ungrounded conductor, in accordance with the NEC. To calculate circuit breaker sizes, we followed the **Sandia National Laboratories** document, “**Photovoltaic Power Systems and the 2005 National Electrical Code: Suggested Practices**” by John Wiles, Southwest Technology Development Institute, also John Wiles’ article, “**Code Calculations for an Off-Grid PV System**” (Home Power Magazine, Issue 95). We have a 30 Amp breaker for the PV input, another 30 Amp breaker for the charge controller output, and a 100 A breaker for our 1100 Watt, 24 V inverter. The array breaker will let us double array size (with the same 6 ga. wiring). If we do expand, we will have to increase the charging breaker, although the charging output conductors are likewise already rated for a 100% increase. The 100 A inverter breaker was chosen based on the inverter’s rated output power at lowest usable battery voltage. We protected the battery meter with a 2 Amp 3AG fuse in a **Radio Shack** in-line fuse holder, wired to the positive battery bus. We may get a panel-mounted 2 Amp breaker, so we can turn the meter off without taking the front off the breaker box.

Earlier, we investigated deep-cycle battery options. Basically there are two general categories; both are lead-acid: (1) Flooded. These have liquid electrolyte and caps where you add water, and (2) Sealed, also called VRLA (valve-regulated lead-acid), which come in two flavors: Gelled electrolyte, and AGM (Absorbed glass mat). Both are sealed except for pressure-relief valves. They don't leak; you can't add water, no spills. They don't gas, unless overcharged. Unfortunately, sealed batteries are approximately twice as expensive per A-H as flooded batteries. They also have more stringent charging requirements, since the electrolyte cannot be replenished. After considering the matter most briefly, we remembered that we had a budget, and ordered 4 ea. L-16 class flooded batteries. Each battery is 370 A-H (20 hour rate) at 6 V, and weighs 113 lbs. Our batteries, like our PV array, are arranged in a single series string, at 24 Volts. The batteries would need a tight enclosure, vented to the outside. And stout.

THE BATTERY BOX

We had several tricky physical restraints, which ultimately led us to construct our own custom battery box: Foremost was wiring distance: For maximum 2% voltage drop between the batteries and inverter, wiring distance could be no more than 10 ft. (one way) for 4AWG, and 15 ft for 2 AWG. We positioned the box on the floor, partially under the electronic equipment, with the vent pipe clearing everything on the right side. Average one-way wiring distance is 9 ft (10 + 8). Generally, it is ill advised to put batteries directly underneath electronic equipment, but we fudged a little, since we were venting the box to the outside. The box was a tight fit: we had to maintain clearance between the door, a stairway and a manhole cover (you don't have manhole covers in your house?), and some storage cabinets. The hinged top had to clear the equipment on the wall above, and not block the walkway. Furthermore, we wanted the top to be sloped, so any Hydrogen gas would float up the vent pipe and not get trapped in pockets inside the box. Since the batteries are quite heavy, even with handles, we made the front of the box removable. The front attaches with T-Nuts and long, ¼ inch screws. The front mating surface is faced with rubber roofing material for an airtight fit. The top opening is capped with rubber weather-stripping where the lid closes. The lid slopes upward 3 inches to the right, with the vent pipe exiting at the highest point. The pipe, made from 2-inch ABS / DWV, goes straight up into the attic and out through a hole in the short vertical wall beneath the Dutch-Hip roof. A screen over the hooded end keeps wildlife out. More screen covers two intake vents on the left side of the battery box, near the floor.



We sanded and stained the whole thing a mellow, reddish Maple color. Finally, we wanted to fortify our box, and or whole project, with an appeal to the higher force. We commissioned the Art Department to paint a Thunderbird on the lid. Powerful. We were now ready to install the batteries and turn the system on.

BATTERIES



We set the batteries directly on the floor of the box. All the extra work that went into the removable front now paid off. L-16 batteries are heavy, even with the built-in handles, and they only had 2 inches clearance to the front and back inside the box. With the front removed, we only had to lift the batteries about 6 inches. Next, we installed flex conduit between the battery box and the DC breaker panel. To keep everything compact, we incorporated a 90-degree pull-box with removable cover where the conduit enters the battery box. This made it a lot easier to bend the 2 ga. conductors into the box. We made up three 15 inch, 2 AWG jumper cables to inter-connect the four 6V batteries, and two longer main battery cables. We attached the ring-lugs on the 2 AWG with a “hammer-crimper,” a sort of anvil that crimps big lugs. Craftsmen that we are, we used a vise instead of a hammer. We put shrink tubing over all the lugs to retard corrosion and give everything a finished look. We connected the series jumpers and measured voltage across the whole battery bank. With no load, we had 25.3 Volts. So far, so good. We left the main cables disconnected, out of harm’s way, on the floor of the battery box, so we could make one last safety check. We turned all the circuit breakers OFF and double-checked all the DC wiring, measuring every conductor for continuity and verifying that there were no short-circuits. All bolted connections were tight.

POWER UP



It was time to connect the battery. We bolted the positive cable to the + terminal of battery # 4, and briefly tapped the negative cable against the – terminal of battery # 1. No sparks! We bolted the negative cable in place, whereupon the **Trimetric** battery meter lit up, showing 25.3 Volts. We turned on the charge control breaker, which connects the battery to the charge controller. The **MX60 charge controller** displayed the Power-Up screen. We followed the procedure in the **Outback** manual to initialize and configure the MX60 charge controller for a 24 V battery. Hey this is easy. We turned on the array breakers in the DC panel and the outside combiner box. The charge controller recognized the array; since the sun was shining, we were now officially charging the batteries. We measured voltage at the battery bus, the MX60 in/out terminals, and the battery posts themselves with a DVM. Displayed battery voltage on the MX60 was 0.2V low, according to the DVM at the MX60 “BAT” terminals. We calibrated the display in the Advanced / Vbat calibration menu, so that all the meters agreed.

THE INVERTER



The final component to check out was the inverter. We turned on the 100 Amp inverter breaker, and flipped the power switch. The green LED lit up. Good. We measured the voltage at the convenience outlets on the front panel with a DVM: 120 VAC from hot to neutral; 120 VAC from hot to ground; 0V from neutral to ground. We plugged in a droplight, and that worked. Following

these brief tests, we shut the inverter back off and turned off the inverter breaker, because we still needed to wire the AC side of the system. We removed the neutral-ground jumper strap on the inverter AC terminal strip. This step is recommended when you plan to make the neutral-to-ground bond somewhere else, like in the main utility breaker panel, which is what we intended to do. We connected the inverter neutral and ground to the grounded neutral bus in the utility panel via separate conductors. As described earlier, the DC and AC grounds were already bonded together at the outside ground stake. We are confident the entire PV system is properly grounded, and that there are no ground-fault currents flowing in any of the grounding conductors.

TEMPERATURE COMPENSATION FOR THE CHARGE CONTROLLER

We sort of knew that **Outback** has a Remote Temperature Sensor, a probe you can plug into the charge controller to adjust battery charging voltage in response to temperature. We thought, “Hey, we don’t need a ‘remote’ sensor; everything is in one place.” Turns out that you need the sensor to have temperature compensation at all, so we got the sensor and wired it in. It was no big deal; the sensor cable has a RJ-11 plug that goes into a socket on the charge controller.



We stuck the sensor to the inside of the battery box with the “peel’n’stick” backing. (Sensor is small black rectangle on top of photo. The white thermometer probe is to the right and down.) Now, the charge controller adjusts charging voltage according to the UL specified $-5 \text{ mv} / \text{degree C} / 2\text{V cell}$ compensation slope for lead-acid batteries. To use the sensor, you program the charging voltages (absorb and float) in the MX60 with recommended voltages for your batteries at 77F. The sensor adjusts charging voltage up or down from there, increasing voltage as temperature drops, and vice-versa. For the **Deka L-16** batteries, recommended 77 F charging voltages are 28.8 – 29.4 V (absorb) and 27.6 – 28.2 V (float). We programmed the MX 60 at the mid-point, for 29.1 V and 27.9 V. The temperature compensation slope works out to 0.6 V for each 5 degrees C (9 degrees F).

THE TRIMETRIC BATTERY MONITOR (AMP-HOUR METER)



Once everything was working, we finished programming the **Trimetric** battery meter. We entered values for “charged” battery voltage, battery capacity (Amp-Hours), battery charge efficiency, and shunt type. The meter keeps track of amps flowing in and out of the battery vs. time. From this raw data, it calculates a Battery % Full value. The accuracy of this number depends on user-input settings, some of which are “estimates”. **Bogart** says to enter battery capacity 50 – 75 % of the manufacturer’s spec. This seemed a bit strange, since we have new batteries, but we entered A-H capacity as 270 A-H, which is 73% of the published spec, 370 A-H. It is possible that the displayed “battery % full” is lower than it really is, although that is probably better than the other way around. Another uncertainty factor is that the Trimetric has no way to track the changes in charging voltage due to temperature compensation. The only remedy is to manually re-adjust the “charged voltage” setting whenever ambient temperature changes by 10 degrees F or so. As it got colder during October and November, we made two 0.3 V increases to roughly calibrate the meter for 59, degrees F (15 C). After that, we just left it alone. Still, we sometimes get the blinking “charged” light while the batteries are still in the “absorb” charging phase. It’s no big deal, as long as you know what is really going on. It’s still a whole lot better than guesswork. You can always read battery voltage and current, and whether

the current is charging or discharging. You can also read “Amp-Hours from full,” which gives you a pretty good idea how long it will take to get the batteries back up to full charge.



To help correlate the temperature-related variations in charging voltage and meter functions, we added a digital thermometer with remote probe. We mounted the thermometer display unit next to the battery meter and routed the probe into the battery box. The 2-channel thermometer displays ambient temperature in the equipment room and temperature inside the box.

PRECISION HYDROMETER



A hydrometer is a tool to evaluate battery state-of-charge by measuring the specific gravity of the electrolyte. We have a decent DVM, and we got the fancy battery meter; that’s all good, but only a hydrometer can evaluate batteries at the

single-cell level. Hydrometer readings are consistent whether the batteries are charging or discharging. In this respect they are more dependable than voltage readings at indicating state of charge. We got a **Freas Glassworks** unit. We made a quick and dirty holster to keep it in, made out of an 18-inch piece of left-over plastic vent pipe with weather stripping around the top, an empty 2 lb. plastic coffee can, some duct tape, and a concrete brick. It’s ugly but it works. It gives you somewhere to put the hydrometer immediately after taking a reading. Any acid, one drop at most, falls harmlessly into the coffee can, instead of on the floor, or on your foot. We have read all 12 cells twice, in November and in December. Specific gravity was between 1.275 and 1.285 for all cells (maximum difference of “10 points”), which is what you would expect for new batteries.

AC CIRCUIT



The AC wiring was pretty straightforward, with one twist. We decided to include a transfer switch, so we could more easily switch our load between the solar system and utility. We purchased a **GenTran** 1-pole, 20 Amp transfer switch. We removed, and blanked off, the plug where you would connect a generator, since we planned to hard-wire both inputs to the switch. We freed up one 20 A circuit in the utility AC panel, which we wired to one side of the switch. The other input went to the AC output of the inverter. We brought together all the necessary circuits in a junction box mounted to a ceiling joist above the inverter. The **GenTran** switch is comprised of two 20

A breakers, common on one side, with a sliding interlock. Both breakers can be switched off, but only one at a time can be switched on. We wired the Switch output to dedicated outlets in the office, using standard indoor-rated NM-B (sometimes known by the trade name, “**Romex**”) 12 ga. 2 conductor + ground. We now had AC power at the point of use. We plugged our Kill-a-Watt meter into the dedicated outlet to track our energy usage.

Our original plan was to leave the computers plugged into their pre-existing UPS via a dedicated outlet strip, then plug the UPS into the new switched outlet. This would keep the UPS energized at all times, except during a transfer. First, we wanted to gather some data on the UPS and the inverter. What was the standby power requirement, when we weren’t actually powering any

“real” load at all? This test handed us our one minor disappointment. The inverter doesn’t have a sleep mode, which turns off the power circuits when there is no demand, keeping only a very low-powered watchdog circuit active. This is a feature found on higher-end inverters. The idle (no-load) specification for our unit is 20 Watts. We saw slightly better, 12 Watts, based on battery discharge current of 0.5 A at nominal 24 VDC. The UPS, with no load, ate up approximately another 12 W, presumably to maintain the rectifier / charger circuit for the internal battery. The inverter and UPS together showed a steady-state draw of 1.0 Amp. Assuming the office computers were off for 16 hours a day (night), the UPS and inverter together would consume 16 A-H (384 W-H) every 24 hours in standby mode. This seemed like too high a price to pay. We decided to leave the inverter on, because we didn’t want to compromise reliability by turning it off and on every day for a measly 8 A-H. We moved the UPS power cord back to a different circuit, where it was before. To switch the load between the inverter and utility, we manually move the computer outlet strip between the dedicated solar outlet and the UPS. This procedure has worked well enough. We can’t switch on the fly, in true UPS fashion, but we can tell in advance when we need to let the batteries charge up by reading the battery monitor and watching the sun. We just have to decide, at the end or beginning of the day, which power source to use for that day. Our transfer switch doesn’t have much to do now; it has become little more than a circuit breaker for the inverter output. That’s OK; we can still activate our original plan if we increase our generating capacity.

HOW DOES IT WORK?



We now have some data for first full month of operation, November 2008. November may not be the worst month of the year for solar energy, but it is pretty close. It has the third least hours-of-sunlight. This November was pretty good for the first half, with mostly sunny days, but the second half was overcast a lot. This is when we saw the limits of our system. Our two computers in tandem draw 11 Amps at 24 Volts. Over 8 hours of operation, this adds up to 88 A-H, or roughly 24% of our total battery capacity. If overcast conditions persist for more than two days, the “Battery % full” readout can drop below 70%. When this happens, we switch the load to utility. It can take the 540 Watt PV array almost a full “sun-day” (4.8 hours of full sun) to put 88 A-H back into the batteries, even if we use all available array power for charging.

For the whole month, we had 3 days when we ran the load on utility, and three more when we ran one computer on solar and the other on utility. If we went five days in a row without completing at least half of the 2-hour absorbing charge phase, we switched the load to utility. Manufacturers recommend that lead-acid batteries be fully charged at least once a week. We have tried to do that. If anything, we have been over-protective of our batteries at the expense of power generation. The batteries are new, and we want to cycle them gently until they are formed. Following a sunny day, Battery % Full typically drops to around 85 - 90% overnight (in November), mostly due to usage in the early evening. In return, the batteries usually start charging before we open the office in the morning. We expect to do better when the days get longer.

Some statistics for November 2008:

Total energy usage (loads)	32.65 KW-H
Average energy usage per day	1.09 KW-H / day

Battery charging input (output of charge controller)	50.9 KW-H
Average charging input per day	1.70 KW-H

We can calculate some sort of benchmark performance from these numbers, at least for comparison purposes. If we describe system efficiency in terms of system output vs. battery charging input, it works out to $32.65 / 50.9 = 64.1\%$. This number is not truly the overall system efficiency, since it does not account for losses that occur in the array, array wiring, and charge controller efficiency (96.5% for the MX60 with a 540 W / 65V array output charging a 24 V battery). It does, however, include the biggest factors: battery charge / discharge and inverter losses.

One efficiency factor that is difficult to track is battery charge efficiency at different states of charge. Laboratory tests have shown that charge efficiency for lead-acid batteries decreases rapidly as the battery approaches full charge. A good way to understand this effect is to observe the charge controller in Float mode. The batteries continue to accept a steady current, even after they are fully charged. On sunny days, the batteries spend much of their time above 90% state of charge, where charge efficiency is lowest. This is an acceptable trade-off, because battery manufacturers agree that even deep-cycle models last a lot longer if they are shallow-cycled and fully charged on a regular basis. If we were truly off-grid, we have to might cycle the batteries deeper. We would also probably need more storage capacity, and/or a generator with AC charger.

Another frame of reference is the electric utility bill for November 2006, when there was no PV system. During that month, total electrical demand was 224 KW-H. If 2008 demand is comparable, we offset 14.6% of our electrical usage for the month. That may not sound like much, but ours is a pretty small system. We're not looking for short-term payback, but rather to validate design goals and demonstrate the capabilities of a working PV system. In those terms, we are satisfied that our system has performed as expected.

The future role of renewable energy is still largely undefined. Who knows; we may see village grids, power sharing, increased localization. Whatever we undertake at Alpha Institute, we will keep you posted. **Power to the people!**