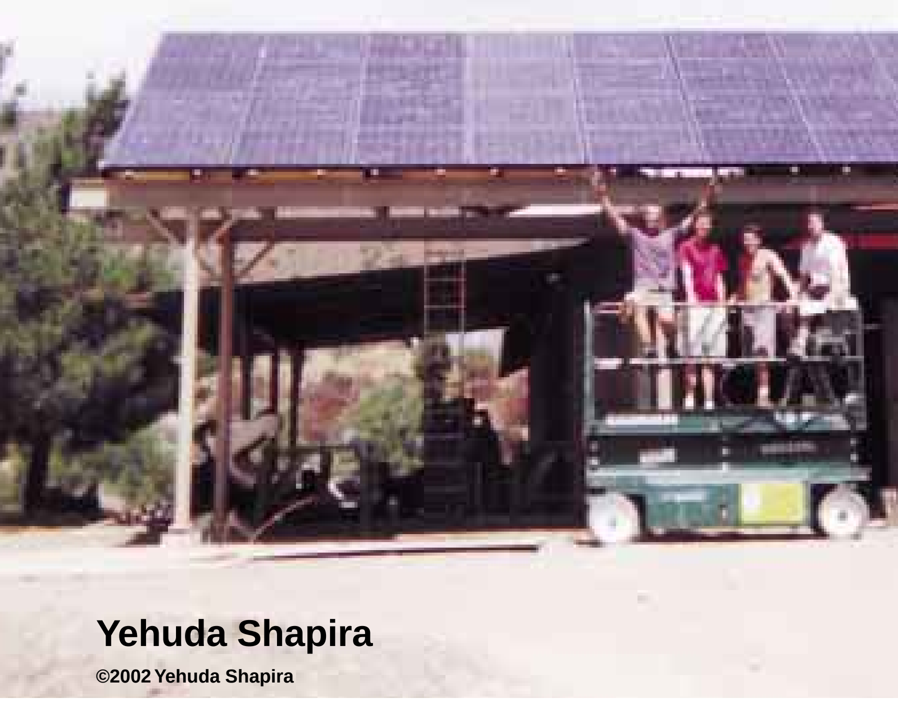
Solar Electricity in California's High Desert

Yehuda Shapira



Yehuda Shapira had his system components prewired and ready for an easy installation day. The proud crew (inset photo, from left to right): Yehuda, Max, Dylan, Barry, and Danny.

California's high desert is an area rich in solar radiation. Last summer, after years of "thinking about it," all the planets lined up correctly for my family and me to build our renewable energy system.

Electricity prices were rising in California, the state's renewable energy rebate program would pay for half the system's cost, and a net metering law was in effect. I was between jobs, and had the time and desire to design and build a photovoltaic system.

I'm a mechanical engineer working in aerospace, and I have tried my hand at a few RE projects over the years. One was building a small homemade wind generator. Another was a 10 watt panel that powered a laptop used in a month-long stay at Lizard Island on Australia's Great Barrier Reef. I've wanted to put together a grid-tied system for many years, and the time was right last summer.

The System

The guiding principle behind my system was keeping it simple and practical to allow minimum maintenance and provide highest reliability. The result is a 5,760 rated watt solar array. The array consists of forty-eight, 24 VDC nominal, Solarex MSX120 panels wired in twelve parallel subarrays, each containing four panels.

The subarrays consist of two sets of two panels. Each set has two series-connected panels, and the two sets are connected in parallel with each other. The whole array is tilted at a fixed 34 degree angle from the horizontal for

Underneath the completed array, the installation is tight and professional. Note the stout rack built by the author.

the best year-round performance. Two Trace ST2500 inverters convert the nominal 48 VDC array output into grid-synchronized 240 VAC, 60 Hz.

The ST2500 provides power and energy information on its liquid crystal display panel. Energy information displayed reflects the watt-hours since DC input was present at the inverter. The display disappears and resets to zero when DC voltage is no longer present at the inverter input. It shows daily energy production summed during that day only. Manual logging of generated energy must be done at the display at sundown each day. A cumulative AC kilowatt-hour meter would be a great addition to this inverter.

A kilowatt-hour meter (not the utility meter) is wired at the joined output of the two inverters. It continuously reads the total energy generated by the array, and never loses its reading. I found a supplier (see Access) that offered refurbished utility kilowatt-hour meters (240 VAC, single phase) and meter sockets.

The meter arrived looking as good as new, with a diagram and clear installation instructions. Installation required bringing the load (grid in this case) and supply (inverters) wiring to the four mounting posts provided in the meter socket box. One additional component of this system is a 240 VAC, 30 amp, fused and lockable disconnect.

System Sizing

Based on our historical usage and budget, we settled on annual photovoltaic energy production of around 7,500 KWH. With this goal, we calculated the realistic output for our locale and the type of system we were considering. At the same time, we tried to match array output with the inverters we chose for the best overall performance.

Shapira Estimated System Loads

Load	*Watts*	*Hrs. per week*	*Avg. WH per day*	*KWH per yr.*
Shop & power tools	2,500	25	8,928.6	3,258.9
House & shop lights	1,500	25	5,357.1	1,955.4
Refrigerator & freezer	400	70	4,000.0	1,460.0
Heating (corrected for winter only)	1,500	15	3,214.3	1,173.2
Radio,TV, & music	500	25	1,785.7	651.8
Cooling (corrected for summer only)	4,000	3	1,714.3	625.7
Well pump	1,000	8	1,142.9	417.1
Washer & dryer	800	8	914.3	333.7
Computers & printer	500	10	714.3	260.7
Irrigation & boost pumps	1,000	5	714.3	260.7
Clocks & phantom loads	200	24	685.7	250.3
Dishwasher	400	4	228.6	83.4
Phones & fax	75	3	32.1	11.7
		Total	29,432.1	10,742.7

Along with the table of estimated loads and their annual usage, we divided the utility meter reading by the number of years since the meter was installed. Since our usage was roughly the same for all of those years, we used that number as our average annual electric energy consumption. Our energy usage includes all the usual suspects found in a modern home. Additional loads include water pumping (submersible well pump) and the booster pumps that are needed for domestic use and for irrigation.

Array size required for a given annual energy production is a function of the following five primary factors.

1. The solar radiation in the geographical location of the array.
This information is available from the NREL Web site for 237 U.S. locations, for flat plate collectors at various mounting angles and tracking situations.

I used 5.5 KWH per meter squared per day for our calculations. This is probably slightly below our actual figure, since Los Angeles is at 5.6 and Dagget is at 6.6, and we are located roughly in between the two locations.

2. The collectors' orientation.
The system designer decides this. For our system, we chose a south-facing fixed array, tilted from the horizontal by the local latitude angle of 34 degrees.

3. Whether tracking is used, and if so, whether it is single or dual axis tracking.
This information will greatly affect your daily KWH production (up to 40 percent depending on location and time of year). Single (east-west) and dual axis tracking array radiation data is presented at the NREL site mentioned above.

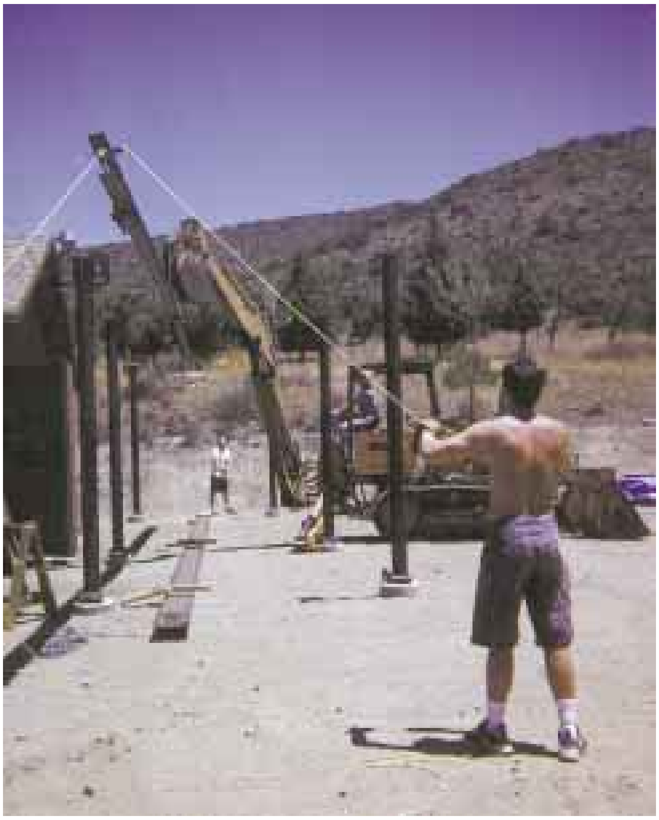
Two primary thoughts formed our decision on tracking. We felt that a purchased and installed dual-axis tracking system wouldn't offset its own cost by much, even at 30 percent gain. And from a reliability point of view, we preferred to stay with the old motto of keeping it simple.

4. Collector efficiency or collector rated output.
The manufacturer provides this information. Output is almost always provided as a peak watt rating. Efficiency is sometimes quoted. If efficiency is not quoted, it can be closely estimated (not actual cell efficiency but the gross panel efficiency) by dividing the rated output by the square foot area of the collector and multiplying the results by 1.076. This is based on the fact that collector published ratings are measured at standard test conditions (STC), employing illumination of 1,000 watts per square meter (92.9 watts per square foot).

So in the case of the MSX120 panel we chose, the area is 37.63 by 43.63 inches (95.6 x 110.8 cm), or 11.4 square feet (1.06 m^2). Dividing the rated peak output of 120 watts by 11.4, and multiplying the results by 1.076 yields 11.33 percent gross collector efficiency.

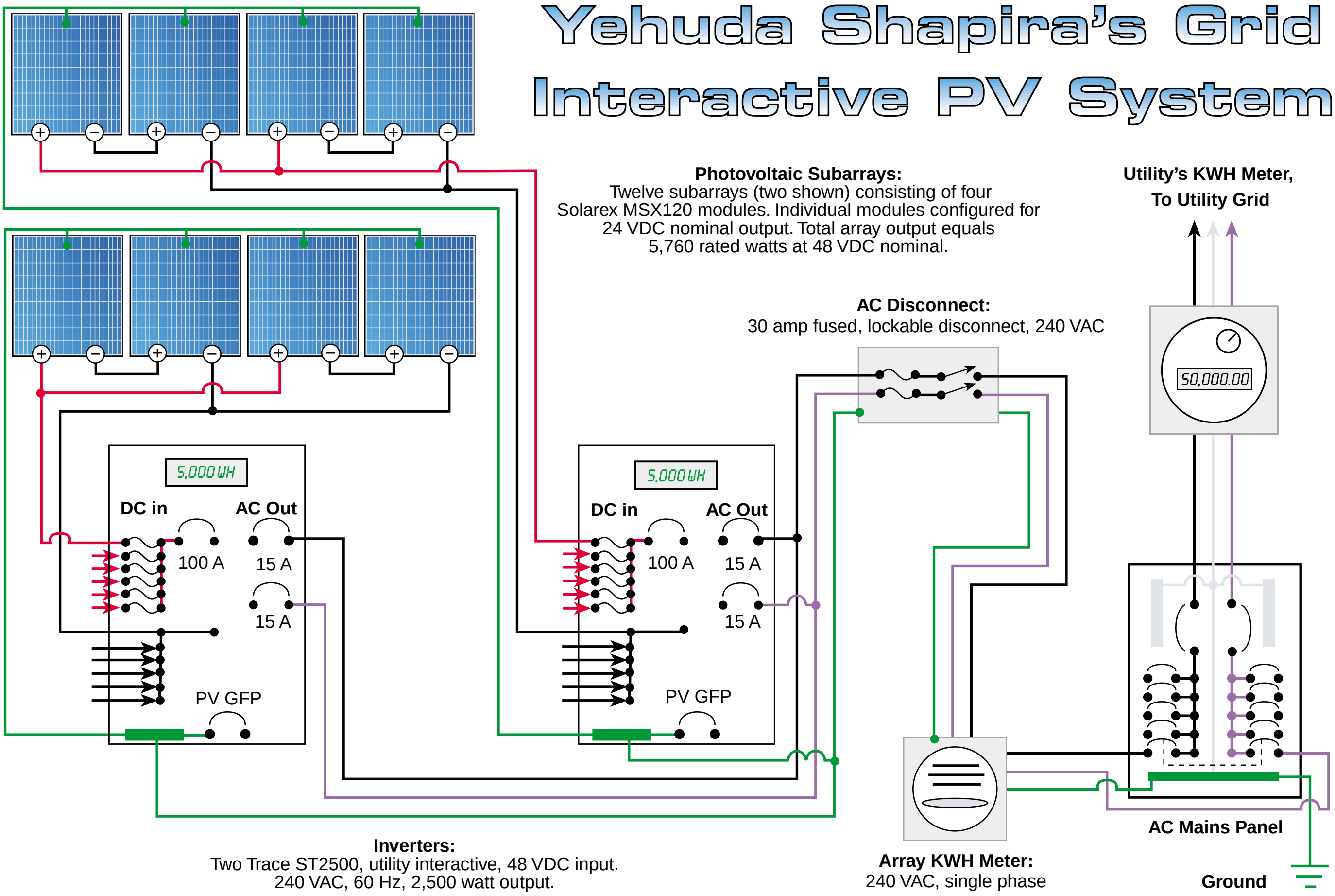
Collector efficiency is important when weight is an issue, or space available for collector panels is extremely limited. In most other situations, it doesn't matter whether the output is 11 or 12 watts peak per square foot of collector. Cost per peak watt is what counts. I only wanted to find the collector efficiency so I could calculate the total array area and the number of panels needed.

Raising the 46 foot long I-beam into position.



Welding the newly placed I-beam.

Yehuda Shapira's Grid Interactive PV System



5. System losses.
This is where enthusiasm learns to live with reality as we find out the true meaning of "120 watts peak." System losses include several factors:

Tolerances on collector rating. As mentioned above, the collectors used are rated at 120 watts. The actual factory test output (STC) for the 48 collectors we used ranged from 121.6 to 114.1 watts. The weighted average was 117.8 watts (98.17 percent of rating).

Collector stabilization. Collector output is reduced by about 3 percent due to a "stabilization process" during the first few months of operation, according to Solarex.

Losses due to cell temperature. Factory ratings are for a cell temperature of 25°C (77°F). Actual cell temperatures can and almost always will be much higher. For these collectors, Solarex quotes 0.45 to 0.55 percent reduction in output for each degree Celsius rise in cell temperature. In our case, I calculated a loss of roughly 18 percent.

Wire losses. These losses, due to wire resistance, were calculated from the maximum current rating provided on the collectors' spec sheet. For the longest cable run of 65 feet (20 m), using #10 (5 mm^2) copper wire, the loss is 1.148 volts. While operating the system, it has become clear that the highest power output occurs at about 61 to 62 VDC. BP Solar (manufacturer of the MSX120) explained that peak voltage is temperature dependent, and it will drop somewhat in temperatures higher than STC. So based on the 61 VDC array operating voltage, the wire loss amounts to 1.88 percent.

Inverter efficiency. This depends on the specific inverter, and the point on its efficiency curve at which it is operating. The DC input to the the inverter will vary during the day, and so will the instantaneous efficiency. Xantrex quotes efficiency ratings between 90 percent and 94 percent for loads higher than 500 watts for the ST2500. Since the inverters are sized to operate at above 50 percent of their rated output for most of the time, my guess for annual inverter efficiency was 80 percent.

Summing up all the applicable efficiency factors, I arrived at the total efficiency:

Collector rating tolerance (0.9817) times collector stabilization losses (0.97) times temperature losses (0.82) times wire losses (0.9812) times inverter efficiency losses (0.8) equals total efficiency (0.613). So 61 percent of our collected energy is actually delivered to the grid.

Total desired annual output (7,500 KWH), divided by total efficiency, times gross collector efficiency (0.613 x 0.1133), equals total annual radiated solar energy (107,987 KWH). NREL data for the closest location says that the average (over the year) daily radiation for a flat plate collector tilted south at fixed latitude angle is 0.51

Shapira System Costs

Item	Cost (US$)*
48 Solarex MSX120 modules	$28,328
2 Trace ST2500 inverters	4,730
Welding, steel, & foundation	4,146
Sunlight resistant cable	753
Warranty, 5 year for inverters	645
Wiring, conduit, breaker, & junction boxes	433
Primer and paint	317
Aerial lift rental	135
KWH meter and base	91
Total	$39,578

*Includes 7.5% state sales tax.

KWH per square foot per day. This gives annual radiation of 186.15 KWH per square foot. Dividing the required annual radiation of 107,987 by this available radiation figure of 186.15 yields a collection area of 580 square feet (54 m^2).

Matching Array & Inverters

We chose the Solarex MSX120 mainly for its size (which meant fewer connections between panels), the competitive price per watt, and the manufacturer's long reputation in the field. Using 48 panels of 11.4 square feet (1.06 m^2) each, yields an array totaling 547.2 square feet (50.8 m^2).

Of course, 52 panels would have yielded 592.8 square feet (55.1 m^2), much closer to the target of 580 square feet (53.9 m^2). We went with 48 panels because the Sun Tie inverters each contain a built-in fused combiner box for six subarrays. This made for very clean connections of the subarrays as long as we did not exceed twelve.

At the same time as the collection area was being sized, the inverters were also being considered. Here the maximum possible array output was considered. Since each inverter is connected to half of the array, the maximum theoretical input is calculated as 24 x 120 = 2,880 watts. This is 15 percent higher than the continuous inverter rating. I contacted Xantrex about this, and they said that the inverter will handle this peak power rating even if the power due to secondary reflection from clouds or haze will temporarily exceed the nominal rating by 50 percent.

Reviewing the inverter specification showed that the DC breaker is rated at 100 amps. At a peak voltage of 61 VDC, the breaker will trip at 6,100 watts of incoming DC power. This is 2.12 times the peak power of each half of the array.

The ST2500's on-board AC breaker is sized for 15 amps, 1.44 times the max rated AC output. To date, the highest observed output was 2,340 watts. This occurred at solar noon on a hazy day with air temperature at about 65°F (18°C), a slight breeze, and the sun shining through the haze. So I conclude that the breakers are up to the task.

Wiring & System Layout

Since the array was installed on a dedicated steel frame rather than an existing roof slope, and since there were no obstructions to solar radiation to consider, solar noon was picked as the array direction (the sun is on the east side of the array the same amount of time each day as it is on the west side).

Next we had to choose the right size and type for the twelve cables connecting the subarrays to the inverters. We purchased the panels, inverters, and cables from Solatron Technologies. Our contact there, Michael Diogo, suggested a cable used on other similar installations. Following his suggestion, we used a sunlight-resistant, direct burial, copper cable with two #10 (5 mm^2) stranded wires.

All the wiring was done with the subarrays facing down on sawhorses. Before starting on the wiring, I prepared my wiring schematic for each subarray, showing the wiring details in the exact way that they would appear when being wired. A map showing the location of each subarray was also prepared. Each assembled subarray was assigned a number corresponding to its location on this map. I did this to minimize the chance of wiring and installation errors.

After the wiring of each subarray, I attached the correct length cable to it. The cable was labeled with its subarray number on the inverter end. This way, if any troubleshooting is needed in the future, I can always know which subarray I am dealing with.

Each completely wired subarray was turned over to face the sun and its open circuit voltage (Voc) and short

The ST2500 inverters feed RE to the utility grid.

The subarrays all wired up and mounted on the frames, which are primed, painted, and ready for installation.

circuit current (Isc) were checked. Turning over the subarrays required the help of another person, since each subarray is an unwieldy 13 feet by almost 4 feet (4 x 1.2 m) and weighs 200 pounds (91 kg).

The MSX120 PV module has two rainproof junction boxes on the back. I don't think that I lost any of the little screws or seals that are used on these boxes. But I liked the fact that Solarex gives you a couple of extras with each panel—just in case. Not having to worry about losing these little guys gives you peace of mind, especially when wiring over dirt or in high places.

The Solarex panels came with rain-tight conduit and wiring between the two boxes on each panel. Those connections only had to be slightly altered for the 24 VDC output. The connections between the panels were made with rain-tight conduit and fittings, and wired with #10 (5 mm^2) THHN/THWN stranded copper. Terminals were spade types crimped and soldered. (Yes, I admit it—sometimes I am the belt and suspenders type.)

Working on the junction boxes required some care in removing the knockouts for the interpanel connections. I did not dare use a hammer or any form of brute force on these glass-mounted boxes, so a little scoring with a utility knife was needed before the knockouts gave way.

The twelve subarray cables meet approximately at the middle of the array's high side. At this point, each group of six cables was fed through a 2 inch (5 cm) nonmetallic conduit into a junction box located inside an adjacent shop building. The numbered cables are divided equally between the two ST2500 inverters, also located indoors.

The inverters' outputs are wired in parallel using #8 (8 mm^2) stranded CU wire in 3/4 inch (19 mm) nonmetallic conduit, into a disconnect mounted outside the shop. From the disconnect, the inverters' output is routed through a kilowatt-hour meter into a dedicated 30 amp, 240 VAC breaker in the shop subpanel.

Mounting the Panels

The array is mounted on a dedicated steel frame structure. Each subarray is constructed of four panels that are individually mounted onto two, 13 foot (4 m) long rails. The rails are made of square tubing with holes predrilled in the appropriate locations for mounting four collector panels on each pair of rails. Each collector was mounted using four, 5/16 inch (8 mm) zinc-plated bolts with approximately 1/8 inch (3 mm) between collectors.

I remembered reading a story in *Home Power* that left an impression. It was about a person who had to file all the holes in the rails he prepared for panel installation. Actual hole locations on the panels did not match those shown on the panel spec sheet.

Since I had not yet taken delivery of the panels, again I availed myself of the good services of Michael Diogo of Solatron Technologies and asked him if he could measure the actual MSX120 panel hole locations. He

Subarray to inverter cables (home runs) were premeasured for each subarray.

After installing the first few subarrays, it became second nature. Sheets of plywood kept the scissors lift from bogging down in the dirt.

My sons Barry and Danny and two friends Max and Dylan did a yeoman's job, raising and attaching the twelve subarrays on top of the frame in approximately four hours. Threading the cables and making the final connections took me another day or so. The final connection of subarrays to the inverters was done after sundown, so the modules weren't producing and I didn't have to guard against any unwanted sparks.

Once we passed the county's final inspection, I called Laura Rudison of Southern California Edison. Laura was helpful and responsive throughout this project. She asked that I fax her the signed inspection card, and then authorized the interconnection to the Edison grid. A week later, the formal authorization letter arrived in the mail.

did, and told me that they were to spec, and that no filing was needed, which was correct.

The top and bottom ends of each rail are received by a specially fabricated channel. The rails are bolted to the top channel with 3/8 inch (9.5 mm) zinc-plated bolts, and are welded to the bottom channel. Each channel was fabricated from two identical sections of angle iron cut to length and drilled with through holes for the mounting bolts. A steel template was devised to replicate the exact spacing dimensions required for the placement of the subarrays. Using this spacing template, the channel sections were prewelded to the long horizontal tubing that supports the twelve subarrays.

Welding in the sometimes 100°F+ (38°C+) days, wearing helmet and leather apparel, can get a bit hot. So during particularly hot periods, I would treat myself to the cool job of working inside in the shade bending conduit and pulling wires for the AC side of the system. Or better yet, I'd go and buy some material for the job and enjoy the truck's air conditioning. Ah, the simple joys of life...

Putting It All Together

For lifting the panels to the top of the frame, I rented a scissors lift with a 750 pound (340 kg) capacity, enough for two people, the 200 pound (91 kg) subarrays, and some to spare. These machines are made to roll around on a relatively smooth concrete floor. Since we were working on hard packed dirt, we had sheets of plywood that we moved around to allow smooth rolling, and to provide a more stable surface for the lift.

Following the Xantrex manual, interconnection was not much more involved than operating your microwave. The manual guides you through the final line voltage and array voltage measurements. Once these voltages are found to be within range, you can start the inverter. All that is required for starting is to switch on the three breakers—AC, DC, and ground fault protection. These breakers are located on the inverter's front panel. At startup, the inverter requires a five-minute wait before energy is delivered to the grid.

There was one more thing to do and that was collect and arrange all the project bills, and submit the expense list to the California Energy Commission (CEC). That done, I received reimbursement for one-half of the project cost about six weeks after submitting the claim.

The inverters come from Xantrex with a two-year warranty. The state of California requires a five-year warranty to qualify for the buydown program. Solatron Technologies sold me the additional three-year warranty with each inverter.

How long did this project take? During the design and construction phases, I maintained an informal hour log. The total hours spent on this project—including occasional friendly helpers—was roughly 700. From design to hookup, including revisions, took six months. Actual construction took about three months.

Problems

I was surprised when I discovered that I could no longer listen to my favorite AM radio station, since the inverters produce too much RFI on the lines. AM reception is impossible near the shop or the house, even on battery operated or car radios.

I contacted Xantrex back in September and then again in December (just before submitting this article) asking for their opinion, but so far have received no response. I have tried wrapping the inverters in a grounded metal mesh, but this made no difference. My hope is that someone reading this knows the cure (beyond switching to FM) and will share it.

To my pleasure, I discovered that the folks at BP Solar are not kidding when they say that you will get an answer to your question within 24 hours. I had questions about wiring the panels, the variation of voltage with cell temperature, and the manufacturing tolerances used for the collector peak power rating. BP directed me to their online wiring schematics for various panel arrangements. Their answers to all of my questions were prompt, informative, and complete. My appreciation is noted.

The PV array almost completed. Proper planning and attention to detail assured that everything went together without a hitch.

The Proof of the Pudding
So, how does it taste so far? In a word—good. The system has been in operation since mid-September. The daily energy production was around 29 KWH a day at first, but has been slowly declining as would be expected based on the seasonal changes. At the end of November, daily production was around 24 KWH on a clear day, and varied between 10 and 15 KWH on partly cloudy days.

Peak inverter output is usually around 4.2 KW, though it was briefly observed once at about 4.65 KW (2.34 KW on one inverter, and 2.31 KW on the other). The inverters turn themselves on in the morning and off at night; absolutely no intervention is required on my part. We found out that we were not immune to the “stand and watch the meter spin syndrome” so aptly described in past *HP* articles. But by now, the meter watching is reduced to daily energy-logging sessions.

We are very happy with the experience. Designing and building this solar-electric system proved to be a bit of a “learn while you do” undertaking, and we took that to be part of the fun. My thanks go to the people at *Home Power,* and to those of you who have written about your projects and experiences. You all participated in my education, and helped me on my solar path.

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