Planning a Code-Compliant, Off-Grid PV System

John Wiles

Sponsored by the Photovoltaic Systems Assistance Center, Sandia National Laboratories

This *Code Corner* presents the planning and design overview for a photovoltaic (PV) system to supply the electrical needs for a new off-grid home. The electrical design is based on the requirements of the *National Electrical Code (NEC).*

Local electrical codes may impose other requirements, and building codes may pose additional requirements on the mechanical installation. The numbers used and the results are very system specific and should not be used in the design of any other particular PV system.

The House

Judy LaPointe, the homeowner, is retired and looks forward to living in an energy efficient house, powered by the sun and a little propane. The PV system will provide electricity for her 1,800 square foot (167 m^2) residence in New Mexico, located about 0.5 miles (0.8 km) from the utility grid. The house is at an elevation of 4,500 feet (1,370 m) above sea level, and the design temperature range is from 10°F to 104°F (-12°C to 40°C). The record low temperature is -20°F (-29°C).

Wells in the area are at least 800 feet (245 m) deep, and two out of three drilled wells do not hit water. Because of the possibility of a dry well and the electricity requirements to pump water from 800 feet (245 m), Judy decided to have potable water for the house delivered by truck and stored in a 2,500 gallon (9,460 l) aboveground tank.

The home is being built with Perform Wall insulated concrete forms and has an R-50 insulated ceiling. A swamp cooler (evaporative cooler) will be used for summer air conditioning and an in-floor radiant heating system will heat the house during the winter months. A solar hot water collector, backed up by the propane-fired boiler, will provide potable hot water and radiant floor heating.

Loads

See the load table for a detailed list of electrical loads planned for the system. The refrigerator, generally one of the largest loads in an off-grid system, is a 26 cubic foot (0.74 m^3) model that uses a third to half the energy of popular, inexpensive models. The controls and circulating pumps for the radiant heat boiler will be DC, and the system will be used only in winter. The swamp cooler will likely be the largest energy load because, even on slow speed, Judy may want to run it day and night for several months in the summer.

Electrical loads that have a continuous draw when turned "off" are connected to switched outlets or power strips to reduce phantom loads. These devices include the satellite receivers and the washing machine. Devices that draw 1 watt or less and have useful functions that need to be powered continuously will be left connected. They include the smoke alarms, microwave oven clock, two clock radios, cell phone recharger, and the TVs (channel memory).

System Size

In addition to anticipated loads, an established upper budget limit and the cost of bringing underground utility service to the area were determining factors for the size of the PV system and related equipment. The initial quote for overhead utility lines was more than US$35,000. The overhead lines were unacceptable to Judy, since they spoiled the magnificent views of the surrounding mountains and represented a "business as usual" use of nonrenewable energy. Underground utility lines would have cost significantly more due to the rocky terrain.

Southern New Mexico has an annual daily average of 6.5 hours of peak sun, and the few cloudy periods do not usually last more than three days. Load management during these cloudy periods and the use of the backup, propane-fired generator were entered into the system design process. Four other off-grid systems in the area were examined to provide additional information on system sizing.

The final system design has a PV array rated at 3,300 watts, DC at standard test conditions (STC)—1,000 watts per m^2 irradiance and 25°C (77°F) module temperature. The array consists of twenty, 165 watt, 24 volt PV modules.

System Planning

After reviewing all of the loads and the various other constraints, a list of equipment required to complete the installation was compiled. Numerous calculations (explained in previous *Code Corners*—see the table on page 108) were made to determine the rating of each piece of equipment for code compliance. Equipment was selected for extended durability and reliability over the expected 30 to 40 year life of the system. Of course, budget constraints prevented the use of gold-plated fixtures, and for the most part, commercially available hardware and electrical components were used.

Two 60 amp, maximum power point tracking charge controllers will maximize the PV array output in hot summer conditions and charge a 24 volt battery bank. The voltage drop due to the long circuit distance and the high summer temperatures resulted in the decision to increase the PV array voltage to 48 volts and to use maximum power point tracking charge controllers. In the hot, dry Southwest, PV module temperatures can exceed 75°C (167°F), and the maximum power points of the modules, when used with 24 volt connections, can be below the battery charging voltage resulting in lost energy. The use of 48-to-24 volt, maximum power point tracking charge controllers avoids this problem. The lower current at 48 volts reduces voltage drop and subsequent energy loss in these circuits.

The battery bank will consist of sixteen L-16 batteries rated at 33.6 KWH at 24 volts DC. A single DC

LaPointe PV System Loads

		Winter			Summer		
Kitchen	*Watts*	*Hours per Day*	*Days per Week*	*Avg. Daily KWH*	*Hours per Day*	*Days per Week*	*Avg. Daily KWH*
Energy Star refrigerator*	110	12.00	7	1.320	12.00	7	1.320
Energy Star microwave*	1,100	0.50	7	0.550	0.50	7	0.550
Vented range hood	150	1.00	5	0.107	1.00	5	0.107
Dishwasher*	350	1.00	2	0.100	1.00	2	0.100
Cell phone recharger	4	24.00	7	0.096	24.00	7	0.096
Toaster*	800	0.05	5	0.029	0.05	7	0.040
Garbage disposal	350	0.10	7	0.035	0.10	7	0.035
Utility Room							
Swamp cooler*	300	0.00	0	0.000	18.00	7	5.400
Energy Star clothes washer	165	2.00	3	0.141	2.00	3	0.141
Domestic water pump	240	0.35	7	0.084	0.45	7	0.108
Clothes dryer, propane heated	150	1.00	3	0.064	1.00	3	0.064
Heater controls & pumps	50	12.00	7	0.600	0.00	0	0.000
Miscellaneous							
Vacuum cleaner	1,400	1.00	2	0.400	1.00	2	0.400
Smoke alarms	12	24.00	7	0.288	24.00	7	0.288
Ground fault circuit interrupt	10	24.00	7	0.240	24.00	7	0.240
Hair blow dryer*	1,100	0.25	5	0.196	0.25	5	0.196
Linear tube fluorescent lighting	104	4.00	6	0.357	3.00	4	0.178
2 Clock radios	6	24.00	7	0.144	24.00	7	0.144
Compact fluorescent lighting*	60	2.00	7	0.120	2.00	7	0.120
Satellite receiver & TV	100	2.00	5	0.143	2.00	3	0.086
4 Ceiling fans	15	0.00	0	0.000	8.00	5	0.086
Halogen lamps	100	1.00	3	0.043	1.00	3	0.043
2 Bathroom fans	20	2.00	7	0.040	2.00	7	0.040
DVD player	20	2.00	3	0.017	2.00	3	0.017
Satellite receiver & TV	100	2.00	1	0.029	1.00	1	0.014
VCR	20	1.00	1	0.003	1.00	1	0.003
*Worst Case Instantaneous Use**	3,820		*Total Winter*	5.146		*Total Summer*	9.817

enclosure will contain a 250 amp battery disconnect, two 75 amp PV subarray disconnects, a 175 amp main PV disconnect, and a 15 amp DC pump disconnect. All disconnects are DC-rated circuit breakers with interrupt capabilities of at least 25,000 amps. These circuit breakers will provide the code-required overcurrent protection for the associated conductors.

A worst-case instantaneous load may occur in the morning if two people are early risers. This type of peak load has happened in my house more than once, and might consist of:

- Hair dryer: 1,100 watts
- Microwave: 1,100 watts
- Toaster: 800 watts
- Swamp cooler: 300 watts
- Lights: 60 watts
- Dishwasher: 350 watts
- Refrigerator: 110 watts

The total AC load for this scenario would be 3,820 watts.

A 24 volt, 4,000 watt inverter will provide the house with 120 volt, 60 Hz alternating current. It has sufficient steady-state output to handle the expected worst-case load and short-term (15 minutes) surge capabilities for added uncertainties. A generator fueled with propane and rated at 6.5 KW (sea level rating) will provide backup during extended periods of cloudy weather or when loads exceed energy production from the PV system.

The entire system will use listed components (where available). It is designed and will be installed in full compliance with the *National Electrical Code (NEC).* Relevant *NEC* sections are cited here for design decisions.

Selected Topics from Past *Code Corner* Columns

Subject	*Home Power Issue*
Ampacity	67, 68, 76, 77, 78, 83
Battery circuits	46, 48
Circuit breakers	50, 52, 54, 68, 84, 85
Conductors & cables	49, 51, 55, 76, 77, 78, 79, 80, 81, 82, 83, 91
Conduit	49, 50, 60, 62, 83
Design	92
Disconnects	42
Grounding	43, 44, 58, 64, 65, 72, 73, 74, 91
Hybrid systems	48
Lightning	57
Listed equipment	43, 56, 76, 77, 82
Multiwire branch circuits	54, 59
Outside resources	92
PV modules	79, 81, 83, 91
Stand-alone systems	46, 48
Voltage drop	80, 81, 83

Array Location, Module Mounting, & Connections

The array was initially going to be mounted on the roof of the home. "Not on my beautiful roof," said the architect. An array site north of the house was considered, but shading from the house required that it be placed too close to the property line, and the homeowner thought that it was too visible in that location. Finally, the array was sited to the south of the house, adjacent to the driveway, and slightly below the level of the house on the side of an arroyo.

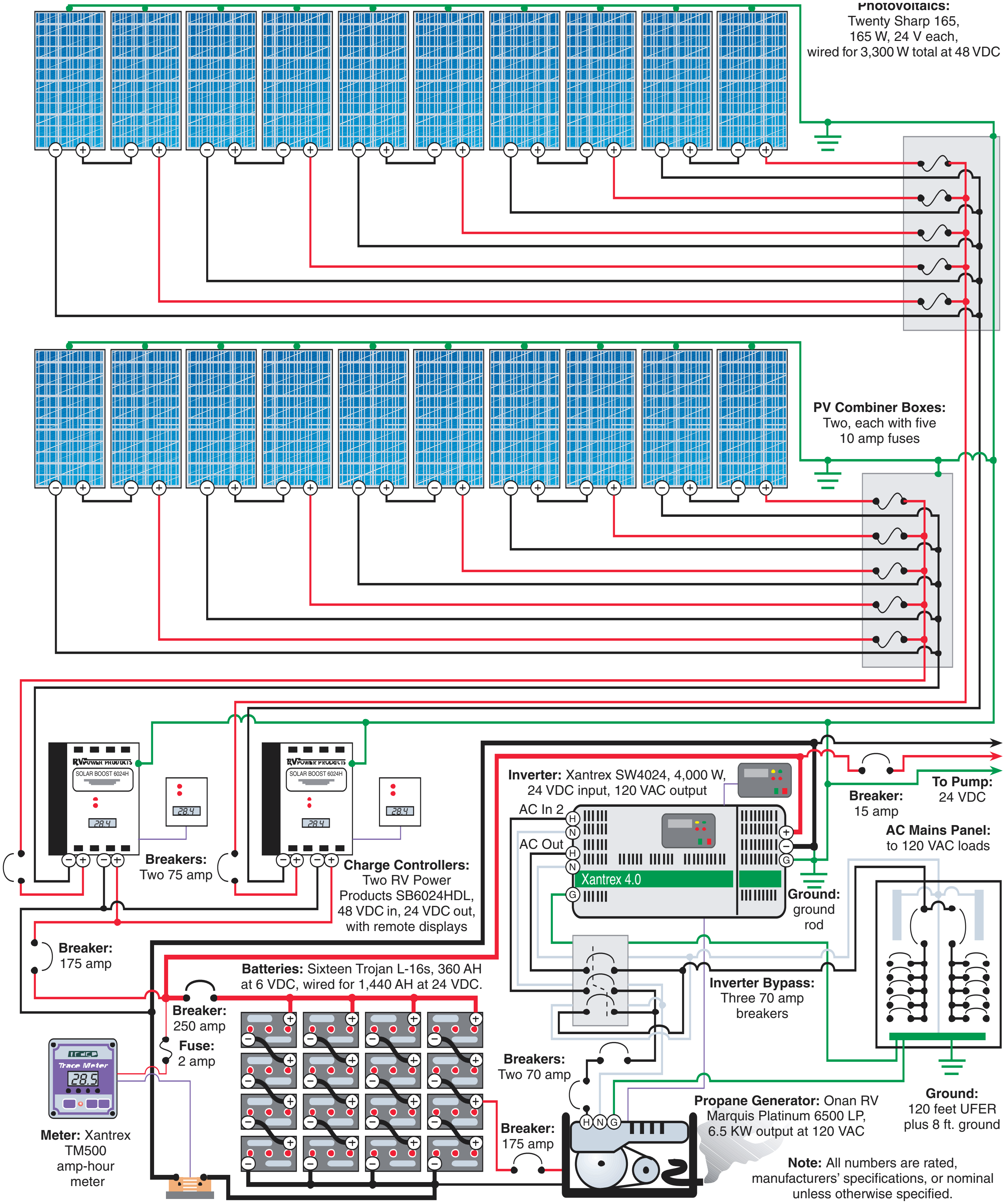
The PV output circuit lengths went from about 50 to 150 feet (15–46 m) when the array site was moved from the roof to the arroyo. This move reduced system costs by eliminating the requirement for an *NEC* 690.5 ground fault protection device, but increased the costs for the array-to-charge controller wiring and the ground mount.

Adjustable aluminum racks will hold the modules in groups of four. The racks will be attached to a set of eight, 2 inch galvanized pipes set in concrete that will be topped with lengths of galvanized steel channels. Nearly all of the hardware used for these mechanical connections will be made of stainless steel.

Additional lengths of #10 (5 mm^2) USE-2/RHW-2 conductors will be spliced to the short pigtails on the modules using solder and UL-listed, thick-wall heat shrink tubing with internal adhesive [110.14(B)]. These conductors will be routed along the module and rack channels and fixed in place with rubber-insulated, stainless steel clamps. Stainless-steel hardware will be used to install the clamps and the fused combiner boxes that are to be attached to the array support rack in the shaded area under the PV array.

Plastic, outdoor-rated strain reliefs (cord grips) will provide mechanical protection for the module conductors entering the combiner boxes [300.4]. Conduit will be used between the combiner boxes and the DC equipment center located some 150 feet (46 m) away [352]. Ampacity calculations and voltage drop calculations dictated that the circuit conductors for each subarray be sized at #1/0 (53 mm^2) with a #2 (33 mm^2) equipment-grounding conductor [690.8, 9, 45]. USE-2/RHW-2 conductors will be used for the underground,

Judy LaPointe's Photovoltaic System



conduit-enclosed PV output conductors to provide additional durability [338].

Module Grounding
The modules will be grounded with a #8 (8 mm^2) bare conductor connected to the designated grounding point on each module using the hardware provided with an appropriate lug [690.45]. These module equipment-grounding conductors will be connected to an equipment-grounding bus bar in the combiner boxes.

The module mounting racks will also be connected to the same bus bars, as well as connected to the grounding system at the module location. Two supplemental ground rods will be driven at the PV array location and, with the rack support pipes, will form an effective supplementary grounding system to meet code requirements and provide added lightning protection [250.54].

Generator Starting Circuit
One of the four strings in the battery bank will be tapped at the 12 volt point to supply the DC electricity to start the generator. This circuit will consist of #2/0 (67 mm^2) conductors run in 2 inch conduit and protected by a 175 amp circuit breaker [310.16].

Water Pump
The DC water pump draws a maximum of 11 amps. A 15 amp circuit breaker will protect the circuit conductors. Minimum conductor size, based on ampacity requirements, is a #14 (2 mm^2) conductor. A #8 (8 mm^2) conductor will be used to lower the voltage drop in the circuit. A 3/4 inch conduit will be used for this circuit.

DC Power Center Lighting
A 24 volt DC fluorescent lamp will be installed above the power center area to provide emergency lighting. It draws 2 amps, will be wired with #14 (2 mm^2) conductors, will be controlled by a DC-rated wall switch, and will be powered via the 15 amp circuit breaker used by the water pump. A 1/2 inch conduit will be used for this circuit.

AC Circuits—Generator
A 70 amp circuit breaker will be used at the generator to serve as overcurrent protection for this circuit and as a disconnect located outside at the generator [240.4, 21]. A second 70 amp circuit breaker will be installed in the garage near the inverter and the inverter bypass switch to serve as an inside generator disconnect. All disconnects from all power sources must be grouped together [690.14].

Inverter Bypass
The inverter bypass switch will consist of a pair of 70 amp circuit breakers (a double-pole and a single-pole) mechanically interlocked so that only one of the pair may be turned on at a time. This pair of circuit breakers will serve as a bypass switch for the inverter. They will be used only when the inverter becomes inoperable and must be removed for repairs. One of the 70 amp breakers will serve as an overcurrent device for the AC output circuit from the inverter (or generator) to the house load center.

House AC Load Center & AC Circuits
The 200 amp AC load center will have both of the ungrounded inputs (Line 1 and Line 2) connected in parallel and then to the 70 amp breaker in the inverter bypass switch [240.4, 21]. This configuration will provide the house with a single 120 volt, 60 Hz service at up to 70 amps, with a continuous rating of about 56 amps (0.8 *NEC* derating factor x 70 A). No multiwire branch circuits will be installed in this house, and appropriate labels will be applied to the house AC load center [690.10(C)].

The house will be wired with several 240 volt AC circuits, and outlet boxes will be installed. Most 240 volt loads are not generally consistent with energy conservation or the limited energy available from this system. The 240 volt circuits will be added to facilitate the sale of the house to any future owner who might bring in the utility lines.

No 240 volt receptacles will be installed, and each 240 volt outlet will be covered with a blank cover plate. None of the 240 volt circuits will be connected in the load center, but sufficient wire will be allowed for future connection if 240 volt circuit breakers are added. The 240 volt circuits will include: electric range, electric dryer, electric space heater, refrigerated air conditioning system, and heated whirlpool bath. These 240 volt circuits will not be used in any way as part of the 120 volt wiring [690.10].

Grounding System
All of the rebar in the house's foundation is bonded together and also bonded to a 120 foot (37 m), #4 (21 mm^2) conductor buried in the bottom of the footer trench [250.52(A)(3)]. This conductor is run without splicing to the grounding block (bonding point) in the DC disconnect. A #4 grounding electrode conductor is also run from the AC load center bonding point to a point on the DC grounding electrode conductor where it enters the slab. At that point, the two electrodes are spliced with an irreversible splicing device [250.64(C)].

A supplementary 8 foot (2.4 m) ground rod is located about 7 feet (2.1 m) from the point where the #4 grounding electrode emerges from the slab, and this rod is also connected with an irreversible splice to that conductor [250.53(B)].

Summary

Designing and planning for a safe, reliable, and durable off-grid PV system (or any PV system for that matter) requires a considerable effort. The use of materials like stainless steel hardware and rubber-insulated conductors helps to improve the system reliability and durability. My next column will explain many of the calculations referenced here. In a future issue, photos and additional descriptions of the system will be presented, after the construction of the house and the system installation are completed.

If you have questions about the *NEC*, or the implementation of PV systems that follow the requirements of the *NEC*, feel free to call, fax, e-mail, or write. From time to time, longer, more detailed versions of the Code Corner columns will be posted on the SWTDI Web site. Sandia National Laboratories sponsors my activities in this area as a support function to the PV industry. This work was supported by the United States Department of Energy under Contract DE-FC04-00AL66794. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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John C. Wiles • Southwest Technology Development Institute, New Mexico State University, Box 30,001/MSC 3 SOLAR, Las Cruces, NM 88003 • 505-646-6105
Fax: 505-646-3841 • jwiles@nmsu.edu
www.nmsu.edu/~tdi/pv.htm

Sponsor: Sandia National Laboratories, Ward Bower, Department 6218, MS 0753, Albuquerque, NM 87185
505-844-5206 • Fax: 505-844-6541
wibower@sandia.gov • www.sandia.gov/pv

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custserv@nfpa.org • www.nfpa.org