FUNDAMENTALS OF PV SYSTEMS: TUTORIAL

Robert L. Hammond
Principal Investigator

Spencer Everingham
Research Assistant

Arizona State Univ.
Tempe, AZ 85282

INTRODUCTION

Year-by-year, the application of photovoltaic (solar-electric) power supplies in telecommunications, telemetry, and other battery charging applications is increasing. Photovoltaic (PV) systems use stationary batteries in a cycling application – unlike the more familiar (e.g., UPS) float-stationary applications.

This paper provides an overview of the photovoltaic power supply with battery as the energy storage device.

Topics covered are:

- Typical PV applications with battery storage
- Basic components of a PV system (e.g., solar cells, modules, charge controller, batteries, and inverters) and their characteristics
- PV system configurations and components
- The solar resource
- Definition of common PV terms
- Battery performance in two typical PV applications
- Useful web sites and other reference material

PV APPLICATIONS DEFINED

Photovoltaic applications can be divided into two broad areas:
1. Stand-alone systems (i.e., no connection to the utility grid) and
2. Grid-connected systems

Except for water pumping applications, nearly all stand-alone systems include batteries for energy storage. Grid-connected systems typically do not include batteries for energy storage, but instead depend on energy from the grid to support the electrical loads during hours of darkness and on cloudy days. The remainder of this paper will focus on stand-alone systems that use batteries for energy storage.

Stand-Alone PV Applications With Battery Storage

The majority of **stand-alone applications with battery storage** will fall into one of the following areas:
- Telemetry, e.g., data transmission and signaling
- Telecommunications, e.g., mountain top repeaters, telephone and cable, highway call boxes
- Lighting, e.g., billboards, railroad crossings, parking lots, walk lights
- Cathodic Protection, the prevention of corrosion, e.g., in underground pipelines)
- Residential/remote home or cabin
- Village Power/Rural communities

THE POWER SOURCE: PHOTOVOLTAICS

Photovoltaic (PV) is the technical name for a technology in which radiant (photon) energy from the sun is converted to direct current (dc) electrical energy. This is a direct conversion process that converts sunlight directly into electricity with no moving part, no noise and no pollution. Solar cells, like diodes, transistors, and integrated circuits, are made of semiconductor materials, typically silicon, doped with special additives such as phosphorous and boron. When sunlight strikes the solar cell surface, a flow of electrons (electricity) is generated. Desired power, voltage and current can be obtained by connecting individual solar cells in series and in parallel, in much the same fashion as batteries.

Bell Laboratories developed the first practical solar cell during the mid 1950s (about the same time that the first transistor was developed).

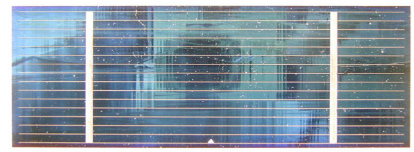

Figure 1. Basic solar cell

Solar Cells

Solar cells, (i.e., photovoltaic devices) are the fundamental building block of PV modules.

Modules

Groups of interconnected solar cells are packaged into standard modules (sometimes called panels or collectors) designed to

a) provide useful voltages and currents and
b) to protect the interconnected solar cells from the environment.

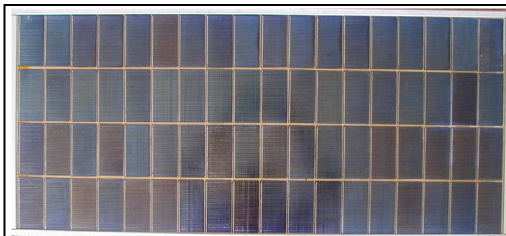

Figure 2. PV Module

The number of cells in series determines the module voltage. Thirty-six series cells are typically used to charge a 12-volt battery. Cell surface area and the number of parallel cells determine the module current

The current-voltage (IV) curve of a typical crystalline-silicon module (36-cells) is shown in Figure 3[1]. This curves defines the characteristics of the module at a given sunlight intensity (irradiance), and cell temperature. As irradiance and cell temperature change:

- Isc and Pp are directly proportional to irradiance. Isc increases about 0.08% for each degree C increase in cell temperature
- Voc and Pp decrease about 0.5% for each degree C increase in cell temperature

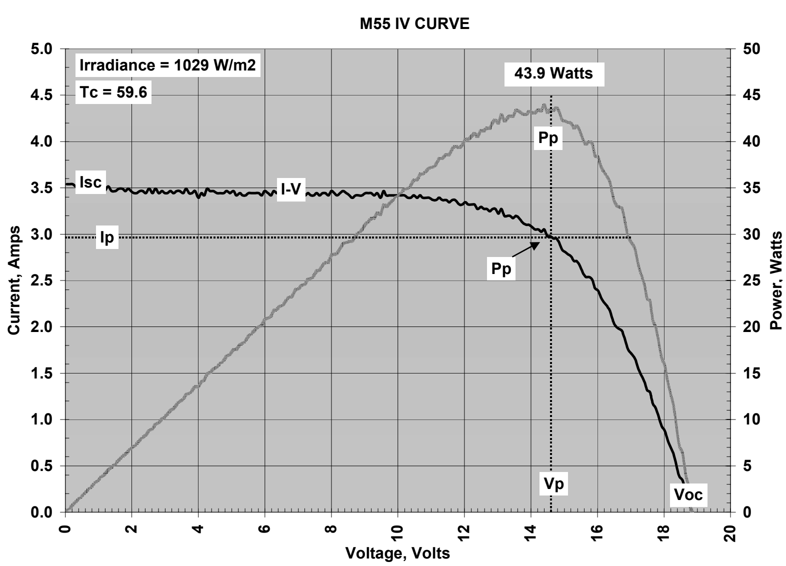

Figure 3. Module IV Curve

The load (which is typically the battery) determines the operating point on the IV curve. As the battery is charged, the operating point will move to the right in Figure 3.

Characteristics for commercially available modules, including IV curves and selectable operating conditions (e.g., irradiance, cell temperature, etc.) are defined in a free software program, IVTracer, developed by David King at Sandia National Laboratories[2].

Arrays

Modules are connected in series and/or parallel to form a larger unit called an array. The number of modules and the series-parallel connections will determine the voltage, current and power characteristics of the array.

PV SYSTEM CONFIGURATIONS AND COMPONENTS

Most PV systems with battery storage can be defined by Figure 4. The most basic system will consist of:

1. **PV Module**(s); the power source
2. **Charge Controller** to prevent overcharging of the battery. PWM (pulse width modulation) or constant voltage charge controllers are recommended for most applications.
3. **Battery** to store energy for use during nights and cloudy weather. Batteries also supply high power to the load that can exceed the power rating of the array (e.g., motors, microwave ovens or compressors).
4. **DC distribution panel** (could be as simple in-line fuse)
5. **Other** fuses or circuit breakers for fire protection as required by the National Electrical Code

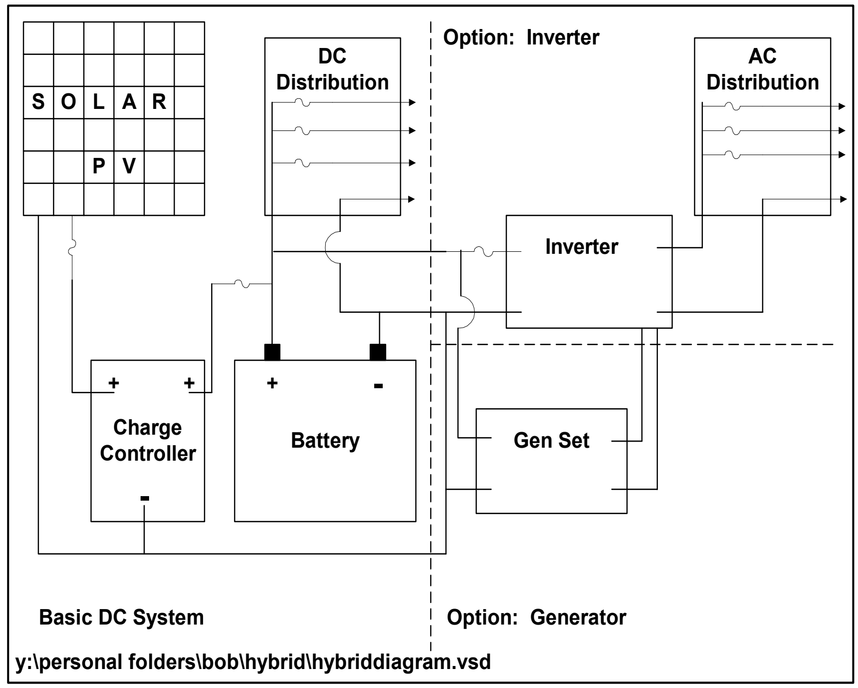

Figure 4. BLOCK DIAGRAM OF A PV SYSTEM

More complex systems could include:

1. **Optional Inverter**. An inverter and ac distribution panel to power ac loads (these are typical for stand-alone residential systems). Inverters can be as small as a few hundred watts at 115 Vac or as large as several hundred KW at 480 Vac, three phase.
2. **Optional Generator**. A standby or backup generator to automatically charge batteries at some predefined minimum state of charge (e.g., 50%). A generator can increase system availability and reduce life-cycle cost. Systems with a prime-power generator are often call "hybrid systems". The generator shown in Figure 4 shows two options: 1) a d.c. generator that directly charges the battery and 2) an a.c. generator that supplies power to a special port on a "bi-mode" inverter. The bi-mode inverter serves as a normal inverter when the generator is not operating and as a battery charger when the generator is operating. In the charging mode, a.c. loads are supplied from the generator and the batteries are charged with the balance of power available from the generator. An a.c. generator could also feed a conventional battery charger instead of the inverter.
3. **Other Power Sources**. Other power sources can operate in parallel with the PV array (or displace the PV array) to charge the batteries (e.g., wind generators, hydroelectric generators, or fuel cells). These sources are not shown in Figure 4.

Systems with critical loads (e.g., remote communications sites) nearly always have a backup generator. Large communications systems and residential applications typically include a standby generator and an inverter. Some remote sites also include wind generators and/or hydroelectric generators, depending on the availability of these resources.

All system components and hardware other than PV modules/arrays are called "balance of system" or BOS. In addition to the components listed above, BOS includes the supporting structure, wiring, bolts and nuts, disconnects, and fuses, for example. Essentially it includes any cost item that is directly related to the cost of the PV system.

THE SOLAR RESOURCE

The amount of energy that the PV modules can produce is proportional to the available solar energy (i.e., the "solar resource") on the PV module surface over a given period of time. The solar resource varies from site to site, day to day, season to season and year to year, and varies with the orientation of the modules. The *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*[3] (also called the "Red Book") is an excellent source of solar resource data for 239 locations in the United States and its territories.

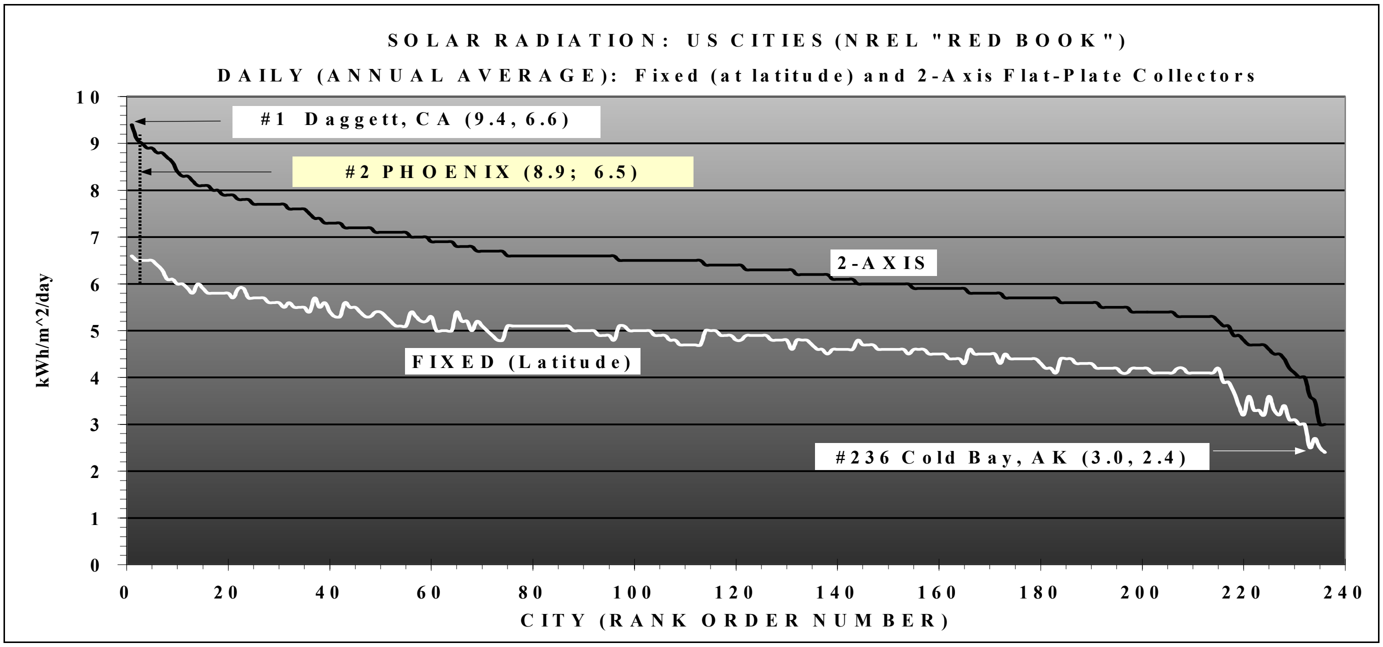

Figure 5. Solar Radiation Data, Annual Daily Average for 239 US cities

Note in Figure 5 that the amount of solar energy in Daggett, California is about 2.75 times greater than Cold Bay, Alaska. In addition to considering the average annual energy for a given site, it is also necessary to look at the monthly values of solar energy. Figure 6 shows the solar resource in December to be 5.2 times higher in Daggett than in Cold Bay. Since the output of a PV system is proportional to solar energy at a given site, the geographic location is a critical part of the design process.

Solar energy on a PV array is a function of the orientation of the array (and array shading, if any). Figures 5 describes two array orientations: 1) Array perpendicular to the sun, 2-axis tracker, and 2) a south-facing array tilted from the horizontal at the latitude angle. The 2-axis tracker represents optimum surface orientation (i.e., maximum energy available). Sunlight energy on a surface is proportional to the cosine of the angle between a line from the array to the sun and a line normal to the surface of the array (assuming that reflections from the surface are ignored). A comparison of solar energy available in Miami, Florida, on a surface for several array orientations is shown in Figure 7.

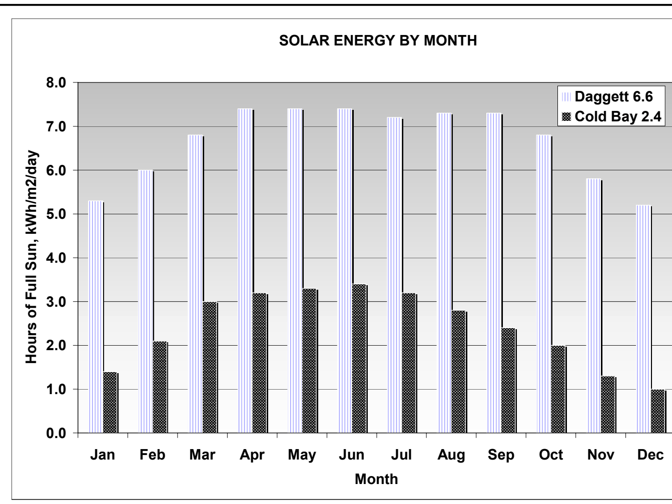

Figure 6. Solar Energy by Month, Fixed Array at Latitude

DESIGN CONSIDERATIONS

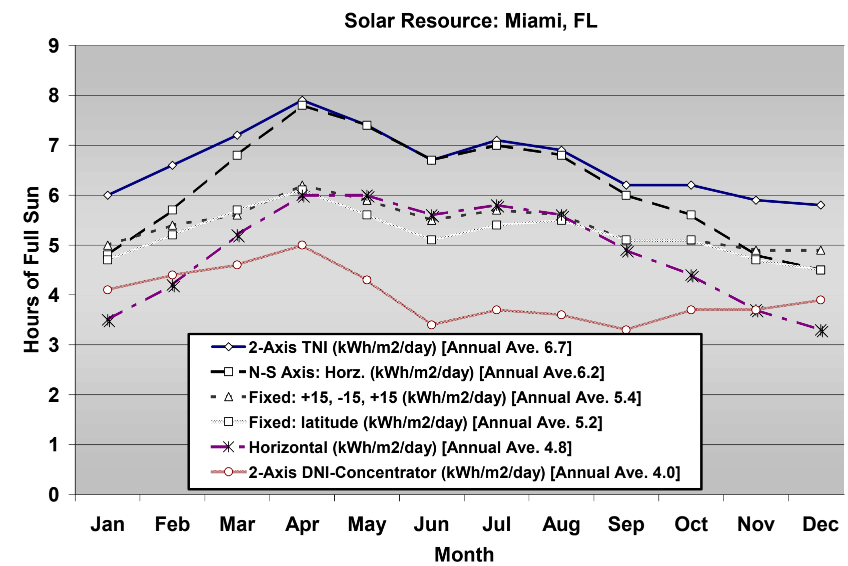

Figure 7. Array Energy as a function of Array Orientation

Step 1. Define Electrical Loads[4]

PV system design starts with a definition of the electrical loads. The initial system cost will be directly proportional to the amount of energy that the system is designed to provide. **Energy conservation and efficient loads are essential if system costs are to be minimized.** Reducing the load requirements (kWh) by 50 percent will reduce the initial system cost by approximately 50 percent - which could save thousands of dollars.

The size, and subsequently the cost, of a photovoltaic system depends upon two factors: 1) the electrical energy requirements of the devices relying on the system, commonly referred to as the daily energy load, and 2) the amount of sunshine on the modules. These factors determine the quantity and size of modules, batteries, and other components.

The load is usually measured as the amount of electric power being used at any given moment. For the purposes herein, the term "average daily load" will refer to the wattage of the electrical devices multiplied by the average daily use in hours per day. To determine the load, it is necessary to identify the devices that will rely on the system for power. If the system is used to power a home, the load might consist of lights, coffee pot, microwave oven, hair dryer, vacuum cleaner, radio, TV, power tools, water pump, and other common household items. “Phantom” loads, such as GFIC, wall power cubes, receivers for remote controls, and clocks must be included in the load

The general strategy in selecting electrical loads include a) use propane instead of electricity for producing heat (e.g., space heater, hot water, cooking), b) selecting electrical loads with high efficiency, and c) avoiding unnecessary load.

Step 2. Determine load wattage

Once the individual electrical loads have been identified, determine the wattage of each item. Nameplate ratings are generally maximum design limits of the device, which could be two to four times the actual power consumed. If possible, measure the actual power of every electrical load to be used.

Step 3. Estimate usage of individual loads

Next, decide how many hours per day (average) each item is to be used. If the load varies from day-to-day or season-to-season, then develop a weekly, monthly, or annual load profile. The load estimate must be as precise as possible to avoid over sizing or under sizing the systems. If system design is oversized, money is wasted on excess capacity. If it is undersized, power shortages during operation may result. This step must be completed before any estimates of array and battery requirements can be initiated.

Step 4. Sizing the System.

Details of system sizing and system design are beyond the scope of this paper. Comprehensive software programs are available to facilitate the system sizing process and some include irradiance and a module database[5]. Such programs walk you through the design options and allow you to select appropriate system configurations and system variables.

For organizations desiring assistance with PV system design, companies that specialize in PV system design (i.e. system integrators), can be found in the Index to Advertisers in Home Power Magazine, www.homepower.com, and from the comprehensive "PV Power" WEB site: http://www.pvpower.com/pvinteg.html.

BATTERIES

Batteries used in typical stand-alone PV systems experience moderate to deep daily discharge cycles and harsh environmental condition. Elevation of installation sites vary from sea level to above15,000 feet (4,572 meters) above sea level, while ambient temperatures may vary from –60F to +122F (-51C to +50C). Proper battery selection, installation, operation and maintenance are essential for good performance and expected life. Management of daily depth of discharge (DOD) and periodic equalization are essential.

It is unfortunate that the battery industry often use the terms "stationary" and "standby" interchangeable when referring to batteries in float applications[6]. Batteries used in PV stand-alone applications are "stationary" batteries, but these applications are a far cry from a float application. Treating PV batteries as a "float" application will quickly destroy the battery. Frequent equalization of PV batteries (both flooded and valve regulated) are essential if expected cycle life is to be achieved. The optimum equalization frequency will depend on the cycle depth.

Battery performance for two applications will be reviewed to demonstrate the cycling behavior of batteries in PV applications. The first application is a stand-alone home application and the second application is a communications mountain top repeater.

Stand-Alone Home Application

This case study consists of a 2,700 square-foot stand-alone home in Prescott, Arizona. The PV system consists of a 2,800-Watt PV array[7], a 24V-1000 amp-hour battery bank[8], and a 4-KW bi-mode sine-wave inverter. Loads consist of a full range of appliances (e.g., lights, refrigerator, microwave oven, coffeepot, toaster, satellite TV, stereo, computers, fax, clothes washer and dryer, shop tools, two evaporative coolers, and water pump). The average battery load current in December 2001 was 10.1 amps (242.4 amp-hours per day). With the batteries fully charged, the system would support the load for 3.3 days with no sunlight, resulting in an 80% depth of discharge. A manual-start emergency generator is available to recharge the batteries during extended cloudy days and/or other causes of low battery voltage. The generator has logged 38 hours of run time since installation in October 1998, or about 12 hours per year. (No backup generator was available from 1987 to 1998, so load were carefully managed during extended cloudy weather to avoid blackouts.) The generator is an emergency standby generators intended for occasional use.

Figure 8 shows battery voltage, battery load current and PV current during the month of December 2001. The inverter switches from the inverting mode to the battery charger mode when the generator is running. This is seen as a negative load current (since the inverter is d.c. current source instead of a d.c. current sink) in Figure 8. The generator ran three times (December 4, 9, and 31).

Battery state of charge (SOC) and bus voltage are shown in Figure 9. The deep-cycle golf-cart batteries are well suited for the occasional 50% depth of discharge and the typical 20 % daily depth of discharge during winter months. Although this is a "stationary battery" application, it is clearly a "cycling" application. Note that the 24Vdc (nominal) battery bank was equalized at 30.2 Vdc (2.52 volts per cell) prior to the capacity test on 8-9 December in order to ensure a fully charged battery prior to the capacity test. It was also equalized after the capacity test to ensure a prompt full.

This PV system has been in service for 15 years and has experienced only one unscheduled outage. The outage lasted two hours and it was due to a failed charge controller. The first set of batteries (1100 AH) was replaced after 7.5 years. The second set of batteries (660 AH) was replaced after 5.5 year. The current set of batteries (1,000 AH) was installed in January 2001.

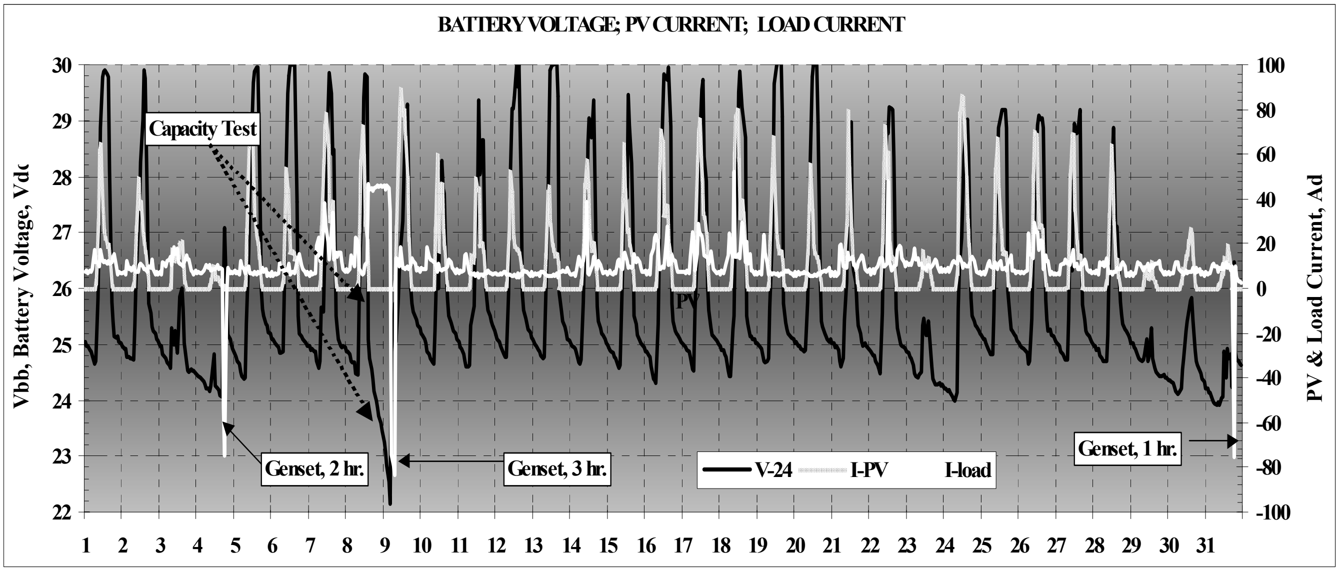

Figure 8. Battery Voltage, PV Current, and Load Current

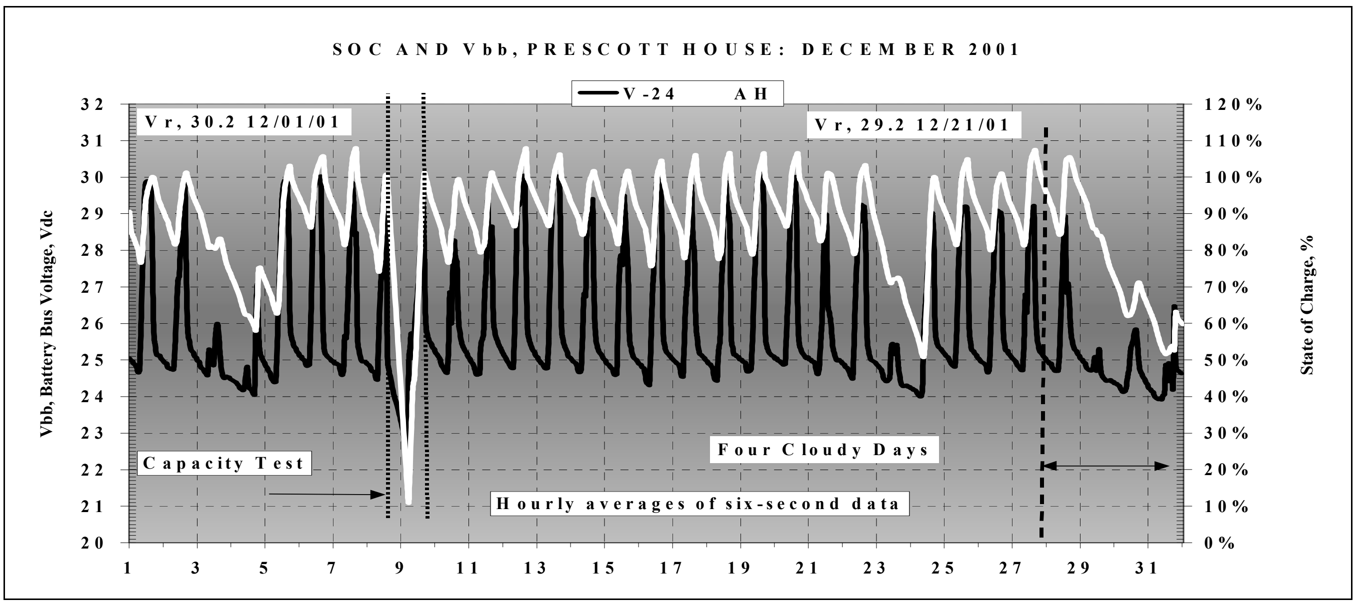

Figure 9. Battery Voltage and State of Charge for a residential PV system (December 2001)

Telecommunications System - Hybrid

Arizona Public Service commissioned a remote stand-alone PV hybrid system atop Carol Spring Mountain (SCM) in October 1995. At 6,600 feet (2012 meters) elevation, this system powers communications equipment, including cellular telephone, cable television, and new services microwave repeaters. The PV system consisted of a 25-KW PV array, a 192V-3100AH-battery bank, a bi-mode 30-KW-ac inverter, and a 60-KW-ac diesel fueled generator (and a 50-KW backup generator). The loads (communications and heating/cooling equipment) are fairly constant year round at 10-12 KW-ac.

Most “hybrid” PV systems are designed to deliver energy at the lowest levelized energy cost. It is not uncommon for the generator to provide 20-50% of the total annual energy. These generators are “prime-power” generators, which are designed for continuous duty and require an overhaul about every 10,000 hours. (The generator used in the earlier residential case study was an “emergency” generator that has a life of about 1,500 hours of run time.)

The original set of VRLA-AGM[9] technology batteries was still in service after 6.25 years in January 2002, but it was rapidly approaching end of life. In January, the batteries had degraded to about 50% of rated value; however, the batteries were still functional, although the generator was supplying more than the typical 25% of the monthly load. The availability of power to the load was still 100%. The old rule of thumb that batteries should be replaced when they reach 80% of rated capacity is not appropriate for hybrid PV systems. Batteries were replace in April 2002 with a similar set of VRLA-AGM batteries.

Figure 10 shows the CSM Load-KWH, the PV-KWH, the generator-KWH, and the battery voltage. The generator is providing about 65% of the total energy, while PV is providing the remaining 25%. This high contribution by the generator is due to the weak batteries, the reduced amount of sunlight in January, and the loads doubling since installation six years ago.

Battery state of charge (SOC) is shown in Figure 11, with battery voltage included for reference. Batteries are working hard with a typical cycle depth of 50% to 80%. This clearly is not a float application. Battery voltage frequently dropped to 1.92 volts per cell during January. Batteries were equalized at 2.35 volts per cell frequently during the month due to the deep cycling.

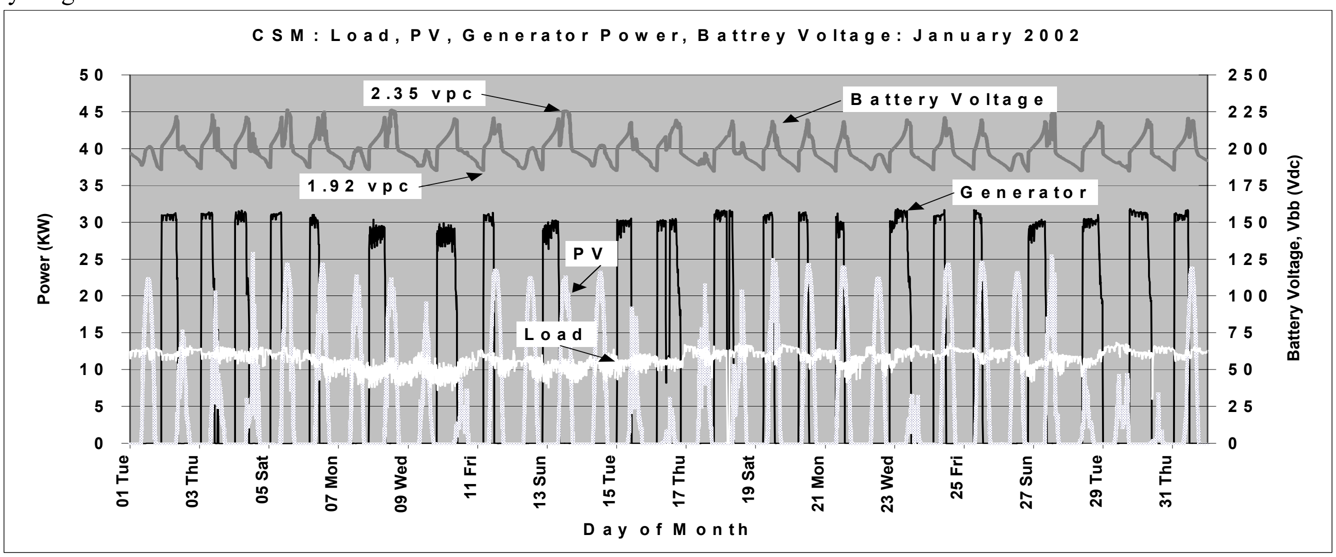

Figure 10. CSM Load KWH, PV KWH, Generator KWH, and Battery Voltage

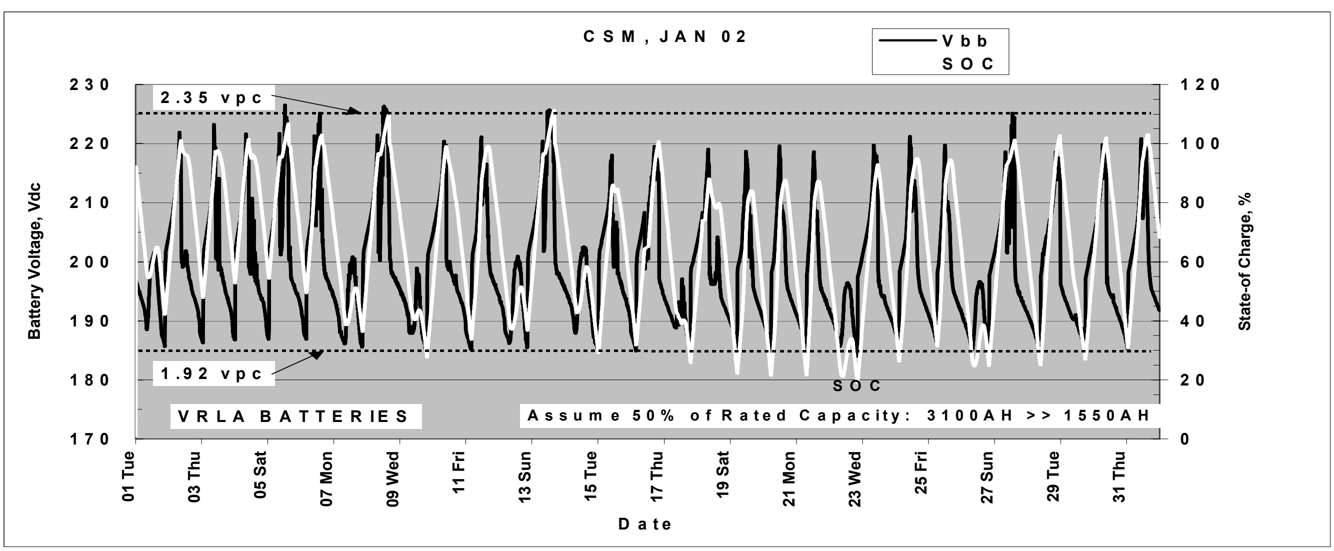

Figure 11. Battery Voltage and State-of-Charge for Carol Spring Mountain, January 2002

CONCLUSIONS

Photovoltaic systems can be designed to provide non-polluting, reliable power. Proper design practices will minimize maintenance and maximize performance. Use of the sun's energy can either eliminate the requirement for fossil fuel, or it can significantly minimize their use. These are ideal characteristics for remote power applications.

The solar energy available for PV at a site is dependent on the geographic location and the orientation of the PV array. If possible avoid shading any part of the array.

The size and cost of a PV system is proportional to the energy consumption by the load. Reducing the electrical load by selecting energy efficient equipment will result in a corresponding reduction in PV system cost. Defining the system load is the first step is PV system design.

Nearly all batteries used in PV systems are deep-cycle lead-acid technologies. Even though PV batteries are "stationary", they are nearly always in a cycling application. Rarely would they ever be in a float mode. Batteries that are cycled must be equalized periodically (e.g., every two week to every two months, depending on the cycle depth. VRLA batteries are not excluded from this required, although VRLA-Gel technologies seem to require the least amount of equalization.

For more information specific to PV battery applications, see *Photovoltaic Battery and Charge Controller Market and Applications Survey*[10] and *Photovoltaic in Cold Climates*[11]. Several others references for PV applications are listed under PV WEB SITES, Bibliography, and EndNotes.

PV WEB SITES

- www.pvpower.com [What's new, History, Technology , FAQ, Industry, Applications, Jobs, Calendar, Resources]
- www.sandia.gov/pv/ [Sandia National Laboratories (SNL)PV Components, BOS, Handbook, Publications
- www.nrel.gov/pv/ information/html [National Renewable Energy Lab. (NREL)
- http://www.osti.gov/html/techstds/standard/std3003/std3003a.html#ZZ28, Backup Power Sources for DOE Facilities. 3.17 Stationary Battery

BIBLIOGRAHPY

1. K Zweibel, Harnessing Solar Power: The Photovoltaic Challenge, Plenum Press, New York and London, ISBN 0-306-43564-0, 1990
2. SJ Strong, The Solar Electric House: A Design Manual for Home-Scale Photovoltaic Power Systems, Rodale Press, Emmaus, Pennsylvania, 1987
3. Home Power Magazine, www.homepower.com
4. *Maintenance and Operation of Stand-Alone Photovoltaic Systems*. Naval Facilities Engineering Command, Southern Division Photovoltaic Review Committee, Department of Defense, Prepared by Architectural Energy Corporation, December 1991
5. *Stand-Alone Photovoltaic Systems, A Handbook of Recommended Design Practices.* Sandia National Laboratories, SAND87-7023, March 1995

ENDNOTES

[1] Definitions for abbreviations used in Figure 3:

- Voc – open-circuit voltage
- Isc – short-circuit current
- Pp – the maximum power available from a PV device at specified operating conditions (irradiance, temperature, etc.)
- Vp – voltage at Pp
- Ip – current at Ip

[2] *Database of Module Performance Parameters*. A Microsoft Access database of PV module performance parameters has been developed and is continuously updated on this site. This database contains performance and physical data as specified by manufacturers, plus other measured parameters required to implement the module performance model developed by Sandia National Laboratories and documented elsewhere. The database can be used directly by the IVTracer program which implements the Sandia performance model providing current-voltage (I-V) characteristics for commercial photovoltaic modules at user selected operating conditions. The IVTracer software is available by contacting David King at Sandia (dlking@sandia.gov). In addition, the module database can be used directly by commercially available PV system design software, such as PV-DesignPro by Maui Solar Energy Software Corporation.

[3] *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, National Renewable Energy Laboratory, NREL/TP-463-5067, April 1994.

[4] Root, B. Doing a Load Analysis: The First Step in System Design, Home Power #58, April/May 1997, pp38-44.

[5] For example, see Solar Design Studio, Maui Solar Energy Software Corporation, 810 Haiku Road #113, Box 1101, Haiku, HI, 96708, 808-573-6712, www.mauisolarsoftware.com

[6] "Large battery installations which are called upon only occasionally to supply power, usually in emergency or auxiliary power supply circumstances, are referred to as stationary or standby batteries". *Battery Reference Handbook*, Reed Educational and Professional Publishing Ltd 1996, ISBN 1 56091 805 5, pg. 32/3

[7] 2,700 Watts at 1000 watt/m^2 and 20°C ambient temperature

[8] 1000 amp-hours at the 100 hour rate

[9] VRLA-AGM: Valve Regulated Lead Acid-Absorbed Glass Mat

[10] Hammond, RL, J. Turpin, G. Corey, T. Hund, S. Harrington. *Photovoltaic Battery & Charge Controller Market and Applications Survey*, Arizona State University TR-96-12-01-ECT; Sandia Report, SAND96-2900, UC1350, December 1996.

[11] Ross, M and J. Royer. *Photovoltiacs in Cold Climates*, James and James, UK, ISBN 1 873936 89 3, 1999