Photovoltaic Power Systems

Compiled by Tracy Dahl

Overview

Photovoltaic (PV) technology converts one form of energy (sunlight) into another form of energy (electricity) using no moving parts, consuming no conventional fossil fuels, creating no pollution, and lasting for decades with very little maintenance. The use of a widely available and reasonably reliable fuel source—the sun—with no associated storage or transportation difficulties and no emissions makes this technology eminently practicable for powering remote scientific research platforms. Indeed, numerous examples of successfully deployed systems are already available. The completely scaleable nature of the technology also lends itself well to varying power requirements–from the smallest autonomous research platforms to infrastructure-based systems. This technology can be limited, however, by annual fluctuations in solar insolation, especially at extreme latitudes.

Based on semiconductor technology, solar cells operate on the principle that electricity will flow between two semiconductors when they are put into contact with each other and exposed to light (photons). This phenomenon, known as the photovoltaic effect, was first discovered by Edmund Becquerel in 1839. Actual development of PV technology began in the 1950s and gained greater impetus through the NASA space program during the 1960s. Research continues today at national laboratories and within private industry, focusing on increasing conversion efficiencies and mass production strategies to further lower the cost of producing PV modules.

For a list of some of the many online resources on PV technology visit the Links Section of http://polarpower.org. The same web site offers presentations from the 2004 Renewable Energy Working Group Meeting and links to the Autonomous Systems in Extreme Environments Workshop report under News > Past Meetings.

Cost

Since the first PV panel was developed in 1954 at a truly astronomical cost, the efficiency of solar cells has risen steadily. At the same time, prices have fallen consistently from $70 a watt in the 1970s to less than $4 a watt today. (Note that this cost does not reflect the total system cost, which will vary widely based on the application.) Despite the remarkable reduction in price over the past several decades, PV technology remains somewhat expensive at $4 a watt ($4,000 per kilowatt). However, if one takes a lifetime-cost approach, PV looks much more favorable: There is no cost for fuel, very little maintenance is required, and PV panels have an estimated lifetime of more than 30 years. When these factors are taken into account, the real price of 1 kilowatt of PV is roughly $133.

Design Requirements

Many factors must be considered when designing any remote power system. The biggest overriding factor is that all systems, regardless of the power source, should make energy conservation a top priority. Simply put, the less power needed, the lesser the amount that must be produced and stored. This can reduce the size, cost, and weight of the system dramatically. There are many strategies that can be used to reduce the total amount of electrical power required to perform a given task. For a more comprehensive discussion of this subject, see the "Efficiency" section further on in this document. To enable you to determine the optimal PV system size for your chosen application, system sizing worksheets follow at the end of this document.

Components

PV Panels

PV panels tend to work much better in cold weather than in hot climates (except for amorphous silicon panels). Add a reflective snow surface and the output can sometimes exceed the rating for the panel. Array currents up to 20% greater than the specified output have been reported (1).

In general, PV materials are categorized as either *crystalline* or *thin film*, and they are judged on two basic factors: efficiency and economics. For remote installations where the actual space available for PV panels is often quite limited, the greater conversion efficiency of crystalline technology seems to have the advantage. It is also worth noting that the conversion efficiency of thin-film panels tends to drop off rather rapidly in the first few years of operation. Decreases of more than 25% have been reported. This performance deterioration must be taken into account when sizing the array for a multi-year project. However, there are still applications where the lighter weight and greater flexibility of the thin-film panels may be more suitable. Which PV technology is more appropriate for a given application will need to be determined on a case-by-case basis.

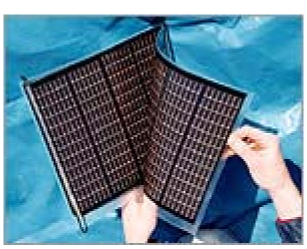
Monocrystalline PV panel

Monocrystalline silicon panels should be utilized when a higher voltage is desirable. This would be in an instance where the DC power has to travel some distance before being utilized or stored in a battery bank. These panels are also the most efficient PV technology, averaging 14% to 17%. New technology charge controllers, which allow for a higher array voltage than the battery bank voltage, somewhat obviate the advantages of the monocrystalline panels.

Polycrystalline silicon panels have efficiencies of 12% to 14% and can often be purchased at a lower cost per watt than monocrystalline silicon panels. This type of panel sees the widest use in polar applications.

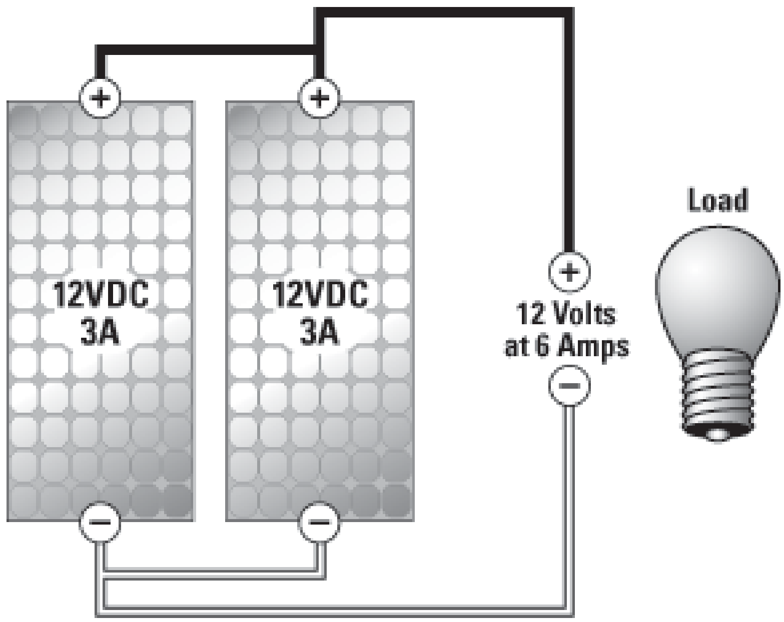
Polycrystalline PV panel

Thin-film technologies include amorphous silicon, cadmium telluride, copper-indium diselenide, and others. Although the cost of these panels appears attractive at first, it is important to note that the efficiencies are comparatively low. The 8% to 10% efficiencies seen in new panels quickly degrade to about 3% to 6% after several months of exposure to sunlight. Furthermore, amorphous silicon and cadmium telluride modules are sensitive to a much narrower band of colors, and the winter shift to redder sunlight results in slightly poorer performance (2). Newer, *triple-junction* thin-film technologies appear to have higher efficiencies and less degradation over time, but they are still subject to the same problems mentioned above, if to a lesser degree.

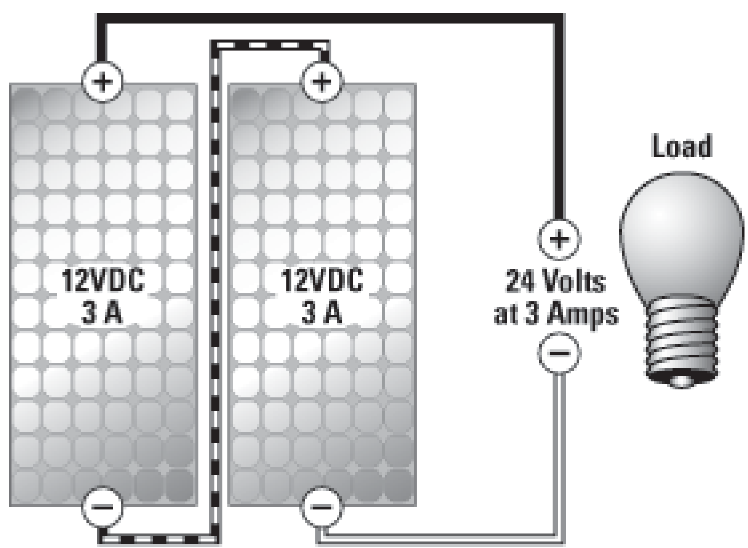


Thin flim PV panels

The somewhat flexible nature of thin-film technology may make it appropriate for some applications, but in general, the higher efficiencies and more robust nature of the crystalline silicon modules make them a better choice for polar applications. Regardless of the technology employed, the researcher would be well advised to look for modules with heavy-duty aluminum frames, UL ratings, easy-to-use junction boxes, and a long warranty (20+ years). All of these are indicative of a quality unit that will withstand the rigors of the polar environment.



PV MODULES IN PARALLEL



PV MODULES IN SERIES

Images courtesy of Solar Energy International.

Batteries

The principal problem to overcome with any PV system is that the sun does not shine on every part of the planet with equal intensity. This uneven availability of solar energy is greatly exacerbated in the Polar Regions. Daily and annual fluctuations in solar insolation necessitate storing excess energy for later use. Batteries are the technological solution most commonly employed for this purpose, but other energy storage mediums do exist. Fossil fuels and combustion generators can be used to provide on-demand power. Dynamic flywheels have been successfully utilized in several larger systems to kinetically store energy. On-site production and storage of hydrogen as an alternative fuel source holds great promise but is not quite ready for prime time as of this writing. All of these means are dealt with in greater detail elsewhere in this web site. For now, batteries provide the most cost-effective solution for energy storage for small- to medium-sized autonomous power systems.

A battery stores electrical energy in the form of chemical energy. For a PV-battery system to function effectively, the electrochemical processes must work in both directions—in other words, the system must be rechargeable. To this end, batteries perform three main functions in a stand-alone PV system:

1. *Autonomy*–by meeting the load requirements at all times, including at night, during overcast periods, or during the winter when PV input is low or absent.

2. *Surge-current capability* –by supplying, when necessary, currents higher than the PV array can deliver, especially to start motors or other inductive equipment.

3. *Voltage control*–thereby preventing large voltage fluctuations that may damage the load (3).

Any battery suitable for PV applications will be a *deep-cycle* type of battery as opposed to a starting (*SLI)* type. Although these two fundamental classes of batteries may appear similar on the outside, the internal structure is quite different. SLI batteries are intended to deliver a high-amperage output for a short period of time, but repeated deep discharges cause rapid deterioration of battery performance. These batteries are typically rated in cranking amps, or cold cranking amps (CCA). Deep-cycle batteries are designed to deliver a typically lower current for the size of the battery, but they are capable of withstanding numerous deep discharges without damage.

The amount of energy a deep-cycle battery can store is referred to as its *capacity.* The unit that describes capacity is the *amp hour (Ah)* . Battery capacity is determined by the manufacturer based on a constant discharge over a period of time. Oftentimes, batteries will appear to have multiple ratings due to this rating process. The 20-hour rate (C/20) and the 100-hour rate (C/100) are referred to most frequently. When determining which battery to choose, be sure to compare all batteries at the same discharge rate.

Deep-cycle batteries vary widely in type, price, and quality. Low-cost trolling batteries represent the low end of the scale and are generally not suitable for use in remote power applications. The most expensive battery per amp hour is generally the gel-cell battery. Battery failure has often been the cause of suboptimal power system performance. Without a doubt, this is not the area to cut expenses. The battery bank for any power system must be of the highest quality available, of the correct type for the application, and of sufficient capacity to ensure that the depth of discharge does not exceed design parameters. The size of a battery bank for even relatively low-power applications can be surprisingly large, particularly if year-round autonomy is a design requirement. Cold temperatures reduce capacity but tend to extend battery life. System sizing worksheets (see the end of this document) are essential for ensuring adequate battery capacity for a given project.

The most common type of battery found in PV systems is the lead acid battery. Although the discussion will focus on this blanket technology, other rechargeable battery types do exist, including nickel-cadmium (NiCad), nickel metal hydride (NiMH), nickel-iron (NiFe), lithium ion, and lithium polymer batteries. Of these, the NiMH and lithium polymer batteries show significant promise for broader application in autonomous power systems. These battery types demonstrate up to a four-fold greater energy density and enhanced performance across a wider temperature range, which might ultimately favor this emerging technology. NiCad batteries have been used in a few polar applications, as they have superior performance in extreme cold. However, the high price, low efficiency (about 65%

vs. 85%-95% for lead acid), and restrictive charging parameters make them unsuitable for most applications. At the moment, the comparatively low prices and well-documented performance of lead acid batteries favor their continued use for remote power systems.

In the lead acid class of batteries, two specific types stand out for their applicability to polar power applications: the *gel cell* and the *absorbed glass mat (AGM).* These two types of batteries represent good choices not only due to performance characteristics but also because they are both suitable for air transportation. Because the electrolyte solution in both of these battery types is immobilized, they represent a lower hazard class than standard *flooded* batteries and do not require a great deal of specialized packing before being shipped via aircraft into the field. Although the performance characteristics of flooded deep-cycle batteries may meet or exceed those of the gel-cell and AGM types, the transportation and maintenance issues can prove to be quite problematic.

Deka AGM type battery

Both of these types of batteries are classed together as *valve-regulated lead acid (VRLA)* batteries. A battery charging at a high amp rating or an excessively high voltage can release gases (hydrogen and oxygen) due to an overcharge condition. In a VRLA-type battery, gases are not released during a normal, controlled charge cycle. There is a closed loop that keeps the chemical levels balanced and internal pressures below the release threshold of the valve.

One very important difference to note between gel-cell and AGM batteries is that the gel-cell battery is a plate-limited design, whereas AGM batteries are an electrolyte-limited design. This can be very important in polar applications where extremely cold temperatures are often the norm. Freezing the electrolyte solution in a battery must be avoided. It causes irreversible damage to the battery, which could lead to catastrophic failure. Also, a frozen battery cannot recharge until it has been thawed out again—not always a simple proposition in the field. Electrolytes freeze at higher temperatures as they discharge and the specific gravity decreases. AGM and flooded-cell batteries can continue to discharge until the electrolytes become severely depleted, resulting in a low specific gravity and a relatively high freezing point. A quality load controller somewhat obviates this concern, as it will typically incorporate a low-battery disconnect capable of opening the circuit between the battery and the load prior to the onset of problems. In a plate-limited battery, the chemical reaction that causes the flow of electrons ceases before the electrolyte specific gravity falls too low. This provides a certain measure of inherent protection by design. Similarly, gel-cell batteries can recover more easily from a deep discharge due to the fact that they can more readily accept a charge when energy from the PV array once again becomes available. For small, low-current solar systems, gel-cell batteries seem to be the best choice. It is important to note, however, that gel-cell batteries are vulnerable to damage in other ways. Charging at excessively high rates can create voids in the gelled electrolyte that significantly reduces the capacity of the battery. Voltage and current must be carefully controlled and cannot exceed the C/20 rate (approximately 5% of the amp hour rating for the battery bank). For larger systems that incorporate other charging sources such as wind turbines or engine generators, AGM batteries may be preferable

Liquid Electrolyte Freeze Points, Specific Gravity, and Voltage

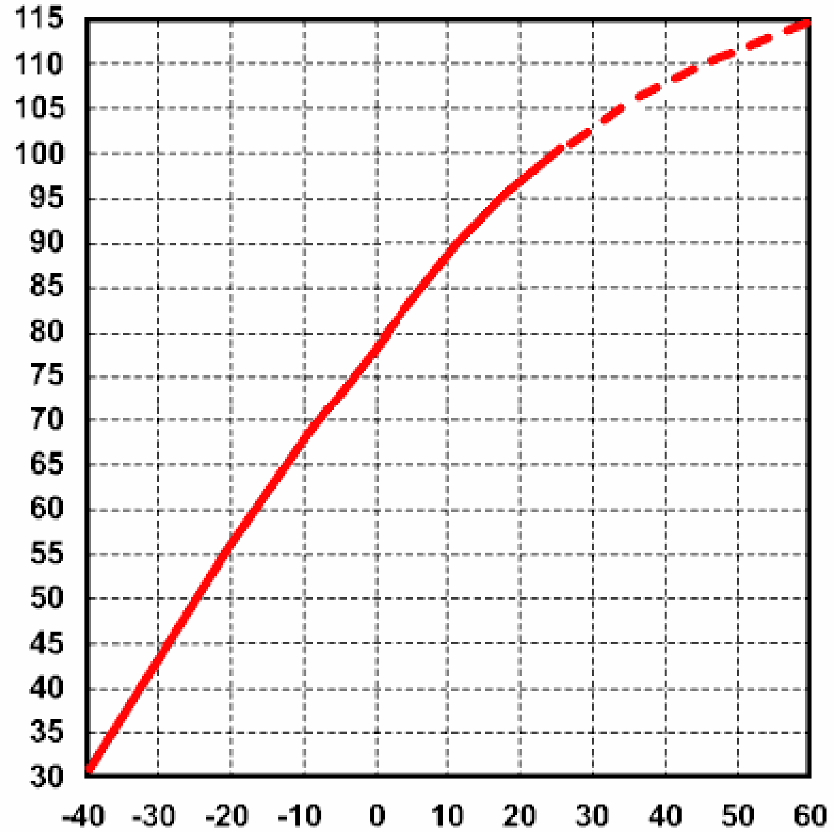
State of Charge	Freeze Point	Specific Gravity	Voltage
100%	-71º F	1.260	12.70
75%	-35º F	1.237	12.50
50%	-10º F	1.200	12.30
25%	3º F	1.150	12.00
0%	17º F	1.100	11.70

* Adapted from *Photovoltaics Design and Installation Manual* (2004), SEI.

due to a superior high-current rate performance (4). It is worth noting that many battery manufacturers offer both gel-cell and AGM types. Gel-type batteries have fallen somewhat out of favor in the industry in recent years, but there are still applications where this is the most appropriate technology to use. The optimal battery choice for a given research project must be determined on a case-by-case basis.

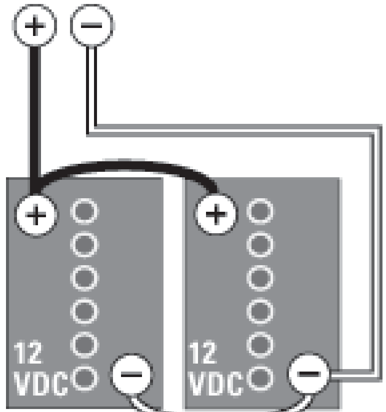
Battery capacity is dramatically affected by the cold. Capacity is reduced by 50% at -10º F, and the risk of freezing becomes much greater. At the same time, battery life is increased by 60% due to a lower rate of self-discharge and generally depressed chemical processes. This applies to all types of lead acid batteries and explains the phenomenal service life of some batteries deployed to polar environments. The reduced capacity must be taken into account when determining the battery bank size required for a system.

Temperature (F) vs. Capacity

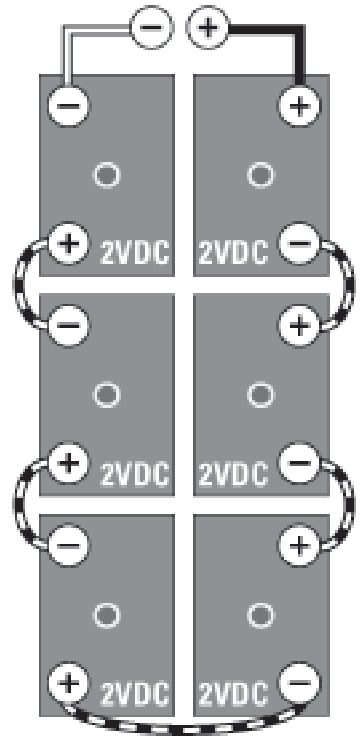


The *depth of discharge (DOD)* also has a direct bearing on how long a battery will last. A battery discharged to 50% on each cycle will last about twice as long as one discharged to 80% per cycle. This is a major issue for polar researchers wishing to run PV-powered experiments over the length of a polar winter when little or no solar insolation is available to recharge the battery bank. Between reduced capacity due to cold temperatures and longevity issues related to the DOD, this type of system will typically require either a very large battery bank or an alternative charging source, such as a wind turbine or engine-driven generator.

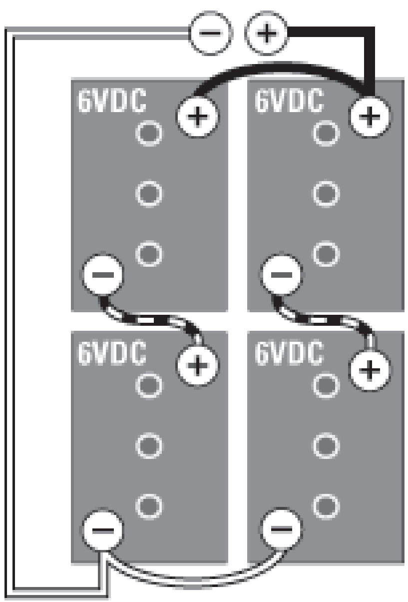
When diagnosing battery problems, be sure to differentiate between the *surface charge* and the actual *state of charge.* A battery still connected to the PV charging source may appear to have adequate voltage, but this can be very misleading. When analyzing a battery, first disconnect it from the charging source and allow it to sit for an hour before taking a baseline voltage measurement. Next, hook it up to a dummy load, which should be a resistive load. Watch the battery over a period of time and observe the voltage decline. If it drops dramatically right away or maintains voltage for a short time before the bottom drops out, the battery is bad. Generally speaking, it is poor economy to replace only one battery or cell in a battery bank. As with any interconnected system, the performance tends to be reduced to the level of the poorest performing module.



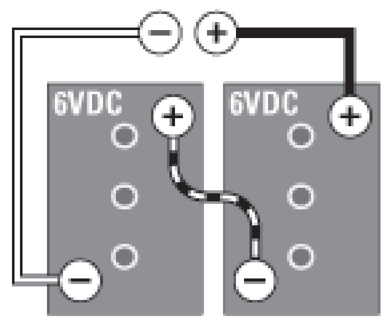
12-VOLT CONFIGURATION
with 12-volt batteries in *parallel*



12-VOLT CONFIGURATION
with 2-volt batteries in *series*



12-VOLT CONFIGURATION
with 6-volt batteries in *series/parallel*

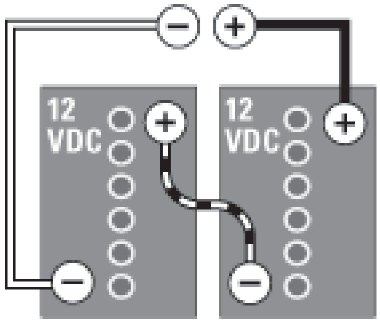


12-VOLT CONFIGURATION
with 6-volt batteries in *series*

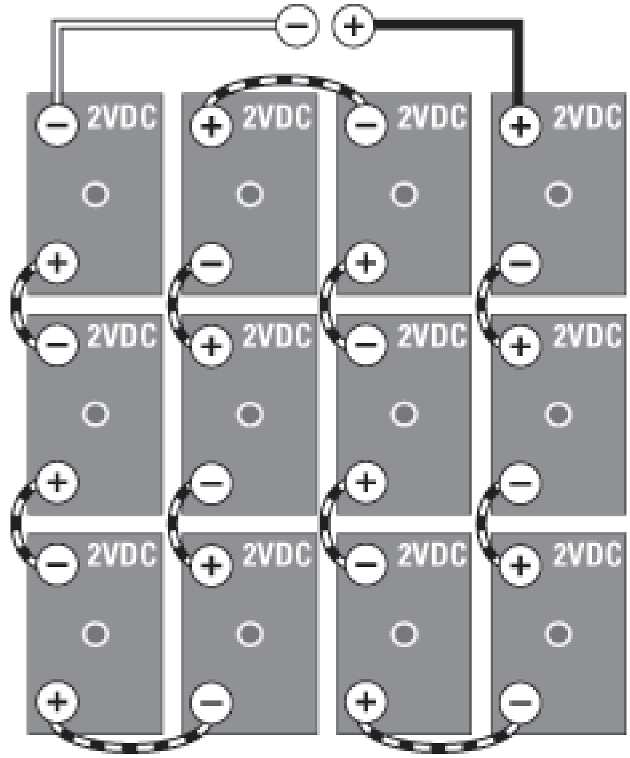
12 VOLT BATTERY CONFIGURATIONS

Image courtesy of Solar Energy International.

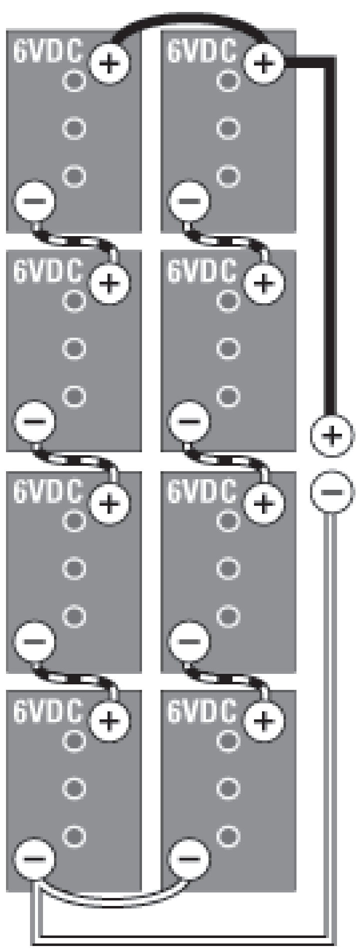
Image courtesy of Solar Energy International.



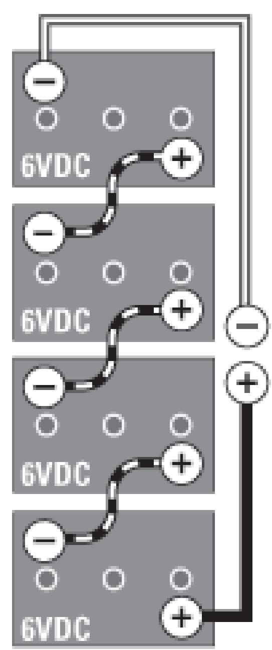
24-VOLT CONFIGURATION
with 12-volt batteries in *series*



24-VOLT CONFIGURATION
with 2-volt batteries in *series*



24-VOLT CONFIGURATION
with 6-volt batteries in *series/parallel*



24-VOLT CONFIGURATION
with 6-volt batteries in *series*

24 VOLT BATTERY CONFIGURATIONS

Charge Controller

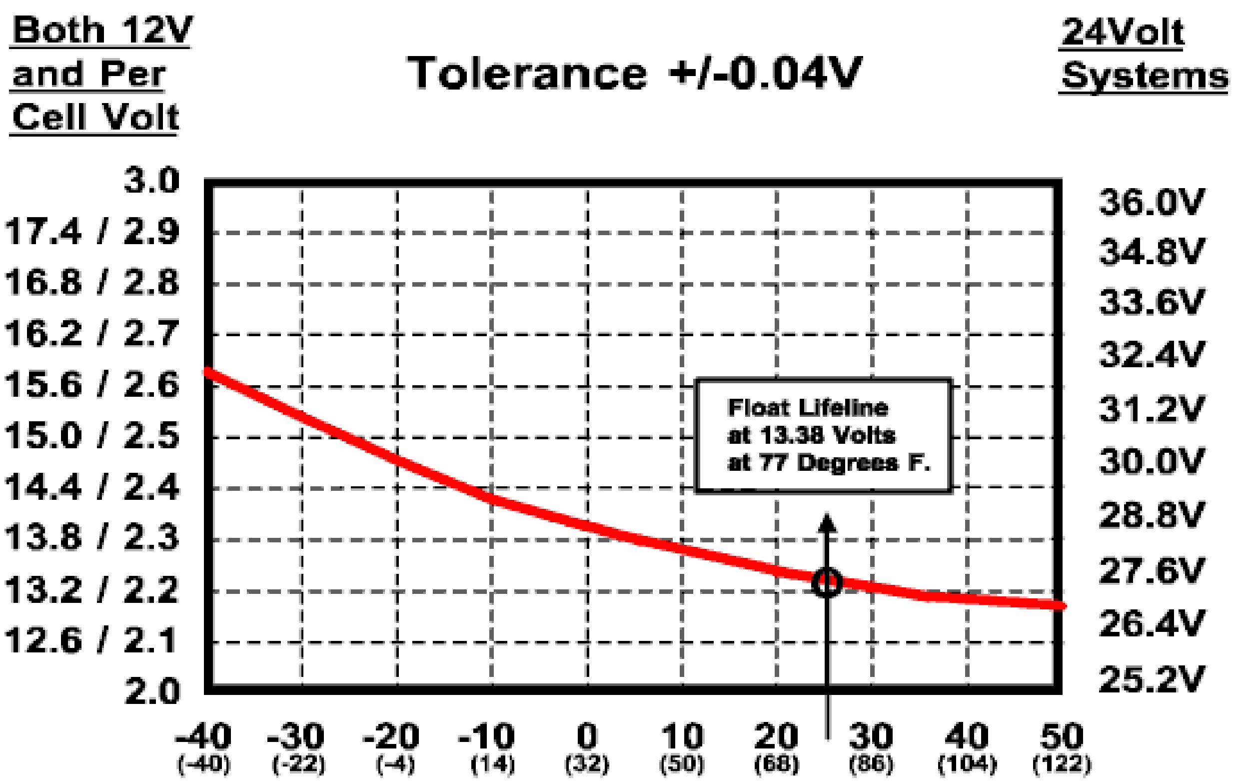
Regardless of the battery type chosen for a particular system, a *charge controller* remains an essential component. The primary function of a charge controller is to prevent the battery bank from being overcharged when there is abundant solar insolation available. Overcharging a battery can lead to electrolyte imbalances and depletion. In cases of severe overcharging, batteries can be completely destroyed along with any instrumentation in the vicinity.

There is a wide range of charge controllers available, and the design requirements of the system dictate which charge controller should be utilized. The maximum charge rate is the first parameter to consider along with the system voltage. The amp rating of the charge controller should be oversized by a minimum of 25% for enhanced reliability. Greater functionality will be required for more complex systems and those that are deployed year-round. Charge controller functions include the following:

1. The simplest charge controllers really only perform the overcharge protection function. It is essentially an on/off switch for the PV panels. They are typically sealed units and cannot be re-set to account for variations in battery type. Nevertheless, the simplicity and sealed nature of these controllers makes them quite appropriate for low-power, summer-only applications.

2. The next level of sophistication allows for changing the charge parameters. For instance, the voltage level can be set to accommodate the differences between flooded-cell, gel-cell, and AGM-type batteries.

3. Temperature compensation is critical for polar applications. Essentially, at colder temperatures, voltages must be increased to achieve the same state of charge. At –40º C, a temperature-compensated charge controller will run about 2.74 volts per cell (16.4 volts in a 12-volt nominal system) to maintain a 100% state of charge. At 50º C, the same temperature-compensated charger would run 2.3 volts per cell (13.8 volts) to maintain a 12-volt battery at a 100% state of charge. Some charge controllers have this functionality built into the circuit board, whereas others use a remote sensor.



This graph shows the importance of temperature compensated charge control. As temperatures decrease, charging voltages must be increased.

4. The next level of functionality involves multi-stage charge control, most typically bulk, absorb, and float levels This allows for a high current rate during the bulk stage, which then tapers off current as the voltage rises into the absorb level. The float stage reduces voltage to prevent excessive gassing and is really meant as a trickle charge to keep the batteries fully topped off. For battery longevity, it is critical that the float level is reached and maintained for fairly long periods of time.

5. Some charge controllers can also function as load controllers, or they can function to send excess energy to a diversion load. As a DC load controller, the function is typically to serve as a low-voltage disconnect. This allows the battery bank to be protected from overdischarge as discussed previously. When used in the diversion control mode, excess energy that would otherwise be wasted when the battery is full is instead routed to a dump load, most typically a resistive air or water heater. This can be a very important function in polar environments where heat is usually a useful energy source. Note that most charge controllers with these capabilities can still only operate in one of the three modes—either as a charge controller, diversion controller, or DC load controller. Multiple controllers may be required.

6. Pulse width modulated (PWM) chargers sense small voltage drops and react by sending out short charging cycles. This can occur many times per minute. It allows for more accurate charging at the float level and tends to reduce sulfation of batteries kept at float for long periods of time.

7. The latest generation of charge controllers incorporates a technology called maximum power point tracking, or MPPT. This function is designed to increase the efficiency of the PV array by converting the typically higher voltage (17-21 VDC in a 12 VDC nominal system) to the 14 VDC or so required to charge the battery. Stated simply, the un-useable high-end voltage is converted to useable extra amps. Remember the relationship between volts, amps, and watts: watts = amps x volts. An MPPT charge controller takes advantage of this relationship to deliver more useable power from the PV array to the batteries. The electronics utilized to make this work are quite sophisticated, however, and the price of the controller is consequently much higher. At the moment, there are only a few MPPT charge controllers available. However, because the benefits are quite obvious and quantifiable, there will no doubt be several more showing up on the market, and prices should start to come down.

8. Finally, some high-quality charge controllers allow for a higher array voltage than the system voltage. For instance, a PV array can be wired for a 48 VDC nominal output to feed a 24 VDC nominal battery bank. The advantage of the higher array voltage is that significantly smaller conductors can be used without incurring unacceptable voltage drops. This can be an important consideration if the PV array needs to be set some distance away from the battery bank due to site or project requirements. For a look at relative conductor sizes and current carrying capacities, see the chart in the section on conductors below. Note that higher array voltages also pose a greater shock hazard. It is nearly impossible for a person to be shocked by a 12 VDC nominal system (although sparks will still fly if an un-insulated positive lead comes in contact with a grounded component) in contrast to a 48 VDC nominal or higher system. The open-circuit voltage on a 48-volt PV array is typically more like 80 to 90 volts and is quite capable of delivering a shock. If relatively untrained individuals will be setting up or servicing the system, it may be prudent to stick with 24 or lower voltages for the system.

In conclusion, select a charge controller that meets or exceeds the requirements of the system. It may not be necessary to spend hundreds of dollars on a charge controller if the needs of the system are quite basic. Also consider that the liquid crystal displays (LCD) usually found on high-end models will likely be inoperable and may even crack at extremely low temperatures.

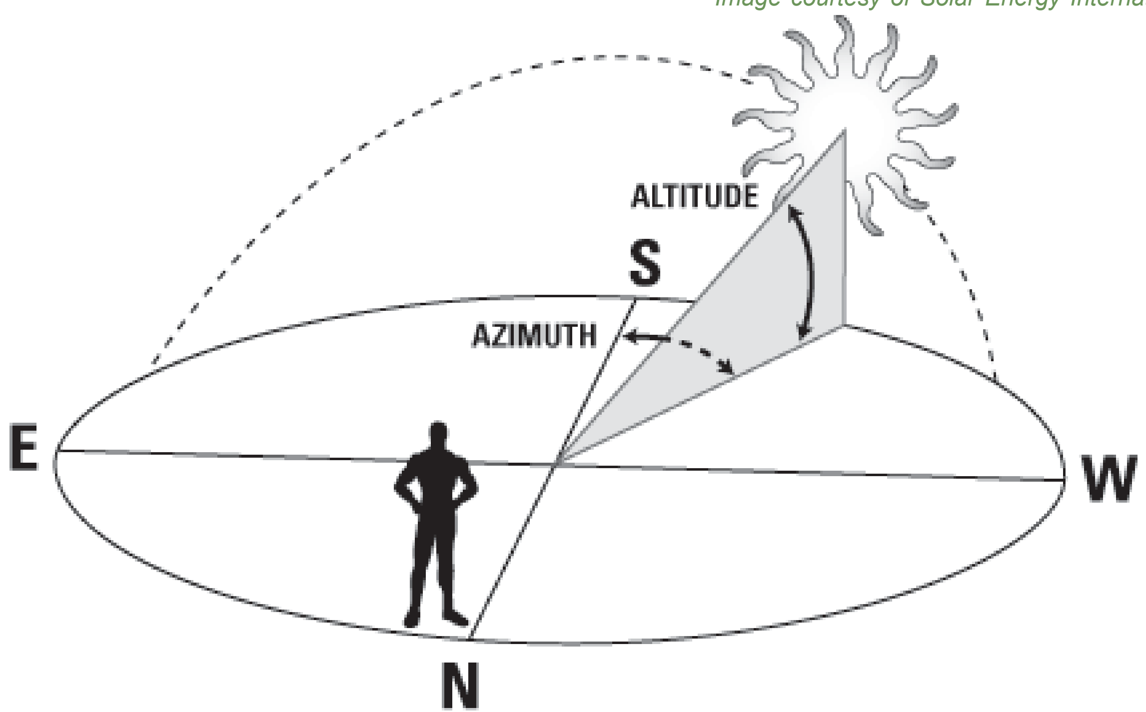
PV Array Mounts

On a clear day at solar noon, about 1,000 watts per square meter will fall on a surface placed perpendicular to the sun. If that surface is a PV panel working at 10% efficiency, the solar energy will be converted into 100 watts of electrical power. The PV array functions to securely mount the individual PV panels and maximize the conversion efficiency as much as possible by maintaining the orientation perpendicular to the sun. There are two basic types of arrays for mounting PV panels: fixed and tracking. Tracking arrays can move in one or two planes and can employ active (motor drive) or passive mechanisms for following the course of the sun. In high latitudes, dual-axis trackers can increase the output of an array by up to 60% in summer applications, yet they are rarely employed for mission-critical applications such as autonomous instrument platforms. The reason is reliability. To date, no automated tracking system has proven to be robust enough to withstand polar weather conditions. Until such tracking mechanisms are more reliable, the power budget is better spent on obtaining more PV modules on a fixed array. If a researcher really needs to make maximum use of the summer sun, multiple arrays or multi-sided arrays can be constructed to take advantage of the longer day. In the wintertime, any benefit from pointing the array toward anything but the equator is negligible. Therefore, for most year-round applications, a fixed array pointing south in the northern hemisphere or north in the southern hemisphere is the best bet for a reliable and efficient arrangement. Because polar areas tend to have very high magnetic declinations, be sure to correct compass readings or use a GPS to obtain a true bearing. ***Note: If a site is continuously occupied, manual tracking of the sun is another option that is reliable and can dramatically increase the output of the array***. Manual tracking arrays have been successfully deployed at Lake Hoare, Antarctica.

Array Orientation

As alluded to above, maximum output from a PV panel is achieved by pointing the surface directly at, or perpendicular to, the sun. The relationship between the angle of beam radiation and the plane of the panel surface is called the angle of incidence. Conversion efficiencies and therefore the electrical output are highest when the angle of incidence is zero. Two angles determine the orientation of the PV array: the tilt angle and the surface azimuth area.

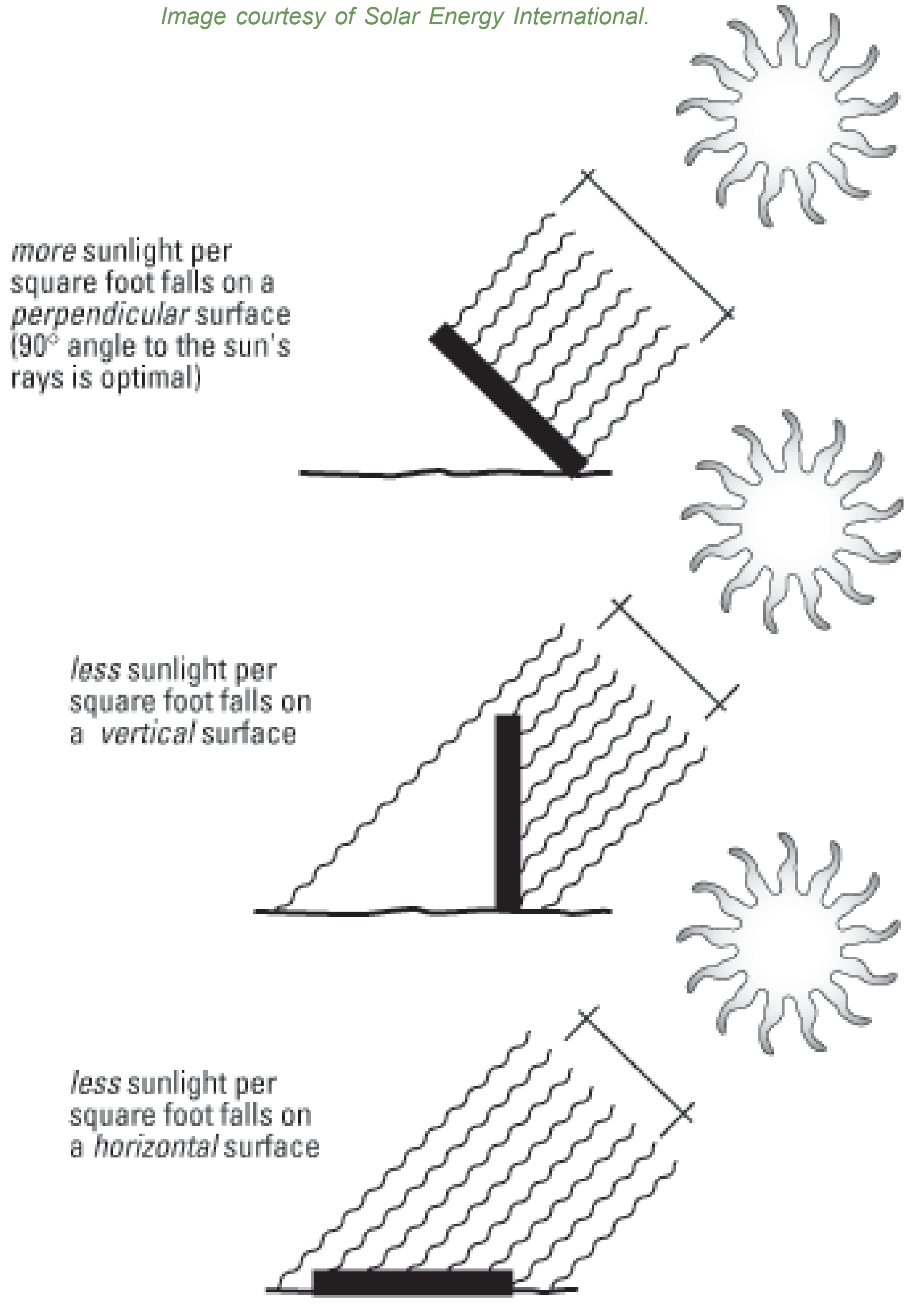
Image courtesy of Solar Energy International.



AZIMUTH AND ALTITUDE FOR ALL NORTHERN LATITUDES

In the real world, the ideal orientation can seldom be achieved for a single day, much less for an entire year. Array orientation always involves a compromised solution, usually determined by site constraints and system requirements. Note that although in certain situations (e.g., solar noon on a clear day on a polar ice cap in mid-summer) a PV panel will produce more than the rated output of the unit, there will more typically be factors that reduce the actual output from the rated output. An angle of incidence greater than 0º, atmospheric conditions, snow on the panels, and so forth will all reduce output. Generally speaking, the rated output of a PV panel mounted on a fixed array can only be obtained for around five hours on even the best solar day. Output drops off on either side of the solar window but can still add significantly to overall energy production. It is a common misconception that because there is 24 hours of daylight during the polar summer that this equates to 24 hours of maximum production. If at 1 a.m. the sun is shining on the backside of the panels, there is little or no electrical output. This all must be taken into consideration when designing the system.

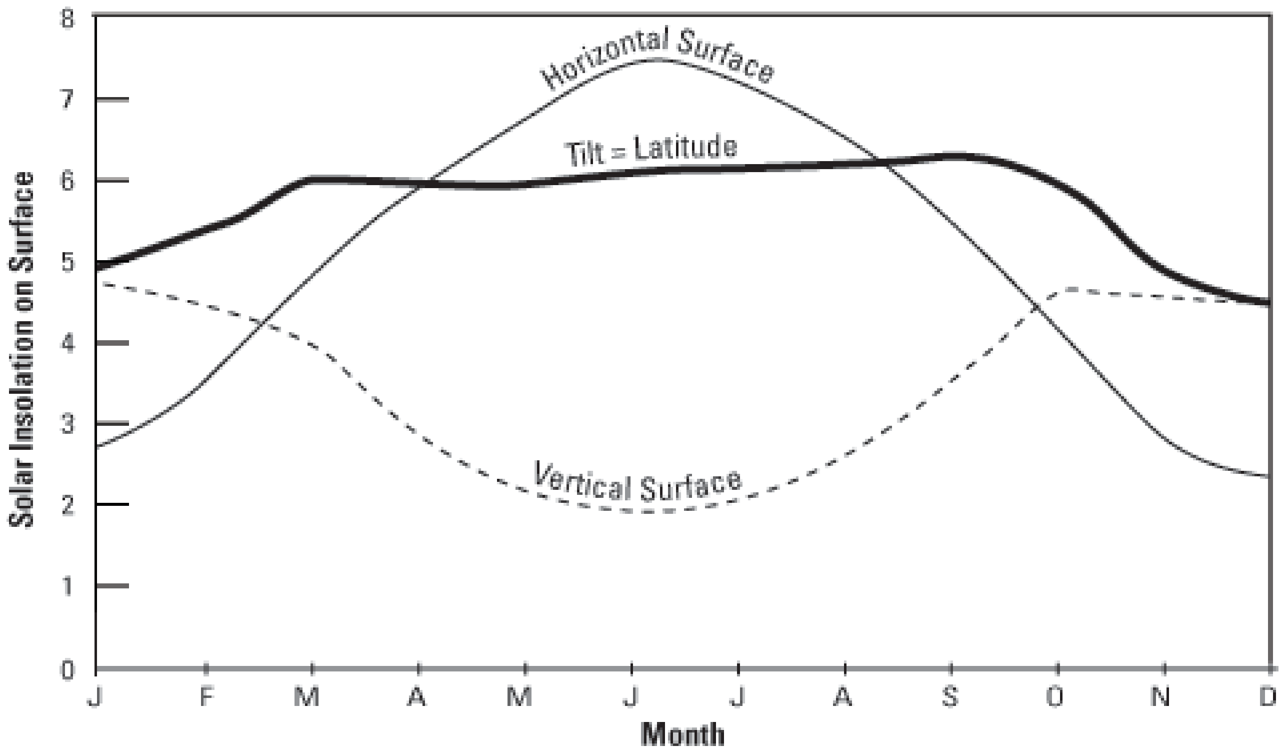
Image courtesy of Solar Energy International.



EFFECTS OF TILT ANGLE

Remember, too, that sunlight becomes scattered by the earth's atmosphere and is reflected from surfaces. As anyone who has experienced the albedo of an overcast day on snow-covered surfaces can attest, the light comes from many directions, not just in a straight line from the sun. Reflected light can definitely enhance PV panel performance and is an asset that polar researchers can utilize with great efficacy. Some work has been done on utilizing reflectors at the top of PV panels to enhance the reflected light capture for low-angle, winter applications. The total solar radiation striking the surface of the PV panel is what ultimately determines electrical output and is the sum of direct-beam radiation, diffuse radiation, and ground-reflected radiation. *Insolation* refers to the energy contained in the sunlight striking a surface area over a specified period of time. Solar insolation is therefore the prime criterion in determining the suitability of a location for PV applications.

Image courtesy of Solar Energy International.



Effect of Array Tilt on Energy Production

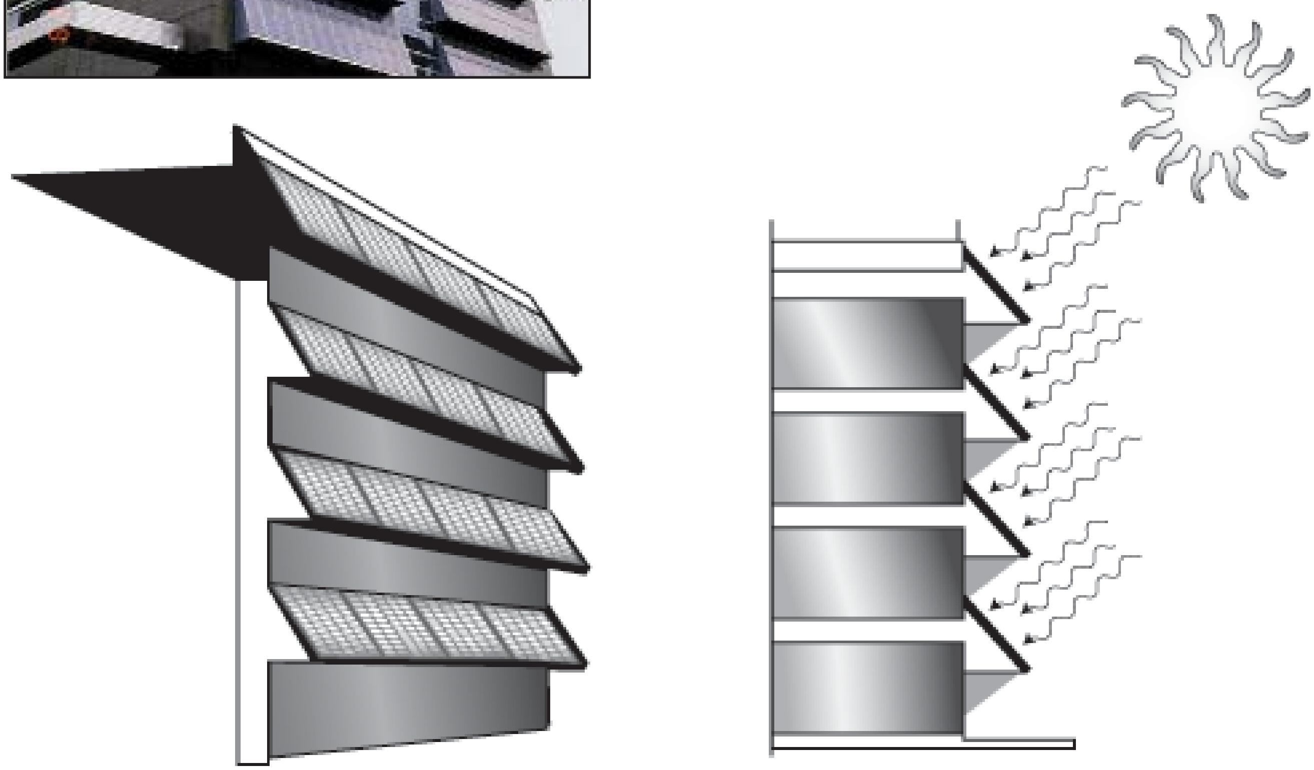
Additional factors that should be taken into consideration for orienting solar arrays include the following:

- Panel orientation should be optimized for summer-only, winter-only, or annual energy production. At the equator, there is essentially no significant variation in the angle of the solar radiation striking the surface. The higher the latitude, the greater the difference between the optimal angles for summer and winter production. For summer-only applications, low tilt angles tend to increase energy production. Winter-only applications should utilize high tilt angles. In the Polar Regions, so much more energy is available in the summer months that lower tilt angles will maximize annual energy production; however, battery banks can seldom be adequately sized to store all of the electrical energy produced.

- Utilizing a lower tilt angle in areas that experience heavy overcast can often significantly increase summer production. Although the utilization of direct-beam radiation is decreased, this orientation allows the panel to see more of the sky over a longer period of time. A summer-only application in interior Alaska is an example of a site that might maximize energy production by utilizing this strategy. PV arrays have been successfully deployed on structures located on the annual sea ice around McMurdo Sound, Antarctica, by securing them flat against the roof. An additional advantage is that there is much less surface area exposed to the wind, and the typically dry snow easily scours from the surface. Use caution, however, as wet snow can pose significant accumulation problems for flat-mounted panels.

- Overcast conditions coupled with snow-covered surfaces can result in high albedo, in which case a higher tilt angle will perform better because it can capture reflected light from the white surface. Vertical orientations can perform quite well at high latitudes and can sometimes represent an excellent compromise for year-round applications, particularly on permanently snow-covered (highly reflective) surfaces. Snow has a very hard time sticking to vertical surfaces. Simple tripod array mounts have been used with success on the Greenland Ice Cap and elsewhere. Pointing panels at different azimuth

For large, infrastructure-based systems, building integrated PV offers an architecturally interesting and cost effective solution. Pictured here is the Kyocera Headquarters in Kyoto, Japan.



PV FACADE—SAWTOOTH DESIGN

Image courtesy of Solar Energy International.

angles can increase production over the course of a 24-hour period. As an example, see the article on the Camp Raven Renewable Energy system. (http://polarpower.org under Examples > By Location > Greenland)

- Is this a manned, summer-only application? If so, the tilt angle should be adjusted weekly to maximize the collection of solar energy. A quick and easy way to make on-the-spot adjustments is to place an object such as a pencil or a ruler perpendicular to the module face at solar noon. If it is a clear day, the object will throw a shadow. Now simply adjust the panel until the shadow disappears, and the panel will be oriented perpendicular to the sun.

- Is this a high snow load area? If so, more vertical orientations may be required to keep the panels from being covered (effectively shaded) by snow. Also, the array must be a sufficient distance from the ground to prevent burial by snow accumulation, either from direct accumulation due to snow sliding off the front of the panels or from drifting snow conditions.

- Is this a high wind area? If so, then it is essential to thoroughly secure the array. By design, PV arrays present a lot of surface area for the mass of the unit. This creates a very effective sail. Substantial frames and bases are critical components to ensure that the array can survive the stresses of high wind conditions. Additional guys can be attached to earth anchors suited to the array location. This aspect of a deployment cannot be overemphasized. Every other aspect of a system design can be flawless, but if the entire thing blows away, it is all for naught. This has all too often been the case with systems deployed to polar environments.

- Will there be animals in the area that might damage equipment? This is a concern more unique to the Arctic where curious indigenous creatures large and small have had detrimental effects on research projects. Typically, if a system is robust enough, that is an adequate solution in and of its self. In deployments experiencing particularly high incidents of damage from animals, more proactive measures may be called for. These can include audible alarms set off by motion detectors or even electric fencing. Remember that these devices will place an increased demand on the power system and must be accounted for in the power balance.

Generally speaking, for a year-round PV system in polar environments, setting the tilt angle at latitude or latitude minus 10º is a pretty good rule of thumb. However, there are obviously many factors that must be considered when determining the best solution for mounting and orienting a PV array.

Inverters

An inverter is a device that converts DC power from the battery bank to AC power for various loads. In smaller PV systems, it may be possible to eliminate this component altogether. In larger systems incorporating components that demand AC power, an inverter must be utilized. Also, if the instrument site is located some distance from the power production site, an inverter allows for an efficient means of getting electricity to the point of use. Alternating current is easier to transport over long distances and has become the conventional modern electrical standard.

There are two fundamental categories of inverters: *synchronous* and *static* or *stand-alone.* Synchronous inverters are capable of being tied into the electrical *grid,* or utility power. Except in the largest of infrastructure-based systems, this type of inverter finds little application in the field of polar research. Static inverters are designed for independent, utility-free power systems and are the type most often used for remote PV applications.

A second inverter classification refers to the type of AC waveform they produce. Inverters are available in *square wave, modified square wave,* and *sine wave* outputs.

- Square wave inverters are inexpensive, but they typically provide poor output voltage control, limited surge capacity, and significant amounts of harmonic distortion. In general, this type of inverter is inappropriate for remote scientific research applications.

- Modified square wave inverters utilize more complex circuitry to create a wave form more closely approximating a true sine wave. They are capable of handling greater surge loads and have an output with less harmonic distortion. Although capable of powering a wider range of loads, there are still issues of concern for the polar researcher. Some electronic devices can pick up inverter noise, or buzz, and any device utilizing a digital timekeeper will run either fast or slow when powered by a modified square wave form.

- Sine wave inverters are best for powering sensitive electronics that require a high-quality wave form. They have little inherent harmonic distortion and typically have surge capacities of double or greater the continuous output rating. This is an important consideration if motors or other inductive loads are part of the overall power budget. Because sine wave inverters are now available in sizes from a few hundred watts to many kilowatts of output, there is little reason to consider any other type for polar research applications. ***Note: If AC power is part of the project requirement, use an inverter with a high-quality sine wave output.***

When selecting an inverter, many additional criteria must be considered:

- *DC voltage input* must match the battery voltage of the system.

- *AC power output* must be adequate to satisfy the maximum-potential combined AC load, or all of the AC-powered equipment that might be on at one time. However, the system designer should also be cautious about over-sizing the inverter, as most operate at their maximum efficiency toward the middle to upper end of their output range.

- *Voltage and frequency regulation* should be very tight in a high-quality unit. Voltage and frequency should match the system requirements (60 Hz/120 volts for U.S. equipment and 50 Hz/240 volts for European equipment). Note that step-up or step-down autotransformers can be utilized to change output voltages if required but at the expense of slightly more power consumption.

- *Efficiency* should be high across a broad range of output levels. Some inverter manufacturers claim high efficiency levels, but they may be measured at or near maximum output where the inverter will rarely operate. Choose an inverter rated for high efficiency over a wide range of load conditions.

- *Construction* should be consistent with the application requirements. Some inverters offer a sealed design or special coatings on the electronics to enhance reliability in wet or corrosive environments. Other inverters utilize open construction with a cooling fan for increased load capacity. A limited range of marine-rated inverters is available for maritime environments.

Balance-of-System Components

We have now discussed all of the major components that form a PV system. Still, there are many more bits and pieces required before proceeding from boxes of parts to a completed system.

Conductors

PV systems always incorporate DC circuits and often utilize an inverter for AC circuitry as well. AC and DC wiring systems have distinct requirements and should never be mixed in conduit, raceways, or junction boxes. DC systems are typically low voltage (< 48 VDC) and thus require much larger wire sizes than AC systems. Indeed, the wire size required to avoid unacceptable voltage drops across any distance or in high-current applications is often surprisingly large. Many systems have experienced poor performance due to inadequately sized conductors.

The polar environment introduces additional challenges in system wiring. Larger cables used for battery connections become incredibly stiff and difficult to work with due to the insulated sheathing. Coarse-stranded wire intended for residential AC-type use exacerbates the difficulty. Pre-assembling as much of the system as possible will reduce field installation woes. However, installing battery cables and runs from the PV array are often difficult to avoid.

Although conventional wire will often work just fine for the majority of applications, there are a few wire types that are of special interest for remote, cold-weather installations:

- “Arctic Flex” is a product that utilizes a special rubber insulating sheath that stays flexible up to very low temperatures. It is also a fine-stranded wire thus making it quite malleable and easy to work with. It is UL rated and National Electric Code (NEC) compliant. A wide range of sizes and colors are available.

- Welding cable, although not code compliant, offers a perfectly safe and considerably less expensive alternative for high-ampacity cabling requirements.

- For smaller wire sizes, automotive “primary” wire tends to be more flexible and easier to work with in the cold.

- Another favorite wire type of the polar installer is “SO” cord. This type of cord contains three or four insulated conductors inside an outer sheath. This is essentially the same material that extension cords are made out of. It is available in bulk in sizes up to #6 gauge. The outer sheathing varies widely in how flexible it remains in cold environments and seems to be somewhat color coded, with yellow and blue remaining the most flexible. Be sure to check the ratings.

- Armored “liquidtight” cable is heavier and more difficult to work with but offers a higher level of protection for the internal conductors. This is the type of cable to use for long runs in rocky or abrasive terrain or where animals might be a problem.

Remember that if wires are to be left exposed to the environment, they must be rated for exposure including UV radiation. The same energy that is providing power to your experiment can really take a toll on certain types of insulation. UV-resistant sheathing is generally marked as such on the outside. If it does not say “UV rated,” it probably is not.

Remember to include the correct adapters to bring the cables and conduit into the junction boxes and enclosures. Every type of conduit, armored cable, or SO cord requires something a bit different. The devil is in the details, so make sure you have the correct adapters—and plenty of them. Again, pre-assembly at your home institution is an effective way to ensure you have what you need when you arrive at the field site.

Combiner blocks, mechanical lugs, split bolts, and a variety of solderless connectors should have a place in your field tool kit. Rubber splicing tape and low-temperature electrical tape are essential as well. Red electrical tape serves as *code tape* to ensure that you know which of those black cables is the DC positive.

The convention for DC color-coding is as follows:

Red is for positive—the current-carying conductor.

White is for negative. (I code tape mine black.)

Green or bare is the equipment ground.

The fine-stranded wire recommended above is much easier to work with in cold environments but poses some additional requirements for system installation and maintenance. Mechanical lugs can damage or break the fine strands resulting in a weak connection and reduced ampacity. Take care during installation, and regularly check the tightness on all connections during all maintenance visits.

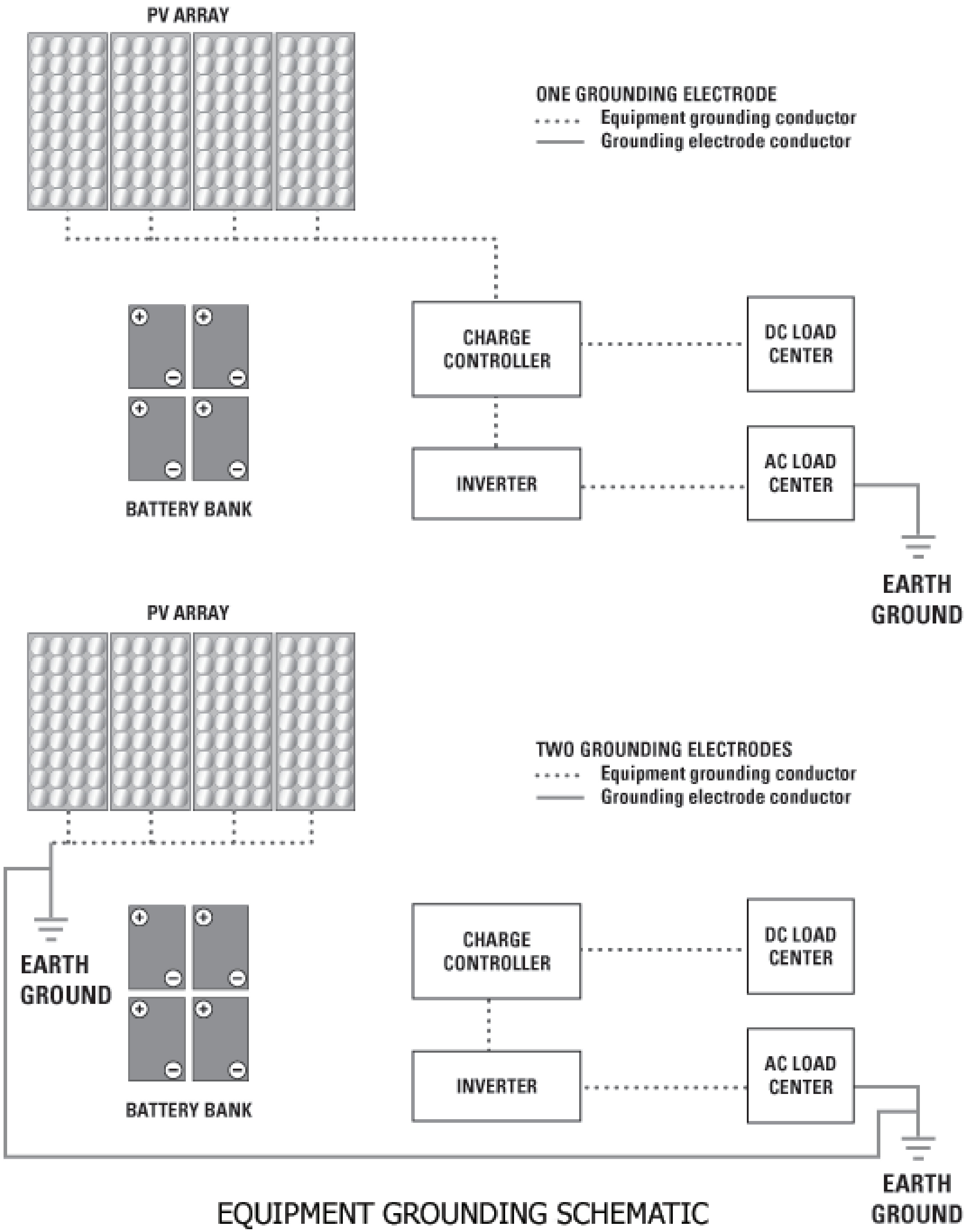
The positive and negative conductors in a DC system should be kept close together and in parallel for any long runs to avoid inductive potential.

Grounding

Grounding is a deceptively complicated issue. Although the NEC requires *equipment grounding* on all PV systems regardless of operating voltage, obtaining a true *earth ground* in polar environments can often be difficult or impossible to obtain. In areas of permafrost, rocky soil, or muskeg, grounding plates or grounding rings made of 4/0 bare copper will typically provide a satisfactory earth ground. This earth ground must be bonded to every metal electrical box or component enclosure, receptacle, and bare metal frame. The PV panels should be interconnected at the point specified on the frame and referenced back to the earth ground. The grounding wire is never fused or switched, and the entire system must be grounded at only one point.

In an ice cap environment, achieving an earth ground is typically not possible. As such, grounding is dealt with in the same way as within the automotive industry. In this method, the frame or chassis becomes the grounding point to which all of the negative conductors are referenced. Although not as good a system as a true earth ground, it does ensure that overcurrent devices will operate as designed.

For an extensive discussion of system grounding, see the Sandia National Laboratories report, *Photovoltaic Power Systems and the National Electric Code: Suggested Practices* (2001). The PDF version is available at: http://www.re.sandia.gov/en/ti/tu/Copy%20of%20NEC2000.pdf



EQUIPMENT GROUNDING SCHEMATIC

Overcurrent Protection

Although remote scientific research projects are unlikely to receive a visit from the Electrical Inspector, it is wise to include adequate circuit protection. Breakers and fuses serve to protect the equipment, provide safety, and allow for easier maintenance of the system. Moreover, these devices protect conductors from currents exceeding the rated ampacity. The NEC specifies the maximum overcurrent protection for each conductor size.

When the current exceeds the rated amperage of a breaker or fuse, the circuit opens and the flow of current ceases. Breakers are typically considered preferable, as they can simply be reset, whereas a blown fuse must be replaced. This necessitates having spare fuses on site. It should be noted that not all breakers are rated to handle DC. The arcing inherent in DC-type power systems will quickly burn out the contact points of a non-DC-rated breaker or switch. Specialized DC-rated breakers are available from most suppliers of PV equipment and should be used for main battery disconnects and other high-amperage applications. For smaller DC load protection, Square D “QO” series breakers are rated for up to 48 VDC and are widely available at a significantly lower cost.

Breakers are triggered by unequal expansion of a bi-metal strip as current flows through it and heats it up. In cold climates, the rated ampacity of a breaker can end up significantly lower than the current level at which it actually trips. Fuses are somewhat less affected by temperature extremes. Remember that overcurrent protection is really providing protection for the conductors or wiring in a circuit rather than the electrical device itself. If multiple sizes of wiring exist within a protected circuit, the breaker or fuse must be sized to protect the smallest wire.

Although your project may fall outside the auspices of the NEC, there is still good reason to comply with the provisions it contains to ensure a safe and reliable system. The NEC requires every ungrounded conductor to be protected by an overcurrent device. This is the positive wire in a DC system and the black and red conductors in an AC system.

At a minimum, DC-rated overcurrent protection should be supplied:

- Between the PV array and the charge controller,
- Between the charge controller and the battery bank,
- Between the battery bank and the DC load center,
- Between the battery bank and the inverter (if present), and
- For each DC circuit originating in the DC load center.

At a minimum, AC overcurrent protection should be supplied:

- For each AC circuit originating from the AC load center.

Power Consumption (Load)

In a well-designed PV system, there should be a relative balance of power. In other words, there should be enough power input to equal (and slightly exceed) the amount of power going out to instrumentation and other loads. In some instances, this will need to be calculated on an annual, rather than a daily or weekly, basis. A PV array or battery bank will ultimately lead to failure if it is too small, whereas the penalty for too large a system is excessive cost, weight, and difficulty of deployment. Essentially, a researcher should always plan on oversizing the system to ensure reliability. How much the system is oversized and where the emphasis will lie (PV vs. battery) are determined by the relative “safety margin” required and the amount of information available on solar insolation for the site. A 25% margin is usually considered normal, although a site with well-documented solar insolation and familiar system components might require only a 15% margin. For a relatively undocumented location and/or equipment, one might choose to run a 35% margin. For the purposes of this paper, the average value of 25% will be used. A couple of simple formulas help to define the relationship between the variables in the power balance:

Power consumption = (instrument loads x time) + (system losses x time)

Power available = (power input x time) – (system losses x time)

Power consumption can best be expressed in *watt hours* per day. A watt is the product of amps times volts: A x V = W. (Amps or *current* can also be expressed as *I.*) Watt hours is the product of watts multiplied by hours: W x time = watt hours. For a more in-depth discussion on electrical concepts, visit http://www.polarpower.org and navigate to Technologies > Power System Fundamentals.

The best way to determine the average watt hours per day that your system requires is to first determine the cumulative amount of power used in a week, then divide by seven. As expressed above, the sum of all instrumentation and other loads should be padded by 25% to compensate for system losses.

Efficiency

Clearly, the greater the operating efficiency of a system, the lower the overall power requirements will be. In designing residential PV power systems, it is generally accepted that every $1 spent on energy efficiency measures results in $3 that will not have to be spent on additional power-producing equipment (i.e., a larger PV array, battery bank, etc.). Equivalent documentation does not seem to exist for this relationship in PV-powered research projects, but it is probably safe to assume that the ratio is equal to or greater than that expressed above. Small systems are relatively easy and inexpensive to deploy, whereas large systems are costly to build and often expensive and challenging to deploy. ***Note: It is in the researcher's best interest to create systems that approach the problem comprehensively and that emphasize efficiency as one of the prime design criteria.*** Too often, instrumentation is selected on other criteria such as familiarity, but running an experiment in a laboratory setting and having it run reliably in a polar environment are two dramatically different things. Oftentimes, there is comparable equipment available that can perform the same function at a fraction of the power requirement. Time used in reducing the power requirement is invariably time well spent.

Here are a few things to consider:

1. DC-Only Systems

    - Most electronic equipment actually operates on DC power, despite the fact that most of the commercially available equipment is designed to plug in to AC power sources. This is because our electrical infrastructure, or grid, is an AC system due to its better transmission qualities. In essence, AC travels long distances better than DC. In a typical research project, however, distances are typically rather small, and DC may provide a more efficient power supply.

    - Another advantage to a DC-only type of system is that it eliminates the inverter (DC to AC converter), which is one of the more costly and complicated items in a stand-alone power system. Although they are typically very reliable, inverters have certainly been known to fail. Keep it simple. The fewer components there are, the fewer places there are for a failure to occur.

    - Consider that PV panels and the battery bank they supply are DC sources. It is best to try to match the system voltages across the board (e.g., 12-volt PV panels feed a 12-volt battery bank, which feeds 12-volt equipment), but this might not always be practical. It is generally easier to convert voltages downward (e.g., 24 volts to 12 volts), although step-up DC/DC converters are also available. Step-down DC/DC converters are very efficient and reliable. Design the system so that the primary system voltage matches or exceeds the highest voltage requirement in the system. System voltages should typically not exceed 48 VDC nominal. Higher DC voltages are suitable for some larger systems but require special equipment and present a much greater shock hazard.

    - The actual DC requirement for a device typically intended for AC service is often listed on the nameplate information. It is often not very difficult to cut a device over to DC operation for dramatically enhanced efficiency. Essentially, the AC circuitry (rectifier and transformer) is bypassed or removed. A DC/DC converter may be required to match the component requirement, but this is still typically much more efficient. ***Note: Familiarity with electronic equipment is a necessity!***

2. Logic Circuits

- The use of a programmable logic circuit, or PLC, allows for much greater control of the system. For instance, does every instrument need to be on all the time for sampling, or could some be quiescent for the majority of the time, waking up to take a sample once an hour? The power reduction can be dramatic when this approach is taken.

- Many pieces of equipment have this functionality built right in.

- Ladder-logic circuitry can often be employed to control when instrumentation is active. As the name implies, ladder logic simply requires one step to be completed (parameter satisfied) before the next step is initiated. This can often be accomplished with relatively simple circuitry.

3. Thermal Strategies

- All electrical equipment performs best within a certain temperature regime, and typically this is not –40º C. (PV panels are the exception: The colder it gets, the more efficiently they work.) Efforts made to control the internal temperature environment can yield great rewards. Batteries have less available power, lower voltages, and accept a charge with greater difficulty at low temperatures. On the positive side, the self-discharge rates are much lower as temperatures decrease. Excessive heat will rapidly deteriorate the performance of a battery bank.

Most electrical components have temperature specifications as well. If they are operated outside of those parameters, reliability and accuracy cannot be assured. Obviously, a system that can maintain a more steady-state temperature—or at least reduce the dramatic swings—will perform better than a system with no thermal strategy employed. Except for medium to large systems of greater complexity, it is typically an acceptable strategy to moderate temperature extremes rather than attempt to hold a system within tight temperature parameters.

To this end, batteries and other equipment should be housed inside enclosures. These enclosures should be well insulated. The inefficiencies discussed elsewhere in this section refer to energy that was not directly utilized to perform a function. The wasted energy is expressed as heat. In most polar environments, heat is a resource we can use. It should be the objective of every system designer to find ways to harness that otherwise wasted heat to modify the environment of the battery and/or equipment enclosure.

Controlling the thermal environment of any type of enclosure, be it a battery box or a home, really relies on just three things:

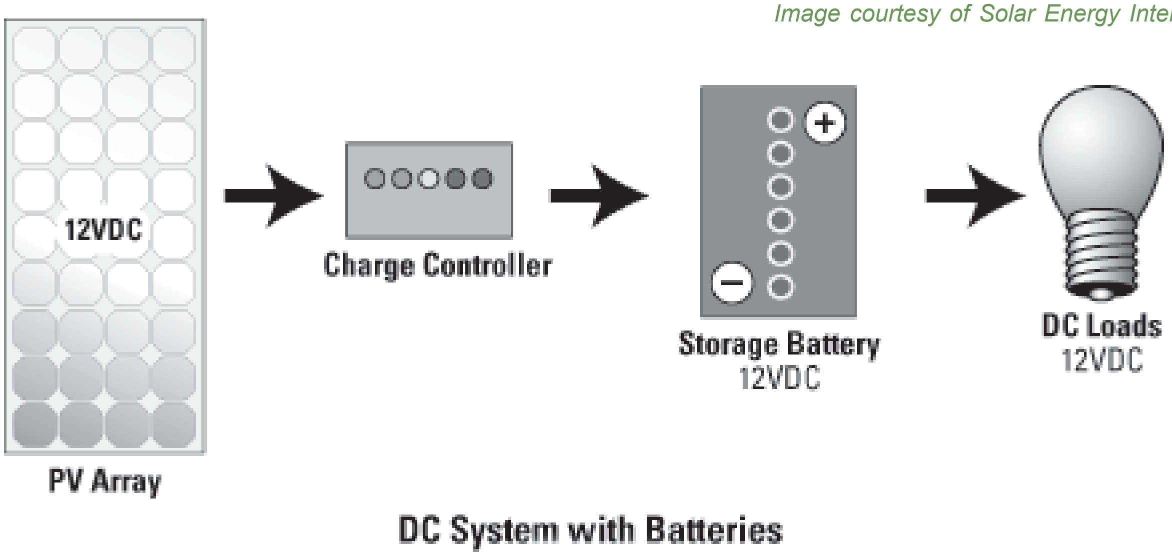
1. A thermal energy source
2. Insulation to prevent the heat from escaping
3. Thermal mass to moderate temperature swings

Methods employed vary widely from simple, passive systems to active systems that control temperature within tight parameters. How this problem is approached will be determined by how closely the temperature needs to be controlled and by the extremes of the environment the experiment is placed in.

The simplest systems rely on waste heat as the thermal energy source, insulation, and the thermal mass of the batteries to moderate the swings. The next step up might incorporate water as an additional thermal mass by actively heating it whenever there is available PV energy in excess of system requirements. Hybrid systems utilizing engine generators can tap into an enormous amount of heat energy that would otherwise be wasted to the environment. Finally, active systems can use stored energy (typically a fossil fuel source) to create on-demand heat as required.

For more information on thermal strategies, see the general section on “Thermal Strategies” (http://polarpower.org under Technologies > Systems Integration).

Image courtesy of Solar Energy International.



Putting It All Together

Safety

Working in remote, polar environments poses some inherent difficulties. Long hours in extreme cold, wind, and blowing snow can make an already difficult job nearly impossible. It is tempting in these conditions to relax one’s standards and take shortcuts to get the job done more quickly. However, this is exactly the time when one should slow down and move more cautiously. Good work habits are safe work habits thereby reducing the risk of accident and injury and increasing the likelihood of successfully completing a project.

In addition to the environmental hazards, installing PV systems bears its own potential hazards. The possibility of electrical shock, though low, does exist. Handling panels in high-wind situations is difficult and potentially dangerous and should be avoided. Batteries are typically the most dangerous components in a PV system. Although the shock hazard in a low-voltage system (< 50 volts) is relatively minor, batteries do have a very high short-circuit potential. Arcs can cause collateral damage by making a person jump back in reaction. In severe short-circuit instances, batteries have been known to explode. The acid electrolyte can cause severe burns, and the installer must be prepared to treat immediately with baking soda and water. Charging batteries can release hydrogen gas, which is highly flammable.

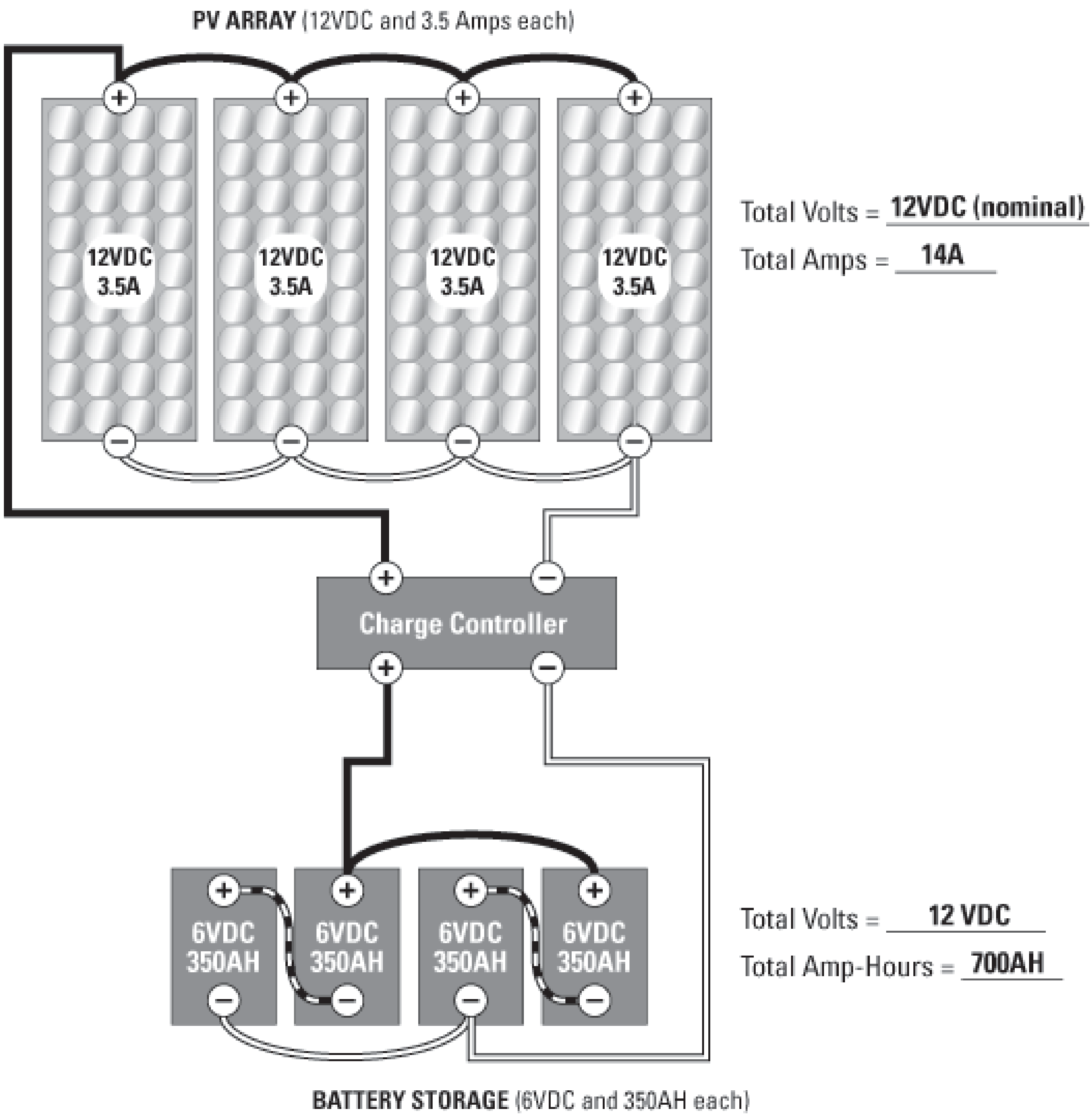
A well-planned and organized work site will dramatically reduce the risks involved with PV installation. Pre-wiring as much as possible and performing a “dry run” while still at the home institution will ensure that everything works properly and will increase familiarity with the system. All of this helps to ensure a safe and successful field deployment. For more on safety, visit http://www.polarpower.org and navigate to Technologies > Power System Fundamentals.

System Voltage

One of the advantages of PV systems is that they are modular in nature and can be configured for 12, 24, 48, or even 120 DC volts or higher. For most smaller, autonomous systems, a 12- or 24-volt configuration will be optimal. These lower voltages pose a somewhat lesser electrical hazard and are closer to the operating voltages of equipment typically deployed for purposes of scientific research. Although 12-volt systems have fallen somewhat out of favor in the industry due to the larger gauge cabling required, for many science experiments, this is still the optimal voltage to utilize. When power requirements or longer distances require it, a 24-volt system will usually provide an adequate solution. For only very large systems with high power requirements or systems that need to run DC power for a substantial distance should one ever consider going above 48 volts. High-voltage DC poses significant safety hazards, and even most DC-rated devices are not rated for voltages above 50 VDC.

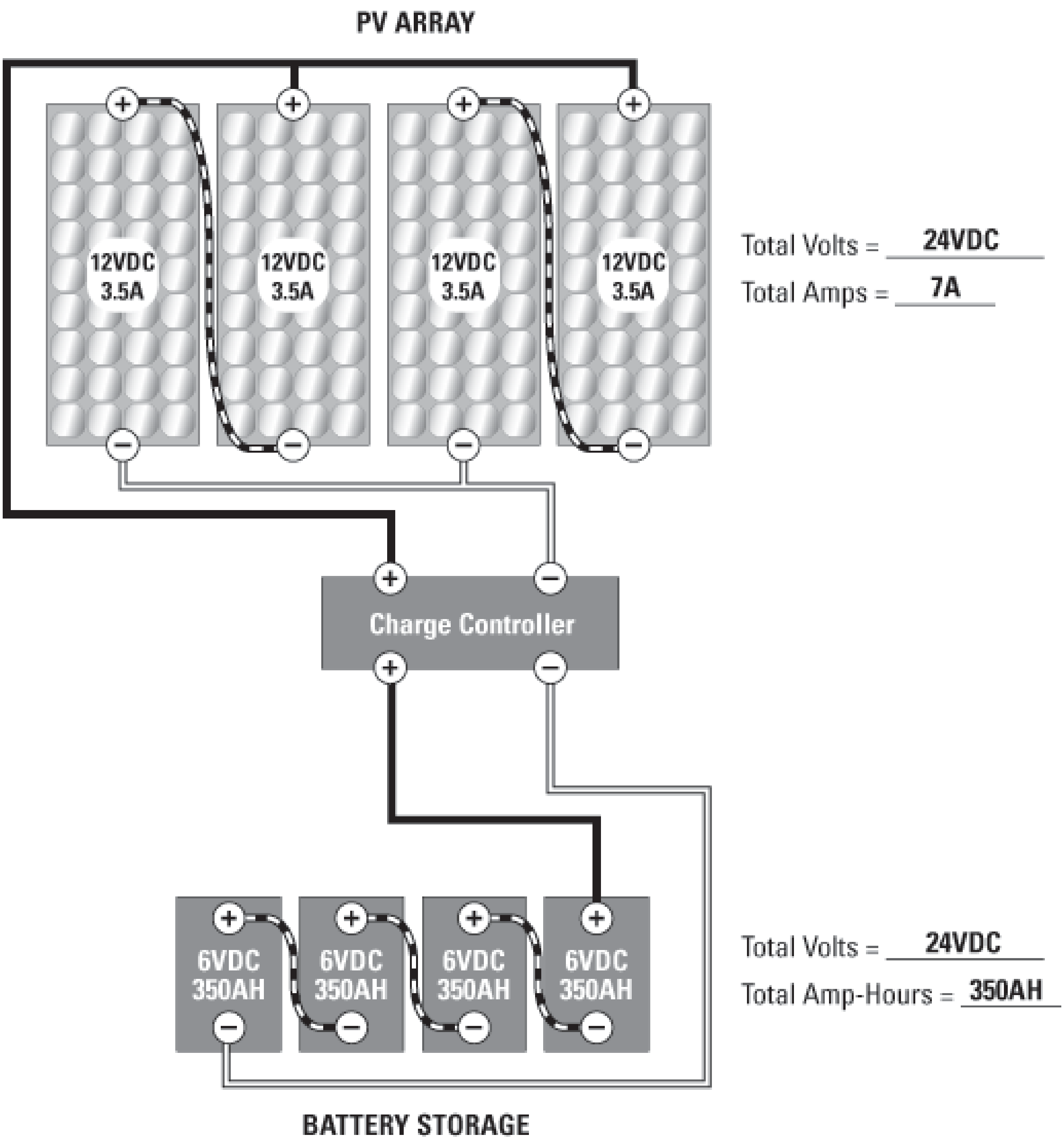
PV panels are typically available in 12- or 24-volt nominal ratings. Panels can then be wired either in series, which increases voltage while the amperage remains the same, or in parallel, which increases amperage while the voltage remains the same. For example, two 12-volt/20-watt PV panels wired in series would yield 24 volts at a 1.67-amp output, or 40.08 watts. The same two panels wired in parallel would produce a 12-volt output with a 3.34-amp capability, which is still 40.08 watts. Series-parallel configurations are often used for larger arrays and result in increases in both volts and amps. These are typically configured in *strings,* with each string running to a *combiner box*. At the combiner box, the smaller leads from each string are bonded to larger conductors to carry the full current to the charge controller(s).

Batteries are also modular and are typically available in 2-, 6-, or 12-volt ratings. The 2-volt cells are typically *industrial*-type batteries and are often already wired in series within an outer container. The 6- and 12-volt batteries are also composed of 2-volt cells, but they are molded into an integral unit. Most researchers will likely utilize 6- or 12-volt batteries. However, for higher power applications or instances where a very large battery bank is required to provide winter power for even low-power experiments, the 2-volt industrial cells can offer some significant advantages. Battery cabling can be expensive and time consuming, and often the footprint of a battery bank can end up being fairly large. Industrial cells are usually pre-configured in an outer container or a rack and utilize solid bars to interconnect a 12-volt string. Although the cells are typically rather heavy and must be handled individually, the finished bank can end up being much more compact and requires far fewer cable interconnections. As with PV panels, series-parallel connections are also possible. ***Note: It is very important to deliver and pull power from diagonal corners of the bank, thus ensuring equal loading of the system***.



12 VOLT SYSTEM WITH FOUR 12 VDC PV MODULES

Image courtesy of Solar Energy International.

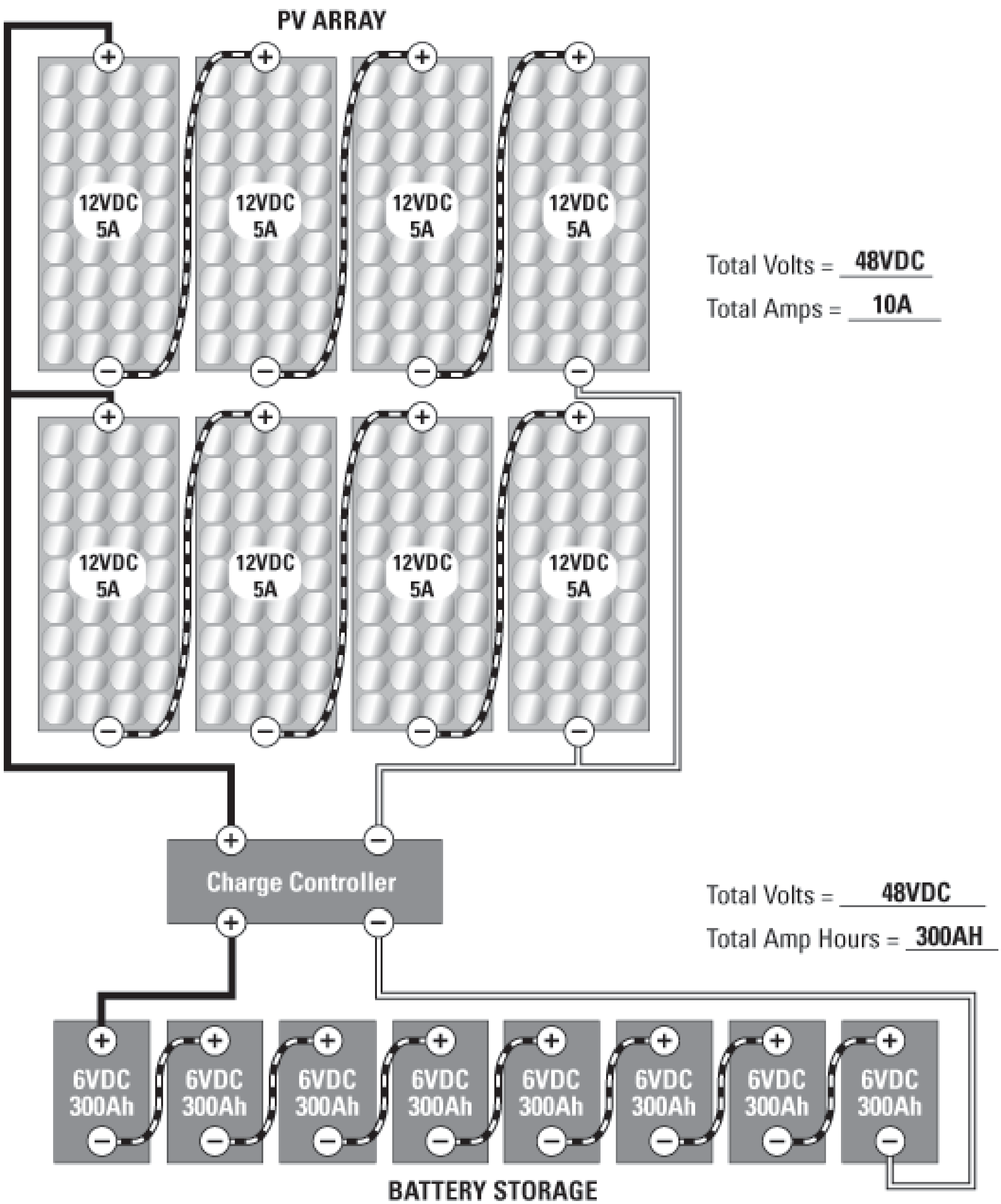


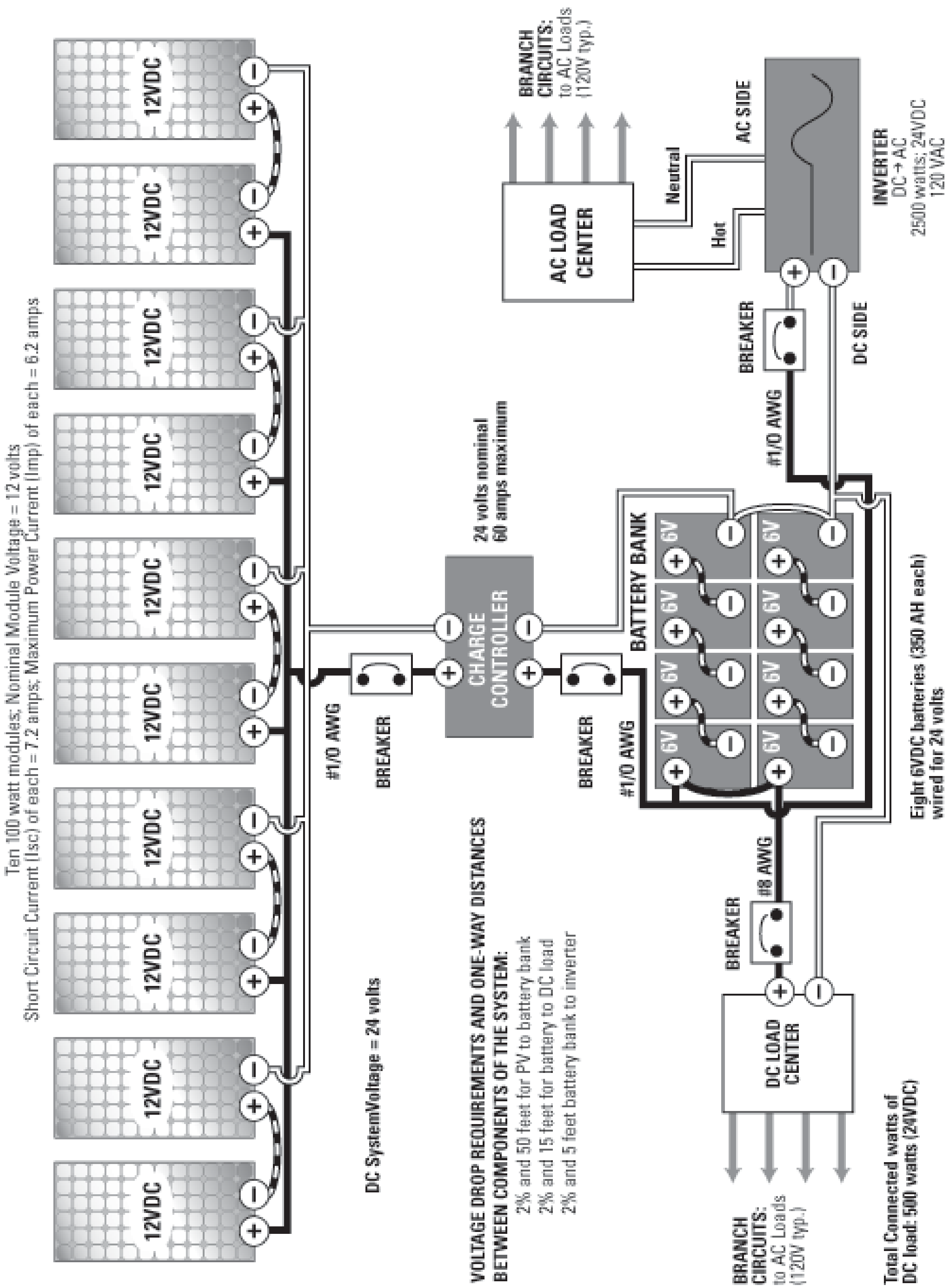
24 VOLT SYSTEM

Image courtesy of Solar Energy International.

Image courtesy of Solar Energy International.

48 VOLT SYSTEM WITH EIGHT 12VDC PV MODULES





AC AND DC LOAD SCHEMATIC

Image courtesy of Solar Energy International.

System Monitoring

At a minimum, every PV system should display the current status in terms of voltage and current flow. This allows the researcher to tell at a glance how the system is performing and what the energy balance looks like. Voltage alone does not tell the whole story and is not an adequate measure of system status. There are now several monitoring devices available that provide a wealth of information on how the system is performing, not only at the present moment but also over time. A cumulative amp hour reading is a very useful tool, as is the battery bank percent-full reading. One excellent, low-power battery monitor is the "Trimetric" (see: http://www.bogartengineering.com/). Any meter of this type will require installation of a shunt to measure energy flowing into and out of the battery bank. Bear in mind that this device utilizes a digital display and microswitches that may not perform well at extremely low temperatures. Some thermal regulation of the environment is advised.

Autonomous systems with remote monitoring access are becoming increasingly popular as polar researchers continue to push the limits of where and when scientific investigations can be accomplished. The advantages of near real-time system monitoring are fairly obvious to anyone who has deployed systems in the field. Without remote monitoring, it is impossible to know if the system is functioning properly. Many researchers have returned to a field site after a year to find that their instrument stopped working shortly after deployment. In some instances, the opportunity to collect that data set might never again be available.

Advances in the communications industry have made remote monitoring a realistic possibility in many cases. Lower prices, reduced power requirements, smaller dishes, and the nearly global nature of satellite coverage have made this technology more widely available to the research community. There is a penalty involved in terms of system complexity and increased power requirements, but in many instances, it is well worth the cost. When this functionality is introduced into a system, near real-time scientific data transfer becomes possible as well. Please visit http://polarpower.org under Technologies > Systems Integration for a more detailed discussion on Communications. Also visit > Examples > By Location > Alaska for a look at the Ivotuk autonomous system with full monitoring and data transfer capabilities. Link to the site live at: http://transport.sri.com/ivotuk/.

Fundamental Design Principles

Before moving on to the worksheet, one more area of basic system design should be covered. That is, how does it all physically fit together as a system? Stated simply, there are three basic approaches:

1. *Single unit:* All of the components are housed in a single enclosure with the PV, the batteries, the balance-of-system components, and perhaps even the science equipment integrated into the design.
2. *Modular:* Components are set up as modules that can be linked together and added onto as system requirements dictate.
3. *Hybrid:* This is essentially a combination of the first two concepts. There is a single main unit that contains the battery bank, the controls, and so forth but with separate PV array(s) as well as other possible power sources.

Each of these approaches is valid with intrinsic positive and negative features that will determine the suitability for a given project. The single-unit approach can be quite attractive and offers the benefit of being able to keep everything together with minimum field set-up required. However, how will it be deployed? Typically, this arrangement requires the use of equipment, be it ground based, helicopter, or fixed wing. Unless it is a very small system, this ends up being a rather large and difficult box to move. If the researcher has access to the required equipment, the advantages are hard to beat. This is also the easiest method for utilizing engine generators for on-demand power and offers the option of heat-recovery thermal strategies.

The modular approach is attractive for smaller projects or for areas where deployment will be an issue. There are numerous possible permutations of the basic design. As an example, consider a central unit containing the battery bank, the integral PV array, and the balance-of-system components including a place for science equipment. Additional PV arrays, wind turbines, battery banks, and so forth can be added on as power requirements dictate. The advantages here are:

- *Ease of deployment:* All of the components can be handled manually without the use of heavy equipment. The individual modules can be transported to the site via small aircraft and moved into position by hand. There are limitations, however.

- *Easy expansion of the system:* It seems almost inevitable that project scopes grow. As additional instrumentation loads are added on, the power requirements go up. Being able to plug in another PV array or battery bank without extensive system modification is a great advantage.

Disadvantages include:

- *More difficult to create effective thermal strategies*.

- *No room for personnel to get out of the weather to work on equipment*. Essentially, plan on working on everything outside, be it fair weather or foul. Setting up a tent adjacent to or even over the top of the system somewhat obviates this drawback.

The hybrid solution offers the option to draw on the best characteristics of both of the previous strategies. This can, however, prove to be a rather costly approach and may not be suitable for all projects. For examples of different types of PV Systems, visit http://polarpower.org and navigate to Examples > By Type of System > Solar.

This document was compiled by Tracy Dahl. Tracy can be contacted at Polarsolar@direcway.com.

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Photovoltaic System Sizing Worksheet

I. Load Analysis

DC Loads

Equipment Qty x volts x amps = watts x hr/day = watt hr/day x 7 = watt hr/week

________ ________________ x ________________ x ________ = ________
________ ________________ x ________________ x ________ = ________
________ ________________ x ________________ x ________ = ________
________ ________________ x ________________ x ________ = ________

AC Loads

Equipment Qty x V x A x 1.2 = watts x hr/day = watt hr/day x 7 = watt hr/week

________ ________________ x ________________ x ________ = ________
________ ________________ x ________________ x ________ = ________
________ ________________ x ________________ x ________ = ________
________ ________________ x ________________ x ________ = ________

1. Total power requirement in watt hours per week. ________
2. Multiply total by 1.2 to compensate for system losses during the battery charge/discharge cycle. ________
3. Enter the nominal voltage of the battery bank. ________
4. Divide line 2 by line 3. This is the amp/hr requirement per week. ________
5. Divide line 4 by 7 days. This is the average amp/hr requirement per day that will be used to size the battery bank and PV array. ________

II. Optimize Power System Demands

Examine power consumption and reduce total power requirements as much as possible. Identify any large and/or variable loads and try to eliminate them or find alternatives. Consider the preferential use of DC devices over AC to reduce losses in the conversion process. If there are large loads that cannot be eliminated, consider periodic sampling, use only during peak sun hours, or use only during the summer. Revise the load sizing worksheet with the now optimized results.

III. Size the Battery Bank

6. Enter the maximum number of days of autonomy the system must support. ________
7. Multiply line 5 by line 6. This is the amount of amp/hrs the system must store. ________
8. Enter the depth of discharge for the battery chosen. The value should not exceed 0.5 (50% depth of discharge). This prevents overdischarge and potential freezing of the electrolyte. ________
9. Divide line 7 by line 8. ________
10. Select the multiplier below that corresponds to the average winter temperature the battery bank will experience. ________

º C	º F	Multiplier
10	50	1.19
4.4	40	1.30
-1.1	30	1.40
-6.7	20	1.59
-10	14	1.65
-15	5	1.80
-20	-4	1.95
-25	-13	2.10
-30	-22	2.50
-35	-31	2.75
-40	-40	3.33
-50	-58	Forget it! Use a thermal strategy to keep batteries warmer.

*Note: The multipliers from –10º C/14º F and below are approximate. Information on battery performance in extreme cold is practically non-existent. This chart illustrates the importance of thermal regulation of the battery compartment.

11. Multiply line 9 by line 10. This ensures that the battery bank will have enough capacity to overcome cold weather effects and represents the total battery capacity needed. _______
12. Enter the amp hour rating for the battery chosen. _______
13. Divide line 11 by line 12 and round off to the next higher number. This is the number of batteries wired in parallel required. _______
14. Divide the nominal system voltage by line 3 and round off to the next higher number. This is the number of batteries wired in series required. _______
15. Multiply line 13 by line 14. This is the total number of batteries required. _______

IV. Determining the Solar Resource

Several factor influence how much solar insolation exposure the PV modules will experience. Latitude is the overriding factor in the Polar Regions and can be determined with some precision. Local weather conditions, the location and angle of the PV array, fixed mounting versus tracking, and whether the system will be running in the summer, winter, or year-round must all be taken into consideration. Determine an hour-per-day average for the desired site.

V. Size of the PV Array

16. Average sun hours per day. _______
17. Divide line 5 by line 16. This is the total array amps required. _______
18. Optimum or peak amps of solar module used. _______
19. Multiply line 18 by 0.8 for normal loads or by 0.7 for critical loads. _______
20. Divide line 17 by line 19 and round off to the next highest number. This is the number of solar modules in parallel required.
21. Multiply line 20 by the number of modules required to achieve the nominal DC voltage of the battery bank. This is the total number of PV modules required. _______

VI. Charge Controller

22. Multiply line 17 by 1.25. This is the minimum amp rating of the controller. The voltage rating of the charge controller must match the system DC voltage. _______

* Worksheet adapted from *Autonomous Systems in Extreme Environments*, a white paper resulting from the 1999 event hosted by JPL.