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Cilt 3, Sayı: 13, Mart 2004
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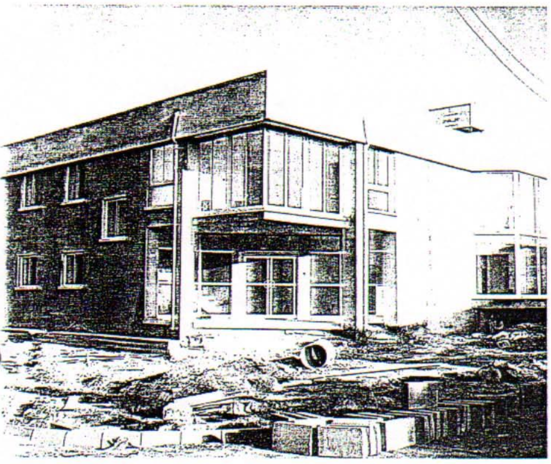

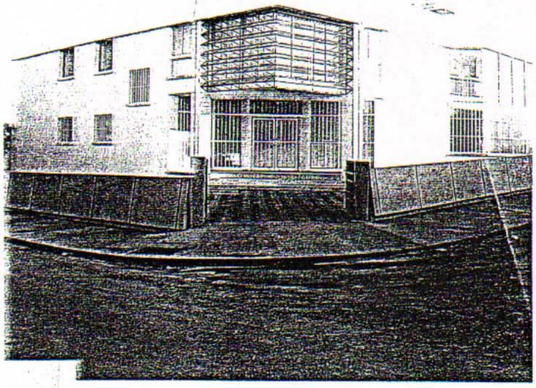

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Photovoltaic I-V Relationships

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1. PV Cell Material Science

This section covers the microscopic structure and operation of solar cells. While the information covered is focused on crystal silicon cells, the general concepts apply to other types of solar cells.

1.1 Structure

A silicon atom has fourteen protons and fourteen electrons. There are four electrons in the outer shell, which is also known as the valence band. Within the diamond lattice, a silicon atom forms covalent bonds with four neighboring atoms. In each bond, the silicon atom is sharing one of its four valence electrons and one of its neighbor's four valence electrons. As a result of the electron sharing, the atom's outer shell, which can have up to eight electrons, is full and the atom is at a stable state. The electrons are held in the valence band and cannot roam around from atom to atom. In order for the electrons to wander, they must gain energy and move to the conduction band.

1.2 Band Gap Energy

The energy difference between the conduction band and the valence band is called the band gap. Different materials have different band gaps. The gap also varies with temperature, decreasing slightly as temperature increases. The band gap determines the open circuit voltage of the solar cell. A material with a high band gap will have a higher open circuit voltage. Band gap energy is important in solar cell operation because the photons from the sun have a range of energy levels. Photons with energy levels below the band gap of a particular material will not be able to move an electron from the valence band to the conduction band.. They will either pass straight through the material or heat it up slightly. If a photon with energy equal to the band gap hits an electron, the electron will move into the conduction band, leaving behind a bond that now has only one electron. The place where there was an electron is called a hole and behaves like a positive charge. The photon is said to have created an electron-hole pair. A photon with more energy than the band gap can only free one electron. Any excess energy (the difference between the photon energy and the band gap energy) will be transformed to heat through the movement of the electron and lost.

1.3 Doping

A solar cell made of pure silicon will not produce useful energy. The electrons that are moved into the conduction band will simply wander around randomly and recombine with holes. There will be no useful current. In order for the cell to produce current, it needs to have an internal electric field. An electric field is created by doping the silicon. Doping is the process of introducing other elements into a material to alter its electrical properties. The elements added are called dopants. As discussed in the Anatomy Section, a silicon cell has two layers, an n-type layer on top of a p-type layer. These layers are silicon with different dopants and are named for the extra charges (n-negative, p-positive) they contain relative to undoped or intrinsic silicon.

2 PV Cells Types

Single Crystal Silicon

Thickness: 200 - 300μm, Band gap: 1.12 eV, Lab efficiency: 24%, Commercial production,
Companies: British Petroleum, Siemens Solar Industries, SunPower, University of New South Wales
These cells, along with poly crystal and amorphous silicon, make up the bulk of the PV market (over 60% single crystal). Of the three, they are generally the most efficient and the most expensive.

Poly Crystal Silicon

Thickness: 200 - 300μm, Band gap: 1.12 eV, Lab efficiency: 17.8%, Commercial production
Companies: Kyocera, Solarex
These cells, along with single crystal and amorphous silicon, make up the bulk of the PV market (approximately 30% poly crystal). They are generally less expensive and less efficient than single crystal cells. Instead of being a single crystal, the cell is made of many small crystals. The grain boundaries (where two crystals meet) are a source of electron-hole recombination. This reduces the current output of the cell and reduces its voltage. Progress has been made in minimizing grain boundaries and their effects.

Amorphous Silicon (aSi)

Band gap: 1.75 eV, Lab efficiency: 13% cell, 7 -9% stable modules, (Asi modules degrad during their first month of use), Commercial production
Companies: Solarex, Uni-Solar.
These cells, along with single and poly crystal silicon, make up the bulk of the solar cell market (roughly 4% amorphous). This is the type of cell found in a solar powered calculator. These cells are good candidates for multijunction cells.

Copper Indium Diselenide (CIS)

Also Copper Indium Gallium Selenide (CIGS)
Band gap: 1.0 eV, Lab efficiency: 17.1% cells, 11% modules, Companies: EnergyPV, International Solar Electric Technologies, Martin Marietta, Siemens Solar Industries, Solarex
These are complex cells with a complex manufacturing process. They do not have a degradation problem when put outside. Very high absorptivity (99%). One application possibility may be the bottom cell in a multijunction module.

Cadmium Telluride (CdTe)

Band gap: 1.44 eV, Lab efficiency: 15.8% cells, 10.5% modules, Companies: British Petroleum, Golden Photon Inc., Matsushita
These cells have high absorptivity. Cadmium is very toxic.

Photo-electrochemical Cells

Lab efficiency: 3.5% cells
In laboratory development at the Swiss Federal Institute of Technology in Lausanne. The cell is simple to construct.

Silicon Spheres

Lab efficiency: 10.3%, Companies: Developed by Texas Instruments, Advantage: Flexible, possibility of inexpensive production.
Texas Instruments was working on this technology in the early '90s. Since then, the technology has not been seen much....have any of you heard anything?

Gallium Arsenide (GaAs)

Band gap: 1.43 eV, Lab efficiency: 25.1% cells, Commercial production: 20% cells
These are very expensive cells that are used almost exclusively in space applications and experimental concentrator systems. GaAs has a high absorptivity which means that GaAs cells don't have to be very thick. Their power output is less affected by heat than silicon.

Multijunction

Lab efficiency: 30.3%
Multijunction cells are cells with different band-gaps that are stacked on top of each other. The top cell has the largest band gap energy. Photons with less energy will pass through to the next cell. Because a multijunction cell has materials with different band gaps, it can utilise more of the energy from the sun. Multijunction cells often have high material and production costs.

Concentrator

Lab efficiency: 27.6% single cell, 32.6% multi-junction, Companies: Spire, SunPower
Concentrator cells are primarily used in research. They are high efficiency cells (generally gallium arsenide or single crystal silicon) that are encased in a light focusing device such as a lens. By using a lens to increase insolation levels, the cell generates more power. The motivation behind concentrator research is that cell area (and therefore the cost associated with the cell) can be reduced because the light is focused.

Focusing the light makes it very important that the cell is receiving direct radiation because it will not be able to utilise diffuse light. This means that a dual axis tracking system is needed. Concentrator systems are also restricted geographically to areas with large amounts of direct solar radiation.

3 PV Cell Efficiency

3.1 Efficiency Measurements

When speaking of efficiency and photovoltaics, it is important to distinguish between different types of efficiencies. Are you referring to the solar cell, the solar array, or the whole photovoltaic system? And when describing the efficiency of a solar cell, it is important to determine what efficiency you are referring to. A solar cell's efficiency changes with the environment. For instance, a cell will operate with higher efficiency at cooler temperatures. In order to compare cell efficiencies, common operating conditions need to be agreed on. These are generally the testing conditions referred to in the Operation Section (1000 W/m^2, 25 C, AM1.5). There are two main ways that solar cell efficiency is discussed. One method uses the total area of the cell and the other method looks at the active area of the cell. For both cases, the general idea is that the efficiency is a ratio of the power out to the power in. The power out is calculated by multiplying the voltage and current of the cell (P_{out} = V x I). The power in is the insolation (S with units W/m^2) times the area (A with units m^2).

$$\text{efficiency} = (P_{out} / P_{in}) = [(V \times I) / (S \times A)]$$

Total Area

In a total area efficiency measurement, the whole face of the solar cell is used to calculate the area in the efficiency calculation. This measurement is useful for determining how the cell will actually perform when in use.

Active Area

In an active area efficiency measurement, the area used is only the area of the cell that is being illuminated. Areas not being illuminated are those that are covered by tabbing material and grid lines. Since they are not getting any power from the sun, they are not producing any power. Because the active area measurement does not include these areas, the efficiency number will be higher than for the total area measurement.

This measurement is more useful for material science purposes because it more accurately shows how the cell material is performing.

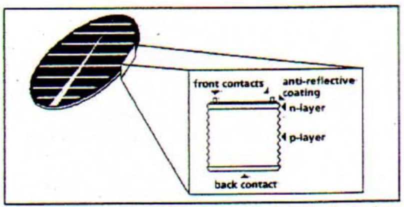
4 PV Cells - Anatomy

This section introduces you to the macroscopic physical characteristics of a solar cell. Microscopic information can be found in the Material Science section. The information is based on a typical crystal silicon cell. Specific details relating to other types of cells can be found in the Types section.

4.1 Dimensions

A typical single crystal silicon solar cell has a deep blue color and weighs under 10 grams. It is roughly 10 cm in length and width. Different manufacturers produce cells with different dimensions. The manufacturer can provide data on the exact dimensions and tolerances of specific cells. When calculating total cell area, it is important to note that some cells, such as the one shown above, have notched corners.

4.2 Cross Section



front contact (tabbing and grid lines)
This collects the current generated by the cell. The tabbing material is generally copper with a tin coating. Large tabbing takes away from productive cell area, but small tabbing has greater resistance losses. The front contact is the negative contact.

anti-reflective coating (150 nm thick)
Coating to help keep light from reflecting off the surface. Without any coating, the silicon would reflect close to one third of the light. Thin layers anit-reflective coating are used to reduce the reflectance to under 5%. Combined with texturing, the reflectance can be under 2%.

texturing
This is common in high efficiency cells. Pyramids and cones are chemically etched on the surface of the cell. These surfaces allow the cell to catch some of the light that would normally reflect off of it.

n-type silicon (300 nm thick)
Silicon doped with phosphorous. This is the negative side of the solar cell.

p-n junction
Where the n-type and p-type layers meet. Also known as the depletion zone.

p-type silicon (250,000 nm thick)
Silicon doped with boron. This is the positive side of the solar cell.

back contact
A metal contact on the backside where electrons enter the cell. This is the positive contact.

5 PV Cell Operation

This section introduces the basic operating characteristics of a single cell, including current and voltage characteristics, the effects of changing temperature and insolation, and fill factor. Understanding the basics of how a cell reacts to changing inputs will help you understand how a solar array functions in the natural environment. Numerous lab tests have been conducted to quantify solar cell performance. Certain conditions have been established as industry standards for testing. In the data given below, unless specifically mentioned, the conditions are as follows:

Standard Testing Conditions (STC)

Temperature = 25 °C, Insolation = 1000 W/m^2, Air mass = AM1.5

Air mass refers to the thickness of the atmosphere that the sunlight passes through. If the sun is directly overhead, the air mass equals 1. Different wavelengths of light are absorbed by the atmosphere and this changes the available energy at certain wavelengths. Air mass is an important indicator of the characteristics of the available light because solar cells utilise solar radiation at specific wavelengths.

5.1 Current and voltage

A solar cell generates dc current. The amount of current produced is a function of the voltage. Solar cell IV curves are graphs that show the relationship of current and voltage. The curves are used to determine how cells will perform under certain conditions and to compare different cells. Figure PVCO1 is a typical IV curve for a crystal silicon cell under standard conditions. Notice that to the left of the knee of the curve, current changes very little with large voltage changes, but to the right of the knee, current changes significantly with small voltage changes. The numbers given below are common values for this type of cell.

I_{sc} = short circuit current = 3.36A, V_{oc} = open circuit voltage = 0.6V,

P_{max} = maximum power point = 1.5W , I_{max} = current at P_{max} = 3A , V_{max} = voltage at P_{max} = 0.5V

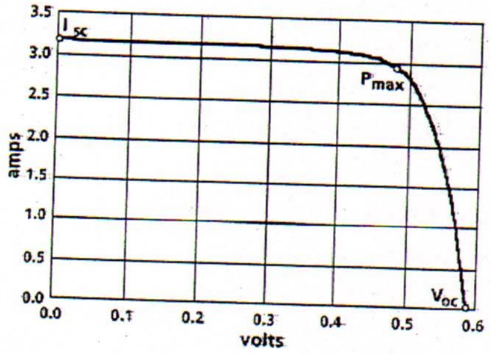


Fig. PVCO1: The IV curve for a typical crystal silicon cell under STC

5.2 Temperature

The graph below shows the cell's IV characteristics at three different temperatures (other conditions being the same).

Power output falls as temperature increases, Voltage falls roughly 0.0023V per increased degree C, Change in current is very small (slight increase with temperature), and is usually ignored in calculations.

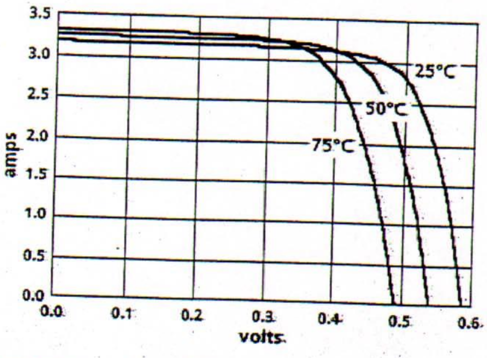


Fig. PVCO2: The temperature variation of IV curves for a typical crystal silicon cell.

Insolation

Figure PVCO3 shows the effects of increased insolation at constant temperature (25 C).
Power output increases as insolation increases. Current increases significantly. If insolation increases by 50%, I_{sc} will also increase by 50%., Voltage change is very small (slight increase with insolation), and is usually ignored in calculations.

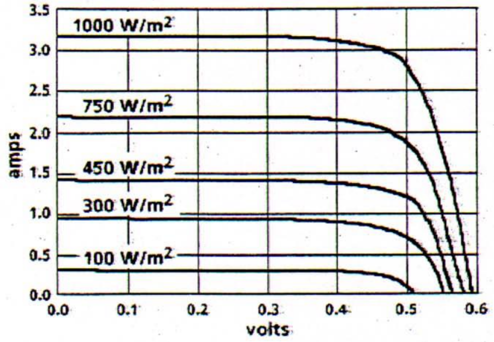


Fig. PVCO3: The insolation variation of IV curves for a typical crystal silicon cell. Courtesy

5.3 Fill factor

While the short circuit current and open circuit voltage is generally the same among solar cells of one type, the shape of the cells' IV curves may vary substantially. The fill factor (FF) is a number used to describe the squareness of a curve. A higher fill factor means that a curve is squarer. The fill factor is the maximum power divided by the product of open circuit voltage and short circuit current:

$FF = P_{max} / (V_{oc} \times I_{sc})$.

The fill factor is always less than one and has no units. The number does not change substantially with temperature and insolation so the value at STC is used for most calculations. A high fill factor is almost always desirable.
Figure PVCO4 shows an IV graph with two curves. Cell 1 has a fill factor of 0.75 while cell 2 has a fill factor of 0.45. Not only does cell 1 have a higher maximum power point than cell 2, but it also has a higher power output at every voltage from zero to open circuit.

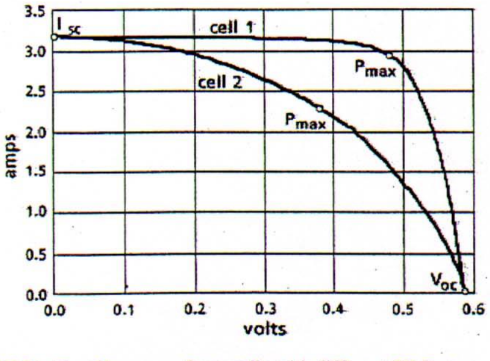
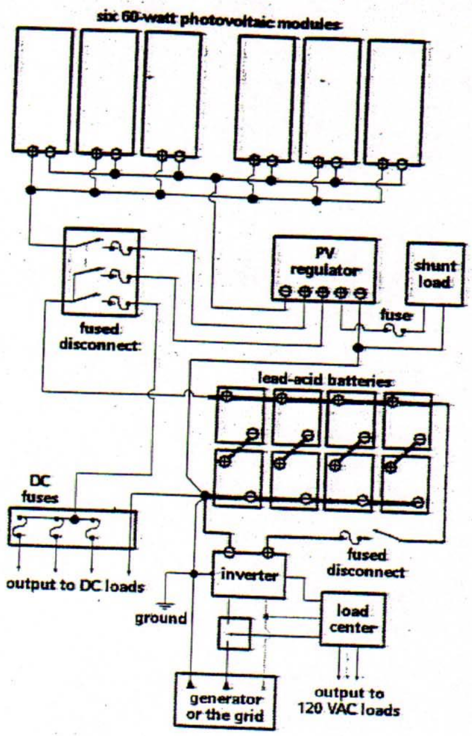


Fig. PVCO4: The IV curves of two cells with different fill factors.

6 PV Systems Components

The components needed in a PV system vary from application to application. This section focuses on systems for houses that are not connected to the grid. Many of the components are similar to those found in other systems. Four of the biggest factors in deciding what components are needed are: the funding available, the need for energy storage, the need for reliability, and the need for AC power. The amount of money available for a system will obviously play a large role in deciding how large and complex a system can be. Below is a map for a photovoltaic system for a house. Not all systems have all of the components shown here.


six 60-watt photovoltaic modules
PV regulator
shunt load
fuse
fused disconnect
lead-acid batteries
DC fuses
output to DC loads
inverter
fused disconnect
ground
load center
generator or the grid
output to 120 VAC loads

6.1 Production

The primary source of energy production is from the solar array. The array may be a simple fixed panel or a number of panels that can track the sun. It is discussed in the Cell and Array sections. Many systems also incorporate a standard combustion generator that is used as a back up in case of long periods of bad weather or high loads. Unlike the solar array, the generator produces ac power. Other systems are tied in to the power grid which accepts any extra energy and provides energy if the system's demand is higher than the array's production. The grid also carries ac power.

6.2 Storage

Energy storage is needed if a system is required to deliver power when the sun is not out or to deliver more power than is currently available from the array. The storage capacity is usually determined by cost and the need for reliability. The most common storage device is a pack of lead acid batteries. More information can be found in the Storage section. There may be times when the battery pack is full and the array is generating more power than is needed by the loads. In this situation, some systems will divert some of the energy to a shunt load. This is often something like a hot water heater.

6.3 Conditioning

Power conditioning equipment is used to convert power from one form to another. A power conditioning device is needed to operate loads at different voltages, utilize alternating current, or to maximize the operation of the array. Power conditioning equipment may include some or all of the following:

Peak power tracker (PPT) -- This is a device that is placed in a circuit between the array and the batteries. It allows the array to operate at its maximum power point which often means that the array will have a different voltage from the batteries. The PPT acts as a dc to dc converter between the voltages. Most peak power trackers are very efficient and fairly expensive.

DC to DC converter --- If the loads operate at a different voltage than the battery voltage, a converter is needed between the loads and the battery.

Inverter -- If the system has AC loads, an inverter is needed to convert the dc current to ac current.

6.4 Monitoring and Safety Devices

Meters are used to monitor the performance of the array and the batteries and to keep track of the various loads in the system. They provide warnings if energy storage is too low.
Safety equipment protect people and equipment from damage. Fuses limit current flow to protect from short circuits and switches allow components to be isolated. The National Electric Code has safety equipment requirements for some systems.

7. DEEP CYCLE BATTERIES

A deep cycle battery is basically a battery that is designed to be deep-cycled. A shallow-cycle battery is like your normal car battery. Deep cycle batteries are different - they have much thicker plates, and are intended for usage where they must supply power over a long period of time, as opposed to the car battery that only needs to supply a lot of amps for a few seconds. A "cycle" is where the battery is discharged to a standard level, usually 10.5 volts (100% discharge), and then recharged. A deep cycle battery is designed to be discharged down to 50% or more without damage. A typical starting battery is usually only discharged around 3% to 5% - and deep-cycling a car battery will lead to rapid failure.There is a wide variety of deep cycle battery types, sizes, and manufacturers.

Practically all batteries used in PV and al but the smallest backup systems are Lead-Acid type batteries. Even after over a century of use, they still offer the best price to power ratio. A few systems use NiCad, but we do not recommend them except in cases where extremely cold temperatures (-50 F or less) are common. They are expensive to buy, and very expensive to dispose of due the the hazardous nature of Cadmium. We have had almost no direct experience with the NiFe (alkaline) batteries, but from what we have learned from others we do not not recommend them - one major disadvantage is that there is a large voltage difference between the fully charged and discharged state. Another problem is that they are very inefficient - you lose from 30-40% in heat just in charging and discharging them. Many inverters and charge controls have a hard time with them. It appears that the only current source for new cells is from Hungary.

It is important to note here that ALL of the batteries commonly used in deep cycle applications are Lead-Acid. This includes the standard flooded (wet) batteries, gelled, and AGM. They all use the same chemistry, although the actual construction of the plates etc can vary considerably. NiCads, Nickel-Iron, and other types are found in some systems, but are not common due to their expense and/or poor efficiency.

7.1 Major Battery Types

Batteries are divided in two ways, by application (what they are used for) and construction (how they are built). The major applications are automotive, marine, and deep-cycle. Deep-cycle includes solar electric (PV), backup power, and

RV and boat "house" batteries. The major construction types are flooded (wet), gelled, and AGM (Absorbed Glass Mat). AGM batteries are also sometimes called "starved electrolyte" or "dry", because the fiberglass mat is only 95% saturated with Sulfuric acid and there is no excess liquid. Flooded may be standard, with removable caps, or the so-called "maintenance free" (that means they are designed to die one week after the warranty runs out). All gelled are sealed and a few are "valve regulated", which means that a tiny valve keeps a slight positive pressure. Nearly all AGM batteries are sealed valve regulated (commonly referred to as "VRLA" - Valve Regulated Lead-Acid). Most valve regulated are under some pressure - 1 to 4 psi at sea level.

7.2 Lifespan of Batteries

The lifespan of a battery will vary considerably with how it is used, how it is maintained and charged, temperature, and other factors. In extreme cases, it can vary to extremes - we have seen L-16's killed in less than a year by severe overcharging, and we have a large set of surplus telephone batteries that sees only occasional (5-10 times per year) heavy service that are now over 25 years old. We have seen gelled cells destroyed in one day when overcharged with a large automotive charger. We have seen golf cart batteries destroyed without ever being used in less than a year because they were left sitting in a hot garage without being charged. Even the so-called "dry charged" (where you add acid when you need them) have a shelf life of at most 18 months, as they are not totally dry (actually, a few are, but hard to find, the vast majority are shipped with damp plates).

These are some general (minimum - maximum) typical expectations for batteries used in deep cycle service:
Starting: 3-12 months
Marine: 1-6 years
Golf cart: 2-6 years
AGM deep cycle: 4-8 years
Gelled deep cycle: 2-5 years
Deep cycle (L-16 type etc): 4-8 years
Industrial deep cycle (Crown and Rolls 4KS series): 10-20+ years
Telephone (float): 1-10 years (these are special purpose "float service", but often appear on the surplus market as "deep cycle").
NiFe (alkaline): 2-25 years
NiCad: 1-20 years

7.3 Starting, Marine, and Deep-Cycle Batteries

Starting (sometimes called SLI, for starting, lighting, ignition) batteries are commonly used to start and run engines. Engine starters need a very large starting current for a very short time. Starting batteries have a large number of thin plates for maximum surface area. The plates are composed of a Lead "sponge", similar in appearance to a very fine foam sponge. This gives a very large surface area, but if deep cycled, this sponge will quickly be consumed and fall to the bottom of the cells. Automotive batteries will generally fail after 30-150 deep cycles if deep cycled, while they may last for thousands of cycles in normal starting use (2-5% discharge).Deep cycle batteries are designed to be discharged down as much as 80% time after time, and have much thicker plates. The major difference between a true deep cycle battery and others is that the plates are SOLID Lead plates - not sponge. Unfortunately, it is often impossible to tell what you are really buying in some of the discount stores or places that specialize in automotive batteries. The popular golf cart battery is generally a "semi" deep cycle - better than any starting battery, better than most marine, but not as good as a true deep cycle solid Lead plate, such the L-16 or industrial type. However, because the golf cart (T-105, US-2200, GC-4 etc) batteries are so common, they are usually quite economical for small to medium systems.Many (most?) Marine batteries are usually actually a "hybrid", and fall between the starting and deep-cycle batteries, while a few (Rolls-Surrette and Concorde, for example) are true deep cycle. In the hybrid, the plates may be composed of Lead sponge, but it is coarser and heavier than that used in starting batteries. It is often hard to tell what you are getting in a "marine" battery, but most are a hybrid. "Hybrid" types should not be discharged more than 50%. Starting batteries are usually rated at "CCA", or cold cranking amps, or "MCA", Marine cranking amps - the same as "CA". Any battery with the capacity shown in CA or MCA may not be a true deep-cycle battery. It is sometimes hard to tell, as the terms marine and deep cycle are sometimes overused. CA and MCA ratings are at 32 degrees F, while CCA is at 0 degree F. Unfortunately, the only positive way to tell with some batteries is to buy one and cut it open - not much of an option.

7.4 Temperature Effects on Batteries

Battery capacity (how many amp-hours it can hold) is reduced as temperature goes down, and increased as temperature goes up. This is why your car battery dies on a cold winter morning, even though it worked fine the previous afternoon. If your batteries spend part of the year shivering in the cold, the reduced capacity has to be taken into account when sizing the system batteries. The standard rating for batteries is at room temperature - 25 degrees C (about 77 F). At approximately -22 degrees F (-27 C), battery AH capacity drops to 50%. At freezing, capacity is reduced by 20%. Capacity is increased at higher temperatures - at 122 degrees F, battery capacity would be about 12% higher.Battery charging voltage also changes with temperature. It will vary from about 2.74 volts per cell (16.4 volts) at -40 C to 2.3 volts per cell (13.8 volts) at 50 C. This is why you should have temperature compensation on your charger or charge control if your batteries are outside and/or subject to wide temperature variations. Some charge controls have temperature compensation built in (such as Morningstar) - this works fine if the controller is subject to the same temperatures as the batteries. However, if your batteries are outside, and the controller is inside, it does not work that well. Adding another complication is that large battery banks make up a large thermal mass.Thermal mass means that because they have so much mass, they will change internal temperature much slower than the surrounding air temperature. A large insulated battery bank may vary as little as 10 degrees over 24 hours internally, even though the air temperature varies from 20 to 70 degrees. For this reason, external (add-on) temperature sensors should be attached to one of the POSITIVE plate terminals, and bundled up a little with some type of insulation on the terminal. The sensor will then read very close to the actual internal battery temperature. Even though battery capacity at high temperatures is higher, battery life is shortened. Battery capacity is reduced by 50% at -22 degrees F - but battery LIFE increases by about 60%. Battery life is reduced at higher temperatures - for every 15 degrees F over 77, battery life is cut in half. This holds true for ANY type of Lead-Acid battery, whether sealed, gelled, AGM, industrial or whatever. This is actually not as bad as it seems, as the battery will tend to average out the good and bad times. Click on the small graph to see a full size chart of temperature vs capacity.One last note on temperatures - in some places that have extremely cold or hot conditions, batteries may be sold locally that are NOT standard electrolyte (acid) strengths. The electrolyte may be stronger (for cold) or weaker (for very hot) climates. In such cases, the specific gravity and the voltages may vary from what we show.

7.5 Cycles vs Life

A battery "cycle" is one complete discharge and recharge cycle. It is usually considered to be discharging from 100% to 20%, and then back to 100%. However, there are often ratings for other depth of discharge cycles, the most common ones are 10%, 20%, and 50%. You have to be careful when looking at ratings that list how many cycles a battery is rated for unless it also states how far down it is being discharged. For example, one of the widely advertised telephone type (float service) batteries have been advertised as having a 20-year life. If you look at the fine print, it has that rating only at 5% DOD - it is much less when used in an application where they are cycled deeper on a regular basis. Those same batteries are rated at less than 5 years if cycled to 50%. For example, most golf cart batteries are rated for about 550 cycles to 50% discharge - which equates to about 2 years.Battery life is directly related to how deep the battery is cycled each time. If a battery is discharged to 50% every day, it will last about twice as long as if it is cycled to 80% DOD. If cycled only 10% DOD, it will last about 5 times as long as one cycled to 50%. Obviously, there are some practical limitations on this - you don't usually want to have a 5 ton pile of batteries sitting there just to reduce the DOD. The most practical number to use is 50% DOD on a regular basis. This does NOT mean you cannot go to 80% once in a while. It's just that when designing a system when you have some idea of the loads, you should figure on an average DOD of around 50% for the best storage vs cost factor. Also, there is an upper limit - a battery that is continually cycled 5% or less will usually not last as long as one cycled down 10%. This happens because at very shallow cycles, the Lead Dioxide tends to build up in clumps on the the positive plates rather in an even film. The graph above shows how lifespan is affected by depth of discharge. The chart is for a Concorde Lifeline battery, but all lead-acid batteries will be similar in the shape of the curve, although the number of cycles will vary.

7.6 Battery Voltages

All Lead-Acid batteries supply about 2.14 volts per cell (12.6 to 12.8 for a 12 volt battery) when fully charged. Batteries that are stored for long periods will eventually lose all their charge. This "leakage" or self discharge varies considerably with battery type, age, & temperature. It can range from about 1% to 15% per month. Generally, new AGM batteries have the lowest, and old industrial (Lead-Antimony plates) are the highest. In systems that are continually connected to some type charging source, whether it is solar, wind, or an AC powered charger this is seldom a problem. However, one of the biggest killers of batteries is sitting stored in a partly discharged state for a few months. A "float" charge should be maintained on the batteries even if they are not used (or, especially if they are not used). Even the "dry charged" batteries (those sold without electrolyte so they can be shipped more easily, with acid added later) will deteriorate over time. Max storage life on those is about 2-3 years.Batteries self-discharge faster at higher temperatures. Lifespan can also be seriously reduced at higher temperatures - most manufacturers state this as a 50% loss in life for every 15 degrees F over a 77 degree cell temperature. Lifespan is increased at the same rate if below 77 degrees, but capacity is reduced. This tends to even out in most systems - they will spend part of their life at higher temperatures, and part at lower. The old myth about not storing batteries on concrete floors is just that - a myth.

7.17 Amp-Hour Capacity

All deep cycle batteries are rated in amp-hours. An amp-hour is one amp for one hour, or 10 amps for 1/10 of an hour and so forth. It is amps x hours. If you have something that pulls 20 amps, and you use it for 20 minutes, then the amp-hours used would be 20 (amps) x .333 (hours), or 6.67 AH. The accepted AH rating time period for batteries used in solar electric and backup power systems (and for nearly all deep cycle batteries) is the "20 hour rate". This means that it is discharged down to 10.5 volts over a 20 hour period while the total actual amp-hours it supplies is measured. Sometimes ratings at the 6 hour rate and 100 hour rate are also given for comparison and for different applications. The 6-hour rate is often used for industrial batteries, as that is a typical daily duty cycle. Sometimes the 100 hour rate is given just to make the battery look better than it really is, but it is also useful for figuring battery capacity for long-term backup amp-hour requirements.

7.8 Battery Charging

Battery charging takes place in 3 basic stages: Bulk, Absorption, and Float.

Bulk Charge: The first stage of 3-stage battery charging. Current is sent to batteries at the maximum safe rate they will accept until voltage rises to near (80-90%) full charge level. Voltages at this stage typically range from 10.5 volts to 15 volts. There is no "correct" voltage for bulk charging, but there may be limits on the maximum current that the battery and/or wiring can take.

Absorption Charge: The 2nd stage of 3-stage battery charging. Voltage remains constant and current gradually tapers off as internal resistance increases during charging. It is during this stage that the charger puts out maximum voltage. Voltages at this stage are typically around 14.2 to 15.5 volts.

Float Charge: The 3rd stage of 3-stage battery charging. After batteries reach full charge, charging voltage is reduced to a lower level (typically 12.8 to 13.2) to reduce gassing and prolong battery life. This is often referred to as a maintenance or trickle charge, since it's main purpose is to keep an already charged battery from discharging. PWM, or "pulse width modulation" accomplishes the same thing. In PWM, the controller or charger senses tiny voltage drops in the battery and sends very short charging cycles (pulses) to the battery. This may occur several hundred times per minute. It is called "pulse width" because the width of the pulses may vary from a few microseconds to several seconds. Note that for long term float service, such as backup power systems that are seldom discharged, the float voltage should be around 13.02 to 13.20 volts.

Chargers: Most garage and consumer (automotive) type battery chargers are bulk charge only, and have little (if any) voltage regulation. They are fine for a quick boost to low batteries, but not to leave on for long periods. Among the regulated chargers, there are the voltage regulated ones, such as Iota Engineering and Todd, which keep a constant regulated voltage on the batteries. If these are set to the correct voltages for your batteries, they will keep the batteries charged without damage. These are sometimes called "taper charge" - as if that is a selling point. What taper charge really means is that as the battery gets charged up, the voltage goes up, so the amps out of the charger goes down. They charge OK, but a charger rated at 20 amps may only be supplying 5 amps when the batteries are 80% charged. To get around this, Statpower (and maybe others?) have come out with "smart", or multi-stage chargers. These use a variable voltage to keep the charging amps much more constant for faster charging.

7.9 Charge controllers

A charge controller is a regulator that goes between the solar panels and the batteries. Regulators for solar systems are designed to keep the batteries charged at peak without overcharging. Meters for Amps (from the panels) and battery Volts are optional with most types. Some of the various brands and models that we use and recommend are listed below. Note that a couple of them are listed as "power trackers" - for a full explanation of this, see our page on "Why 75 watts does not equal 75 watts". Most of the modern controllers have automatic or manual equalization built in, and many have a LOAD output. There is no "best" controller for all applications - some systems may need the bells and whistles of the more expensive controls, others may not. These are some of the charge controllers that we recommend at this time for all systems. Exact model will depend on application and system size and voltage.

7.10 Batteries for Deep Cycle Applications

7.10.1 Lead Acid

The common automobile batteries in which the electrodes are grids of metallic lead containing lead oxides that change in composition during charging and discharging. The electrolyte is dilute sulfuric acid.

Even after over 100 years, the Lead-Acid battery is still the battery of choice for 99% of solar and backup power systems. With the better availability during the last few years of the new AGM batteries and the true deep-cycle batteries, we feel that there is little reason to use any other type. Industrial type batteries can last as long as 20 years with moderate care, and even standard deep cycle batteries, such as the golf car type, should last 3-5 years. Intermediate batteries, such as the 16 and other motive power batteries made by Surrette and Trojan should last 6 to 10 years.

7.10.2 NiCad (Nickel Cadmium)

Alkaline storage batteries in which the positive active material is nickel oxide and the negative contains cadmium.

Downsides:

Very expensive, Very expensive to dispose of - Cadmium is considered VERY hazardous, Low efficiency (65-80%), Non-standard voltage and charging curves may make it difficult to use some equipment, such as standard inverters and chargers.

7.10.3 NiFe (Nickel Iron)

Energy storage density = 55 watts per kilogram

Alkaline-type electric cells using potassium hydroxide as the electrolyte and anodes of steel wool substrate with active iron material and cathodes of nickel plated steel wool substrate with active nickel material. This is the original "Edison Cell". Very long life.

Downsides:

Low efficiency - may be as low as 50%, typically 60-65%,very high rate of self-discharge,high gassing/water consumption, high internal resistance means you can get large voltage drops across series cells, high specific weight/volume

This also means that the output voltage varies with load and charge much more than other batteries. If you are using an inverter, the inverter needs to be designed with these voltage swings in mind. You may not be able to use NiFe's if your system depends on a stable voltage, for example if you are running certain common DC appliances such as a refrigerator directly off the batteries. Also when using NiFe's to power DC lighting, you will notice the light intensity fluctuates. One could always use a voltage regulator to feed those appliances that need it, but that would decrease the efficiency even more.

Currently, it appears that the only source for new NiFe batteries is from Hungary, and we have heard mixed reports on them. In short, we do not recommend them unless they are nearly free. The high losses in charging and discharging will add an extra 25-40% to the size of the solar panels you will need for the same energy usage.