IEA INTERNATIONAL ENERGY AGENCY

Lead-Acid Battery Guide for Stand-Alone Photovoltaic Systems

IEA Task III
Report IEA-PVPS 3-06:1999
December 1999

PVPS

POWER SYSTEMS PROGRAMME

CONTENTS

Foreword

The international Energy Agency (IEA) founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its 23 member countries. The European Commission also participates in the work of the Agency.

The IEA PhotoVoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA, and since 1993, its Participants have been conducting a variety of joint projects in the applications of Photovoltaic conversion of solar energy into electricity.

The Overall programme is headed by an Executive Committee composed of one representative from each participating country, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. Currently nine Tasks have been established in the IEA PVPS programme.

The Twenty one members are: Australia (AUS), Austria (AUT), Canada (CAN), Denmark (DNK), European Commission, Finland (FIN), France (FRA), Germany (DEU), Israel (ISR), Italy (ITA), Japan (JPN), Korea (KOR), Mexico (MEX), The Netherlands (NLD), Norway (NOR), Portugal (PRT), Spain (ESP), Sweden (SWE), Switzerland (CHE), The United Kingdom (GBR), and The United States (USA).

Task III of the PVPS programme, active since 1993, focuses on the exchange of information, quality assurance and technical surveys on stand alone PV applications. Stand-alone PV systems will continue to represent a significant PV market segment, not only in developing countries, but also in the important home markets of industrial countries. Experts from 15 IEA countries are sharing their experiences in this area.

This battery guide is intended for a wide use also close to the end customers to increase the hands on battery knowledge and thereby increase the system reliability and reduce the lifecycle cost for battery storage in small stand alone photovoltaic systems. Also some basic environmental concerns are addressed. The report has been prepared under the supervision of Task III by:

Bo Andersson, Catella Generics, (battery expertise) (SWE)
Staffan Ulvönäs, (illustrations) (SWE)
Bengt Perers, Vattenfall Utveckling AB (PV system and applications expertise) (SWE)

06 December 1999

Summary

This is a document from the international co-operation within IEA PVPS Task III. It is a compilation of mostly well known information on lead acid batteries for professional users. Still this information is seldom available for the user/installer of stand alone (not grid connected) solar photovoltaic (PV) systems. The battery is the weakest part of a stand-alone PV system today. *Even by using only part of the information given in this guide the battery lifetime can be extended and the lifecycle cost can be reduced substantially in a PV system.*

In most cases a modern controller in the PV (Photovoltaic) system will take care of the main facts mentioned in this document. *Therefore a good PV charge controller is a very cost-effective investment.* A comprehensive compilation of important information on charge controllers for stand alone PV systems is given in an other IEA PVPS Task III document (Ref. 1). Still some details like check of water level and cleaning of connectors has to be done manually at regular intervals. Also the right choice of battery type and proper installation is very important. The more specific advice in this guide is written *for open (also called vented) lead acid batteries* that is still the most common type in these systems due to significantly lower initial investment costs.

The safety advice is also an important part of this guide. Even small batteries can be a safety hazard in several ways if mistreated.

For the reader that wants to go deeper into the details of batteries for stand-alone PV systems, the reference list at the end can be recommended, especially (Ref. 1 and 2).

1. Introduction

The dissemination of existing and adapted storage battery knowledge from PV system and battery experts to installers and users, for small stand alone PV systems, was identified by IEA Task III as an important area.

This document is mainly written to serve the user and installer of small stand alone PV systems and not for the professional PV expert that can derive more detailed information from other sources as for example the references given at the end of this document.

A small stand-alone PV system is typically in the range from 10 Wp installed PV module power up to maximum 1 kWp. These systems are seldom installed, operated and maintained by PV experts and they are often located on places far away from traditional support and infrastructure for service and repair. The lack of sufficient hands on battery knowledge was identified in this area as a barrier to satisfied PV users and lifecycle cost reductions for small PV systems.

This guide is written mainly for systems **with open (also called vented) lead acid batteries**. They are the most commonly available and cheapest batteries used today in small PV systems.

For professional stand alone PV systems other battery types should also be considered as the need for top up of water in the case of vented batteries requires frequent and sometimes expensive travel to the site. Other arguments, including life cycle cost for battery replacement, also will most often lead to a different choice of battery type in a professional system.

1.1 Solar energy

Almost all of the energy we use today on earth comes from solar energy. The sun can be described as an enormous fusion reactor that sends huge amounts of energy into space. A tiny part of that energy but still an enormous amount, compared to our needs, reaches the earth all the time.

Ever since the beginning of time, man has known how to use the thermal energy of the solar rays to fulfil his most urgent needs. As time has gone by however, man has increased his demand for energy and energy in different forms. Energy can appear in many different forms and also be converted from one form to another. Solar energy, which will be the main source of energy that we will deal with in this manual, gives us of course energy in form of heat. But it can also be stored chemical energy in plants and trees, which are the basis of biofuels and fossil fuels such as wood, coal and oil.

Another form of solar energy is kinetic energy, which means the energy amount is, stored in a movable mass e.g. water. If you let running water in a river or stream make a turbine wheel with an attached electric generator move around, the kinetic energy in the water is converted into electrical energy which, as we all know, can be used for a multitude of applications.

Also the running water comes from solar energy via rainwater that is evaporated from the sea and lakes by enormous amounts of solar radiation. Rainwater is in fact solar distilled water! Therefore if no other clean water source is available on site, filtered rainwater may be used to top up a battery.

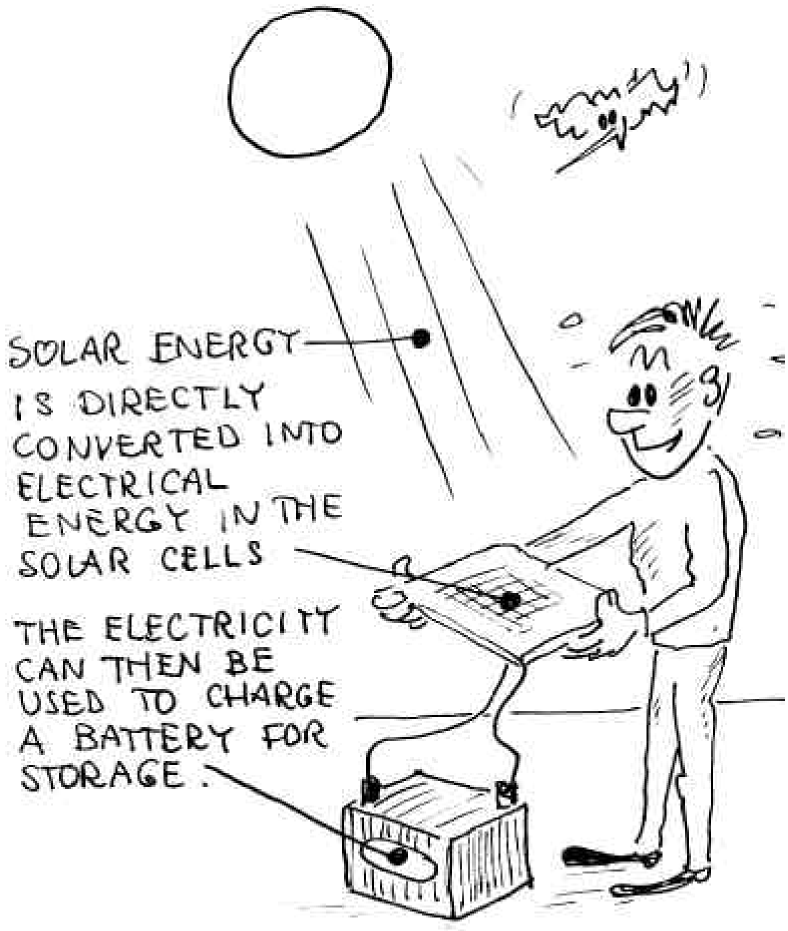
1.2 Sun power into electricity

Electrical energy can also be the result of other conversion methods and it has been possible, as we shall see, to convert solar energy directly to electrical energy with the help of so called photovoltaic modules.

But since the sun does not shine all around the clock it is necessary to store the electrical energy. This is done in accumulators, also called batteries, from which electrical power can be drawn at any time of the day. This manual will help you to operate photovoltaic module - battery systems.

1.3 Lead-acid batteries all over the world

Ever since the invention of the starter engine for motor cars, the lead-acid battery has been a commodity available in almost every part of the world. A starter battery for cars is made to withstand very high loads during short



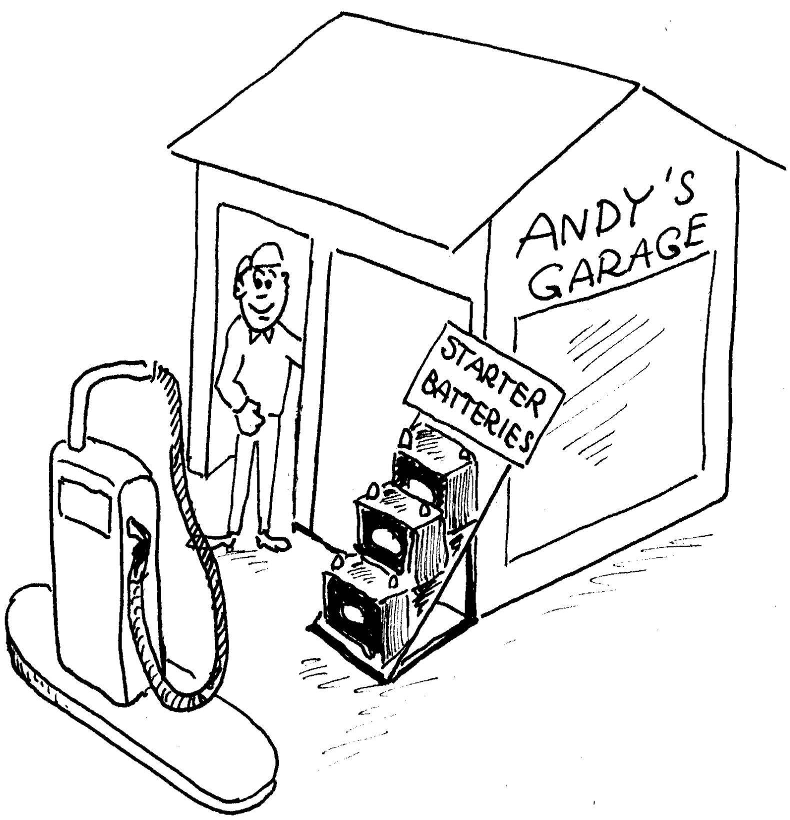
periods of time when the starter engine runs. During the rest of its operating time it serves as a backup power station in the car supplying energy to ignition, lights, radio etc. all consuming very moderate amounts of energy at the same time as the electric generator of the car restores the energy used. There is in other words no demand for especially high storing capacity.

In normal operation of a storage battery there are four major reasons for the ageing process:

- **deep discharge** (this gives irreversible sulphation)
- **overcharge** (this increases the corrosion velocity)
- **low electrolyte level** exposing the electrodes to air (this reduces the capacity permanently and increases the corrosion velocity)
- **high battery temperature** (this increases the corrosion velocity)

These topics are discussed in more detail later in the text.

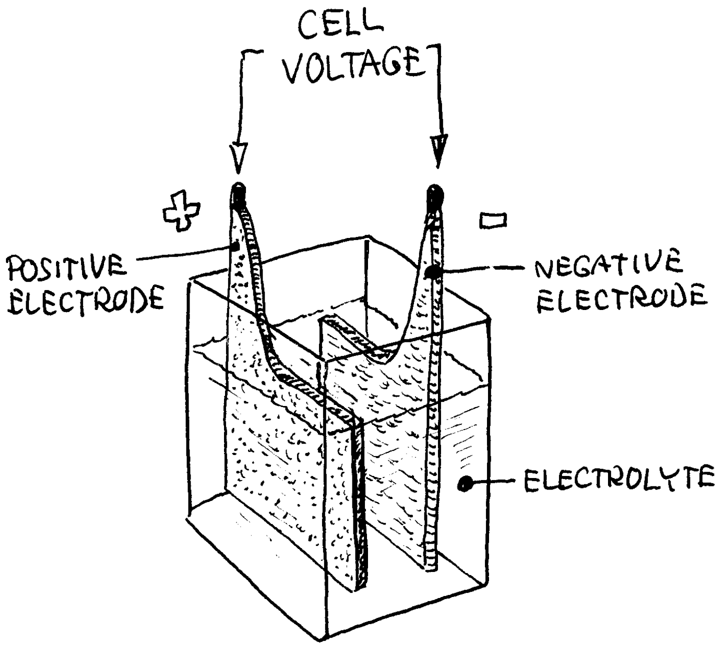
As an example the battery life is shortened dramatically if the battery is left in a deeply discharged condition for a long time (more than a few days). This situation can occur if the load is too large compared to the energy from the photovoltaic module and the controller does not have a low state of charge warning or disconnect function. In such an instance the battery shall be completely disconnected from the load or recharged by other means if possible until the battery is fully charged again. A good controller will avoid this situation and warn the user if the load is too high. A good controller will also disconnect the load if someone forgets to turn off the light or other load when leaving the house.



The lead-acid battery can of course also be made suitable for other applications than cars. To serve as a buffer battery in a photovoltaic power system there is no need for high current discharges or rapid charges. On the other hand a battery for this purpose should have high capacity. This does not mean that a starter battery cannot be used in a photovoltaic system. It works very well for a shorter time (in the range of 1-5 years) but the economics of the system is less favourable due to the fact that the number of charge/discharge cycles obtained from a starter battery is lower than that of a battery designed for photovoltaic systems. In the next section we will present the lead-acid battery and its characteristics.

2. The battery - a "container" for electricity

An electric battery is built up of one or more cells. Each cell includes an electrolyte and two electrodes, one positive and one negative between which a voltage is built up. The energy is stored in chemical form in the active masses of the electrodes.



When a battery is connected to an external load a chemical reaction takes place between the electrodes through the electrolyte. The chemical energy is converted to electrical energy and current flows from the positive electrode through the load and back to the negative electrode.

There are two main types of batteries: *Primary batteries,* which cannot be recharged (as standard batteries for radio, freestyle, electric torches etc.) and *secondary batteries,* which can be recharged again.

In this manual we will deal with **secondary or rechargeable batteries** since that is what we need to store the electrical energy supplied by photovoltaic cells, from day to night and from sunny to cloudy weather.

The battery system we will describe here is the open or vented lead-acid battery but there are also other systems on the market. For instance more advanced "sealed or valve regulated" lead acid batteries, alkaline batteries of nickel-iron or nickel-cadmium type. These batteries usually have a longer lifetime but are also much more expensive than the open lead-acid battery.

Characteristic of the **open (or vented) lead acid battery** is that the small amounts of hydrogen and oxygen produced at the electrodes during battery operation can be vented to the atmosphere through small holes at the top of the battery. **In a sealed (or valve regulated) battery** a special catalyser arrangement inside the battery is used to recombine the hydrogen and oxygen back to water.

One advantage of the sealed battery is therefore that no loss of water will occur during normal operation, whereas water has to be added at regular intervals in an open or vented lead acid battery. By using a modern PV charge controller the water loss can be minimised so that the need to top up water can be reduced to once or twice a year.

3. A closer look inside a lead-acid battery

3.1 Positive electrode design

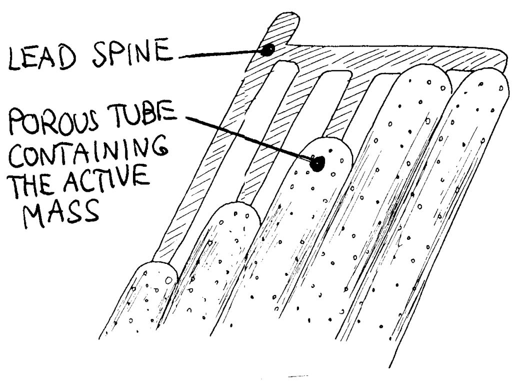
If we start with the positive electrode we shall find that there are different designs of this electrode depending on what application it is made for.

Pasted grid plates are primarily used for automotive applications like the SLI (starting, lighting and ignition) battery used in conventional cars. The power capability for this battery type is very high while the deep discharge capability is poor. Except for the SLI application, batteries with positive pasted plates are used in many applications because of their low price.

As a carrier, pasted grid plates have a lead grid into which the active material is pasted. The grid is both conductor and mechanical carrier of the active mass. The corrosion stability over longer periods of time is indeterminable; thus its use in stationary applications is only possible with reservations.

If still a SLI battery is going to be used in a PV system, choose a truck battery. They have thicker plates than a car battery almost of the same thickness as special solar batteries. This will extend the battery life in a PV system significantly compared to a car battery.

Tubular plates are often used for traction batteries, i.e. for electric industrial or road vehicles. The main feature is a fairly high specific energy per volume and good capability for deep discharge. The charging time is medium, 5 - 10 hours.



In tubular plates, where a lead spine is surrounded by a highly porous, plastic tube, the active mass is located between the lead spine and the tube. The high current capability of this type of electrode is nevertheless limited, since one cannot reduce the dimension of the tubes. The normal tube diameter is 8 mm (discharge time 3 - 10 h), which can be reduced to 6 mm for specific higher power applications (discharge time 1 - 3 h).

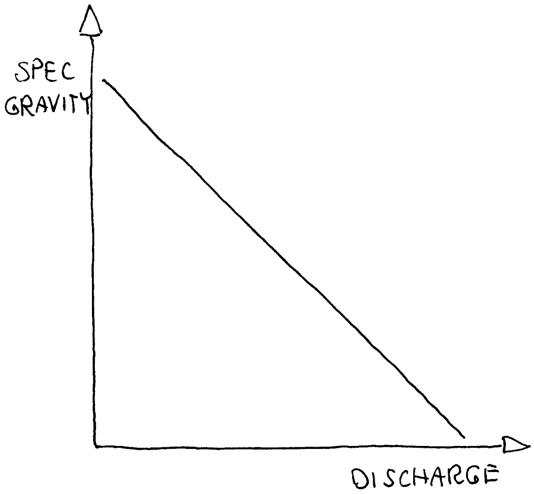
Rod plates are used in batteries for lighter traction as well as for some stationary applications. Rod plates consist of vertically arranged rods. The active mass surrounds the rods, and is completely enveloped in a pocket. The lead rods correspond largely to the spines of the tubular plate. Because of the construction, the utilisation of the active material is high, so is also the high current capability.

3.2 Negative electrode designs

The negative electrodes in all types of lead-acid batteries are of a *pasted grid plate* design.

3.3 Electrolyte

The lead-acid battery electrolyte is a solution of sulphuric acid in water. The specific gravity of the acid in a fully charged battery is 1.20 - 1.30 g/cm^3 depending on the type. Stationary batteries have lower concentration than traction batteries. A typical value for a fully charged SLI car battery is 1.28 g/cm^3. The acid is participating in the reactions as its sulphate ions are consumed. As a result, the specific gravity is decreasing when the battery is discharged. The gravity is traditionally used for measuring the battery state of charge. But readings can be very misleading (too low values) especially during the slow charge without mixing of the electrolyte in a PV system.



During charge strong acid is created at the electrode surfaces. During overcharge, the acid in the cell is stirred by the gas evolution, which helps the concentration equalisation. If the charge rate is low and the overcharge limited, it happens that the strong (and heavy) acid does not mix with the bulk electrolyte, but accumulates at the bottom of the cell. This is often the case for tall cells (>200 mm plate height). The time for equalisation will be several days. Such strong acid increases the corrosion of the electrodes, which decreases life. As the acid sample is taken at the top level of the electrolyte very wrong results (too low state of charge values) can be derived if mixing has not occurred. This is most often the case in a PV system. ***Therefore acid density measurements in a PV system during charge is often misleading (gives too low values on state of charge).***

The electrolyte is a strong acid. When working with a battery, ***safety glasses should always be worn***.

Rubber gloves should be used when working directly with the acid. Droplets or mist of acid will destroy many materials used for clothing. This is often not observed until the clothes are washed.

The concentration of the acid has to be adjusted on a regular basis by addition of deionized water. (This is automatically done when topping up the electrolyte level with water. The acid is never leaving the battery except for very long overcharge periods when electrolyte mist can carry acid away). If the electrolyte level is too low, the acid concentration is accordingly higher, which increases the corrosion.

Especially during the end of the charging process water will be separated into hydrogen and oxygen gas at the electrodes. These gasses will leave the battery in an open or vented battery. This gives a water loss that has to be replaced by distilled water at regular intervals. A water loss of at least 0.5-1 litre per year can occur even in a small stand-alone system. A good controller can minimise this loss but **a check of electrolyte level every half year is a minimum recommendation.** If the water level is not adjusted in time parts of the battery plates will be above the electrolyte surface and exposed to air, in time those parts will become permanently damaged. The water loss also has the result that the acid strength will be increased and the corrosion of the electrodes will accelerate.

In cold climates **the electrolyte may freeze if the battery has a too low state of charge**. This can seriously damage the battery. In case of a stratified electrolyte the risk of freezing is even higher. A good controller with automatic low state of charge warning and disconnect will reduce the risk of freezing significantly. If the controller has a built in equalisation stage in the charge control this will further reduce the risk of freezing.

3.4 Cell cases made of moulded plastics

The first thing you see when you have a lead-acid battery in front of you is the case. Historically, rubber was found to be a suitable material for cell cases and covers. They were easily formed to the right dimensions and the cells were easily sealed. However, the material was quite brittle, especially at low temperatures, which made these cells sensitive to mechanical abuse.

Most cell cases manufactured today are made from injection moulded plastics. Such cases are form stable and quite resistant against mechanical abuse. The cost for tooling is very high which requires quite large production volumes for each size of battery to lower component costs.

Some cell case materials may have a dimensional instability. If the cell walls are bulging, the electrolyte level will deviate from that predetermined. To avoid this situation, such cells should be put into a frame, which facilitates the dimension integrity.

On top of each cell there is a plug that in the case of a vented battery has small holes that will release gasses but will prevent acid to come out. In a sealed or valve regulated battery the plug contains a catalyser and a safety valve that will release overpressure in case of catalyser failure or too high charging rate.

3.5 Battery boxes for small systems

For small systems an extra battery box covering also the wiring and connectors on top of the battery can be recommended. This box will also take care of water and electrolyte droplets that otherwise may destroy the floor. When a battery box is used the battery can be placed indoors more freely closer to the load. Still the requirement for good ventilation in the room should not be forgotten.

3.5 Standardised terminals and connectors

The positive and negative terminals are part of the cell cover. There are standard configurations with a conical layout for standardised connection cables and different layouts for special connectors.

In a monoblock (e.g. a 12 V) battery the series connection between the individual 2V cells are made inside the case, penetrating the walls between the cells.

If a metal object is dropped onto the battery so that the terminals are connected, the battery is shorted which can end up in an explosion. ***Use only insulated tools when working with batteries. Do not wear watches with metal bracelets.***

When connections are made, protect the terminals by an insulated material like rubber, plastics or wood to prevent short cuts between the terminals.

It is very important to keep the terminals clean from oxides to avoid voltage drop due to higher resistance between terminal and connector. Clean terminals will also help to reduce creep currents between the terminals. Otherwise this will increase the rate of self-discharge.

4. What type of battery should be chosen?

The chart on the next page presents an overview of advantages and limitations with different types of lead acid batteries concerning their use in PV systems.

For a typical small PV system (10Wp to 1kWp) both the initial investment cost and the life cycle cost has to be kept low and the following battery types can be recommended according to the order in brackets. (1)Solar Batteries, (2)Leisure/Lighting, (3)SLI truck batteries (ref. 2). *SLI car batteries should be avoided due to the short lifetime in a PV system.* In practice of course also the local availability of batteries will decide. Therefore SLI truck batteries can be the best option in some developing countries with no other batteries than SLI´s available.

It has also been shown that local factories for SLI batteries can be changed to also produce modified SLI batteries with thicker plates that has a significantly better performance in small PV systems.

For professional use the more advanced and expensive batteries are often more cost effective in the long run. Their lifetime is longer, the maintenance requirement is sometimes lower and the performance higher, concerning frequent deep cycling. Therefore a smaller battery bank in nominal Ah can be used for the same load and the number of exchanges during the system lifetime is lower. The main disadvantage is the higher initial investment cost

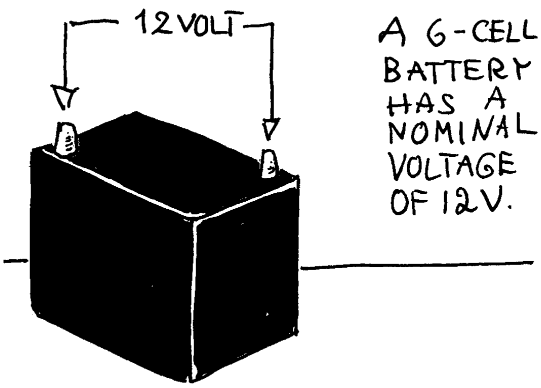
In professional applications comprising daily discharging and recharging, the traction battery design is preferred. A semi-traction design with pasted plates can be acceptable if the lead grid is stable enough. The stationary battery design is recommended for applications with random discharge/charge cycles but where a reliable power source is needed for emergency alarm systems, etc.

Stationary batteries of the Plante ¢type are not recommended for PV systems as the lifetime will be very short due to the special charging conditions in a PV system (Ref. 2). They are also very expensive.

Battery selection table for PV systems

Battery type (Standard application area)	**SLI** (Cars)	**SLI** (Trucks)	**Lighting/Leisure** (caravans boats cottages)	**Solar** (modified for PV use)	**Semi Traction** (golf carts, lawn mowers etc.)	**Traction** (fork lift trucks i.e.)	**Stationary** (telecom i.e.)
Positive plate design	Pasted	Pasted	Pasted	Pasted	Pasted/ Rod	Tubular	Tubular/ Rod
Advantages	High power	High power			Fairly high power	Accepts deep discharge	Rugged
	Rapid recharge possible	Rapid recharge possible			Acceptable cycle life	Accepts overcharge	Reliable
		Longer PV- life than car battery	Longer PV- life than car battery	Longer PV- life than car battery		Good for cycling application	
Disadvant-ages	Sensitive to deep discharge	Sensitive to deep discharge	Limited cycle life	Limited cycle life	Limited cycle life	Require high overcharge	Sensitive to high overcharge and deep discharge
Relative invest-ment cost (Ref. 2)	1.0-1.3	1.3-1.5	1.5-2	1.4-1.6	1.5-2.0	4-8	4-7
Comments	**Very short life in most PV systems. Not recommended for PV systems**	**Can achieve acceptable lifetime in low cost PV system with shallow cycling**	**Can achieve accept-able lifetime in low cost PV system with shallow cycling**	**Best lifetime in low cost PV systems**	May give favourable life cycle cost in professional PV system with shallow cycles	May give favourable life cycle cost in professional PV system with deep cycles	Plante type is not recommended for PV systems.

5. Battery voltage characteristics



The voltage of a battery can be compared to the *height difference* in meters between the surface of a hydropower dam and the turbine outlet. (The current in Amperes can be compared to the water flow in m3 per second)

If you connect a voltmeter over the terminals of a 6-cell monoblock lead-acid battery at rest, it will show about 12-13 volts. (During charge up to 15 volts may be acceptable and during very rapid discharge down to 9 volts can be normal).

The theoretical voltage of a lead-acid battery cell depends on the chemical reactions inside it. Under standard conditions it is 1.93 V (or 11.6V for a 6-cell monoblock battery).

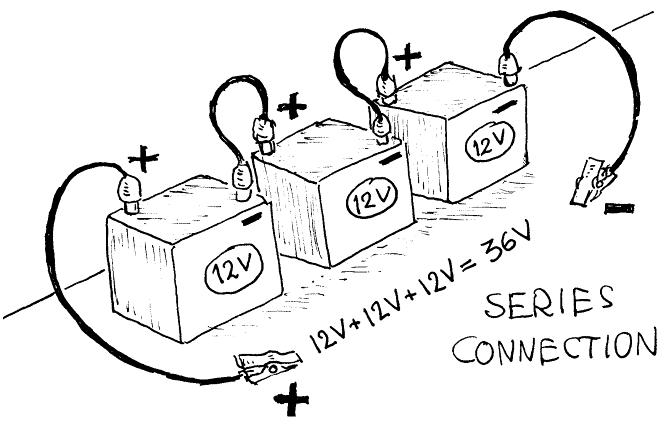
In practice 2.0 V is used as a reference value for a single cell. This is called **the nominal voltage**. According to this a 6-cell battery is referred to as a 12 V battery.

5.1 The higher the discharge rate - the lower the battery voltage

In reality the voltage varies with the operating conditions. During high power discharge, as low values as 1.5 V per cell (9 volts in a 12V battery) is acceptable as cut-off voltage, but normally the voltage should stay above 1.8 V per cell (10.8 volts in a 12V battery) when the battery is being discharged. At lower cut off voltages, there is a risk of permanent damages to the electrodes.

The battery manufacturers often provide curves in their data sheets showing the voltage/current relationship for their products.

5.2 Higher voltage with series connection



For some purposes one might need a higher voltage than that of a single battery. It is then possible to connect batteries in series. This means that you connect the negative terminal of one battery to the positive terminal of another battery.

If you have connected three 12 V batteries in series you will have 36 V between the positive terminal of the first battery and the negative terminal of the last battery.

This way you can connect several batteries in series and the total voltage will be the sum of the voltages of the batteries. The capacity in Ah will be the same as for a single battery but of course the energy content in Wh (Wh = V ∗ Ah) will increase with the number of batteries.

6. Battery capacity - the amount of electricity stored

Capacity is the measure of the amount of current that can be stored and withdrawn from a battery. The unit for capacity is ampere-hours (Ah). The battery capacity can be compared to the *volume* of water stored in a hydropower dam. The voltage is comparable to the height difference in the power station as mentioned above.

In the same way as we talked about a theoretical voltage there is a **theoretical** value of the **capacity** of a battery depending on several factors.

In lead-acid batteries, there are three active components, the positive electrode active material, the negative electrode active material and the electrolyte. One of these substances will limit the capacity. When one of the active substances is consumed the battery voltage will collapse and the battery is discharged. Most often, the positive electrode material is limited in a new battery. The amount of that material will, as a result, determine the capacity.

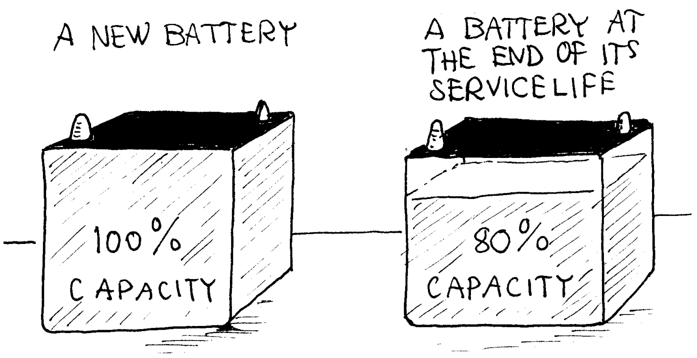
Again it is practical to use an approximate value of the capacity of a battery called **the nominal capacity.** The nominal capacity of a battery is a measure *given by the manufacturer* for the capacity guaranteed to be reached when a new battery is discharged according to a standardised test procedure.

For starter batteries (SLI), the battery is discharged 20 hours with a constant current down to a predetermined cut-off voltage. This current is called I_{20} and the corresponding capacity value is denoted C_{20}.

6.1 Capacity can differ from battery to battery

The capacity available to the user might differ substantially from the nominal value. Multiple parameters will influence capacity such as temperature, the previous charge, the time spent after charge, the age of the battery, the current profile, the cut-off voltage, etc.

6.2 Design your system based on 80% of nominal battery capacity



It is also important to understand that the nominal capacity relates to the capacity obtained from a new battery. The end of life is defined as the point where the capacity has declined to 80 % of the nominal value.

When designing a battery installation, one must take into account how the capacity decreases from a new battery to the end of life. It is important that the battery can fulfil its duty even when the capacity has decreased.

In a PV system an extra margin is also recommended as the recharge of the battery can take several days or weeks under some parts of the year with low solar radiation. A rule of thumb is therefore to size the battery for only 50% discharge under the worst conditions. This will extend the battery life significantly in a PV system, as the probability for deep discharge will be smaller.

6.3 How to size the battery for a certain system and load.

As an example one can take a small 12V PV solar home system with 2 lamps of 11W used 5 hours a day and a 15W Television set used 3 hours per day.

1. First calculate the daily energy use or load in the system: The daily energy use will be < Number of appliances ∗ Power consumption ∗ operating per day >. Example with data from above: 2 ∗ 11W ∗ 5h + 1 ∗ 15W ∗ 3h = 155 Wh per day.

2. Then calculate the design energy content of a suitable battery available locally: For example a 12V / 75Ah battery contains nominally about 1 kWh. More exactly 75Ah ∗ 12V = 900Wh if fully discharged. According to the rules given above only 80% of the capacity can be counted on in the long run. Further more to extend the battery life only 50% of that should be discharged each day at the most. Totally only 0.8 ∗ 0.5 = 0.4 or 40% of the nominal energy content should be base for sizing. In this case 40% of 900Wh = 900 ∗ 0.4 = 360Wh. The design energy content of this battery is 360Wh or 0.36 kWh.

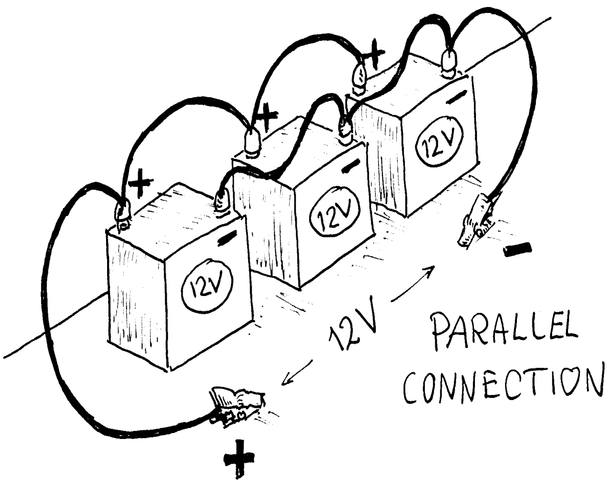
3. Calculate the number of batteries needed: Normally the sizing of a small system is done so that the battery has enough energy for 3-7 days energy use without sunshine (This is also called autonomy, ref. 2). In this case one 12V / 75 Ah battery has an energy content of about 2 days use (360Wh / 155Wh/day = 2.3 days).

At latitudes close to the equator (± 40° latitude) with more even annual distribution of the solar energy, 2 batteries should be enough in this example giving (2 ∗ 2.3 = 4.6 days autonomy). At latitudes higher than 40° 3-4 batteries can be recommended giving 7-9 days autonomy in this case.

In a real application there will be a close connection between the service you can get and the battery size and installed PV module power, but also the user interaction can have a large influence. With a modern controller the user can read the battery state of charge and the load can be adjusted to the available energy stored in the batteries. This means that more energy than design can be used during sunny weather and less during very cloudy or rainy periods.

For continuos year round use at latitudes higher than 50-60° larger battery banks (larger autonomy), often with seasonal storage, will be needed. This requires professional system sizing and is out of the scope of this document.

6.3 Higher capacity with parallel connection



In case you need increased battery capacity or the possibility to connect heavy loads you can connect batteries in parallel. This means that you connect the positive terminal of one battery to the positive terminal of another battery. The voltage of this connection will still be that of one single battery but the capacity will be increased and the ability to handle heavier loads will increase.

In the same way it is possible to connect several batteries in parallel, all the positive terminals connected to each other and the negative to each other depending on how much capacity you need. In case of non-professional batteries and installations not more than 3-4 batteries in parallel can be recommended. One bad cell may otherwise destroy the whole battery bank. All batteries should also be of the same age and size to give the best total lifetime.

When connecting batteries in parallel it is important that each battery will have the same cable resistance between the terminals and the other system components as controller, load and PV modules. The figure above shows a good way to achieve this.

6.4 Capacity will increase slightly in the beginning of operation

A new battery will not reach its full capacity during the first discharge cycle. In the standards, it is described that up to 10 charge/discharge conditioning cycles are allowed before performing the first capacity verification test. Normally, a battery shall be fully charged and discharged a few times to activate the electrode materials.

This is often difficult to achieve when PV panels are used for charging, as their charging capability is limited. This might delay the activation. The full capacity might not be reached during the first 50 cycles.

This effect should not be overestimated. It will be in the range of 10-20% of the nominal capacity.

6.5 Temperature effect on capacity

The nominal capacity is normally measured at 20°C battery temperature, with a constant current discharge, down to a certain fixed cut off voltage for the battery.

In cold climates the usable capacity may be significantly reduced, as low temperatures will slow down the chemical reactions in the battery. This will result in a useable capacity at for example minus 10°C battery temperature of only 60% of the nominal one at 20°C. The capacity is still there if the battery is heated to 20°C but at low temperature one can not utilise the full amount.

When possible the battery should therefore be placed indoors or otherwise sheltered from low temperatures by insulation or perhaps even placed in the ground if any other heat sources are not available. Seasonal storage containers with phase change materials with water as the main storage component has shown to work well.

In warm climates the opposite effect on capacity does not occur at battery temperatures above 20°C. In this case the battery should be placed in a way to avoid high temperatures. Already 10°C temperature increase above 20°C will double the corrosion velocity of the electrodes and reduce the battery lifetime significantly.

7. Charging fills your energy storage

A lead-acid battery can generally be charged at any rate that does not produce excessive gassing, overcharging or high temperatures. In the laboratory, constant current charging is often used. Constant voltage charging is preferred in many stationary installations. This is especially true for sealed or valve regulated (VR) batteries. However, for deep cycling applications, the constant voltage charging is not recommended due to the fact that the charging time is much longer than acceptable, several days or weeks. If the battery is charged at too high a voltage, which will shorten charging time, the corrosion is enhanced and the battery lifetime will suffer.

In a PV system the energy source is not regular and special charging considerations has to be made.

7.1 Different steps in the battery charging procedure

The charging steps mentioned below are all taken care of by a good PV charge controller and are mainly mentioned here for information and motivation to look for better controllers. The steps used in charging of an open or vented lead acid battery are named:

- **main charge**, used for charging the battery up to a voltage level when gassing starts and the voltage rises. (The voltage limit is 2.39 V at 25°C and 2.33 V at 40°C).

- **top-up charge**, to reach the 100 % state of charge from a level of 90 - 95 %. (Retain the voltage limit by decreasing the current).

- **equalisation charge**, used for equalising the capacity of the individual cells, in a multi-cell battery. This is an important issue for improving life, but requires a special controller mode to create this in a system charged by PV panels. (Increase the voltage to 2.5 - 2.6 V/cell for a short time, 0.5 - 1 h, at regular intervals, once a week).

- **maintenance charge**, used for maintaining the full capacity in a battery that is already fully charged but not frequently used for some period. (Approx. 2.20 - 2.25 V/cell or a current value equal to the capacity value divided by 100 (C/100)).

The battery is not very sensitive to the abuse created by the main charge, except for the temperature rise. It is preferable not to start charging of a very warm battery (>50°C) if there is a possibility to cool the battery first.

When controlling the charging process according to the voltage of the whole battery, it is understood that the individual cells of the battery have the same voltage. If not, some cells may not be fully charged (undercharged). It is therefore important to check the voltage of each unit regularly.

Undercharging may result in sulphation of some cells of a battery. In this case an equalising charge may restore the capacity of the undercharged cells.

On the other hand, one shorted battery cell in a series string of separate 2V cells or in a monoblock battery will result in extensive overcharge of the other cells. This shortens the life of the whole battery or even creates a potential safety hazard.

In the top-up charge, the battery is extremely sensitive to abuse, especially to high voltage, which will cause the corrosion process to start. The battery shall not be kept at the highest charging voltage recommended by the supplier for extended periods.

7.2 Always use a good PV charge controller

The special PV charge controllers now available on the market are strongly recommended for protection of the battery. So called self regulating PV modules may work but the battery life will be significantly shorter in most applications due to the risk of overcharge.

Except for protecting the battery from abuse situations, most of the regulators have built-in charge controllers. It is always important to investigate the type of charging procedure and to check if control parameters like temperature compensation for the battery temperature is incorporated. A good lead acid battery charger should include:

- Charge control including regular **equalisation mode**
- Charge control with **battery temperature compensation**
- **Battery state of charge display** for the user (LCD or LED)
- **Discharge control** with low state of charge warning and disconnect
- **Protection against lightning and wrong polarity**.
- **Overcurrent protection** (built in fuse for example)

Some advanced features as MPPT (Maximum Power Point Tracking of the PV module voltage) used in grid connected systems has been shown to be less important in a stand-alone system and may reduce the reliability.

To make full use of a good charge controller it is very important to follow the recommended cable size and maximum length between the battery and controller. A too thin or too long cable may fool the controller to end the top up and equalisation charge too early. This will give lower system performance and shorter battery life.

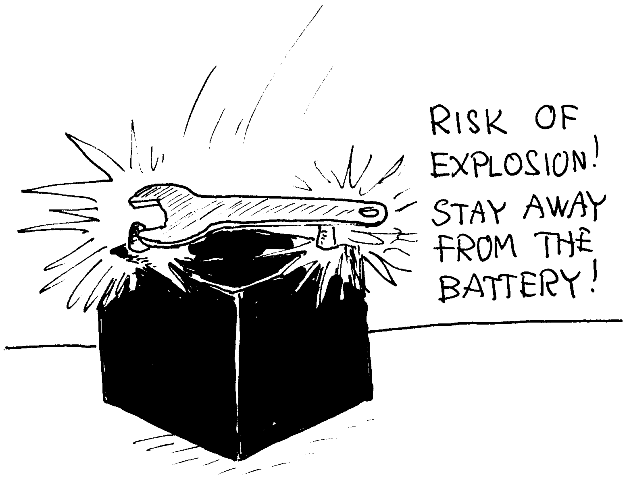
Further detailed information on charge controllers can be found in (ref. 1).

8. Your battery is a small power station

When the battery is properly charged it is ready to be used and discharged, serving as a small power station. As we mentioned earlier the discharge current can vary widely. Especially for starter batteries which can easily take high discharge currents for short periods. For design purposes, however, it is practical to use what is called **the nominal discharge current.**

Nominal discharge current refers to the value related to the nominal capacity value. If the nominal current is related to the C_{20} capacity, then the corresponding current is named I_{20}. If you consequently divide the nominal capacity value of a battery by 20, you will, as a result, get the average discharge current I_{20} you can take out of the battery for 20 hours.

8.1 A shorted battery - a dangerous hazard



The short circuit current is normally very high, especially for a starter (SLI) battery. Severe accidents have been reported when a person has tried to remove the object creating the short. These objects are most often extremely hot and will create severe damage to the hands. The arc that will come when removing the tool may also start an explosion.

If the short circuit is created by an external short, do not try to remove the object. Do not stay close to the battery, as an explosion is the most probable result of a short circuit. Acid will spray all over the surroundings of the battery. (During the short both hydrogen and oxygen will develop inside the battery in an explosive mixture. An arc will start burning when removing the object causing the shortcut. This will give a very high risk of explosion).

Therefore always install a main fuse in the system close to the positive battery terminal. Always use insulated tools when working with batteries.

9. How to store a battery before installation

This is often forgotten, but a new battery may have lost a major part of its potential lifetime already on the shelf of the dealer. Here are some important factors to consider and check before buying a new battery.

9.1 Dry and cool

Lead-acid batteries, which are waiting for installation, should be stored in a dry and cool atmosphere. The long time storage at high temperature will have a detrimental effect on life as the corrosion of the lead electrodes is accelerated at elevated temperatures.

Humid atmosphere will create a leakage current flowing over the battery cover between the positive and negative terminals. In the long run, but much faster than due to the internal self discharge, the battery will be deeply discharged which shortens the battery life due to sulphation of the electrodes. The lead sulphate that will form at a low state of charge will deteriorate both the charge and discharge characteristics and the nominal battery capacity can never be recovered.

9.3 Periodic recharging

It is recommended to recharge batteries (if filled with electrolyte), periodically (typically every six months), if they are to be stored for a long time. The capacity drain is otherwise very harmful to the battery life since there is always a discharge reaction, self-discharge, going on inside the battery. Permanent damage is created if the self-discharge of the battery drains the battery completely. The lead suphate will form on the electrodes that reduce the battery capacity dramatically.

9.4 Dry-charged batteries is one option

Batteries can be protected against deterioration when stored before installation by a process called dry charging. The battery is then shipped fully charged but in dry condition and the acid is not filled in the cells until it is to be installed.

Such dry charged batteries can usually be stored up to a couple of years without degradation. When acid is introduced, the battery becomes operational within minutes. Dry charged batteries, of course, need no recharging during storage. They can be left unattended for longer periods of time.

10. How to install new batteries

Several factors have to be considered when installing the battery in a PV system.

10.1 How to arrange the "battery room"

It is important to arrange for a suitable installation of the battery. In large systems a separate battery room can be recommended. In smaller systems part of an existing room may have to be used. When the batteries are placed on a floor, materials, which are not affected by acid leakage, shall be used and the batteries shall be placed in a way to permit easy management and service. It is also important to be able to clean the floor space with water.

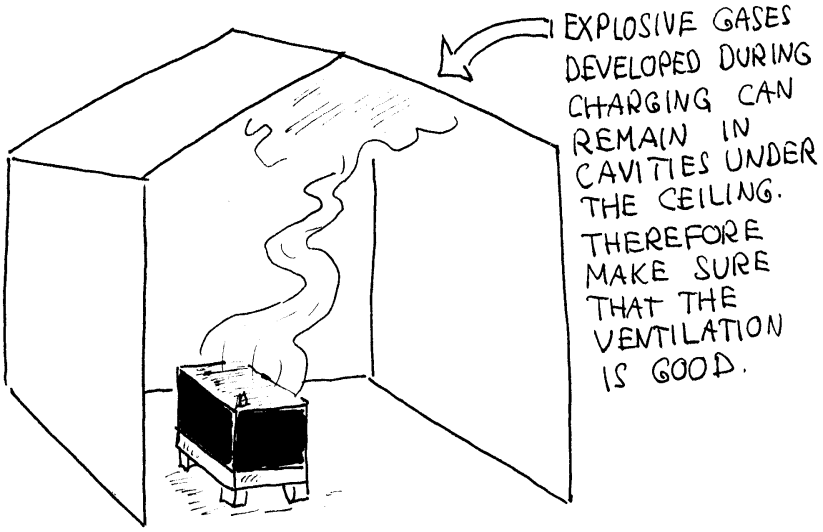
For small systems battery boxes are available that takes care of possible acid and water spillage and also gives protection from direct electrical contact with the battery terminals when the installation is finished.

10.2 Batteries are heavy and need space

When the batteries are rack mounted or put on a shelf, the strength must be high enough to allow for the weight of the batteries.

Batteries shall be installed with sufficient spacing (at least some cm in between) to allow for cooling and to avoid creep currents between adjacent batteries.

10.3 Good ventilation - a safety factor



Most important is to facilitate ventilation of the battery room to prevent accumulation of explosive gases as well as acid mist.

Hydrogen, which is developed during the charging process, is a very light and highly flammable gas, which accumulates in cavities under the ceiling. It mixes with the surrounding air and is then explosive. The ventilation therefore has to be arranged to avoid such accumulation. The vent should be at the highest point in the room. For larger systems good advice is given in (ref. 2) how large vents and fans are needed in the individual case. For smaller solar home systems up to approximately 100 Ah battery capacity a check that the normal ventilation in the room works well should be enough.

Inside the battery casing on top of the electrolyte level the gas mixture is extremely explosive as both hydrogen and oxygen is developed in a perfect mixture, most of the time, when the battery is in operation. Therefore open fire (candles, match or cigarettes) should never be used when working with a battery system. Use an electric torch for working and emergency lighting.

11. Good maintenance - high reliability

11.1 Voltage chain

Batteries should be mounted in such a way that the voltage of adjacent cells is as low as possible. If there is a high voltage between adjacent cells, it is extremely difficult to avoid creep currents in the long run when acid mist is condensing on the surface of and between the batteries.

11.2 Terminal lubricants against oxidation

Terminal lubricants are used to protect battery contacts from oxidation. This is a special paste mixed with graphite to improve conductivity.

11.3 Low electrolyte level - an alarm signal

During the charge/discharge reactions, water from the electrolyte is decomposed into hydrogen and oxygen with the result that the amount of electrolyte decreases and water has to be added. Water maintenance has therefore to be performed periodically to keep the acid concentration at the right level. The water should be clean and distilled or even better deionized. ***Water should preferably be added when the battery is fully charged to derive the correct acid concentration.*** Still in a PV system it is better to add water when on site than waiting for the right state of charge. In cold climates one should of course also be careful not to top up the water level during freeze conditions as mixing of the electrolyte may take days.

If the electrolyte cannot be seen above the plates, fill immediately so that the level is above the plates, and adjust the level when the battery is fully charged.

Normal, clean rainwater can be used occasionally if no other possibility exists. However this will have a slow negative influence on the life of the battery.

With too low an electrolyte level, several problems can be foreseen. Firstly, the upper part of the electrodes will not participate in the charge/discharge reactions and the electrical stress of the part, which is immersed in the electrolyte, will increase, increasing the temperature substantially. In some cases, the temperature will rise to the boiling point, which will dry out the cell still more. Overheating can also start a fire or ignite an explosion.

The water loss will increase the acid concentration. This will increase the corrosion of the electrodes, which, as a result, will shorten life. A low electrolyte level will expose the electrode surfaces to air and as a result, the electrodes will be permanently damaged by oxidation.

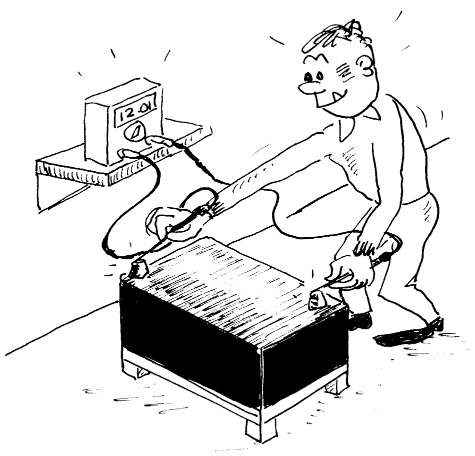
11.4 Centralised watering systems

If the battery is equipped with a centralised watering system, the water chain must be the same as the voltage chain. If not, the piping system may create a conductive path between batteries of high voltage difference. This is only applicable to larger PV systems but is then important to consider.

11.5 Expansion of the battery terminals can crack the cover

One mechanism that makes lead-acid batteries fail is the growth of the terminals. Following an expansion of the plate pack, the terminals will press the terminal upwards. It is not unusual that the cover is cracked as a result of such a terminal expansion. To allow for a limited expansion it is recommended to use flexible connections (wires) between the batteries.

11.6 Read the cell/battery voltage periodically



When servicing a lead-acid battery, the minimum is to read the voltage of all cells or monoblocks to check if any cells deviate from the average values. At rest (no charge or discharge) the single cell voltage should be in the range between 2 and 2.15 V (12.0 and 12.9 V for a 12 V monoblock battery) depending on the state of charge. During operation voltages down to 9 V at very high discharge currents and up to 15 V at top up- or equalisation charge may be correct. If several batteries are used they should show almost equal voltages otherwise something is wrong.

It is difficult to predict the state of charge as well as the state of life by voltage readings. Still it is of course easy to find a shorted cell also in a monoblock by a lower voltage, and if so, this cell or monoblock has to be replaced by a new one to avoid excessive stress on the other cells or monoblocks around.

There is state of charge meters available, especially for fork lift truck applications. These instruments often have low accuracy, but they can certainly be used to give a rough idea of the battery state of charge. Some of the more advanced meters are able to store values of the accumulated discharge and charge capacities over a longer time period.

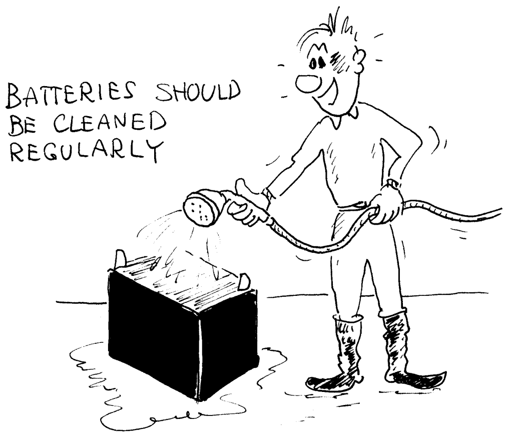
Unfortunately this kind of Ah instrument is of limited value in a PV system due to the long charging and discharging periods. The internal self discharge in the battery will influence the available capacity significantly. Other state of charge indicators that are built into a PV charge controller may therefore be as accurate in a PV system and can be recommended.

11.7 Acid density measurements

A hydrometer is often used to measure the state of charge of SLI lead-acid batteries. In deep cycling applications, the density value will unfortunately not be an accurate measure of the state of charge. The measurement assumes an even acid density in the cell. This is commonly not the case unless the battery has been in the gassing stage for some time (resulting in acid agitation). More frequently is that the acid density between the plates or at the bottom of the cell, deviates from the concentration above the plates, where the measure is taken. The state of charge values derived with this method will therefore often be too low when used in a PV system especially during charge. Only after an equalising charge one can be sure to derive accurate acid density readings.

In the case of plate passivation and sulphation, the acid density can be right but the full capacity is still not achievable. This can be detected as a lager voltage drop over the battery terminals than normal during discharge. Especially at higher discharge currents. The voltage during charge will also rise much earlier and before the battery has received the full Ah capacity. The higher voltage will fool the controller to end the charge too early.

11.8 Rinsing and drying



Clean the exterior of the battery periodically from dust and salts from the electrolyte. Water is commonly used unless the voltage is too high (>100 V). Note that if the waste water system has iron piping, any remaining acid will corrode the pipes heavily.

After having been washed with water, the batteries can be wiped off with a dry cloth, which afterwards must be rinsed thoroughly with water to remove remaining sulphuric acid.

With a good charge controller with limited overcharge periods the acid deposition on top of the battery will be reduced and the intervals between cleaning can be longer.

11.9 Replacements of cells in a larger system

In large systems separate 2V cells are series and parallel connected to the desired voltage and capacity.

As mentioned above, any such shorted 2V cells in a battery string, has to be replaced. The cell has to be of the same size and capacity. But even so, if the replacement cell is new and the rest of the battery much older, there will be differences in behaviour of the new and old cells which sometimes will deteriorate the capacity.

The new cell should also have, as closely as possible, the same state of charge as the other cells when connected. Otherwise the battery bank will be unbalanced and some cells will suffer from over or undercharge.

12 Safety precautions

The lead-acid battery is an energy pack. It is quite sensitive to abuse. When treated in a wrong way, it is easy to pass over the limits to unstable conditions. ***Never stress the battery mechanically, electrically or thermally beyond the limits.***

12.1 Always use insulated tools

The tools used for connecting batteries have to be insulated to avoid the potential shorting of batteries. Plastic tubes or plastic tape can easily be used for home manufacturing of insulated tools.

12.2 Protect eyes and skin

Safety goggles must always be worn when working with batteries**.**

Rubber gloves should preferably be used to avoid skin contact with the electrolyte**.**

Special clothing is recommended to avoid droplets of acid destroying the normal dress. Such droplets are not always recognised until the clothes are washed and the acid has already made holes in the dress.

Large amounts of water should be used for rinsing if acid has come into contact with the skin, clothes or the construction of the installation. ***It is very important to have a water bottle available within easy reach in the working area.***

12.3 Protection against explosion

Explosions may result from different abuse situations. An explosion forces the cell case to burst and parts will fly around together with a spray of acid. A fire may also start as a result of the explosion.

The battery should be protected against short circuit by an electrical fuse sized correctly to protect the battery from currents above the maximum load and charge values. The fuse is preferably placed in the middle of the voltage string in the battery pack. The location of the fuse in the middle of the voltage string will be safer if a shortcut only involves some part of the battery. In a small 12V monoblock battery system the fuse should be placed as close as possible to the positive terminal.

When assembling the parts of the installation, ***never connect the battery terminals until all cabling is finished and checked for faults***.

Mechanical abuse may well result in an explosion. Protect the battery from pieces that could fall down on the battery or be injected from the side. Mechanical damage to the battery may result in an explosion, which starts as an internal short circuit when the plates or connectors of different polarity are contacting each other as a result of the damage.

A gas explosion is commonly created by an external spark. When batteries are fully charged and in the gassing mode, the internals of the cells are filled with an explosive gas mixture and gas is issuing through the vents. This gas is highly explosive and a cigarette, a match or even by an electrical spark, can easily ignite it. Such a spark may result from a static discharge when two materials are statically charged or from an electrical circuit.

A gas explosion in one cell will immediately propagate from one cell to all other cells, damaging the whole battery.

12.4 How to carry a battery

Now and then it is necessary to move a battery from one place to another. Since a battery is a heavy piece of equipment it is recommended to use a special strap which is placed around the terminals. ***Never try to carry a battery without it.***

First of all this could do severe harm to your back and secondly there is a definitive risk of you dropping the battery on the floor. The result is possible harm to your feet not only from the impact when the battery reaches the floor but also from sulphuric acid if the case breaks.

12.5 Disposal of the battery at end of life

Lead is a heavy metal, which is considered to have a negative influence on the environment. For this reason, it is important to reuse the materials for the manufacturing of new batteries. Such processes for recovery of the metal content of lead-acid batteries are established. If batteries are thrown away, they may leak poisonous metals and acid into the soil.

Be careful to collect old batteries for metal recovery or renovation (mainly in developing countries). They may represent a significant value in some countries.

13 Battery standards

Standards are produced to facilitate replacement of battery cells (standardised dimensions and designs) and the understanding of performance data (standardised testing methods), etc. The standardisation bodies represent groups of companies and organisations with a common interest in the production or availability of comparable products from multiple suppliers or comparable measures of different parameters.

13.1 IEC standards

The International Electrotechnical Committee (IEC) develops and publishes standards for batteries. Several standards are covering the lead-acid battery and its different versions and applications. The most relevant standards are:

IEC 95	Lead-acid starter batteries
IEC 254	Lead-acid traction batteries
IEC 896	Stationary lead-acid batteries
IEC 1429	Marking of secondary cells and batteries with the international recycling symbol
IEC 1431	(Technical Report type 3) Guide for the use of monitor systems for lead-acid traction batteries.

13.2 Other standards

Other bodies are also developing standards for specific purposes or for geographical regions. It is important to investigate if some standards are valid for your application and put specific demands on the installation at its specific location.

Standards are for example produced by:

CENELEC	produces standards for Europe
SAE	produces standards for the (American) car industry
DIN	produces German national standards
JISC	produces Japanese national standards

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2. D Spiers, J Royer "Guidelines for the use of batteries in Photovoltaic systems". NESTE and CANMET 1998. ISBN 952-9553-14-5.

3. M. Hill, Mc Cathy " PV Battery Handbook". Hyperion Energy Systems Ltd. Ireland. 1992.

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5. Most external reports from IEA PVPS Task III are published by James & James. They have a homepage http://www.jxj.com where the reports are presented and can be ordered.

Nomenclature

PV system
Photovoltaic (PV) system. System with energy production by photovoltaic modules, as the main energy source. (Photovoltaic cells that are series connected in a photovoltaic module).

open or vented lead acid battery
The most common and least expensive to buy battery type. The gas space above the electrolyte level in the battery is in open contact with the ambient air. Oxygen and hydrogen developed during charge and discharge can leave the battery without restrictions.

sealed or valve regulated battery
In this case a device (catalyser) is inserted into each cell that will recombine the oxygen and hydrogen into water. Heat is developed during this process that has a limited rate. This kind of battery therefore needs special (lower) voltage settings in the controller during charge.

charge controller
The most important device in a PV system to maintain a long battery life, high performance and a trouble free operation. It does not only handle the charge but also gives user information on remaining capacity during discharge and automatically warns the user and cuts off the load at a safe level to avoid sulphation and other damages of the battery at low state of charge.

sulphation
When a battery is too deeply discharged for more than some days a layer of lead sulphate will develop on the electrodes. The lead sulphate slows down the charge and discharge reactions and fools the controller so that the charge and discharge is terminated too early. This gives an accelerated ageing process of the battery and the useful battery capacity goes down too early.

corrosion

The electrolyte in the battery is a strong acid. Especially when the battery is in the final stage of charging and at high battery temperatures. In the long run the electrodes will be destroyed by corrosion so that material will fall off the electrodes and reduce the capacity or in some cases give a short cut. This will limit the battery life. Therefore the acid concentration and charging voltage should be reduced at high operating temperatures.

state of charge (SOC)
When a battery is fully charged, to the nominal capacity, the state of charge is 100%. A fully discharged battery has 0% state of charge. In normal operation a battery should not be discharged below 20% state of charge to avoid effects that will dramatically shorten the lifetime of the battery. A PV system should not be designed for a daily discharge below 50% SOC.

depth of discharge (DOD)
Opposite of state of charge. (100% minus state of charge in %). A fully discharged battery has reached 100% depth of discharge. Maximum 80% depth of discharge is recommended to give a reasonable lifetime of a lead acid battery. A maximum 50% design DOD is recommended in a PV system due to the often very slow and irregular recharge.

nominal capacity
The nominal capacity is an approximate value of the Ah capacity of a battery given by the manufacturer. This is determined under standardised conditions that very seldom occur in a PV system.

nominal voltage
A practically chosen value of 2 V/cell for lead-acid cell or monoblock (series connected 2 V cells).

autonomy
The number of days that the PV system can deliver full power to the load, from the batteries, without any charge from the PV modules. This is important during for example rainy or cloudy periods.

main charge
This is used for charging the battery up to a level when gassing starts and the voltage rises.

top-up charge
This is used to reach the 100 % state of charge from a level of 90 - 95 %.

equalisation charge
This is used for equalising the capacity of the individual cells in a multi-cell battery.

maintenance charge
This is used for maintaining the full capacity in a battery, which is not frequently used.

SLI battery
The same as a car or truck battery. (SLI = Starter, Lighting, Ignition).

To Remember

Check the water level at least once every half year and top up if needed with clean water (preferably distilled, but rainwater is better than none at all).

Invest in a good PV charge controller. This will increase the battery life and also improve the system performance.

Safety first. Read the safety advice carefully in this guide.

Never fully discharge a lead acid battery. Design the system for maximum 50% daily discharge of the battery and the lifetime will be much longer.

Install a main fuse as close as possible to the positive battery terminal.

Always use appropriate cable size (cable area). At least 2.5 mm2 for a system with a 10A fuse and 4 mm2 with a 20A fuse.

Good ventilation of hydrogen to the ambient is needed at the battery location to avoid risk of explosion.

Check that the battery you buy is in good shape (has been kept in good condition during transport and storage).

In warm climates locate the battery in a shaded and as cold place as possible. This will increase the battery life significantly.

In cold climates chose a place indoors or in a place sheltered from extreme low temperatures. This will increase the battery capacity and prevent freezing.

Arrange the battery, controller and electrical wiring so that children can not damage or get hurt from the system.

Never use an open fire close to a battery. Have an electric torch at hand instead.

If still an SLI (car or truck) battery is going to be used in a PV system choose a truck battery or a modified car battery with thicker plates.