A Discussion of Solar Home Systems in Developing Countries, Including a Course Scope for SHS

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Preface

This report is submitted as part of project work no. SIO–17: Energi, miljø, utvikling (Energy, Environment, Development), given at the Department of Energy and Process Engineering, The Norwegian University of Science and Technology (NTNU).

I want to thank Erik Hoff and Håvard Karoliussen for their inspiring help with the lab exercises. I also want to thank my supervisors Edgar Hertwich and Lars Norum, Nyeng Drani for a nice and informative discussion on the PV situation in Uganda and Eilif Hugo Hansen for providing me with a lamp.

Place	Date	Signature

Summary

This project aims to examine the problems facing the current use of solar home systems (SHS) in developing countries, with focus on Uganda. Also the basic knowledge that is necessary to understand the function of SHS is introduced. The project also gives guidelines for educational material that can be used for educational purposes concerning SHS. In order to get a broader perspective on the system components, there are presented some basic laboratory exercises on the SHS components.

Contents

1 Introduction

The photovoltaic electrification process has not been without problems in most developing countries. Uganda is no exception. It is important to evaluate the current status: What knowledge has been aquired in Uganda and from other countries on PV electrification? This report will begin with a general discussion about PV in developing countries with focus on Uganda and experience with technical problems. The report does not focus on the financial part of the PV electrification. Then in Sections 3–11, issues concerning the theory, installation and usage of SHS are presented. In Section 12, some basic laboratory exercises on two of the SHS components are presented with results. In the last section material on SHS which can be used for educational purposes is listed.

2 Solar electricity in developing countries

Nieuwenhout et al. (2001) estimated that, by 2000, around 1.3 million solar homes systems had been installed in rural areas in developing countries, where one third had been financed by foreign donors and two thirds by commercial dealers. As of 2002 50-125 MWp of off grid PV had been installed in Africa, and Solar Home Systems are estimated to account for approximately one third of this amount. One of every 100 households that gains electricity in developing countries use solar power (Nieuwenhout et al. 2001). The major obstacle for wider spread is the high price of PV systems, including high import taxes. Many people that live without electricity prefer getting a connection to the national grid, rather than gaining electricity through solar home systems, but solar electricity can be used as a pre-grid electrification process to let the user adjust to using electricity (Hankins and van der Plas 1997).

2.1 Lessons learned from PV projects

There are many problems facing the PV electrification in developing countries. PV is expensive, there is lack of awareness, there is often lack of infrastructure to handle the problems of PV applications, and there is a need for improved quality assurance (Vervaart and Nieuwenhout 2001). Badly maintained systems and lack of educated personell working in rural areas often cause premature damage on the system and reduced lifetime for the storage battery (Nieuwenhout et al. 2001). Recently graduated electricians often prefer working in the city in the computer industry rather in remote areas. Many of the manufacturers of PV system components that are situated in developing countries have limited guidelines for producing reliable products. The lack of approved testing laboratories hinders the progress in that field (Vervaart and Nieuwenhout 2001).

Most people hear about PV from there neighbors, which emphasize the importance of well functioning systems. The end user is often given high expectations that can destroy the satisfaction with the system. It is very important that people are aware of the limitations of the system before they invest in it (Nieuwenhout et al. 2001).

Projects that have used donation delivery models[1] have often resulted in neglect in maintenance and service requirements (Nieuwenhout et al. 2001). In a donor project from Guatemala, where the users were trained in maintenance, 45% of the systems were not working after 5

[1] The donor provides the hardware free or almost free.

years. The users were not able to repair basic failures correctly. This was linked to the fact that maintenance training was not aimed at the right persons (Nieuwenhout et al. 2001). Also, when people have been given systems, a lack of interest in maintenance of the system has often been observed (Vervaart and Nieuwenhout 2001). In Kiribati, a Solar Energy Company had a cash sale model where system failure was widespread. The problem with cash sale models is the after sale service, especially when the customer lives in the countryside and the dealer in the city (Nieuwenhout et al. 2001). The company tried again with another model, fee for service[2], which turned out to be a great success (Wade 1997). In Wade (1997), the benefits of the fee for service model are described. In stead of focusing on sales it is important to focus on providing energy services to remote areas. People are interested in energy services, not to own a solar home system. With a fee for service model the system works reliably without attention from the user (Wade 1997). Experience with fee for service models is still limited. The cash sale model, where the system is sold directly to the consumer, is the most used model. Sometimes special loans are provided to the buyer (Vie 2003). Choice of delivery models for PV systems has do be decided depending on conditions in each location.

The mainstream international development institutions, like the UNDP and the World Bank, emphasize the use of renewable energy technologies, including PV systems. Green (2004) finds this emphasis surprising, given the lack of data on how previous PV projects have managed to accomplish their aims. There is need for more analytical information, to be able to make policy makers better their knowledge on how to improve their current strategies (Green 2004).

2.2 Advantages and disadvantages of solar electricity

When deciding on a new energy supply for the household, it is important to know the advantages and disadvantages of the system the end user is planning to invest in. In the following subsections some of the main advantages and disadvantages of SHS are listed.

2.2.1 Advantages of SHS

- It is possible to electrify households and institutions far away from the electricity grid
- PV systems are modular, and they can be enlarged
- Low operative expences
- PV systems provide brighter light and create less pollution than traditional lighting sources[3]
- Quality light can prolong the evening activites
- Some users in Uganda have reported health benefits after installing a PV system (Langseth 2003)
- The energy consumption of an electric light is 65 times less than with traditional lighting (Vervaart and Nieuwenhout 2001)
- Silent energy supply (Louineau 1998)

[2] The customers do not own the system, but pay a periodical amount for the electricity service.
[3] The traditional lighting sources are kerosene, kia and candles.

- Improved safety[4]

2.2.2 Disadvantages of SHS

- High initial cost, unaffordable for most rural households.
- Limited power supply, cannot power an electric kettle (Louineau 1998).
- PV seldom increases the household income (Karekezi and Kithyoma 2002).
- Often insufficient infrastructure to deal with system breakdowns (Stapleton et al. 2002).
- Even total saturation of the SHS market would have negligible direct impact on global carbon emissions (Duke and Kammen 2003).
- Energy from PV cannot be used in agricultural activities (Karekezi and Kithyoma 2002).
- Requires user training and maintaining.
- Machinery[5] which can generate income is usually not run on DC current.
- Many of the system components are not produced locally, thus many developing countries have to rely on import (Karekezi and Kithyoma 2002).

2.3 Solar electricity in Uganda

The applications of photovoltaic systems (PV) have been increasing in Uganda since the late 1980s (Bbumba 1999). These applications have focused on the electrification for rural households, health centres (emphasizing vaccine refrigeration) and community services, e.g. water pumping. As of 1996, Uganda had installed PV capacity of approximately 150 kWp (IEA 1999).

Around 1.1% (around 300000 people) of the rural population in Uganda have access to electricity (Langseth 2003). Uganda is situated near the equator, with high levels of solar radiation; the average solar radiation is 4.8 $kWh/m^2/day$ (Bbumba 1999)[6]. The greatest obstacle for widespread use of SHS in Uganda is unaffordability. However, recent news from Uganda are positive. Production of solar panels will start in Kyambogo near Kampala early in 2004. This is a project funded by the Danish Development Agency, expected to result in a reduction in the prices for SHS in the country (Olanyo 2003). Remote areas in Uganda have a scattered population, and it is often not appropriate with bigger PV systems that provide electricity to larger consumer groups (Vie 2003). In 1999-2000 a solar electric light fund had solar electrification projects in Uganda. Solar Energy for Africa, which is a solar energy company situated in Kampala, was contacted to undertake the training, end user education, PV system installation and the after sale service during the projects.[7] The University in Bergen and the physics department at Kampala University have cooperated in measuring solar radiation in the regions of Uganda.[8] International NGOs and aid organizations have played

[4] The traditional lighting sources can easier cause burning accidents.

[5] For example sewing machines.

[6] See Appendix D for more solar irradiation data in Uganda.

[7] Solar Electric Light Fund, see http://www.self.org/uganda.asp.

[8] PRO 39.2/91: Basic Science for Technological Development in Uganda see http://www.uib.no/fa/intkont/nufu/nufu2/pro39291.html.

an important role in the PV electrification in Uganda, as in many other developing countries. In Uganda, the Ministry of Energy and Mineral Development (MEMD) is responsible for rural electrification[9].

2.3.1 Lessons learned from PV projects in Uganda

According to Sandgren (2001) most of the companies installing SHS in Uganda do not give the end user sufficient information on maintenance of the system. Information is mostly given orally to the man of the house. The technicians have to be aware of the importance of training the end user. There is also a problem with lack of educated personell, which has been reported by Vie (2003). In Uganda, there is little experience with organized after sale services. It is assumed that this will be very costly because of the scattered systems (Sandgren 2001). Sandgren reports that most end users were generally satisfied with their system, but sometimes unsatisfied with the limited capacity. Langseth (2003) and Vie (2003) report cases where the end user was unsatisfied with the system, often due to technical problems that could easily be fixed. The usual size of a SHS in Uganda is 20-80 Wp and the typical load is a lamp, a radio or a black and white TV (Langseth 2003). In Uganda, quality has been a key word, unlike the PV electrification prosess in Kenya, where there is a widespread use of amorphous[10] PV modules with low capacity (around 12W). Also, the systems in Kenya usually do not have a charge regulator. In Vie (2003) it is mentioned that Uganda can learn from the PV progress in Kenya, because the systems in Uganda are very expensive, which is a major impedement for the wider spread of PV. In Uganda the use of a charge controller in the SHS is widespread, but the use of a DC/AC converter is not widespread in the smaller SHS (Vie 2003) .

2.3.2 Uganda Photovoltaic Pilot Project for Rural Electrification

The Uganda Photovoltaic Pilot Project for Rural Electrification (UPPPRE) was designed as a three year pilot project, funded by UNDP/GEF[11] in June 1998 and was supposed to finish in December 2001. The project was prolonged for 1 year due to funding-flow problems (Hirshman 2002). UPPPRE focused on the three main barriers for the wider spread of PV in Uganda:

1. Public awareness
2. Affordability
3. Technical and economic capacity of retailers

To promote public awareness, courses were held. Different financial methods were introduced. UPPPRE arranged courses to train technicians, URDT[12] and Intrafex Solar Systems have also held similiar courses (Vie 2003). In Hirshman (2002) it is stated that one of the benefits of the project was that MEMD removed import and value-added taxes on modules, and the elimination of taxes on the balance of systems components is under discussion.

[9] The Energy policy document from MEMD, is available on the World Wide Web at: http://www.energyandminerals.go.ug/PDFs/EnergyPolicy.pdf.

[10] Amorphous modules have lower efficiency, around 6-8%, while poly and mono cristalline modules have efficiency around 13-15%. Amorphous models also have a shorter life time expectancy.

[11] United Nations Development Program/Global Environmental Facility.

[12] Uganda Rural Development and Training Programme.

The road to the aim of the Uganda government, that 10% of the rural population should have access to electricity by 2010, where 10% should gain electricity through PV, seems to be quite long and difficult.[13]

2.4 Technical problems

In many field study reports the statistics on the function of PV systems are disturbing. Batteries and fluorescent lights are the two components that cause the most frequent technical problems (Vervaart and Nieuwenhout 2001). In Table 1 below, some statistics on the status of SHS are reported.

Table 1: Overview of the status of solar home systems for a few reported cases (Nieuwenhout et al. 2001)

Country	Good	Partly none-op.	Non-op.	Year of publ.
Kenya	69	12	19	1998
Tunisia	38	37	25	1999
India, Sundarbans	72	26	2	2000
Swaziland	73	17	10	2001

In the following sections the problems with the different components (in the field) will be discussed.

2.4.1 Problems with the module

Some of the registrated problems with the module are; reduction of the energy production when parts of the module are shaded by near vegetation growth or buildings, cracks in the glass covering the panel, intrusion of water into the panel, polarity reversal damaging the PV junction boxes and dirt or algal growth on or around the panel (Green 2004).

2.4.2 Problems with the battery

In 2001, Anna Maria Sandgren visited the owners of SHS in the Kibale, Bushenyi, Rukungiri and Mbale districts in Uganda, checking the status of the storage batteries. Her results are interesting: In the households visited, 54% of the installed systems needed immediate service, 39% due to battery related problems. One fifth of these problems could easily have been fixed with proper end user maintenance. In 21% of the cases the battery connection was bad, and in 55% of the cases the electrolyte level was not balanced (Sandgren 2001). In Hankins and van der Plas's (1997) study from Kenya it was reported that 10.5% of the batteries checked were in an uacceptable state of charge (SOC) and 25% were not functioning. The lack of maintenance was not registered in Hankins and van der Plas's (1997) report. Most households claimed that they maintained the battery well, after having learned the hard way — experiencing the results of not maintaining it. The possible aging mechanism for the battery in the field is not very well documented (Diaz and Lorenzo 2001). In October 2002,

[13] For more information about the electrification process and the status of renewable energy technologies in Uganda read Vie (2003) and Langseth (2003).

IEA[14] tested different kinds of batteries used in PV systems to try to analyse what causes the accelerating reduction of battery lifetime. The cycling processes used causes significant battery sulphation[15], but no acceleration in battery corrosion (IEA 2002a). In IEA's (2002a) report, it is stated that there is a lot of research to be done in this field, and international collaboration is needed.

2.4.3 Problems with the charge controller

The proper operation of charge controllers is supposed to garantee a sufficiently high battery lifetime, but this has not been supported by field data, according to Nieuwenhout et al. (2001). Malfunctioning battery charge regulators[16] can often be the cause of failed batteries (Nieuwenhout et al. 2001). In Kenya the use of charge regulators is unusual. The fact that the charge regulator consumes one third of the energy provided by a 12W SHS system makes the charge controller be more like a parasite than a helpful instrument (Hankins and van der Plas 1997). In Diaz and Lorenzo (2001) 20 different charge regulators from 7 countries were tested, the results were that none of the charge regulators disconnected the battery at LVD[17], which means that the regulator is not protecting the battery as it should. Sometimes the technician that is supposed to find the cause to the problem with the charge controller, bypasses the regulator.

2.4.4 Load related problems

It is important to pay attention to the load types that are used in SHS, because many of the problems with SHS are related to inefficient appliances and processes or unmatched loads. If the user leaves an instrument on stand by, the energy consumption can be significant. It is important to disconnect the load when it is not in use, to avoid unwanted energy consumption (IEA 2002b). It is not unusual that the end user of SHS has restricted economy, and tends to invest in instruments with low efficiency because they are less costly. As mentioned, this can cause problems with the sizing of the system, and it is advisable to invest in efficient load instruments to avoid unneccesary energy loss. That investment is more economic in a longer time perspective.

As discussed before, solar home systems are mostly used for lighting, where 12V DC[18] energy efficient fluorescent lights are commonly used (Vervaart and Nieuwenhout 2001). There have been reported many problems related to this lighting source. Roughly one third of all fluorescent lamps suffer from early blackening, mainly because of under-voltage supply with limited quality inverters (Hankins and van der Plas 1997). Some small local companies that make fluorescent lights do not have enough highly educated technicians available. The most common problems are related to early blackening and a luminous flux that degrades or stoppes totally very quickly (Hankins and van der Plas 1997). The degradation of the fluorescent lamps starts when the ends of the tubes become black (Vervaart and Nieuwenhout 2001). The causes of DC lamp failures in rural areas can be attributed to the following factors (Vervaart and Nieuwenhout 2001):

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[14] The International Energy Agency.

[15] Sulphation is the formation of large lead sulphate crystals at the plates, which hinders reversible chemical reaction.

[16] The terms "charge regulator" and "charge controllor" refer to the same instrument.

[17] Low Voltage Disconnect

[18] Direct current.

- Overvoltages across the tube can cause damage to the filament in the tube.
- Gas inside the tube is polluted by other gases
- Excessive current flow while preheating the gas
- Inefficient design
- Unavailability of reliable components for use in lamp construction
- Misuse by users that have not been given sufficient instructions
- Insufficient quality control during manufacture
- The operating conditions vary from the rated design

3 Introduction to the course

This course literature and course scope is the theroretical basis for my further work with PV systems. Here I present the basics for the components that have been discussed in the previous section, emphasizing theory concerning the battery. Also other basic knowledge about electric solar energy is presented. This course literature is focused on small stand alone PV systems. In the beginning of each section, there will be reference to the literature that has been a main source for that section. If other sources are used, they will be referred to directly in the text. For some topics, I have found literature that is very suitable for educational use, in those cases there there will only be a reference to that literature.

4 What is Solar Energy?

This chapter is heavily drawn from Markvart's (2003) "Solar Electricity" and Karoliussen (2003).

4.1 Energy from the Sun

The energy from the sun is electromagnetic radiation, which is the energy in the photons:

$$E_{ph} = hf = \frac{hc}{\lambda},$$

where $h = 6.625 \times 10^{-34}$ Js is Planck's constant, f is the frequency of the light in s^{-1}, λ is the wavelength of the sunlight in meters and c is the speed of light, $c = 3.00 \times 10^8$ m/s.

With good approximation, the sun acts as a perfect emitter of radiation at a temperature close to 5800K. The resulting energy flux that falls on a unit area perpendicular to the beam outside the earth's atmosphere is known as the solar constant. The solar constant, S, is

$$S = 1367 \text{ W/m}^2.$$

The total power from a radiant source falling on a unit area is called irradiance. The total energy flux incident on the earth can be calculated by multiplying the solar constant S byπR^2, where R is the earth's radius. This is the area which is presented to the sun's radiation by the earth. The average flux on a unit su

4.2 Testing the Charge Regulator

The energy consumption, HVD and installation.

4.3 Load testing

The laboratory exercice on loads are presented in Appendix B They were not performed in this project, but are very interesting for further work.

rface area of the earth is obtained by dividing this number by the total surface area $4\pi R^2$ of the earth, given by

$$\frac{S}{4} = 342 \text{ W/m}^2.$$

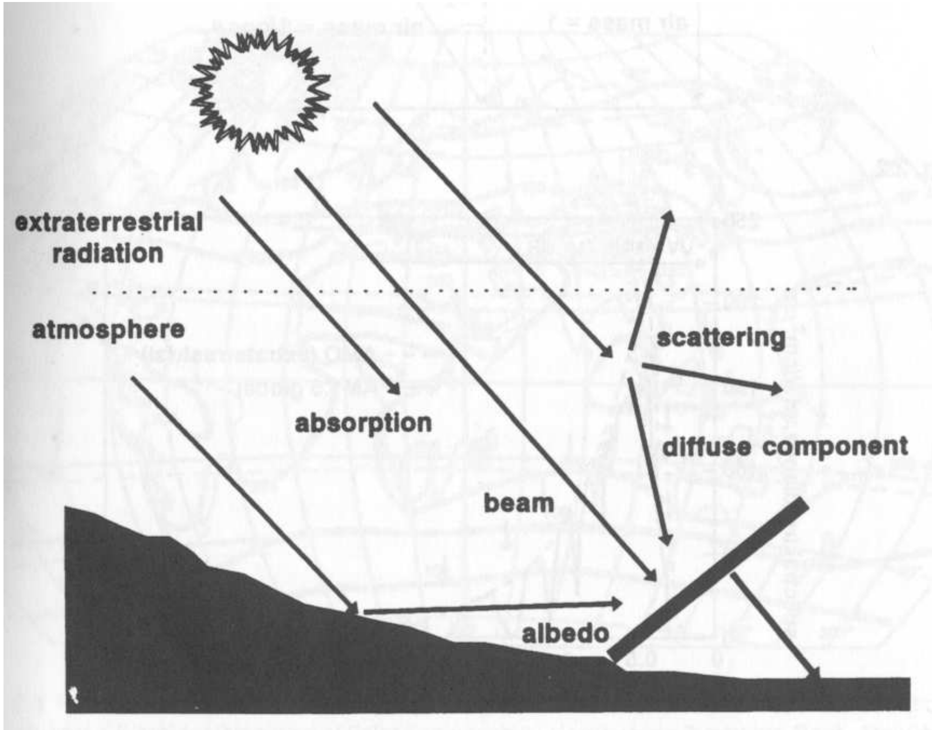


Figure 1: The solar radiation. Figure from Markvart (2000), p. 7.

When the solar radiation enters the earth's atmosphere, a part of the energy is removed by scattering or absorption by air molecules, clouds and particles often called aerosols.

The radiation that falls on the surface directly is called direct or beam radiation. The scattered radiation which reaches the ground is called diffuse radiation. Some of the radiation may reach a receiver after reflection from the ground, and is called the albedo. This is illustrated in Figure 1. The amount of radiation that reaches the ground is very variable, and it depends on various factors, for example weather conditions, air pollution, the time of the year, the time of the day and location.

Air mass (AM) is a a concept which characterizes the effect of a clear atmosphere on sunlight, referred to as AM. The AM value depends on the year, the time of the day and the location on earth. AM is equal to the relative length of the direct beam path through the atmosphere. Which means that it is importand to know AM to be able to analyse the intesisty of the solar irradiation. On a clear summer day at sea level the radiation from the sun at the zenith corresponds to AM1, at other times the AM is approximately equal to $1/\cos\theta_z$ where θ_z is the zenith angle shown in Figure 2. For example, θ_z =0°C, gives AM1, θ_z =60°C,) gives AM2 and θ_z =60°C, gives AM1.5.

AM1.5 is a typical solar spectrum on the earth's surface on a clear sunny day, which with total irradiance of $1kW/m^2$ is used as the standard test irradition for solar cells. Although the global irradiance can reach 1 kW/m^2, this is very unusual. The available irradiance is usually much less then this maximum value, because of the diverse weather conditions and the rotation of the earth. It is possible to measure the AM value: AM=$(1+\frac{s}{h})^{\frac{1}{2}}$, where s and h are shown in Figure 3.

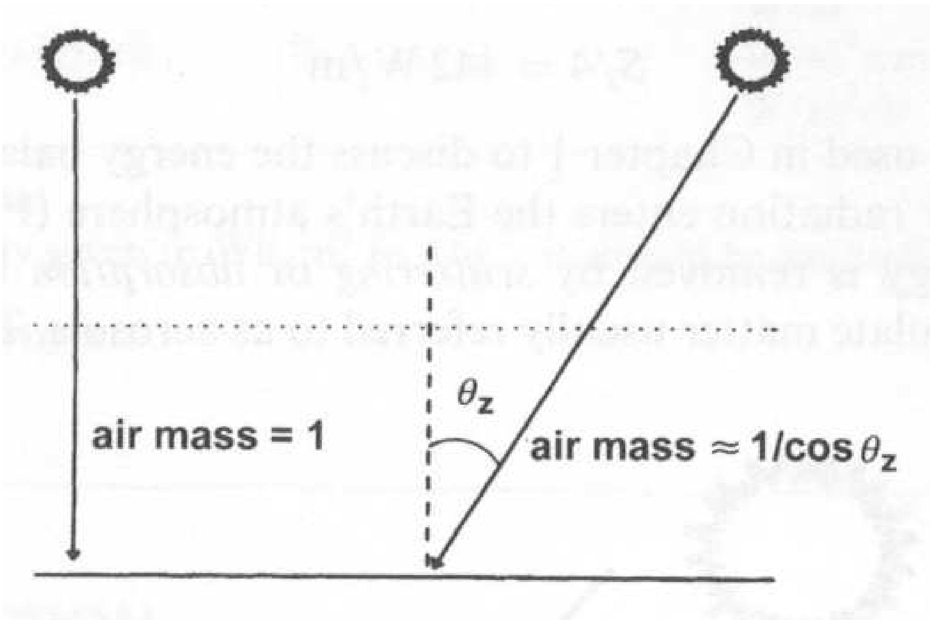


Figure 2: Air mass. Figure from Markvart (2000), p. 8.

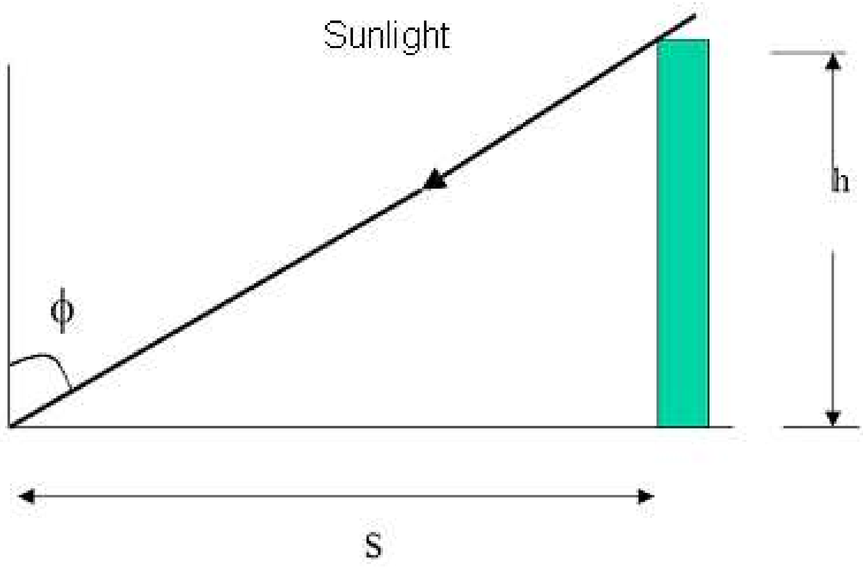


Figure 3: How to measure the AM value. Figure from Karoliussen (2003), p. 17.

Solar irradiance integrated over a period of time is called solar irradiation. It is significant in the design of a PV system to know the approximate irradiation at the site over one day. The average daily solar radiation G_v on the ground refered to both the location on earth and time of the year can be obtained by a simple calculation:

$$G_v = 0.7 \times 342 \text{ W/m}^2 \times 24\text{h} = 5.75 \text{ kWh/day},$$

where 0.7 represents that 70% of the solar radiation is useful, 30% is lost in scattering and reflection. When gathering data to make an estimate of the irradiation at a possible PV site, it is important that the measured data is close to the site.

4.4 What is the structure of SHS?

Usually a small SHS consists of the solar module, a storage battery, wires, a charge controller and a load, but there are different types of SHS. In some cases the electricity from a solar module can be used directly, in other cases the energy must be stored. In big SHS it is often necessary to be able to convert the direct current produced by the PV module into an alternating current. Then there is need for a DC/AC converter. In the smaller PV systems there is usually not a DC/AC converter. Very small systems often operate without a charge regulator. All the components besides the DC/AC converter are described in the following sections. Figure 4 shows the basic structure of a PV system (a more detailed figure is included in Appendix C). Specifications for an 80W PV system are listed in appendix E.

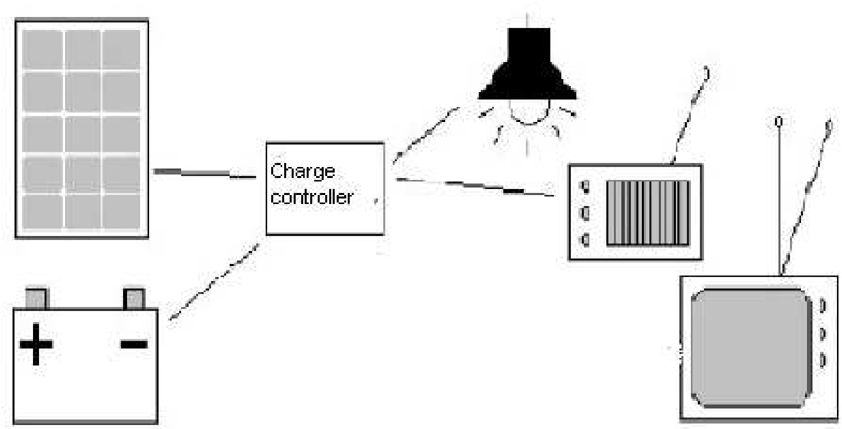


Figure 4: A simplified picture of the structure of a PV system. Figure adapted from Sandgren (2001), p. 3.

5 How does the solar cell function?

How the material in the solar cell functions is described very well in Markvart (2003), pages 26-43, and will therefore not be repeated here.

This section is heavily drawn from Vervaart and Nieuwenhout (2001) and Karoliussen (2003).

Solar cells are made from semiconductor material. The elements Si, Ge, As, Sb, Te and Po are accounted as semiconductors. It is important to understand the difference between a solar cell, a solar module, an array and a solar system. The solar cell is the smallest element, usually around 100-150 cm^2. The solar module is made of solar cells (for example of 36 cells), a solar array is made of for example three modules and a solar power system is made of many arrays (Karoliussen 2003). There are many different types of solar cells available in the market. Crystalline silicon cells are the ones that are the most common. There are two types of these; mono and multi crystalline silicon cells.

5.1 Characteristics of solar cells

The current voltage characteristics and the power voltage characteristics for a typical silicon solar cell are shown in Figure 5. The maximum power output of the solar cell is the top of the power voltage curve. The efficiency of a solar cell is the ratio between the input power and the output power. The usual efficiency of a solar cell is less than 15%.

One way to judge the quality of a solar cell is to measure the open circuit voltage and short circuit current, V_{oc} and I_{sc} and the voltage and current at maximum power output, V_m and I_m. The *fill factor* FF is defined as follows:

$$\mathrm{FF} = \frac{I_m V_m}{I_{sc} V_{oc}}.$$

The fill factor lies between 0 and 1. The higher the fill factor, the higher the quality of the solar cell.

When you look at a solar cell, you can see silvery lines, which are the contact lines; these are to make electrical contact to the front side of the cell. The contact lines are clearly visible in Figure 6.

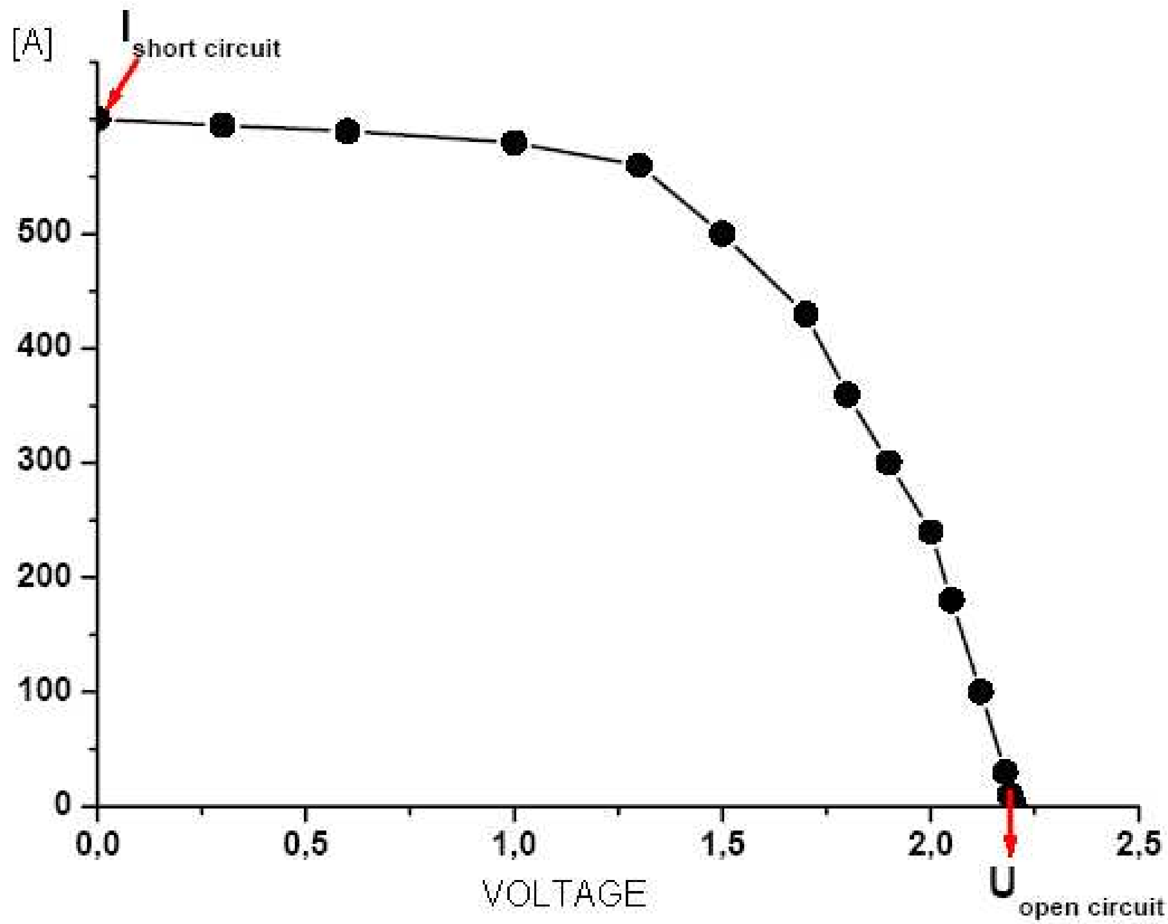
The current produced in the solar cell is very dependent on the irradiation on the cell, but the voltage is less dependent on the irradiation. The power output of the solar cell is therefore dependent on the irradiation level.

The electrical power generation of a solar cell also depends on its operation temperature, as illustrated in Figure 8. The short circuit current I_{sc} increases slightly with increased temperature, but the open circuit voltage V_{oc} decreases significantly. Normally a high quality module has a temperature coefficient of about -2.5 mV/$\circ$C/cell. In solar cells of less quality the temperature coefficient can be higher.

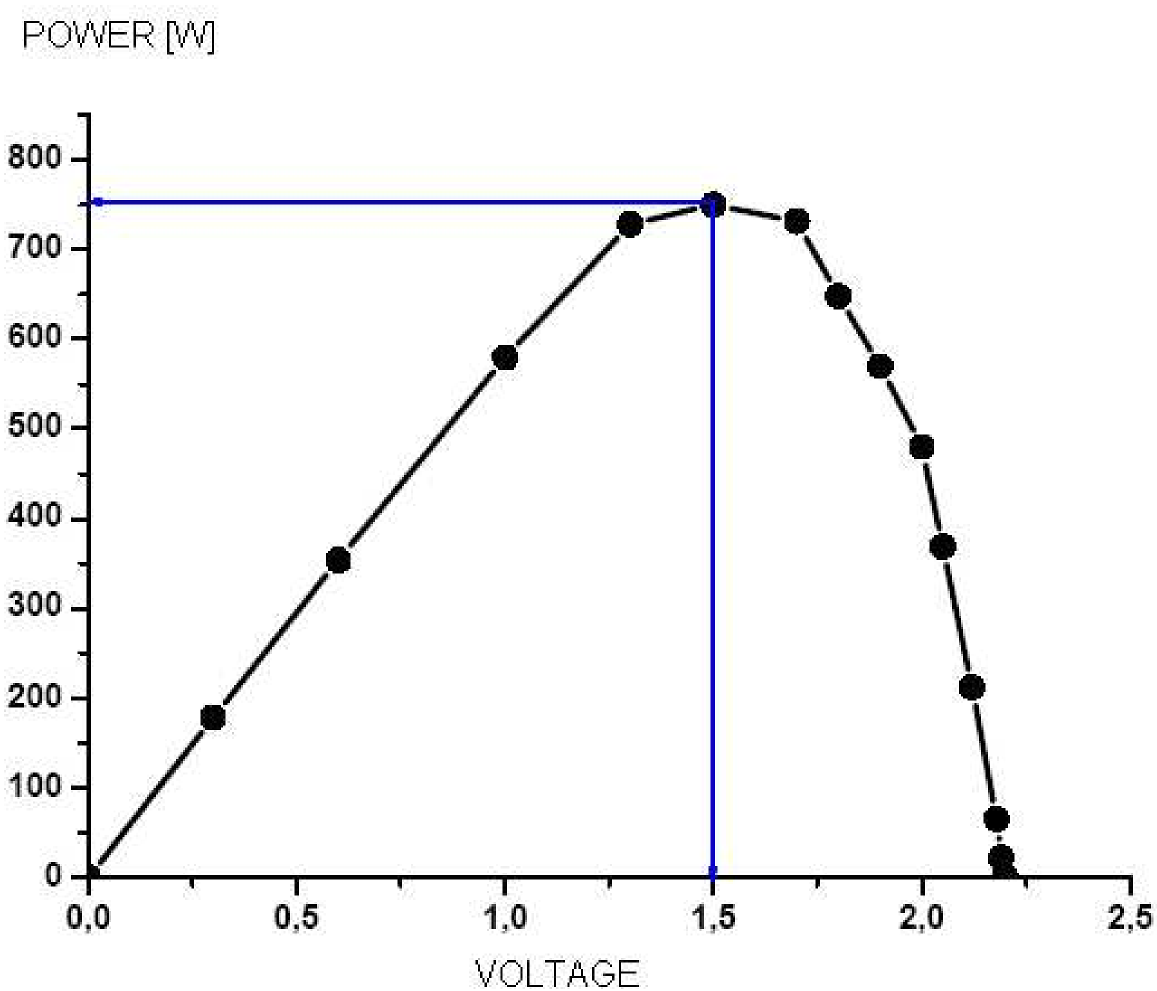
5.2 Module

The solar PV module is the most reliable component of the solar home system. In Vervaart and Nieuwenhout (2001)the following characteristics are listed concerning module testing:

- visual inspection
- performance at standard test conditions (STC)
- measurements of temperature coefficient
- measurement of nominal operating cell temperature (NOCT)
- performance at low radiance



[A]
I short circuit
500
400
300
200
100
0
0,0
0,5
1,0
1,5
2,0
2,5
VOLTAGE
U open circuit



POWER [W]
800
700
600
500
400
300
200
100
0
0,0
0,5
1,0
1,5
2,0
2,5
VOLTAGE

Figure 6: A solar cell. Figure provided by Erik Hoff.

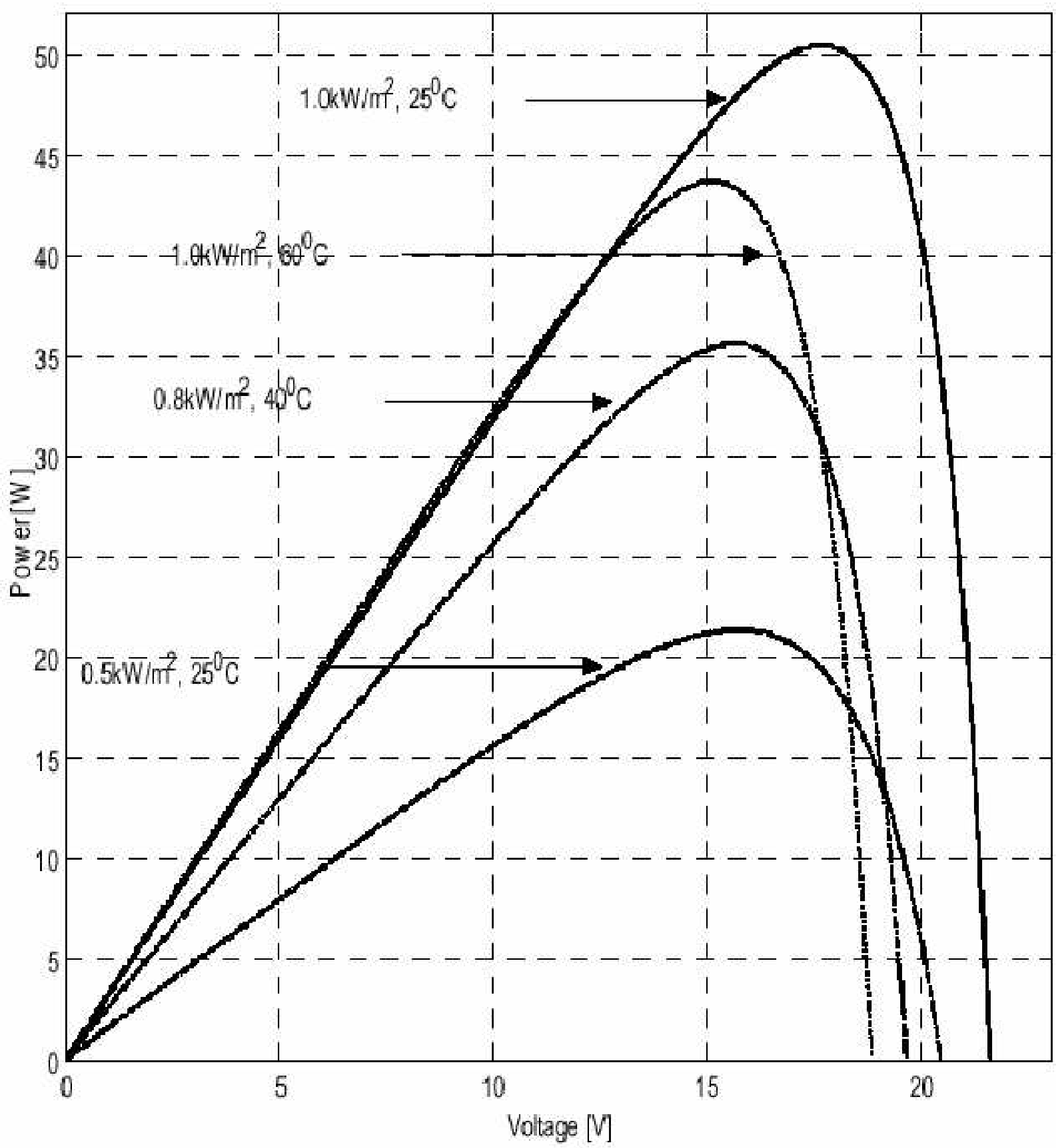


Figure 7: The power output of the solar cell is dependent on the irradiation. Figure provided by Erik Hoff.

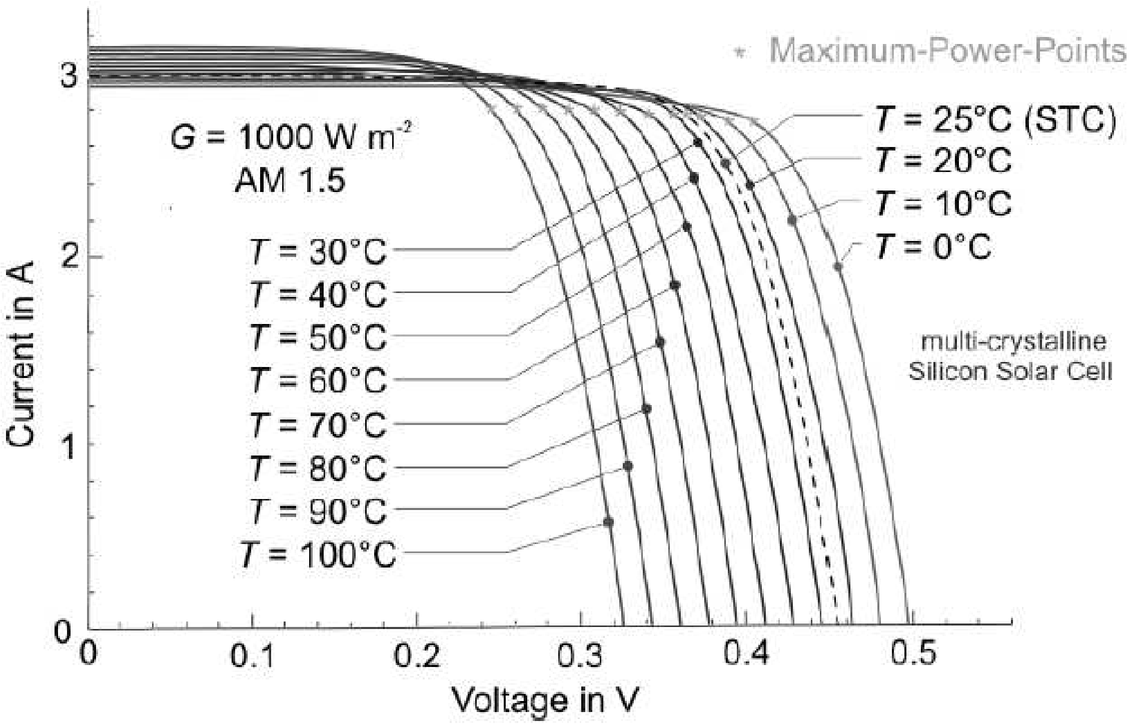


Figure 8: The voltage is dependent on the temperature in the cell. Figure from http://www.rio02.de/proceedings/pdf/101_Krauter.pdf.

- outdoor exposure
- robustness

There exist modules with various capacities. The optimal orientation of the module to gain maximum irradiation is described in FSEC (2003).

The effects of shading parts of the module have been tested by e.g Florida Solar Energy Center[19].

6 The battery: When is it needed, and how does it function?

The module in a PV system generates electricity when the sun shines on it, but in the evening, when the user needs the electricity for example for lighting, there is almost no current coming out of the module (Markvart 2003). Therefore, in most PV systems there is a need for some kind of energy storage. There are different ways of storing energy, for example using the electricity to pump up water, in which case the energy is stored as potential energy in the water. The method that is most usual in PV systems is using an electrochemical battery. The battery is charged during the day, and it can be discharged during the evening. This section descibes some of the main battery characteristics.

The section is based on theory from GEP's (1992) "Rechargeable Batteries, Application Handbook", on Markvart's (2003) "Solar Electricity" and Patel's (1999) "Wind and Solar Power".

6.1 The battery

The battery is the most expensive life cycle component of the SHS system. It accounts for approximately 13% of the initial cost, but around 30% of the life cycle cost (Diaz and Lorenzo 2001). The batteries used in SHS should allow for deep discharge without seriously reducing the lifetime of the battery. It is recommended in UNBS (2000a) that the batteries used in the PV systems should be designed for PV applications. The batteries that are most usual in solar home systems in developing countries are the ones locally produced (Vervaart and Nieuwenhout 2001). Common battery types in Uganda are three types of lead acid batteries, solar batteries, car batteries, modified car batteries and truck batteries[20] (Sandgren 2001). Lead acid batteries are generally the most commonly used battery in SHS (Diaz and Lorenzo 2001). To reduce the cost of the SHS it is important that the battery is used in an optimal way, to ensure that the life time will be as long as possible. The battery lifetime depends on various factors, including battery type, correct sizing of the system, local environment, charge regulation and maintenance.

The performance characteristics of a battery mentioned in Patel (1999) and Louineau (1998) are typically:

- Charge/discarge voltages

[19] A document on the evaluation of shading on a PV module can be found at http://www.fsec.ucf.edu/pvt/Resources/publications/pdf/ASESHADINGTESTS.PDF

[20] Truck batteries have thicker plates than car batteries and modified car batteries have thicker plates than the ordinary car battery.

- Charge/discharge ratio[21]
- Efficiency
- Internal impedance R_e
- Temperature rise
- Lifetime in number of cycles
- Self discharge
- Consumption of distilled water

6.2 Different types of batteries

Batteries can be primary or secondary type, which means they are none rechargeable or rechargeable, respectively. Secondary batteries are those used in PV systems. In the market there are various types of secondary batteries, for example nickel cadmium (NiCd), lead-acid (Pb), nickel metal hydride (NiMH) and lithium ion batteries. Here only the lead acid battery will be discussed further.

6.3 The lead acid battery

The lead acid battery is as mentioned the most common battery used in PV systems, mostly because it has high performance compared to its cost, but it has the least energy density by weight and by volume. The lead acid battery is available in various terminal voltages, e.g. 6V, 12V and 24V, and in various capacity rates, e.g. 75 Ah, 100 Ah and 115 Ah. The lead acid battery is made up of cells, one cell has two electrodes + and −, one electrode has lead and the other lead dioxide, and the electrolyte consists of sulphuric acid diluted with water. The chemical reactions that take place in the battery are:

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$$

The charge/discharge reaction is also shown in Figure 14.

6.4 The cell connections in the battery

For example, a typical 12V lead acid battery consist of six 2V cells, where each cell has both a positive and a negative terminal. When connecting the cells together, there are two options; connecting them in series or in parallel. If the series connection is chosen, the positive terminal of one cell is connected to the negative terminal of another cell, and if the parallel connection is chosen, then the negative terminals are connected together and the positive terminals are connected together. In a series connection the voltages are added, but in the parallel connection the voltage remains constant but the current can be added.

[21] The charge/discharge ratio is defined as the ratio of the Ah input and the Ah output with no net change in the state of charge.

6.5 Characteristics of the battery

The efficiency of a battery is defined as the ratio of the delivered energy to the energy that the battery is charged with:

$$E = \frac{\mathrm{Ah}_{out}}{\mathrm{Ah}_{in}}.$$

Where the energy can be calculated in ampere hours. The battery efficiency is usually around 85-90%. The internal resistance in the battery is the total resistance of all resistance contributors in the battery, for example the resistivity at the terminals and the ionic resistance in the electrolyte. The internal resistance increases with deeper state of charge, because when the battery is discharged the sulfate ione concentration decreases, which corresponds with an increased R_e, as shown in Figure 9.

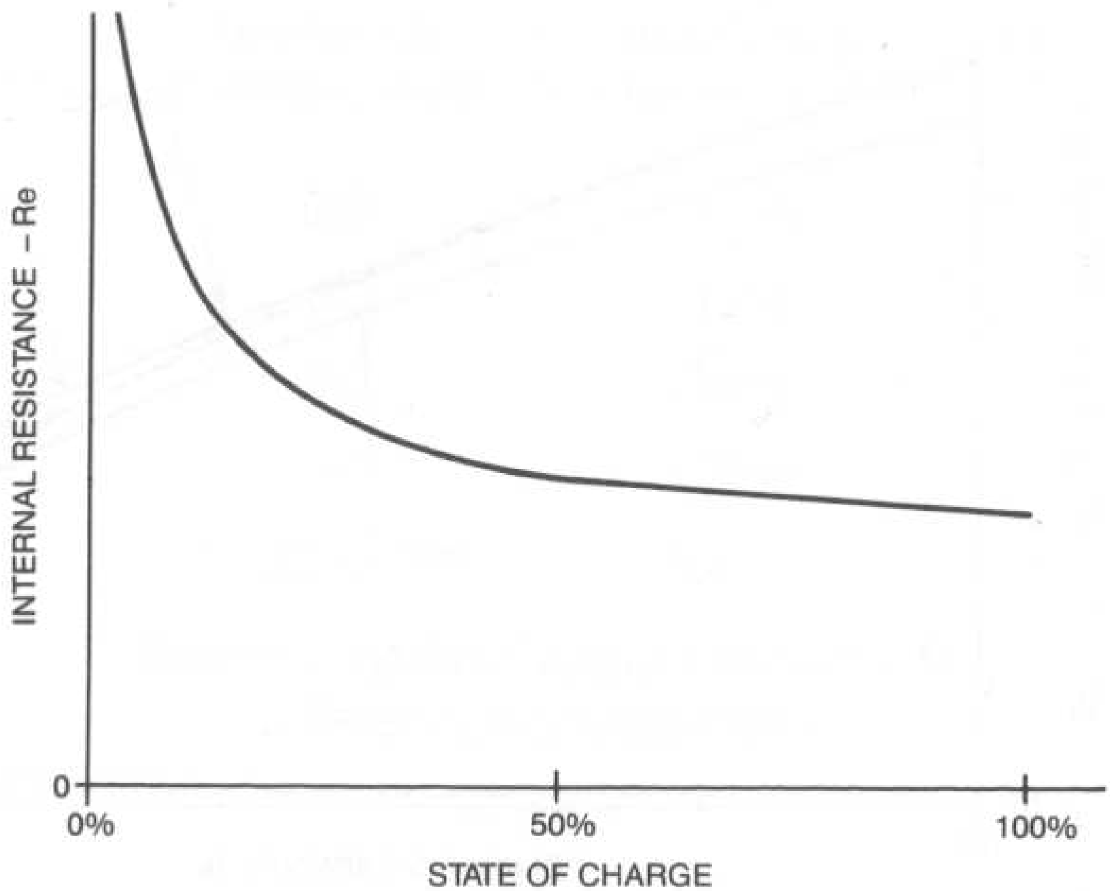


Figure 9: Effective R_e as a function of SOC. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 168.

As the battery gets older R_e increases; the contact resistance between the active material in the plates and the plate grid increases. As observed in Figure 10, this increase is quite slow in the beginning of the battery lifetime but increases as the battery lifetime gets closer to the end.

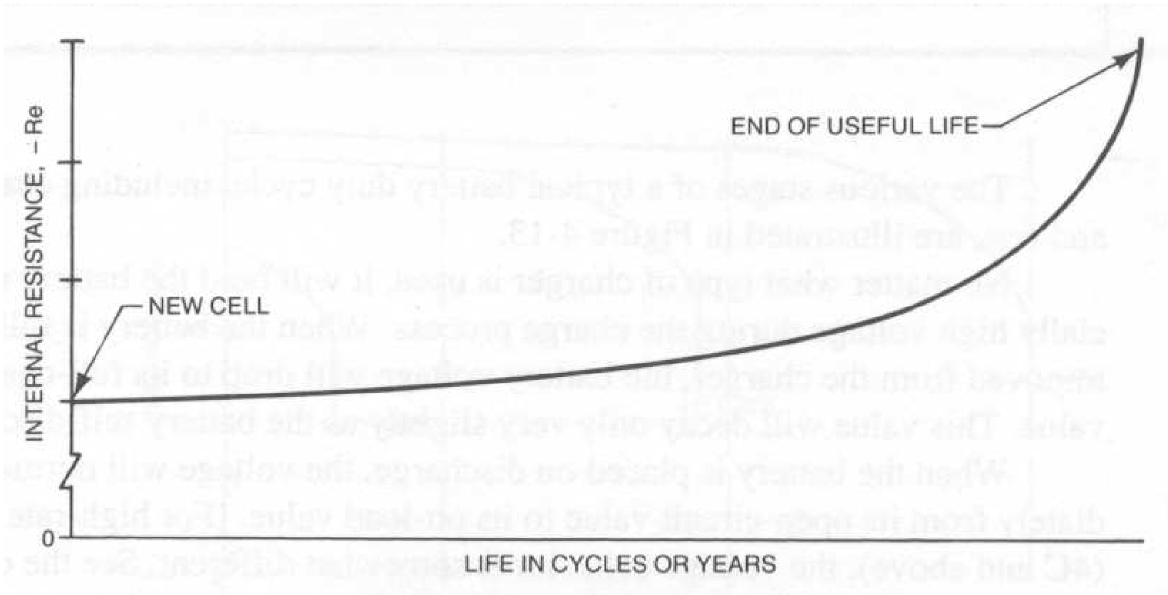


Figure 10: Effective R_e as a function of cell life. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 168.

6.6 Discharging

If a 100 Ah battery is discharged at C/10 rate the discharge current is 10A, and if the discharge rate is C/20 the dishcarge current is 5A. Sealed lead acid batteries are usually rated at 10 or 20 Ah.

The state of charge (SOC) is defined as

$$\text{SOC} = \frac{\text{Ah capacity remaining in the battery}}{\text{Rated Ah capacity}}$$

The battery capacity decreases with increasing discharge current and vice versa, as shown in Figure 12. The voltage drop is greatest in the first period of discharge, then it goes into a more stabilized phase until it starts to drop significantly at the knee of the discharge curve, as shown in Figure 11.

The duration of the discharge is depended on the discharge rate. As shown in Figure 13, it is a linear relationship. The cycling procedures have impact on the battery lifetime, which has to be considered in the system design. To obtain a long life for the battery the daily depth of discharge should be less than 20%.

6.7 Charging

A lead acid battery can be charged at a rate that does not cause excessive gassing, overcharging or high temperatures in the battery. In Vervaart and Nieuwenhout (2001), the following steps are mentioned for charging a lead acid battery:

1. Main charge, used for charging the battery up to a level when gassing starts and the voltage rises

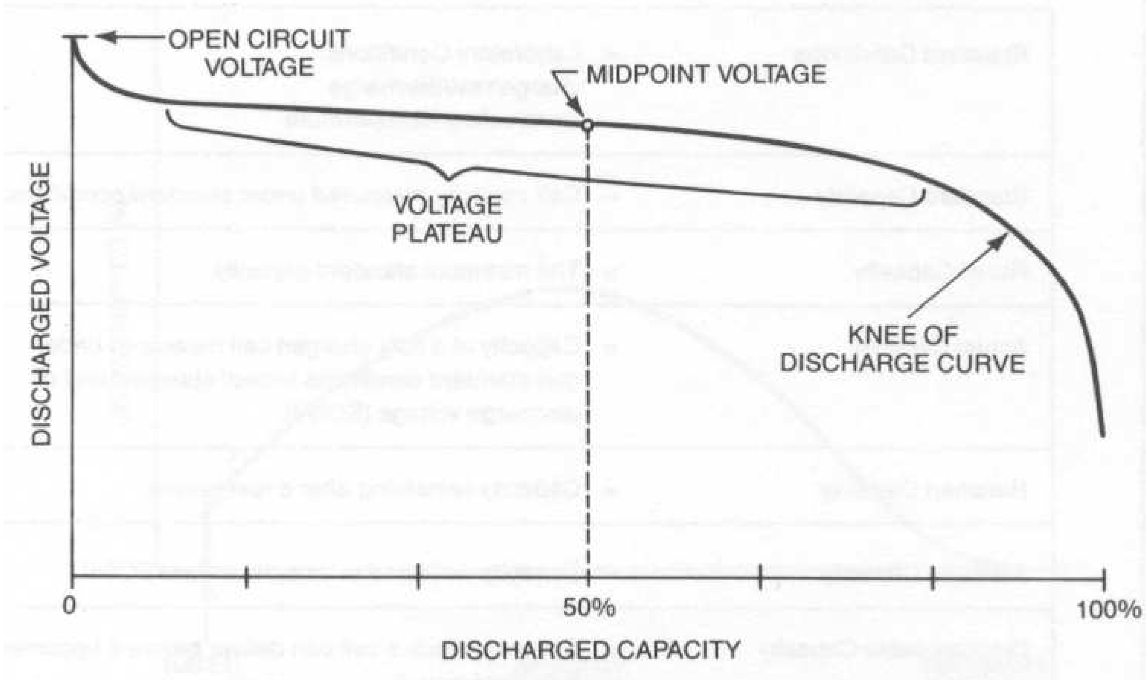


Figure 11: Voltage discharge performance of a sealed lead acid battery. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 159.

2. Top-up charge, to reach the 100% state of charge from a level of 90-95%
3. Maintenance charge, used for maintaining the full capacity in a battery that is already fully charged, but not frequently used for some period
4. Equalizing charge

The parameteres operating when the battery is being charged are the current, voltage and temperature. The battery should not be charged with too high voltages, because the corrosion in the battery can increase which leads to a shorter lifetime for the battery. The battery can be damaged by overcharging or by undercharging. It has been observed that undercharging of the battery is a greater problem than overcharging. When charging the battery, it is possible that some generation of gas takes place. This can reduce the battery efficiency, but is generally not a big problem.

The voltage control, when the battery is being charged, assumes that the battery charge is the same for each cell in the battery, but this may not always be the case. It is therefore recommended that, if possible, the voltage of each unit in the battery should be measured regularly. If one unit is not fully charged, this can cause sulphations in the battery (Vervaart and Nieuwenhout 2001).

6.8 Battery capacity

The nominal capacity for the battery is specified for a reference discharge period in hours, with a cell temperature of 20°C and a minimum voltage of 1.80V per cell (IEC 1999).

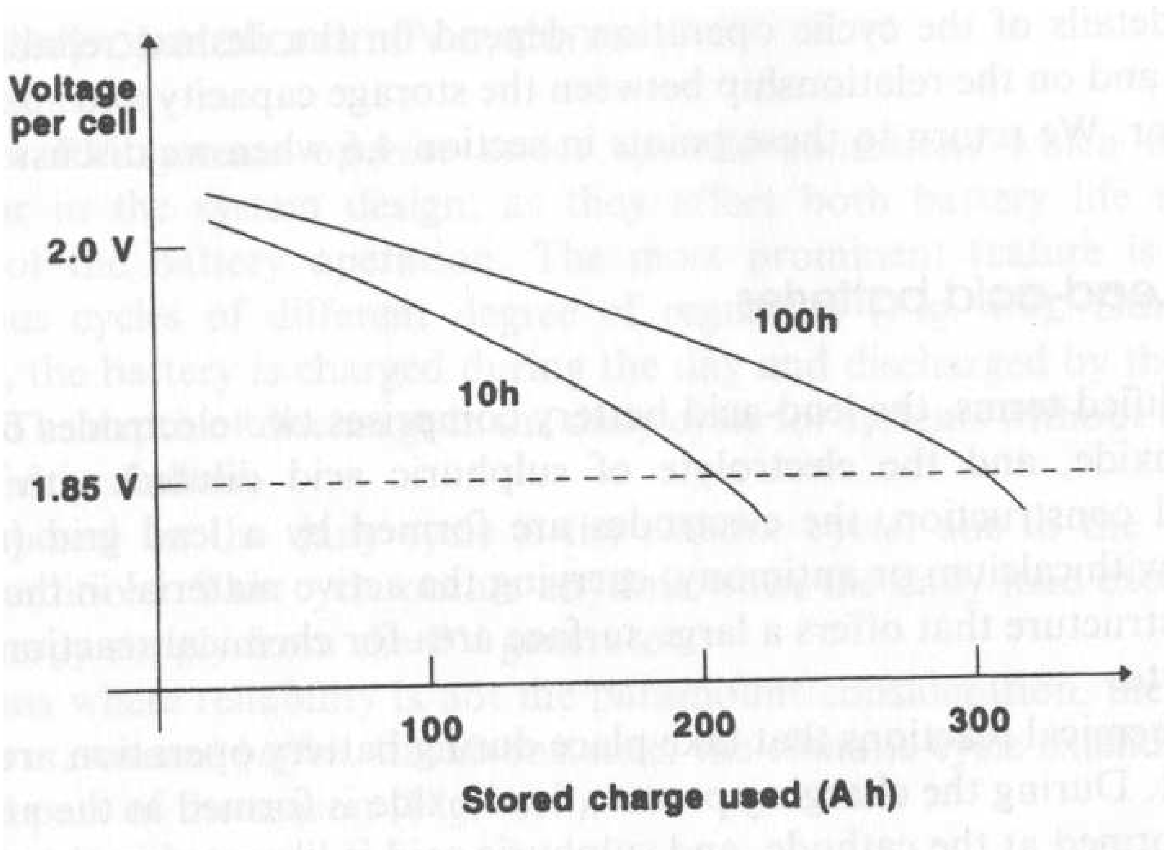


Figure 12: The battery discharge characteristics. Figure from Markvart(2000), p. 96.

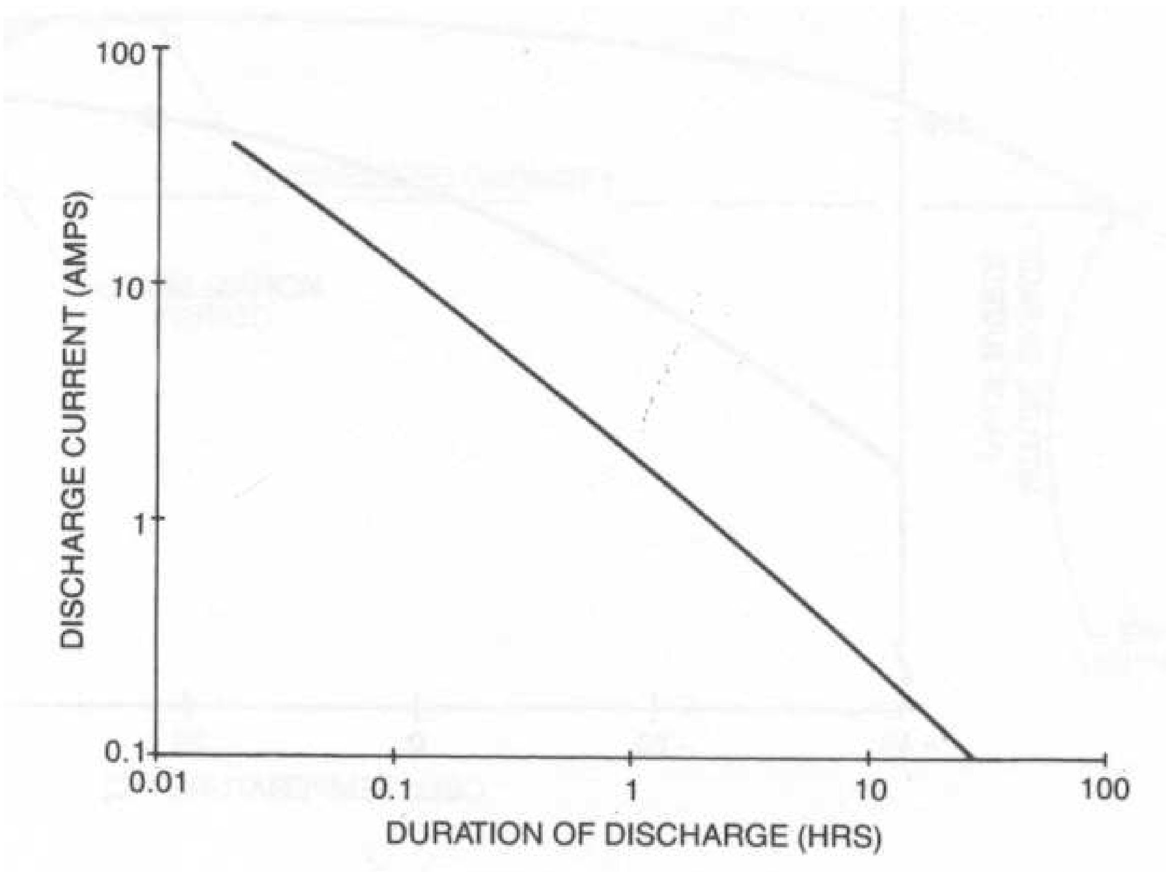


Figure 13: Typical dicharge time for a sealed lead acid cell. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 163.

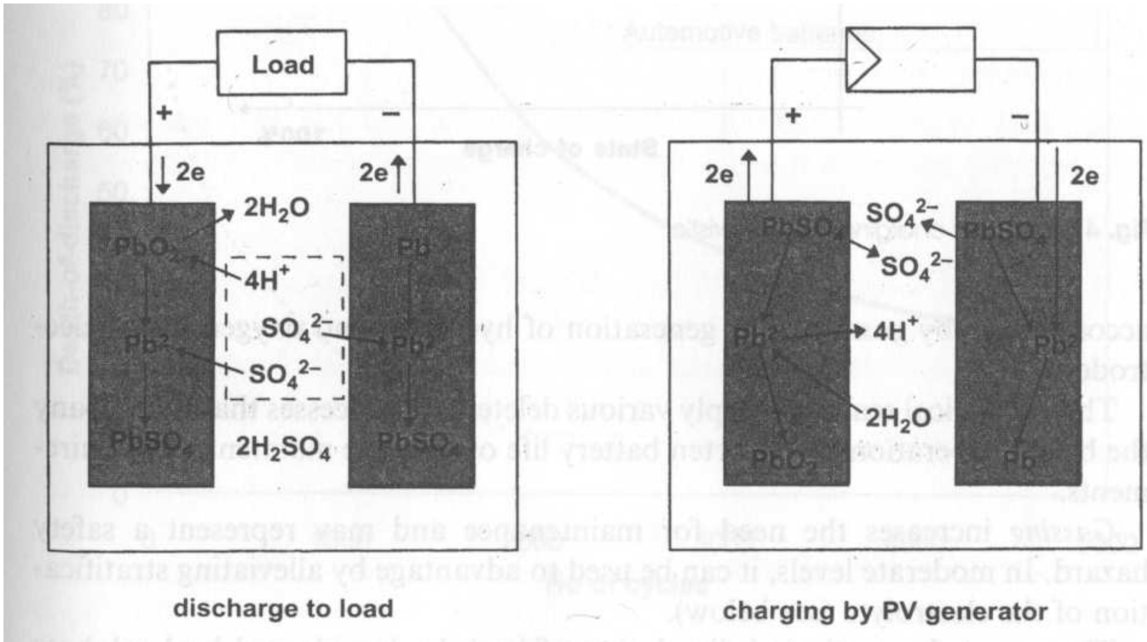


Figure 14: Charge and discharge of the battery. Figure from Markvart (2000), p. 95.

The capacity of a cell is essentially the number of electrons that can be obtained from it. The current is defined as the number of electrons per unit of time, thus the cell capacity (relative to a time interval $[0, t]$) is the current i supplied by the cell integrated over time:

$$\text{Capacity} = \int_0^t i \, d\tau.$$

This equation applies both to the charge and discharge capacity of the battery. A new battery will not operate under full capacity before it has been charged/discharged up to 50 times. This effect can be in the range of 10–20 % of the nominal capacity (Vervaart and Nieuwenhout 2001).

In Figure 15 the typical cell capacity during its lifetime is illustrated. The battery is assumed dead when its actual capacity falls to 80% but is often used much longer (Diaz and Lorenzo 2001).

If the charge/discharge rates are not controlled well the battery performance can suffer, some of the problems can be

- Low charge efficiency, low SOC
- Loss of capacity to maintain Ah charge
- Excessive gassing and heating

Battery capacity is sensitive to temperature,e.g if the temperature gets much higher than 20°C the corrosion in the battery can increase.If the temperature in the battery is 30°C the corrosion effect is twice as high as at 20°C (Vervaart and Nieuwenhout 2001).

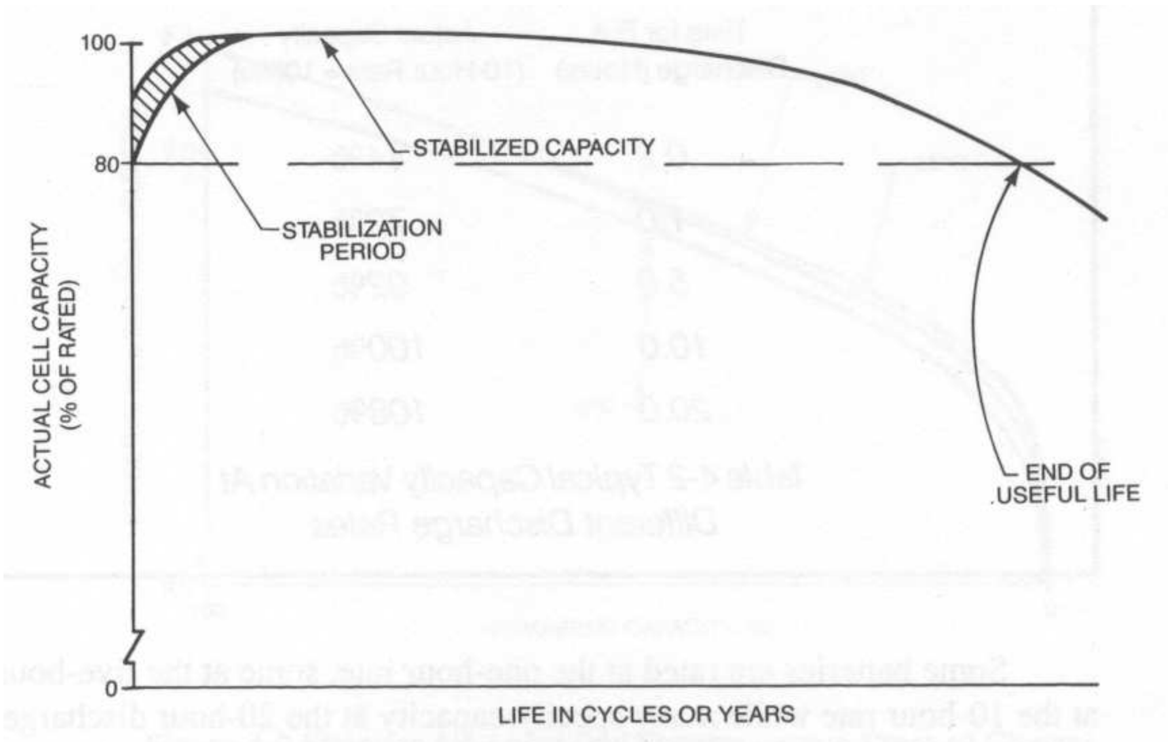


Figure 15: Cell capacity during its lifetime. Figure from Gates Energy Products (1992): "Rechargeable Batteries", p. 165.

6.9 Battery maintenance

Sulphation of the battery is the formation of large lead sulphate crystals at the plates, these crystals hinder the reversible chemical reactions. If the battery is in a low state of charge for a long time, sulphation is likely to occur. When the battery is in operation the electorlyte distribution becomes uneven, the electrolyte becomes thicker at the bottom of the battery. This uneven distribution of the electrolyte can also couse sulphation at the bottom part of the negative electrode.

Maintaining the battery includes equalizing the battery regularly by overcharging it to stir up the electrolyte. The charge controller in some cases does this automatically, but in other cases this has to be done manually. Another maintenance procedure for a lead acid battery is to fill up the electrolyte with distilled water, this is necessary because the electrolyte uses the distilled water in the chemical reactions. If the battery is not filled up with distilled water, the electrolyte becomes thick, the chemical reactions become slower and the sulphation problem becomes greater.

7 Power regulation in PV systems

This section is heavily drawn from Vervaart and Nieuwenhout (2001).

7.1 Power regulation

In a PV system, there is almost always need for some kind of power regulation. When the battery and the PV generator are connected together directly, the PV generator can act as a load during the night. This is because of the characteristics of the solar cell, which acts as a diode in the dark. This means that the battery can leak current to the PV generator and energy is lost. This effect can easily be avoided by placing a blocking diode between the module and the battery. In the day time there will be a slight voltage drop over the diode, which should be taken into consideration while dimensioning the system losses (Markvart 2003). When using high quality solar modules this type of diode is not necessary, it can cause unwanted loss.

7.2 Charge regulator

As mentioned, the battery is the most expensive component of the PV system. This means that if the charge controller can manage to optimize the battery lifetime, it could have a big impact on the life cycle cost for the PV system. Typically, the charge controller accounts for only about 5% of the initial investment cost of a solar home system. It has been mentioned that lack of progress in the charge regulator technology can be linked to the fact that lowering the price of the charge controller has little effect on the life cycle cost (Vervaart and Nieuwenhout 2001). However, the quality of the charge controller is very important in order to reduce the life cycle cost and optimize the battery life time (Diaz and Lorenzo 2001).

The function of the charge regulator is that it disconnects the module when the battery is fully charged, in order to protect the battery from getting damaged. The disconnect point is called high voltage disconnect (HVD). The charge regulator should also disconnect the load before the battery charge level is too low, this is called low voltage disconnect (LVD) (Patel 1999). The controller should reconnect the battery when the voltage has dropped to the reposition voltage, and then reconnect the load when the voltage has risen above the higher threshold (Diaz and Lorenzo 2001). Some regulators are not designed for LVD. The charge regulator is in some cases also used to protect the load under extreme conditions and to supply the user with operational information (Diaz and Lorenzo 2001). The charge controller should be temperature compensated if there is expected wide variations in the battery temperature, this can be done with a simple temperature sensor. Most charge regulators use voltage control. Functional parameters that should be taken into consideration (mentioned in Louineau (1998) and Patel (1999)) include:

- Maximum current accepted from PV panel
- Maximum current delivered to the load
- Low battery voltage indicator
- High battery voltage indicator
- Voltage threshold for charging
- Regulation type
- Reset time when battery voltage has reached a certain limit
- Electric protection (from lightning)
- Protection against reverse polarity
- Adjustability to the system voltage

Keywords for a quality charge controller are: battery protection, safety, reliability and energy saving.

7.3 Different types of charge regulators

When the battery is fully charged and the module is still producing energy, the charge controller should as mentioned disconnect the battery. This can be done in different ways. Usually the charge regulator will open the circuit between the battery and the module, but the charge regulator can also direct the current to a load. The latter method can be very convenient in stead of wasting the energy, the user of the system can e.g. listen to the radio during the day (FSEC 2003).

A basic controller has an on/off function and can easily be made by limited electronics. Two basic methods can be used: the shunt type and the series type regulation. The shunt type, shown in Figure 16, is a very common method. The voltage drop while charging is less when using a shunt type than when using a series type. As mentioned above, the battery can leak to the PV generator, in Figure 17 a schottkey diode is used to hinder that. The disadvantage of this system is that after the high voltage disconnect (HVD) the module is in short circuit, which causes heat in the controller. It has been noted that these kinds of controls often suffer from early breakdown because of the heating effect.

Some types of charge regulators can charge the battery in different manners, such as multiple charge rates, where the battery is charged in multiple steps; then the charge regulator needs to be designed for the different charge rates.

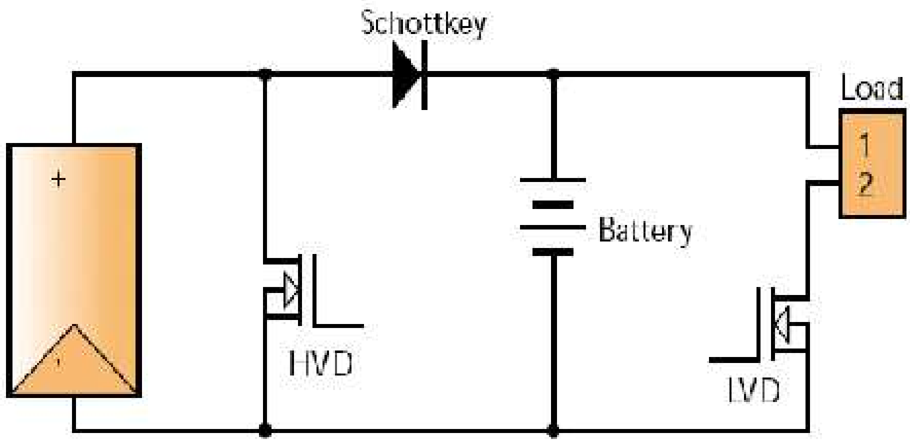


Figure 16: The shunt type regulator. Figure from Vervaart (2001), Chapter 3.

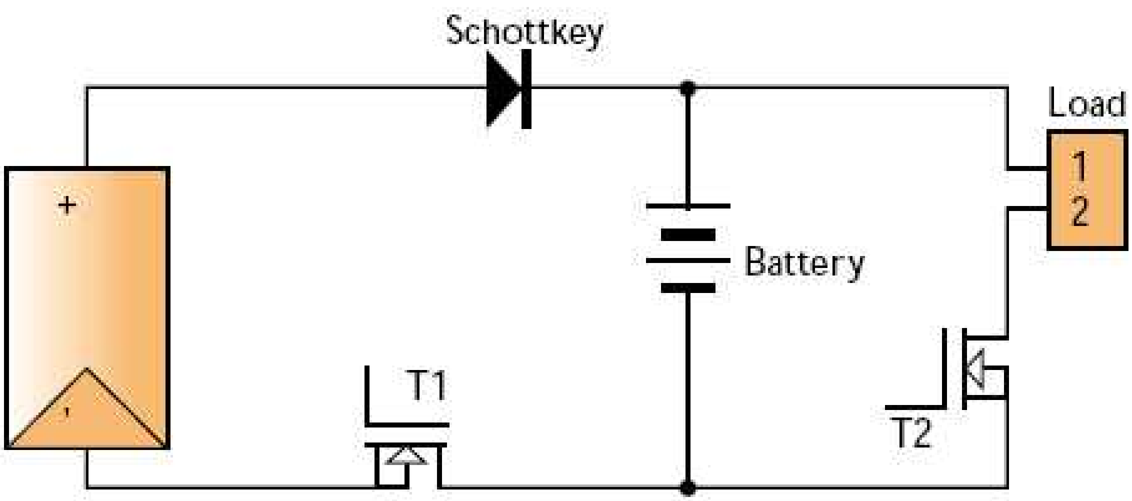


Figure 17: The series type regulator. Figure from Vervaart (2001), Chapter 3.

The controller using the series principle is shown in Figure 16. The disadvantages of the series type is mainly the extra loss in T1, where it is optimal that the internal resistance is as low as possible.

In the data from the manufacturer of the charge controller, the maximum input voltages and currents are specified. The PV generator should not be able to generate voltages or currents that will exceed the manufacturers specifications. The charge controller should be able to handle 125% of the PV array short circuit current, and a voltage that is higher than the maximum system voltage.

Several charge controllers have an incorporate equalizing mechanisim, which means that the charge regulator charges the battery until the battery comes into the gassing phase, which is a kind of a boiling action in the electrolyte. The gassing is helpful in maintaining an even electrolyte distribution. Some charge controllers perform this automatically at specified time intervals, e.g. 30 days. However, sometimes this has to be done manually. The equalization process in not recommended for all types of batteries. Sealed lead acid battery should not be equalized (FSEC 2003). It is sometimes a good solution that the charge controller closes the circuit between the battery and the module, but leads the current being produced by the module directly to a load. This can be convenient, in stead of wasting the energy, the user of the system can e.g. listen to the radio during the day (FSEC 2003).

7.4 How to use the charge controller

It is not possible to give any specific instruction on a how to use the charge regulator, because there are many different types that exist in the market.

The charge controller should be installed as near the battery as possible. The energy consumption of the charge controller should be low.[22] The controller should not be placed where the sun is shining directly at it, that can make it difficult to see the display of the regulator.

In Chapter 3 of the World Bank Manual on Solar Home System design and modification, different types of charge regulator constructions are described. Thus, for further reading and understanding of the design of the charge regulator, that literature is suggested, see the reference list.

7.5 Load in PV systems

See Section 2.4.4 for load related problems. For more information about lighting in solar home systems, read Chapter 2 in Vervaart and Nieuwenhout (2001).

8 Deciding the capacity of the system components

Parts of this section are drawn heavily from Vervaart and Nieuwenhout (2001) and from Stapleton et al. (2002).

8.1 Sizing of the PV system

When sizing a solar home system, the energy demand of the end user has to be calculated. When the demanded energy output of the system is known, the module and the battery

[22] 5-10 mA is usual.

have to be dimensioned to be able to fulfill those demands. The system losses must also be estimated.

- Determine the average daily electricity demand
- Calculate system losses
- Calculate module wattage
- Determine the battery storage capacity

The system losses are e.g the cable losses, energy consumption in the diode, energy consumtion of the charge controller and losses in the battery.

8.2 Estimating the load

When estimating the load, there are only simple calculations involved. The following steps are involved:

1. Determine which items that will be used
2. determine the rated power in watts for these items
3. estimate the number of hours each day that the item will be in use
4. multiply the rated power for each item with the estimated hours it will be in use to get watt-hours
5. add up the Wh needed for all the items

Examples of the energy consumptions of different loads are shown in Table 2 below. Also, an illustration of the calculation of energy demand is presented as Example I.

Table 2: Energy consumption of different loads used in a PV system

Instrument	Rated Power	Nr.of hours/day	Energy per/day
TV	60W	2	120Wh
Fluorescent lamp	15W	4	60Wh
Radio	12W	3	36Wh
Orientation light	1W	16	16Wh

Example I: Calculating the energy demand

Problem: A family of six people want to be able to watch TV for 1.5 hours, listen to the radio for 3 hours and to use a reading lamp for 4 hours every day. They also want to be able to orient themselves in the house in the night time with two orientation lights. How much energy do they need to fulfill their needs?

Solution: They need $1.5 \times 60 + 3 \times 12 + 4 \times 15 + 2 \times 16 = 218$ Wh.

8.3 The capacity of the module

The module capacity is given in peak watts (W_p). 1 W_p module capacity is defined as 1 Wh of electricity produced each hour with 1kW/m^2 of insolation (Vervaart and Nieuwenhout 2001). To know how to dimension the module size, the solar insolation data must be available. It is safe to design the system, based on the average daily solar insolation in the area, where the module is planned to be innstalled, for the month with the lowest insolation rate. In Uganda the lowest average daily solar insolation is around 4kW/m^2/day. Then the amount available for the user, per watt-peak of the PV capacity, can be calculated by multiplying the average solar insolation by the system efficiency. Module losses can be caused by suboptimal orientation, shading of the module, dust on the module, temperature effect on the module and nameplate mismatch[23]. The following example shows how to calculate the capacity of the module in a specific case:

Example II: Calculating the capacity of the module

Problem: The end user wants 100Wh from the system. At the site the average daily solar insolation, for the month with the lowest insolation rate is 4kW/m^2/day and the efficiency of the system is $\mu = 0.6$. Decide how many peak watts the module has to be designed for?

Solution: At the site the average daily solar insolation, for the month with the lowest insolation rate is 4 kW/m^2/day, and the energy demand is 100 Wh. W_p can then be calculated as

$$\frac{100 \text{ Wh/day}}{4 \text{ kW/m}^2\text{/day} \times 0.6} = 42 \text{ Wh/kwh/m}^2.$$

A 50W_p module can generate the required effect for this user.

8.4 The capacity of the battery

The battery capacity depends largely on how many days of storage capacity is needed. According to the Uganda standards for PV installation the battery capacity should be at least five times the maximum daily load in Ah, which provides a normal cycle depth of around 20% or less (UNBS 2000b). The need for autonomy differs from site to site, since the weather conditions are different. In Nieuwenhout et al. (2001) it is suggested that the battery capacity should be 7.5 times the daily load in Ah, but in Stapleton et al. (2002) it is mentioned that in SHS there is only need for a battery autonomy for 3–5 days. When the battery capacity is determined you need to

1. Multiply the daily load with the number of days of the autonomy that is required, and
2. Divide this number with the maximum depth of discharge allowed for the battery

In some PV systems there is need for more than one battery, than the batteries can be connected in parallel to get a greater energy storage capacity.

The manufacturers of batteries specify the maximum depth of discharge for the battery. It most often in the range of 50–80%.

[23] Manufacturers often state the output power 10% higher than actual output power

The operating temperature of the battery is important, if the battery is operating in temperatures higher than 30°C or more than 8°C below 20°C it is necessary with temperature correction.

The required number of batteries needed to fulfill the desired capacity can be calculated by dividing the Ah capacity that is desired to the Ah capacity of the battery type that will be used. For example, if a system needs 200Ah/day and batteries are available with 100 Ah capacity, $\frac{200\text{ Ah}}{100\text{ Ah}} = 2$, so you need two 100 Ah batteries connected in parallel. If the number had been 2.1, the number of batteries should have been three — always round upwards.

Example III: Deciding the battery capacity

Problem: Decide the battery capacity for the users in example I, when; the system voltage is 12V, the maximum depth of discharge for the battery is 40% and the demanded autonomy is 4 days.

Solution: The energy demand was 218 Wh. By using the simple equation $P = IV$ we get $I = \frac{218\text{ Wh}}{12\text{V}} = 18.2$ Ah. With an autonomy of 4 days, 18.2 Ah $\times$ 4 = 72.8 Ah. Since the battery is not allowed to be fully discharged, the battery capacity is then $\frac{72.8\text{ Ah}}{0.4} = 182$ Ah.

It is the responibility of the design engineer to calculate the power request of the household and to calculate the power output.

Charge regulator energy consumption, the regulator continuously uses small amounts of energy, currents between 5-25 mA is usual, losses in the battery.

9 Deciding what wires to use in the PV system

This chapter is based on Stapleton et al.'s (2002) "The Solar Entrepreneur's Handbook".

9.1 Wires

This section focuses on the system wiring, i.e. how you determine the correct sized cables to be used in the PV system. The wires discussed apply to systems which do not have system voltages exceeding 32V AC or 120V DC on the load. The Uganda electric installation standards must be read before determining which wires to use. It is stated in the standards that wires with a cross section area less than 2.5 mm^2 are not recommended for use in PV systems. Often the company selling the system also provides the wires needed , but it can be helpful when sizing the system to know exactly how much energy is lost in the wires and what ambient temperature is allowed for the wires. Some cables that are specially designed for use in DC applications are also available in the market. The wiring of the components should fulfill the following demands:

- The system must be safe
- The wires must not degrade the performance of the components of the system
- Each component should perform to its optmimum potential

9.2 Cable sizing

The wires must be sized correctly so you can avoid

- Excessive losses in the cables
- Excessive current going through the cables compared to the safe current capability

Current carrying capacity (CCC) is a term which refers to the maximum current carrying ability of a conductor Most cables that are available commercially can be used in solar home systems wiring, as long as the voltage drop and maximum current is within a specified range. The manufaturers of the cables specify the maximum current carrying capacity of their cables. The current carrying capacity (CCC) is a term which refers to the maximum current carrying ability of a conductor. This instruction must be followed. If the system will be expanded the wires may have to be exchanged in the whole system, new calculations must be made. Possible enlarging of the system is often taken into consideration before installing the first wires. The losses in the wires are a function of three parameters:

- The conductors cross section in mm^2
- The length of the wire
- The current flow in the wire
- The resistivity in the wire material

These calculations relate to Ohms law: $V = IR$. The losses are measured in terms of voltage drop, which is the loss of voltage due to the wire's resistance. The greater the wire's length the greater the resistance to the current flow. Therefore it is important that the wires are not excessively long. Excessively long wires can result in a reduction of the life expectancy of the appliances and equipment. If the cross section is to small, the resistance for the current will increase. If there is much voltage drop, there might be insufficient voltage to charge the batteries. Cables from the solar array to the batteries should be selected in a way that the voltage drop does not exceed 5% of the system voltage. It is also recommended that the voltage drop between the battery and the load should be limited to 5% especially in 12V systems. The larger a cross section of the conductor is the greater the capacity to carry current. If the cable is carrying a current higher than the CCC the cable can overheat. Overheating is dangerous and can result in wasted energy and inefficiency, melted insulation, short circuit or fire. The current in the cable should be less then the maximum CCC.

9.2.1 Calculations

For every country there are typical cable sizes available. These typical cables are often presented in tables and can easily be used[24]. However, it is practical to be able to perform the simple calculations involved.The maximum current drawn from the battery can be calculated with the following eqation:

$$I = \frac{P_{max}}{V_n},$$

[24] In annex A and B of the Uganda standards for PV installations there are tables for the maximum CCC for different wire types and the maximum cable lenghts.

where P_{max} is the power drawn from the battery when all loads are operating and V_n is the nominal battery voltage. The voltage drop is given by

$$V_d = \frac{2LIR}{A},$$

where L is the length of the wires in metres, I is the current in amperes, R is the resistivity of the wire in $\Omega/\text{m}/\text{mm}^2$ and A is the cross sectional area of the cable in mm^2. The most usual material used for SHS wiring is copper, which has resistivety $R = 0.0183\Omega/\text{m}/\text{mm}^2$. Therefore, when the cable length, the cross sectional area of the wire and the current are known, the voltage drop can easily be determined. Figure 18 shows a circuit drawing of a typical solar home system, between the load that is furthest away from the battery or charge regulator the wire loss must not exceed 5%. The total voltage drop is the voltage drop in all the cables that lead to the load. From Figure 18, the following calculations can be made: The total voltage drop is

$$\text{voltage drop cable 1} + \text{voltage drop cable 2} + \text{voltage drop cable 3} + \text{voltage drop cable 4}.$$

Below two examples are given. The calculations are based on the equations $P = VI$ and $P = RI^2$.

Example 1: The distance between the module and the battery is 10 metres, the cable cross section area is 2.5 mm^2 and the current is 4A. Determine the voltage drop. Solution:

$$V_d = \frac{2LIR}{A}, \text{and}$$

$$V_d = \frac{2 \times 4\text{A} \times 10\text{m} \times 0.0183\ \Omega/\text{m}/\text{mm}^2}{2.5\ \text{mm}^2} = 0.59\text{V}.$$

This voltage drop is below the 5% recommended.

Example 2: The cross section area A of the wire can be calculated by the formula

$$A = \frac{2LIR}{\text{Loss} \times V},$$

where loss is the maximum voltage loss = 5% = 0.05. If the array is 12 m from the batteries, the maximum current is 6A and the system voltage is 12V, what is the smallest cross section allowed? Solution:

$$A = \frac{2 \times 12\text{m} \times 6\text{A} \times 0.0183\Omega/\text{m}/\text{mm}^2}{0.05 \times 12\text{V}} = 4.4\ \text{mm}^2$$

10 Standards for PV systems

There exist several different standards for PV systems, both national and international. According to IEA it is difficult to ensure quality assurance for PV systems, because there are very many different partners involved. The following institutions have all made standards

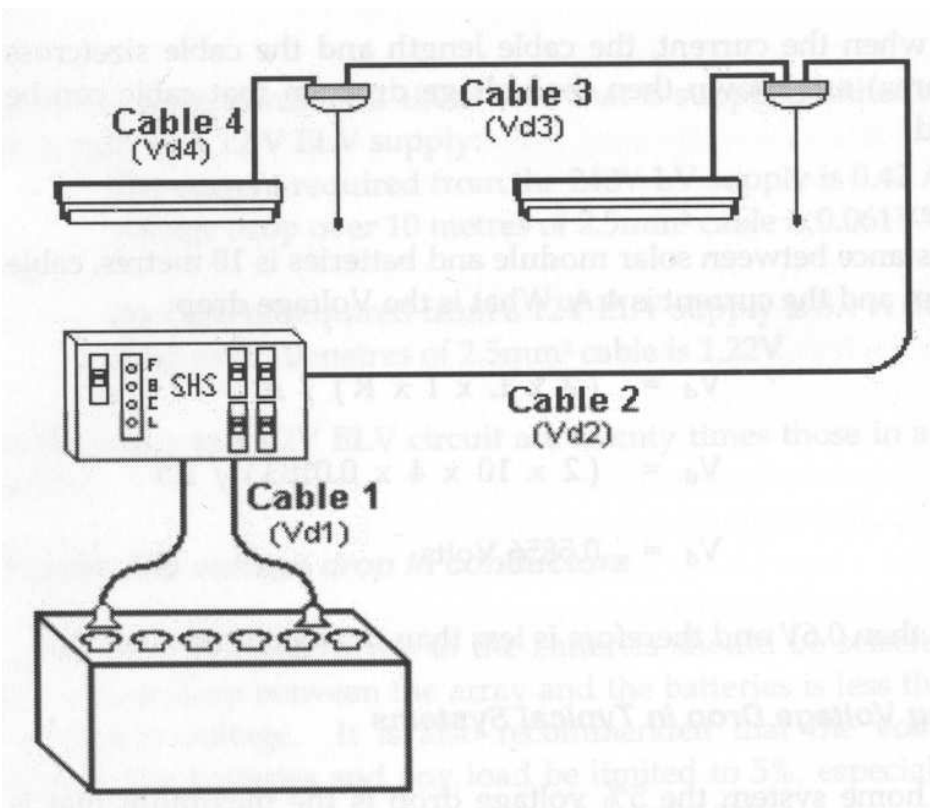


Figure 18: Typical cables in SHS. Figure from Geoff Stapleton (2002): "The Solar Entrepreneur's Handbook", p. 62.

for PV systems: NEC, CENELEC, IEC and IEEE.[25] In Wiles (1996) the implementation of NEC[26] on PV systems is described. This is a very helpful document. Also IEA has made a survey of the existing national and international standards and guidelines for stand-alone PV Systems.[27]

10.1 The Uganda standard

As part of the UPPPRE project the Uganda government made standards for PV systems the standards were puplished in 2000. The standards focus on important parts of the secure and optimal use of PV systems. The standards included among other things a code of practice for installation of PV and the fluorescent lights, which are a typical load for a PV system (Langseth 2003). The installation code of practice should be read carefully before installing a PV system. It can be of great help to avoid problems related to insufficient intallation procedures.

11 Issues concerning installation and use of PV systems

Regarding a course implementation, the material presented here must be made more adjustible for educational purposes.

11.1 Working safely with PV systems

When working with PV systems it is important that every safety instruction is followed carefully. Each component must be handled with care. Standards on installation and usages must be followed at all times. In FSEC (2003) there are references to material on how to ensure safety while working with PV systems.

11.2 Environmental issues

Small PV systems do not present any immediate environmental hazard. A correct disposure of the battery used in the system is important. Usually, the battery can be returned to the manufacturer. If that is not possible, possible other safe solutions can be discussed with the manufacturer or local authorities.

11.3 Installing a PV system

In Louineau (1998) the general installation methods for installing a small PV system is described in pages 14–19. A company selling e.g. the solar modules usually has a specific installation manual for the component. In Shell (2002) an installation manual for the Shell solar module is available. Also, for many other manufacturers of PV system components, e.g. NAPS, the installation manual is available on the World Wide Web. In FSEC (2003) there is a great deal of practical information on how to install a PV system, more detailed than in Louineau (1998).

[25] National Electric Code, European Committee for Electrotechnical Standardization, International Electrotechnical Comission, Institute of Electrical and Electronics Engineers.

[26] Here refering to the US National Electric Code.

[27] This document is available at: http://www.oja-services.nl/iea-pvps/products/download/rep3_07.pdf

11.4 End user and maintenance

As discussed in Section 2, the importance of end user training is obvious. The user of the solar system is a key person in maintaining the system and making the system function well. It is not enough to orally train one member of the household on the system maintenance. It would be a good idea to give a maintenance and safety poster to the end user. In Louineau (1998), the following topics are mentioned on what the technician needs to keep in mind in the relation to the end user:

- The user must get information on the advantages and limitations of small solar systems
- Listen to the users needs
- Ensure that the spare parts for the systems are available
- Be available to the user
- Train the end user in maintenance

12 Laboratory exercises with SHS components

In the lab exercise there will be used two standard components in SHS the module and the battery. It is difficult to perform some of the battery tests because they are very time demanding, but since it would be interesting to perform them in furhter work, they are introduced in Appendix A. Since DC/AC conversion and maximum power tracking are not usual in small SHS in Uganda, that will not be discussed here. Nevertheless, it is highly relevant for further studies. The lab exercises are built up in a manner of first asking the student to perform each exercise, and then the results of the exercises are given. The module exercises are inspired by **?**. The plotted results are included in Appendix B.

12.1 The aim of the laboratory exercises

It is important to test that a device meets certain requirements, even though it might seem unnecessary. It can increase the understanding of the behavior of a certain component when you try it out and experiment with it, to see what happens if small changes are made. The goal of this laboratory exercise is to get a basic functional understanding of two of the components in a typical solar home system.

12.2 Instruments

The following instruments were used in the laboratory exercises:

- PW 750 series module, with 36 multi crystalline cells, with the following parameters at STC[28] (as supplied by the producer): $V_n = 12$V, $I_p = 4.6$A, $V_p = 17.3$V, $V_{oc} = 21.9$V, $I_{oc} = 5$A, $P_{max} = 80$W and $P_{min} = 75$W.
- Wires, two multimeters and a variable resistance.

[28] Standard test conditions: the module performance at 25°C, with irradiance 1000 W/m^2 and AM1.5.

- Power source for the module: Two lamps 300W type KFB 93307, two lamps 500W type Malmberg QH 505. MacSolar solar power measuring unit (measuring irradiation on the module in W/m^2).
- Jacket for blocking the module.
- Lead acid battery with a capacity of 115 Ah/20h, 12V output voltage (2V/cell, 6 cells)
- Power source acting as a PV generator
- 12V 35W halogen lamp
- 3Ω Resistance

12.3 Laboratory setup for the module measurements

The connections in the laboratory are shown in Figure 19 below, where A is a multimeter measuring the current and V is a multimeter measuring the voltage.

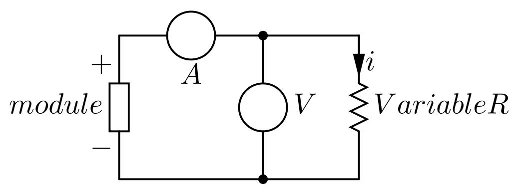


Figure 19: Circuit diagram of laboratory setup.

Exercise I: Module characterisitcs

Task: Do the following:

1. Measure the voltage with different resistance.
2. Measure the short circuit current I_{sc} and the open circuit voltage V_{oc}.[29] Before starting the voltage measurements, measure the irradiation on the panel with the MacSolar instrument, and find the area of the module.
3. Make a graph of the V-I characteristics, $V = IR$.
4. Calculate the power output, $P = VR$.
5. Make a graph of the power-voltage characteristics, $P = VR$.
6. Calculate the fill factor FF, which is a measurement of the quality of the solar cell:

$$\text{FF} = \frac{I_m V_m}{I_{sc} V_{oc}}$$

   V_m and I_m are the voltage and current at maximum power output.
7. Calculate the efficiency μ, which is the fraction of output power/input power.

[29] I_{sc} is the current with no load and V_{oc} is the voltage with an open circuit.

Results: First the module was situated in a way that the irradiation from the lamps would be optimal. The module and the lamps were situated on the floor with support on both side. Then the irradiation was measured in 20 places on the module, with the following results: 211, 310, 250, 459, 240, 400, 260, 450, 360, 300, 293, 540, 441, 450, 570, 515, 400, 250, 400, 370. Average irradiation: 315 W/m^2. Area of the module in m^2: 12 cm $\times$ 12 cm $\times$ 36 = 0.51 m^2. The voltage and current were measured at different resistance. The results are given in Table 3 below. The values $V_m = 17.4$V, $I_m = 0.87$A, $I_{sc} = 1.1$A and $V_{oc} = 19.44$V were measured, giving a fill factor FF of

$$FF = \frac{0.87 \times 17.4}{1.1 \times 19.44} = 71\%.$$

The power input was 315W/m^2 $\times$ 0.51 m^2 = 160W, and the maximum power output 15.2W, giving an efficiency of $\mu = 9.5\%$.

Table 3: Results, Exercise I

Resistance	DC current	Voltage	Power
0Ω	1.10 A	0 V	0W
7Ω	1.03 A	7.2V	7.4W
10 Ω	0.98 A	9.8V	9.6W
20Ω	0.87 A	17.4V	15.2W
30Ω	0.66 A	19.8V	13.0W
40 Ω	0.48 A	19.2V	9.2W
60Ω	0.32 A	19.2V	6.1W
90Ω	0.21 A	18.9V	4W
100Ω	0.19 A	19.0V	2.9W
150Ω	0.13 A	19.5V	2.6W
190Ω	0.10 A	19.0V	1.9W
200Ω	0.10 A	19.0V	1.9W

Exercise II: Blocking parts of the module

Task: One sixth of the area of the module should be blocked, the rest of the panel should have the same irradiation as in Exercise I. Measure the V-I characteristics and make a graph of the results. Measure the short circuit current and the open circuit voltage. Calculate the fill factor and efficiency.

Results: $V_m = 9.8$V, $I_m = 0.140$A, $I_{sc} = 0.220$A and $V_{oc} = 17.8$V, so the fill factor was

$$FF = \frac{0.14 \times 9.8}{0.220 \times 17.8} = 35\%.$$

The input power was 315 W/m^2 $\times$ 0.43 m^2 = 135W and the maximum power output 1.4W, giving an efficiency of $\mu = 1\%$. The other measurements are listed in Table 4.

Table 4: Results, Exercise II

Resistance	Current DC	Voltage	Power
2Ω	220 mA	0.44V	0.1W
6Ω	210 mA	1.26V	0.26W
10 Ω	160 mA	1.6V	0.26W
60Ω	150 mA	9V	1.35W
70Ω	140 mA	9.8V	1.37W
100 Ω	110 mA	11V	1.21W
150Ω	90 mA	13.5	1.21W
180Ω	80 mA	14.4	1.15W
200Ω	60 mA	12V	0.72W
300Ω	30 mA	9V	0.27W

Exercise III: Blocking the whole module

Task: Measure I_{sc} and V_{oc} when the whole module is blocked.

Results: $V_{oc} = 20$ mV and $I_{sc} = 0.04$ mA

12.4 Battery testing

To try to analyse what kind of state a battery is in, there will be presented simple tests to determine some of the battery characteristics.[30]

The battery used in this laboratory exercise was a battery that had stood without being discharged in temperature less than 15°C for over five months. The initial battery voltage was measured to be 11.9V. The battery was charged with constant current of 4.6A ± 0.4A over night. The battery voltage at the end of charging was 14V. The battery was in the gassing state when it was disconnected from the source.

Exercise IV: Measure the voltage at the terminals

Task: Connect the − and + wires of the battery directly to the multimeter, and registrate the voltage over the battery.

Result: The voltage over the terminals was measured to be 13.1V.

Exercise V: Measuring the electorlyte level

Before measuring the electrolyte level, safetey instructions must be read, because the acid in the battery is dangerous. If it is a sealed lead acid battery the electrolyte level cannot be measured, but if it is a open battery, the electrolyte level can easily be measured[31]

[30] Many of the battery tests are very time demanding when there is no automatic registration of the measurements. Erik Hoff, a PhD student at the electronics department at NTNU, has made a microcontroller that measures the current going in or out of the battery and the voltage over the battery automatically, which can be used for further measurements.

[31] A guide on how to test the battery with a hydrometer can be found on the World Wide Web: http://uuhome.de/william.darden/carfaq4.htm.

Task: Open one of the cells in the battery, put the hydrometer into one of the cells, register the electrolyte level. If the level is under the specified level you should put distilled water into the battery. Sometimes a visual inspecition is sufficient, if you can see where the electrolyte level should be.

Result: A visual inspection was performed. The electrolyte level was seen to be below the specified level. Distilled water was unavailable.

Exercise VI: Discharge capacity test

This test is from Diaz and Lorenzo (2001). The battery should be fully charged when performing a discharge test. This discharge test uses approximately constant discharge current. The battery should be connected in series with a resistance and a 12DC 35W lamp. The voltage should be measured over the battery and over the resistance. The voltage measurement over the resistance is for current measurements. The resistance can be a 3Ω resistance.

Tasks: The voltage over the battery and the current in the circuit should be measured every two hours. How many Ah did you receive from the battery before the battery voltage reached the level of 11.3V? In which state of charge was the battery at that level?

Results: As mentioned, before starting, the battery was charged to 14V. The self discharge over the battery was 1.1V over 28 hours. Thus the initial charge of the battery was 12.9V. The instruments were connected as in Figure 20, with the multimeter over the battery and over the 3Ω resistance. The initial current in the circuit is $I = \frac{6.3\text{V}}{3\Omega} = 2.1\text{A}$. The battery was discharged until the battery voltage was 11.3V, the Ah output of the battery was approximately $2\text{A} \times 25\text{h} = 50\text{Ah}$, the initial capacity is 115Ah, then 115Ah-50Ah=65Ah and

$$\text{SOC} = \frac{65\text{Ah}}{115\text{Ah}} = 56.5\%.$$

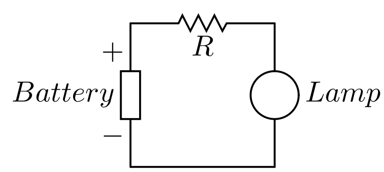


Figure 20: Simplified circuit drawing of laboratory setup

Exercise VII, Voltage drop in the wires

Question: How much voltage drop was there in the wires used in Exercise VI, when the wires are made of copper, with a $5mm^2$ diameter and the total length is 8 m?. The voltage drop can be calculated from

$$V_d = \frac{2LIR_c}{A},$$

where $R_c = 0.0183\ \Omega/\text{m}/\text{mm}^2$.

Table 5: Results, Exercise VI

V_b	V_r	Time in hours
12.3V	6.33V	0
12.3V	6.33V	1
12.0V	6.24V	3
12.0V	6.25V	5
12.0V	6.25V	7
12.0V	6.22V	9
11.9V	6.22V	11
11.8V	6.17V	15
11.8V	6.16V	17
11.7V	6.12V	19
11.7V	6.12V	20
11.5V	6.04V	21
11.4V	6.02V	23
11.3V	5.98V	25

Answer: The voltage drop was

$$V_d = \frac{2 \times 8 \times 2.1A \times 0.0183\ \Omega/\mathrm{m}/\mathrm{mm}^2}{\pi(2.5\mathrm{mm}^2)^2} = 0.03.$$

The total voltage drop in the wires is approximately 3%. This is below the 5% limit.

13 Cost evaluation for laboratory instruments

Instruments needed for the course implementation:

- Multimeter measuring voltage and current
- Wires and fuses
- MacSolar power measuring unit W/m^2
- Variable resistance, 1–1000 Ω
- Distilled water
- 12V load with 35-50W energy consumption
- Lead acid battery
- Charge regulator
- Solar module
- Source for the solar module, sunlight

In Table 6 the approximate prices for the instruments needed in the course are listed.[32] These are the prices if the instruments were bought new in Norway.

Table 6: Prices of the Laboratory Instruments

Instrument	Number/amount	Approx. prices, NOK
125Ah Lead acid battery	2	1400
MacSolar, SLM018c-E	2	1300
Distilled water	2l	45
Charge regulator, GTR 7VA	2	1200-1500
Variable resistance	4	350
Multimeter	4	150
12V, 65W Solar Module	2	6000
Misc. cabling and fuse instruments		1000
12V DC 30-50W load	2	50
Instrument to measure the electolyte	2	50
Total price for the instruments		23200

Since the course is not fully planned, the number of instruments might increase or decrease — that depends on the implementation of the course. Table 6 gives an idea of how much it will cost to perform the laboratory exercices suggested. It is possible that only some parts of the course will be implemented, e.g. only battery tests will be performed; then the instruments can be very simple and portable.

14 Educational material for SHS

The educational material I have used in the project is listed in the reference list. Quality Eductional material I have found and only used partly or not in the project include:

1. World Bank's Quality Program for Photovoltaics. This program can be found at the following website: http://www.worldbank.org/astae/quappv/

2. "Solar Electric Systems for Africa" by Mark Hankins and Mike Glen-Williamson (1995), has been suggested as course litterature, and has been referred to as the bible of PV in Africa.

3. Sandia University in Florida has various course manuals on maintenance, operation and installation of PV systems, which can be found at http://www.sandia.gov/pv and ordered from http://www.sandia.gov/pv.ordrfrm.pdf.

4. The international energy agency (IEA) is working on operational performance, maintenace and sizing of PV power systems. IEA has published many educational reports available also on the World Wide Web at http://www.task2.org/public/index.htm

[32]Sources: Hyttebutikken: http://www.dkdigital.no/akershus/skedsmo/hyttebutikken.nsf/ and SOLARC: http://www.solarc.de.

5. Jean-Paul Louineau's manual "Small Solar Electric Systems Handbook" is useful for shorts courses for community based technicians.

6. John Wiles: "Photovoltaic Power Systems" and the National Electrical Code: "Suggested Practices" can be found at http://www.nmsu.edu/%7Etdi/NEC.pdf. The document is based on the National Electric Code in USA.

7. IEC has written: IEC/PAS 62111, Specifications for the use of renewable energies in rural decentralised electrification.

8. Home Power magazine has a website where there are many helpful guidelines in how to use solar home systems: http://www.homepower.com/.

9. Progress in Photovoltaics is an excellent journal on PV systems.

15 Conclusions and further work

There are many technical problems involved in the PV electrification process. The current strategies in PV electrification projects need to be improved, where education should be more emphasized and infrastructure strengthened.

The World Bank has made a PV quality program which is promising. Further work could include contacting the World Bank, to learn more about their plans for Uganda.

While learning more about PV systems, the subject becomes larger. There is an enormous amount of theory concerning each component. Further work could include going deeper into a particular component. It would be most interesting to look at the most problematic components. Also, further laboratory exercices on the battery should be done.

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Appendix A: Further testing on the components

Testing the battery efficiency

The IEC 62093 Draft Efficiency Test Procedure is described accurately on pages 32–35 in the IEA PVPS Task 3 document. This document is listed among the references. This test can be performed within 56 hours.

Testing battery capacity

A test procedure to test the capacity of a battery is suggested at http://www.usbr.gov/power/data/fist/fist3_6/fist3603.htm. Also, in Eduardo Lorenzo's and Pablo Diaz' article "Solar Home System Battery and Charge Regulator Testing" from Progress in Photovoltaics (2001), a method of testing the charging capacity of the battery is described.

Testing the performance of the fluorescent light tube

In the Uganda standard for fluorescent light tubes there are described tests on fluorescent lamp performance. These tests include e.g. a starting test, a duration test and a reverse polarity test.

Appendix B: Plots from exercises

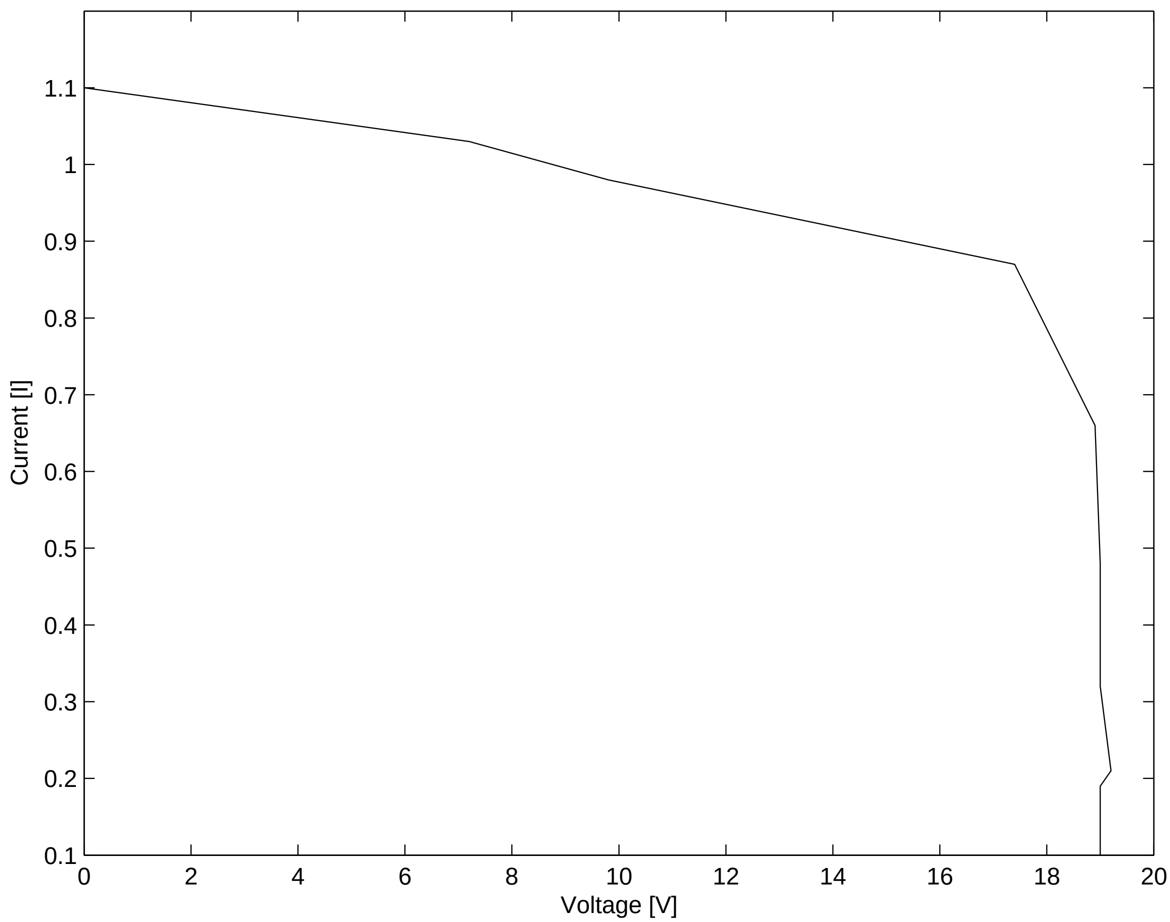

Figure 21: V-I Characteristic, Exercise I

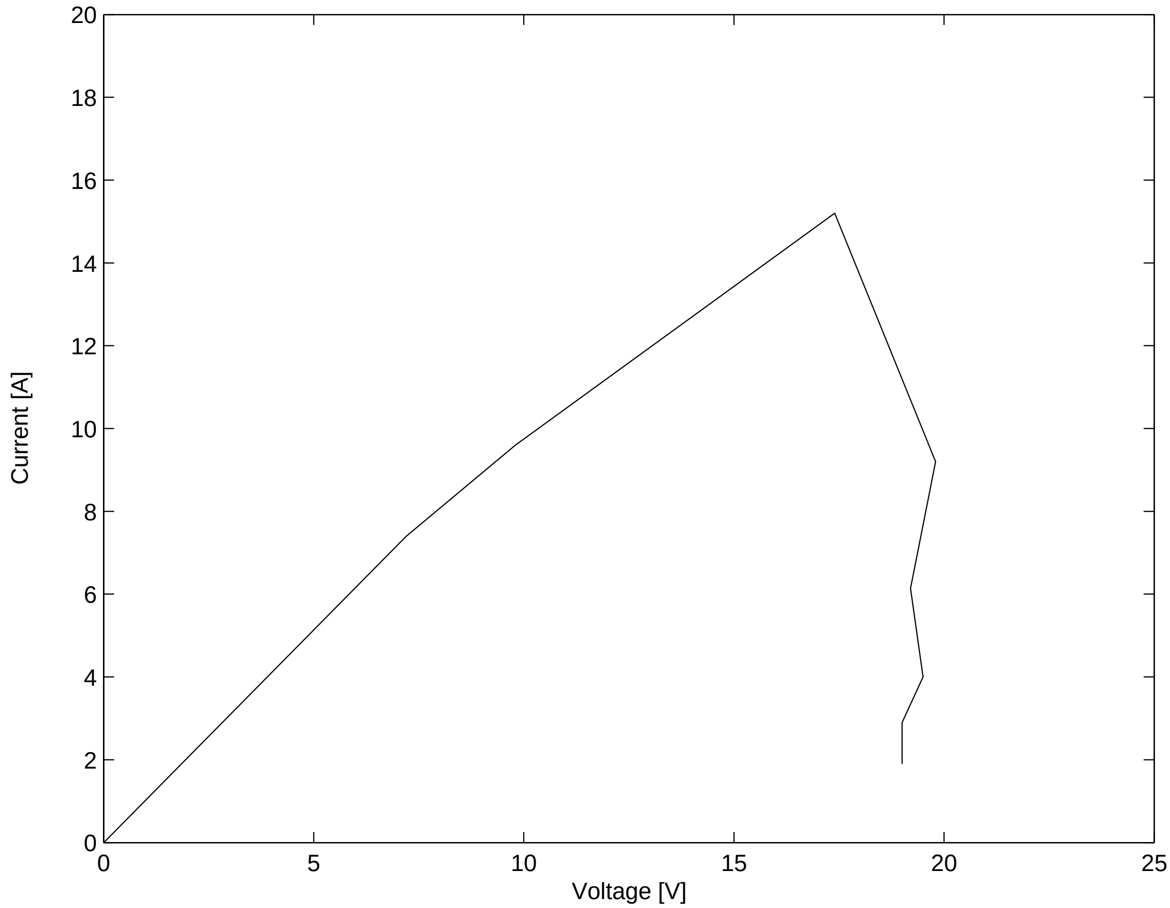

Figure 22: P-V Characteristic, Exercise I

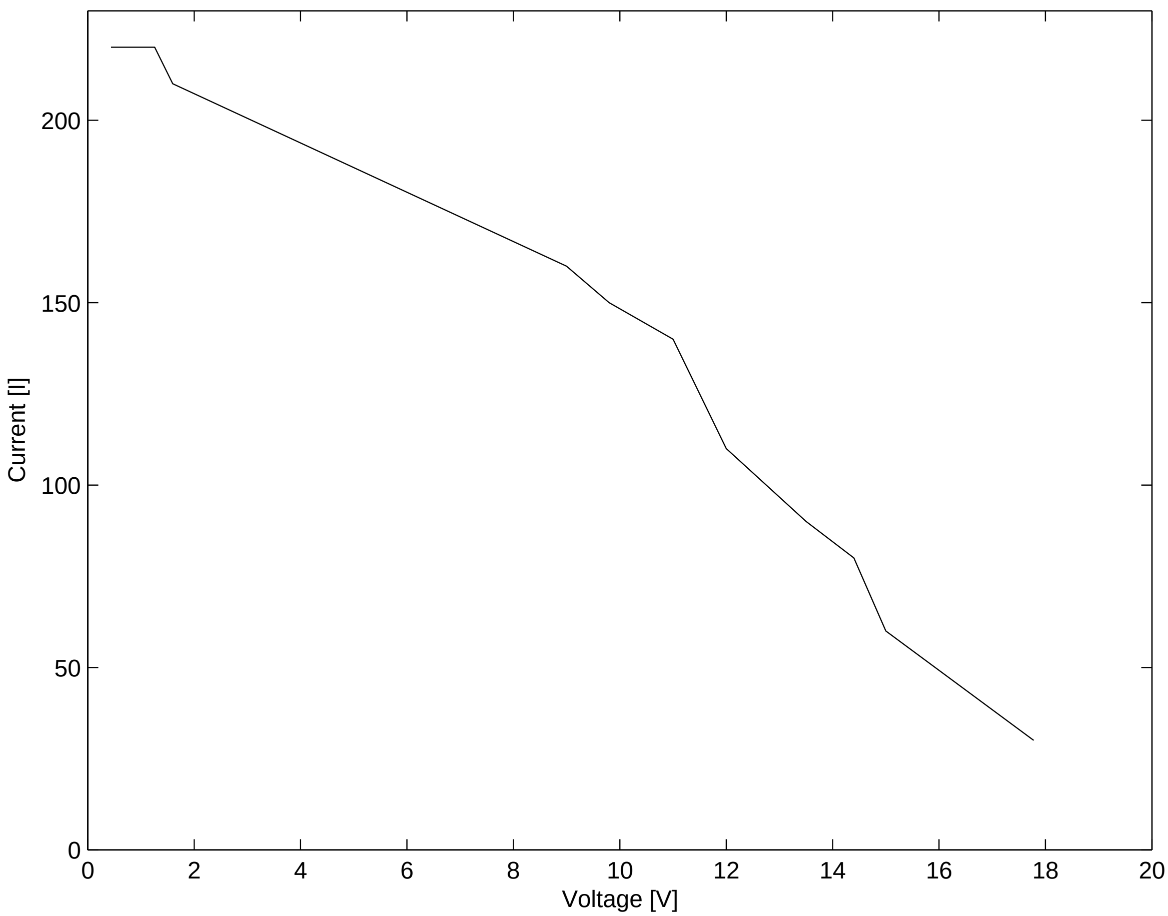

Figure 23: V-I Characteristic, Exercise II

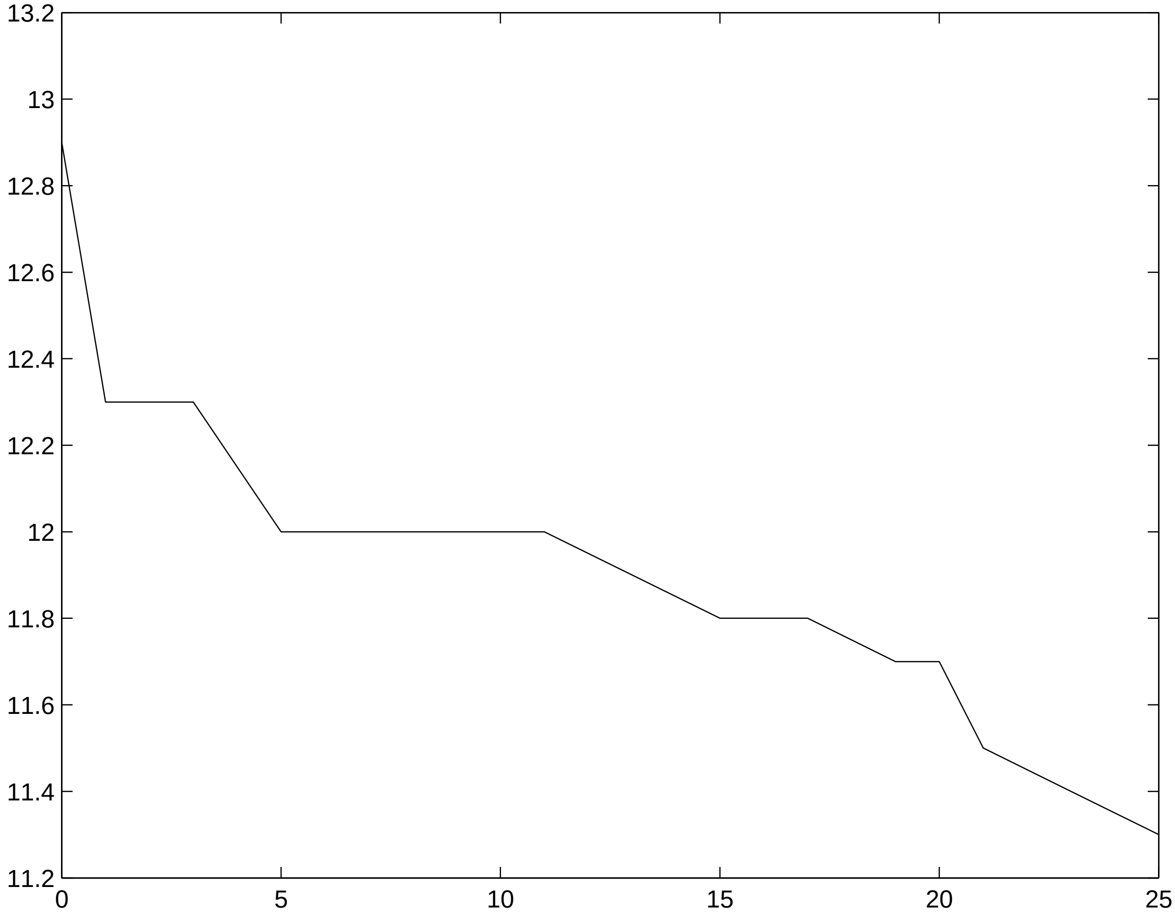

Figure 24: Exercise IV: Battery voltage versus time

Appendix C: An example of the connection in a PV system

Figure 25 on the following page, showing an example of the connection in a PV system is taken from Home Power magazine, available on the World Wide Web at http://www.homepower.com/files/cabinskiz.pdf.

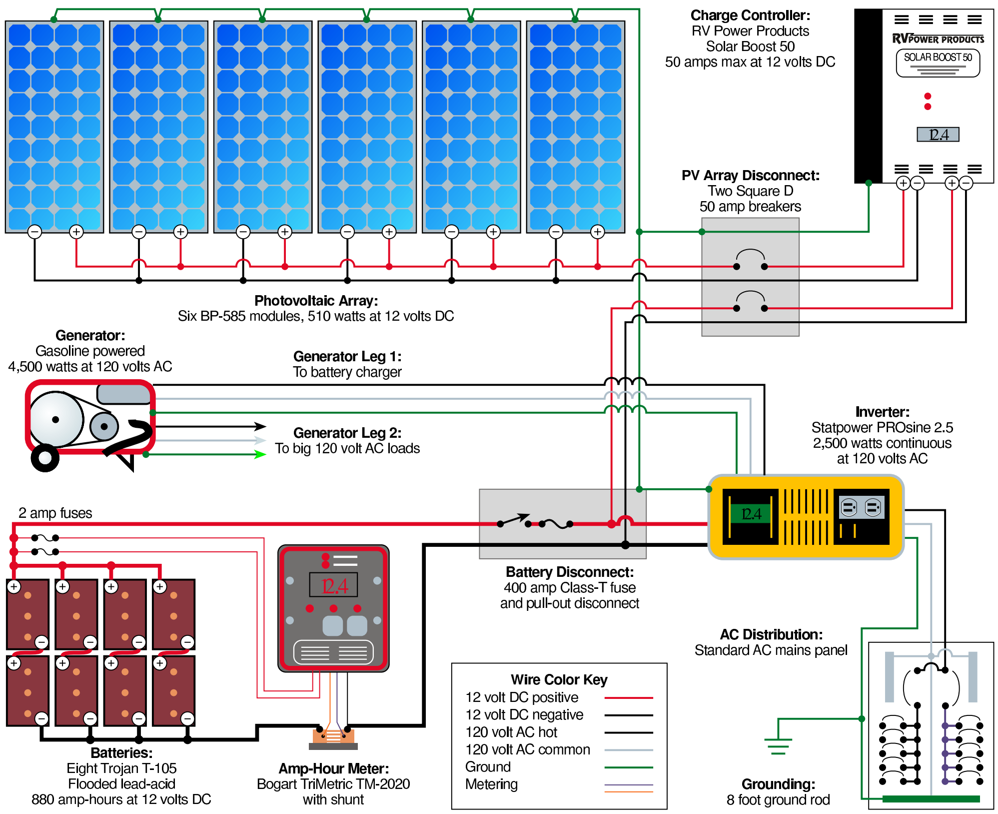

Figure 25: An example on the connection in a PV system

Appendix D: Insolation data in Uganda

The solar potential in Uganda is very good, where the north east region is the most favorable. The following tables give some information on the insolation data at different locations in Uganda. Table 7 illustrates the solar resource distribution and potential in four sites, Jinja, Kasese, Mbale og Entebbe in Uganda in 1999. The table is taken from http://www.ctech.ac.za/conf/due/documents/PdaSilva.doc.

Table 7: Solar Resource Distribution and Potential in Uganda in Kwh/m^2/day

STATION	MEAN	MAX	MIN
Jinja	4.80	5.10	4.51
Kasese	5.21	5.28	5.15
Mbale	4.34	4.71	3.54
Entebbe	5.08	5.27	4.71

In Entebbe near Kampala the solar radiation for the 12 months of the year 1999 is shown in Table 8. This table is also taken from http://www.ctech.ac.za/conf/due/documents/PdaSilva.doc.

Table 8: Solar Data converted in KWh/m^2/day in Entebbe Station near Kampala along the 12 months of the year

MONTH	MEAN	MAX	MIN
Jan	5.16	5.83	4.15
Feb	5.13	5.56	4
Mar	5.21	5.68	4.79
April	5.2	5.68	4.2
May	4.94	5.71	4.63
June	5.05	5.59	4.33
July	4.66	5	4.13
Aug	4.92	5.35	4.16
Sept	5.23	5.57	4.59
Oct	5.19	5.52	4.51
Nov	5.19	5.2	4.78
Dec	5.12	5.3	4.74

In Figure 26 the location of some of the districts is shown. Toronto is in the east side of the country, further north than Mbale, and Kasese is not far from Lake George in the west side of the country. Figure 26 is taken from http://141.51.158.34/iea/DevelopingCountries/Uganda.pdf.

The University of Massachusetts Lowell PV program, has made an international solar database, available on the Internet at http://energy.caeds.eng.uml.edu/solbase.html. Table 9 is taken from there. The irradiation unit is kWh/m^2/day.

Figure 26: Map of Uganda

Table 9: Solar irradiation for different months in Arua and Tororo districs in Uganda

SITE	JAN	FEB	MAR	MAY	JUN	JUL	AUG	SEP	NOV	DEC
Arua	5.92	5.52	5.72	5.31	5.05	4.56	4.62	5.48	5.66	5.72
Tororo	5.59	5.52	5.59	5.04	4.88	4.67	4.86	5.50	5.41	5.59

Appendix E: Specifications for a typical 80W DC solar system

These specifications are taken from a typical solar home system produced by Shenzen Topway Solar co, from the internetlink http://www.suntopway.com/solar.

The system charge controller 10A, specifications

- Minimum working voltage: 6V
- Minimum user voltage: 11V +2%
- Nominal voltage: 12V +2%
- Maximum user voltage: 17V
- Absolute maximum voltage: 30V
- Maximum output current: 10A
- Tested output current: 10A
- Peak surge current: 45A

The stand by current for the charge controller should be lower then 6mA. The charge controllers charging system is

- Suitable for sealed and lead-acid batteries
- Automatic boost-charge after deep-discharge and after first power up
- Temperature compensated battery voltage monitoring
- Over voltage protection on solar panel
- Voltage drop between solar panel and battery less than 0.176V
- Solar panel disconnect: 14.1V
- Solar panel reconnect: 13.8V
- Full batter voltage at boost charge: 14.9V

At the user output:

- Low voltage disconnect after 5 minutes below 1.4V
- High voltage disconnect above 17.0V
- Overload and over heating protection on output MOSFET
- Voltage drop between battery and user output: 0.088V
- Working Temperature −20°C–60°C ambient temperature

Specifications for the 80W Solar Panel

- Configuration: 12V
- Number of cells: 36
- Rated power: 80W
- Minimum power: 75W
- Open circuit voltage: 21.0V
- Short circuit current: 5.17A
- Voltage at load: 16.8V
- Cell type: multi-crystalline
- Factory instate by pass diode: Yes
- Hours of Autonomy/day: 8 hours

Specifications for the 105Ah Solar Battery

- Nominal voltage (volts): 12V
- End or charge voltage: 14.5V
- Permanent charge voltage: 13.4V
- End of discharge voltage: 11.0V
- Scope of temperature: 20°C–48°C
- Expected life time (at 10% D.O.D): 1000 cycles
- Self discharge per month at 15°C: 2.5%
- Weight of battery: 22.6 kg
- Maximum discharge current: 400A
- Ah capacity: 105Ah
- Life Span: 10 years (min)