Study of Photovoltaic System and its Efficiency

Submitted to the Department of

ELECTRICAL & ELECTRONIC ENGINEERING

Of

STAMFORD UNIVERSITY BANGLADESH

In partial fulfillment of the requirements for the

Degree of Bachelor of Science in EEE

August, 2009

Declaration

We declare that thesis paper is our own, unaided work. It is being submitted to the Department of Electrical and Electronics Engineering, Stamford University Bangladesh for the program of B.Sc. in EEE. It has not been submitted before for any degree or examination in any other university.

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Abstract

The main aspire of the present study is to contribute to a better understanding of the potential impact and of the limitations of solar photovoltaic (PV) applications on sustainable agriculture and rural development (SARD), with a special attention to the effects on income-generating activities and social welfare. There are many different resources of renewable energy. Among them, photovoltaics are getting popular for its various advantages. In Bangladesh, there is a huge opportunity of using solar energy as new energy technology. The main problem for implementing this technology is its high cost of implementation. The price of the conventional solar cell is so high that it is quite impossible for people (especially for Bangladesh).To get beneficial advantage from the PV system, Recently a new type of solar cell called nano solar cell has been invented. The debut of this low cost new solar cell would make the PV system economically feasible. So, now, developing countries which have the advantage of available solar energy can implement various types of photovoltaic systems and use the new energy technology for their welfare. In this context the study of photovoltaic system and its efficiency analysis has been done in this work. Here the PV system which is taken into account has six functional units. These are PV panel, energy storage, control unit, storage device, concentrators, and insolation. The aim of this study is acquiring knowledge about PV system and future prospect in Bangladesh on this sector.

ACKNOWLEDEMENT

First of all, we are grateful to the almighty Allah to allow us to complete this thesis successfully.

Our sincerest thanks will go to our Head of the department **Professor A.M. Rezaul Karim Talukder** and our thesis supervisor **Md. Atiqul Islam** for providing us with continuous support, guidance and valuable instructions all the time during our thesis work.

We would also like to thank all of our teachers at the department for their sincere guidance and teaching that lead us to this level.

Our heartiest thanks will also go to **Dilshad Mahjabin**, lecturer, Dept. of EEE, Stamford University Bangladesh, **Himangshu Ranjan Ghosh**, Research associate, Dept. of renewable energy, Dhaka University, **Mr. Shahinujjaman** and **Mr. Sharif,** Technical Manager, Stamford University Bangladesh for their generous help and support in solving some problems.

Special thanks to our dearest friends Arefeen, Salakin, Zia for their continuous encouragement and valuable suggestions in many regards.

Finally, all credits are for our parents and our brothers and sisters for their moral support, inspirations and deep love towards us to complete this thesis.

August 2009
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Introduction

1.1 Introduction

Thomas Alva Edison (1847-1931), "the father of the electrical age", said: "We are like tenant farmers chopping down the fences around our house for fuel when we should be using nature's inexhaustible sources of energy—sun, wind and tide. I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."

Apparently, we have paid little attention to Edison's advice—rather, warning, and many other warnings over the years. Instead, we continued to rely more and more on the fossil-nuclear energy path of oil, coal, natural gas and uranium to fuel the economy. But these resources are limited. All the reserves of oil, natural gas and uranium are estimated to be depleted by 2050, and coal by 2250.

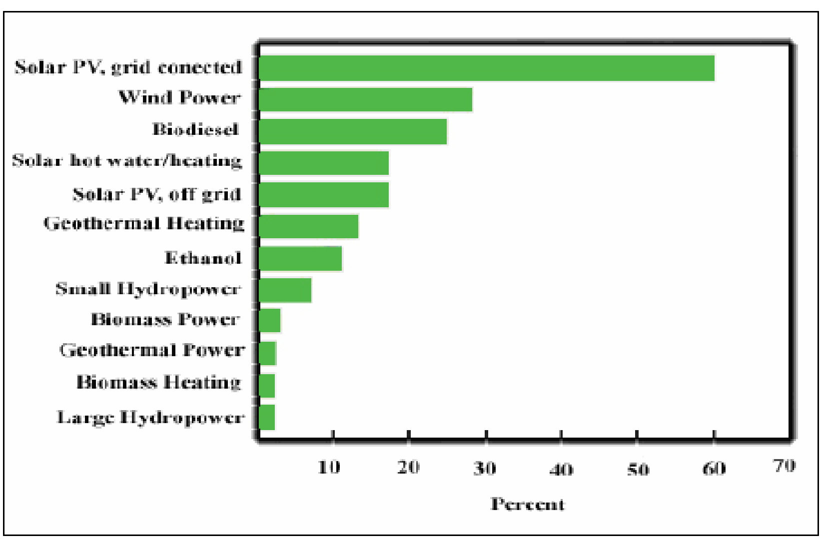


Figure 1.1: Average Annual Growth Rates of Renewable Energy, 2000-2004 (REN, 2005)

The earth's temperature is currently rising and the changing climate is predicted to have severe consequences that will change the way we live. Collins, Colman, Haywood, and Manning (2007) suggest that one reason for the elevation in global temperature is due to the increase of greenhouse gasses in the atmosphere. Greenhouse gasses are byproducts of the fossil fuels we burn daily to provide heat, electricity, and transportation. As more fossil fuels are burned, more damage is done to our environment.Solar energy is in great abundance and can easily be converted into electricity or heat. The energy contained in the photons emitted can be harnessed and utilized for our own benefits. The use of solar power is currently being implemented around the world.

Solar energy is becoming a popular energy source due to the fact that it is the most abundant and most cost effective energy source on the planet. Put simply, solar energy is energy derived from the sun, and this energy is not only clean, but renewable and costs nothing. Solar energy is created when the power of the sun is harnessed in order to produce energy. It is said that the amount of energy that the Sun provides to the Earth in a single day can power the entire planet and all of its energy needs for a whole year. Because solar energy is available as long as the Sun is available, it is also considered a renewable source of energy. It is a clean source of energy as well, due to the fact that it does not produce byproducts or pollutants that will harm the environment.

Solar energy was in fact the first source of energy used by humans. It was initially used to dry clothing or items, or to heat through direct contact. However, since the 1950's, solar energy is used to create sources of power to fuel technology, homes, and many businesses. Given that technology is evolving at the speed of light, solar energy is becoming more proficient as an energy source, and is recognized as a feasible alternative to fossil fuels.

1.2 Photovoltaic system; Today's technology

Today's technology allows for the harnessing of solar energy through cells known as solar cells. These are also called photovoltaic cells. Photovoltaic cells are placed in direct sunlight and as the sun hits these cells, a chemical reaction takes place to produce electric currents. These currents are then converted into electricity that can be used to power everyday items or even households.

Solar energy is used today to power homes, buildings, appliances, gadgets, and many other items. It is commonly used across the world and is recognized as a leading renewable, clean, and cost effective source of energy.

The use of photovoltaic systems on a large scale in order to reduce fossil fuel consumption and greenhouse gas emissions requires that the energy associated with the construction, operation and decommissioning of PV systems be small compared with energy production during the system lifetime. That is, the energy payback time should be short compared with the system lifetime.

A distinction needs to be drawn between energy consumption and carbon dioxide production associated with PV systems. Although there appears to be relatively limited reserves of oil and gas, coal is abundant. The most likely cause of a cessation of coal burning is not depletion of supplies, but rather unacceptable climatic consequences. In addition to energy payback time for PV systems, carbon dioxide payback times need to be considered. Both times must be short compared with the PV system lifetime if a large sustainable PV industry is to the established. In general, energy intensity and carbon dioxide intensity are closely related. Over the next few decades at least the energy used to construct PV systems will be derived primarily from fossil fuels. In the long term "solar breeding" will be possible, whereby energy for the production of PV systems will be derived from PV systems. This will reduce or eliminate carbon dioxide emissions associated with PV system manufacture.

By far the largest fossil fuel inputs for a photovoltaic system are associated with production and installation. Fossil fuel derived energy required for the operation and decommissioning of a PV system is trivial. Hydroelectricity and wind energy share this characteristic. Many studies have looked at energy inputs to PV systems. It is difficult to arrive at definitive numbers because production technology is constantly improving and because the fossil fuel intensity of various operations depends on production scale and production location.

An important conclusion can be drawn from the various studies. The cost of the various components of a PV system is well correlated with the energy content of that component. The reason for this is that PV is a material intensive technology, and the energy content of materials is reflected in their price. Thus the most expensive component of a conventional PV system, the silicon wafers, is also the most energy intensive component. It is clear that as the cost of PV systems declines, then so will the energy content.

Most PV systems are based on panels that comprise about 40 single or multicrystalline silicon wafers encapsulated behind glass using an EVA pottant material. An aluminium frame and a junction box complete the panel. Groups of panels are connected together on supporting structures that are mounted on buildings or in open fields. The cost of the silicon wafers amounts to about half of the cost of a PV panel. It is likely that thin film solar cells based on thin layers of crystalline silicon or alternative materials (amorphous silicon, copper indium diselenide, cadmium telluride) will challenge wafer based crystal silicon solar cells over the next decade. The result will be a substantial reduction in the energy and carbon dioxide intensity of PV systems.

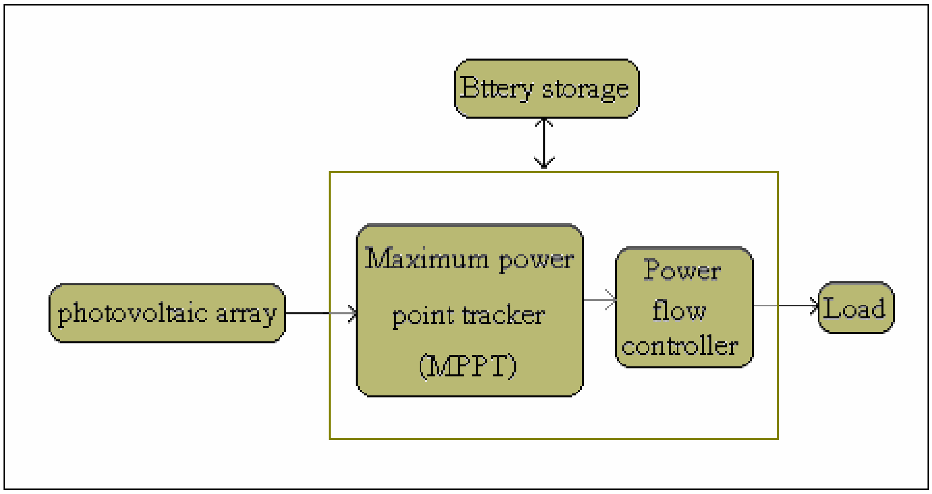


Figure 1.2: The basic components of photovoltaic (PV) system.

This study focuses on crystalline silicon PV panels. At present, crystalline silicon wafer panels have 85-90% of the world market. There is a high likelihood that the dominance of crystal silicon solar cells will continue for many years to come because of the abundance and non-toxicity of silicon, the high and stable efficiency of silicon solar cells, the ability to share R&D, infrastructure and human resources with the IC industry and its present market acceptance and dominance. Although solar cells based on silicon wafers are likely to eventually be replaced over the next decade by thin film solar cells, there is every chance that the thin film solar cells will in fact be fabricated from thin films of crystalline silicon rather than from other materials.

Chapter 2
Energy Storage

2.1 Introduction

Solar energy, being a time-dependent energy resource, must be stored and used in day-to-day life. The energy storage must be considered, keeping in view, a solar process system, the major components of which are the collector (see chapter 5), storage units, conversion devices (see chapter 3), loads, auxiliary energy supplies, and control systems (see chapter 7). The performance of each of these components is related to that of the other. The dependence of the collector performance on temperature makes the whole system performance sensitive to temperature.

The optimum capacity of an energy storage system depends on the expected time dependence of solar radiation availability, the nature of loads to be expected on the process, degree of reliability, the manner in which auxiliary energy is supplied, and an economic analysis weighting the relative use of solar and auxiliary energy. The solar thermal energy storage can be classified as follows:

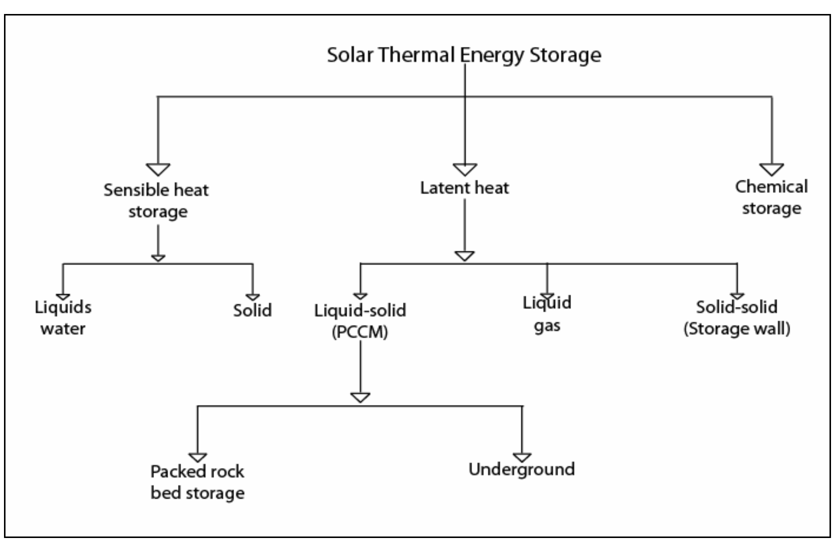


Figure 2.1: Classification of Solar Thermal Energy.

2.2 Sensible Heat Storage

Thermal energy may be stored as sensible heat or latent heat. Sensible heat storage systems use the heat capacity and the change in temperature of the material during the process of charging and discharging. The temperature of the storage material rises when energy is absorbed and drops when energy is withdrawn. The charging and discharging operations, in a sensible heat storage system, can be expected to be completely reversible for an unlimited number of cycles, over the life-span.

The sensible heat Q gained or lost by a material in changing temperature from T_1 to T_2 is:

$$- (mC_p)_c(dT_c/dx) = (U2pr)_c(T_c-T_s)$$

where m is the mass (kg), C_p the specific heat (J/kg°C), x the density (kg/m^3) and V is volume of the material (m^3). As seen from Equation, the higher the specific heat and density of the material, more will be the energy stored in a given volume of the material. However, there are several other parameters affecting the performance of the system, viz., the operating temperature, thermal conductivity, thermal diffusivity, vapor pressure, compatibility between the storage material and the container, stability of the material at the highest temperature of the cycle and the cost of the system.

The efficiency of thermal storage can be defined as the ratio of heat output to heat input, heat output being lower than the input by the amount of heat losses. In the case of sensible heat storage, however, the temperature of stored medium drops due to heal losses and the energy is available at a lower temperature. Thus the efficiency, in this case, can be defined as the ratio of availability of the energy discharged to the availability of the energy charged. Sensible heat storage, on the basis of the heat storage media, may be classified as: (i) liquid media storage (ii) solid media storage and (iii) dual media storage.

2.2.1 Liquid Media Storage

Of the available liquids, water can be considered to be the most suitable liquid media for storage below 100° C. Water has the following advantages:

a. It is abundant and inexpensive.
b. Easy to handle, non-toxic and non-combustible.
c. Its flow can take place by thermosyphon action.
d. It has a high density, high specific heat, good thermal conductivity and low viscosity.
e. Can be used both as a storage medium and a working medium.
f. Charging and discharging of energy can occur simultaneously.
g. Control of a water system is variable and flexible.

Apart from above advantages, water has certain disadvantages,

a. Limiting temperature range
b. High vapor pressure at high temperatures.
c. A corrosive medium.
d. Low surface tension.
e. Difficult to stratify.

Through water is the choice in space heat system; oils and molten salts has also been used in solar thermal power plants.

2.2.1.1 Well Mixed Liquid Storage

This is the mostly widely used method of sensible heat storage. The analysis presented here is for water storage but is also valid for other liquids. The transient energy balance equation for a hot liquid storage tank assuming the temperature in the storage tank to be uniform (well mixed storage), can be written as:

$$(MC_p)_s(dT_s/dt) = Q_c - Q_L - (UA)_s(T_s - T_a)$$

where M is the mass (kg) and C_p the specific heat of liquid in the tank (J/kg°C), T_s and T_a are the liquid temperature (°C) in the tank and the ambient temperature respectively, Q_c is the rate of charging energy from the heat source (W), Q_L is the rate of heat removal by the load (W), U is the overall heat transfer coefficient between the liquid in the tank and the outside (W/m^2 °C) air and A the surface area (m^2) of the storage tank.

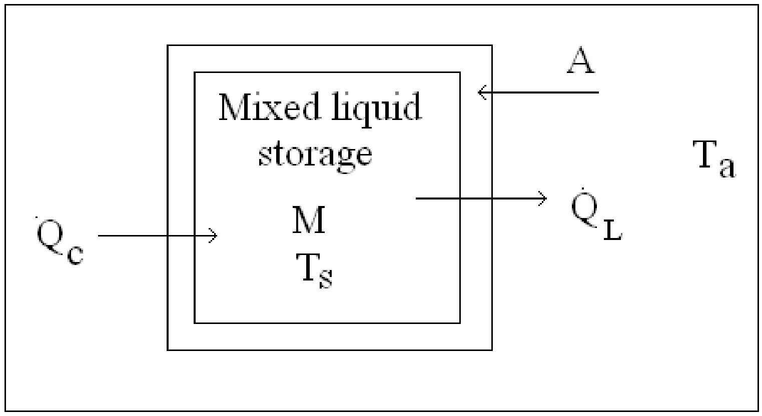


Figure 2.2: Mixed liquid storage

If the amount of heat addition and removal is assumed constant for a selected finite time interval, then Equation, for each time interval, can be written as

$$T_{s.new} = T_{s.old} + \{?t/(MC_p)_s\}[Q_c - Q_L - (UA)_s(T_{s.old} - T_a)]$$

This equation can be used for the estimation of hourly storage water temperature if the hourly heat addition and withdrawal are known. If solar energy is used for charging the storage, the above method gives successful results when one hour intervals are taken. Knowing the variation of the solar energy collection rate Q_c in terms of flow rate of the fluid in the collector, and the time variation of load Q_L, storage temperature T_s can be determined as a function of time.

2.2.1.1.1 Storage tank without heat exchanger

Without heat exchanger, the liquid flows directly into and out of storage, the solar collector inlet temperature T_{ci} is the same as temperature in the storage T_s. Referring Equation the energy rate is given as

$$Q_c = A_c F_R[(\alpha\tau)I(t) - U_L(T_s - T_a)]$$

F_R is a control function given by $F_R = 1$, if the pump operates

= 0, otherwise

It has been assumed here, that there is no drop in temperature of the fluid between the collector and the tank. The rate of heat withdrawal by the load. Q_L, can be written as

$$Q_L=(mC_p)_L(T_s-T_L)$$

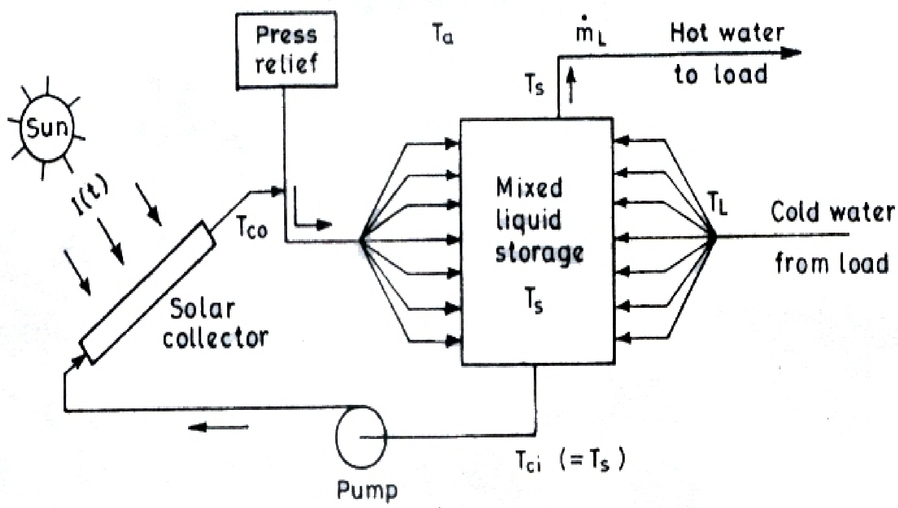


Figure 2.3: Storage tank without heat exchanger

2.2.1.1.2 Storage tank with heat exchanger

A well mixed liquid storage with heat exchanger for both the collector and the load circuits is shown in Figure (2.4). In this case, the collector inlet temperature T_{ci} is not the same as the storage temperature T_s. The rate of charging is given by

$$Qc = (mCp)_c(T_{co}-T_{ci})$$

where (mC_p) is the product of specific heat and the fluid mass how rate through the collector.

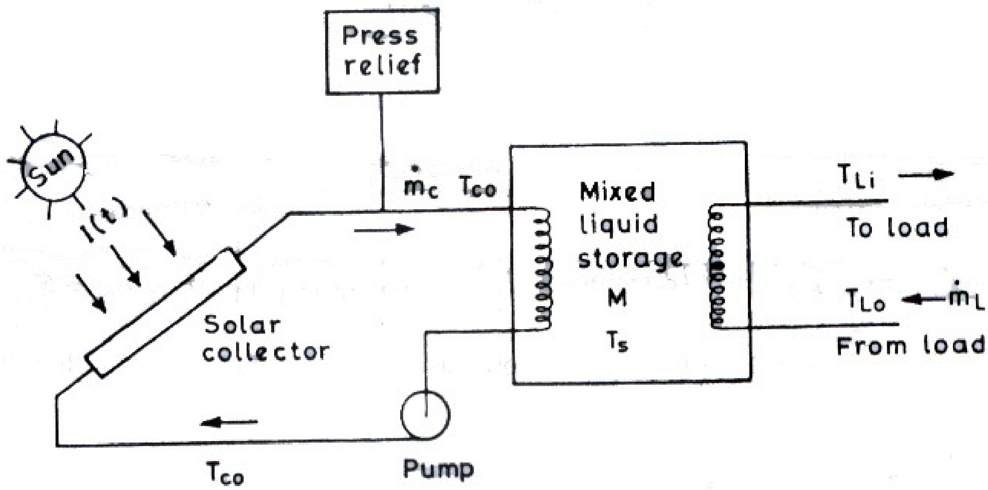


Figure 2.4: Storage tank with heat exchanger

The energy balance for an elemental length dx of the heat exchanger can be written as:

$$\mathbf{-(mC_p)_c(dT_c/dx) = (U2pr)_c(T_c\text{-}T_s)}$$

From this equation we have

$$\mathbf{(dT_c/T_c\text{-}T_s) = \{-(U2pr)_c/(mC_p)_c\}dx}$$

Integrating the above equation and using the initial condition:

At x=0; $T_c=T_{c0}$, we have

$$\mathbf{ln(T_c\text{-}T_s/T_{c0}\text{-}T_s) = -(U2prx)_c/(mC_p)_c}$$

At x=L; $T_c=T_{ci}$

$$\mathbf{(T_{ci}\text{-}T_s)/(T_{c0}\text{-}T_s)=exp\ \text{-}\{(UA)_c/(mC_p)_c\}}$$

or $$\mathbf{T_{c0} - T_{ci} = T_{c0} - T_s\{1\text{-}exp[(UA)_c/(mC_p)_c]\}}$$

Hence,

$$\mathbf{Q_c= (mC_p)_c(T_{c0} - T_{ci})=(mC_p)_c\{1\text{-}exp[(UA)_c/(mC_p)_c]\}(T_{c0} - T_s)}$$

where the factor [I - exp{- $(UA)_c/(mCp)c$}] is known as the penalty factor for the heat exchanger

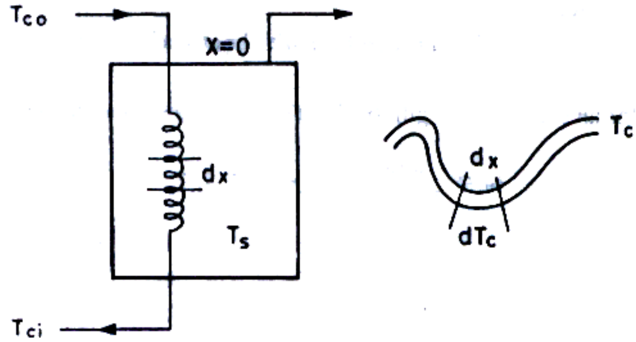


Figure 2.5: Cross-sectional view of collector loop heat exchanger

Similarly, the energy withdrawn by the load is

$$Q_L = (mC_p)_L(T_{Li}-T_{Lo})$$

and $(T_{Li} - T_{Lo})$ is obtained from

$$(T_{Li} - T_{Lo})/(T_1 - T_{Lo}) = \{1-\exp[(UA)_L/(mC_p)_L]\}$$

Where $(UA)_L$ is the product of surface area and the overall heat transfer coefficient for the heat exchanger between liquid in storage and load stream.

2.2.1.1.3 Energy storage in water storage tanks

In case of storing heat energy in water the density of energy is calculated by:

$$Qd = (c_p(T)?(T)?T)_{water}$$

Where $c_p(T)$ is heat capacity of water, ?(T) is the density of water and ?T=To – Tu is the temperature difference of the water at the storage level To (90°C) and the "user temperature" Tu (40 °C). With this temperature levels the energy density Qd in a water tank is 57 kWh/m^3. So with the assumption of "seasonal" heat energy storage the average water volume for a storage tank is 50 m^3 (season: 180 days; 16 kWh per day; no additional heat source like solar collectors). The loss of energy by heat conduction, convection and radiation depends on the temperatures inside the storage tank and the surrounding of the tank. To suppress the heat loss out of the tank a thermal insulation has to be installed. The thermal insulation leads to an increase of the total volume of the storage tank system.

2.2.2 Solid Media Storage

The difficulties of high vapor pressure of water and the limitations of oilier liquids can he overcomes by storing thermal energy as sensible heat in solids. Pebble-beds or rock piles are generally preferred as the storage material due to their low cost. A pebble-bed consists of a bed of loosely packed rock material through which the heat transport fluid can flow. At low temperatures, air is used as the heat transport medium. The large surface area of rocks and greater contact time due to the rough path for air flow through the bed ensures good heat transfer to/form air by direct contact. The heat loss through the pebble bed (in no air flow condition) by conduction is very low, the rocks having a small surface contact with surrounding rocks and presence of air in the voids (stagnant air being a poor heat conductor). Not much insulation is thus required around the storage. Large pebble-bed storage may conveniently be placed underground. The energy stored in a packed-bed storage system depends on the thermophysical properties of the material, the rock size and shape, packing density, heal transfer fluid etc. The following are the advantages of a packed-bed storage system.

a. Rocks are abundant and low-cost, arc easy to handle, non-toxic and non combustible.
b. High storage temperatures are possible in this case.
c. Heat exchanger can be avoided.
d. No freezing and corrosion problems

Apart from the above advantages, certain disadvantages of the system are:

a. Storage volumes are large.
b. High pressure drop.
c. Simultaneous charging and discharging is not possible.

This energy storage system is used in space heating by storage in rock-bed with air as the heat transport medium, and in the wall known as Trombe wall.

2.2.2.1 Packed-bed Storage

A packed-bed (pebble-bed or rock pile) storage unit utilizes the heat capacity of a bed of loosely packed particular material to store energy. A fluid, usually air, is circulated through the bed to add or remove energy.

A packed bed storage unit consists of a container, a screen to support the bed, support for the screen, and inlet and outlet ducts. Flow is maintained through the bed in one direction, during addition of heat and in the opposite direction during removal of heat. The heat, in this case, cannot be added and removed at the same time, in contrast to water storage systems.

Well-designed packed beds using rocks have several characteristics that are desirable for solar energy applications, the heat transfer coefficient between air and solid is high, which promotes thermal stratification; cost of the storage material and container are low; when there is no air flow, the conductivity of bed is low; and the pressure drop through the bed can be low.

Although there are many studies available on the heating and cooling of packed beds, the first one was done by Schumann (1929) and the equations, given below, describing a packed bed are often referred to as the Schumann model. The basic assumptions leading to this model are: one-dimensional heal flow; no axial conduction or dispersion; constant properties; no mass transfer; no temperature gradients within the solid particles and no heat loss to the environment.

2.2.3 Dual Media Storage

Solid and liquid sensible heat storage materials can be combined in a number of ways. One of them is to jointly use the rock-bed and water tank; hybrid systems with water tank surrounded by rock-bed have been used for solar space heating.

Another one is to incorporate rocks and oil in a single vessel. Such a system has been used in solar thermal power applications, to improve stratification and to minimize the amount of, relatively expensive, liquid.

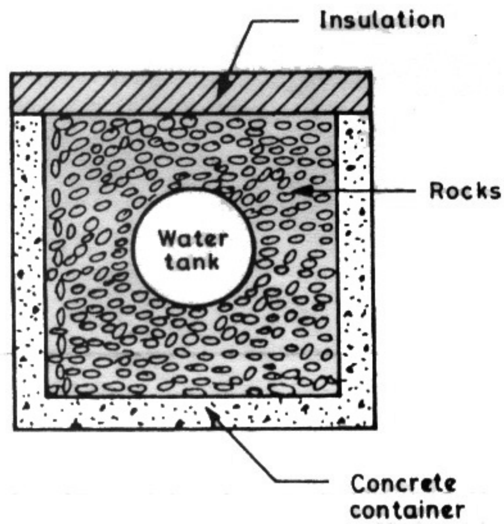


Figure 2.6: Hybrid sensible heat storage system.

Figure 2.7 shows an open flow collector mounted on a inclined south facing roof. The collector is integrated with water tank and rock-bed storage system in the basement of the building through a pump P_1. The thermostat sensor T_1 is connected to the pump P_1. The water is pumped from the bottom of the tank to a perforated pipe located at the top of the corrugated metal collector by pump P_1 as shown in Figure 2.7. The water is heated as it flows downward through open troughs to the collector channel at the bottom of the collector. The water drains back to the storage tank in the absence of solar radiation due to stoppage of pump P_1 after getting signal from T_1 thermostat. The rocks in contact with the tank are heated by hot water in the tank. The thermal energy is spread throughout the rock bed by radiation, convection and conduction.

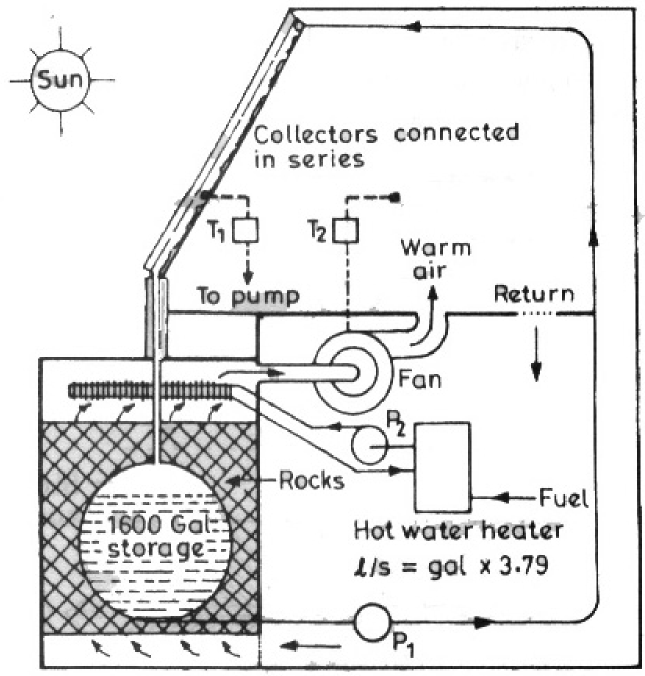


Figure 2.7: Configuration of water tank and rock-bed storage system in the basement of the building.

Cool air from the room enters the bottom of rock bed through return and the basement of the building. The fan operates after getting signal from thermostat T_2. In this case, the cool air available at bottom of rock bed passes through it. During the flow of cool air though the rock bed, it gets heated and warm air is allowed to enter into the room. There is a provision of auxiliary heating of air either by conventional hot water heater or by other fuels through a heat exchanger provided at the top of rock bed through pump P_2.

2.3 Ground Collector

It is well known that the ground has a large thermal capacity and hence acts as a large reservoir of solar energy. Ground, therefore, can potentially be used for solar energy collection-cum-storage purposes in low temperature ranges. A brief description and working principle of ground collector is given. The cross-sectional view of a ground collector is shown in Figure 2.8.

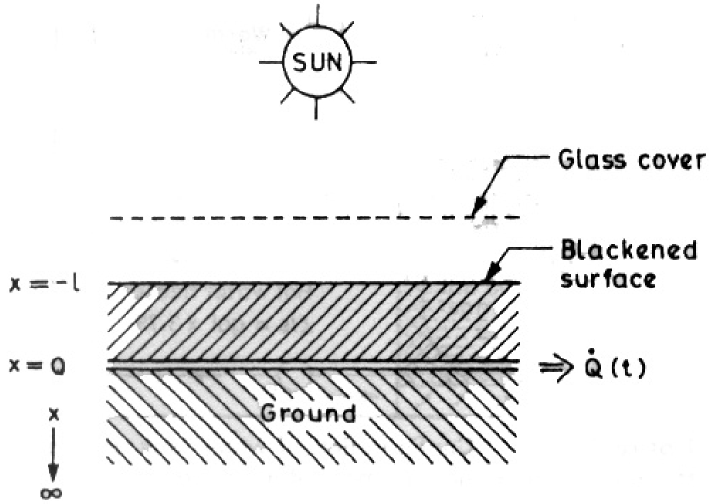


Figure 2.8: Ground collector

The top surface of the ground is blackened and glazed. A network of pipes is laid down at some depth under the earth surface. An arrangement of water how through a network of pipes can be made either at constant flow rate or at constant collection temperature. In this case, the solar radiation after reflection and absorption by the glass cover is absorbed by the blackened surface. A part of the absorbed energy is condemned to the ambient, through the glass cover, and the rest is conducted inside the ground.

2.4 Basics of Latent Heat Storage

Phase change materials (PCM) have considerably high thermal energy storage densities as compared to the sensible heat storage materials and able to absorb or release large quantities of energy at a constant temperature by undergoing a change of phase. The following changes of phase are possible:

i. Solid - gas.
ii. Liquid – gas.
iii. Solid – liquid.

Any latent heat thermal energy storage system should have at least following three components:

i. A PCM in the desired temperature range.
ii. Container for holding the PCM.

iii. A suitable heat exchanger for transferring the heat from the heat source to PCM and then from PCM to the required point of use.

Latent heat storage systems are more expensive than the sensible heat storage media, viz, water. The PCMs undergo solidification and cannot generally be used as heat transfer media in a solar collector or the load. Thus a separate heat transport medium is required, with a heat exchanger in between Many PCMs have poor thermal conductivity; others are corrosive and require special containers. Due to the high cost of latent heat storage; these system are usually used when:

a. High energy density or high volumetric energy capacity is desired,
b. The load is such that energy is required at a constant temperature; or within a small range of temperature.
c. The storage size is small.

2.4.1 Heat transfer in PCM

A proper designing of a thermal storage system using phase change material requires details regarding heat transfer and phase change processes in PCM. The information generally required is (i) the distance of the melting front from the heated face, (ii) the temperature distribution, and (iii) the amount of heat stored as sensible heat and latent heat. The involved heat conduction problems are difficult to solve due to variable properties and moving boundaries. The analysis, however, is much simplified. by the assumption that the properties of any given phase are independent of temperature. Moreover, the convection effect (arising due to the density differences between the solid and liquid phases and the buoyancy forces produced by density differences due to temperature variations in the liquid) and the effect due to super cooling of liquid arc generally not considered.

The simplest form of the heat transfer problem with phase change from liquid to solid is the freezing of upper layers of water in a pond when ambient air temperatures are below. The ice formed on the surface, being poor conductor of heat reduces the rate of cooling of the water below.

2.4.2 Thermal analysis of freezing of top of ponds

A thermal analysis of freezing of tops of pond is given below: For an approximate solution of this problem certain assumptions arc made:

i. $T_m = T_l$

ii. $R_l = (l/h_l) \approx 0$, i.e. resistance to heat transfer on the liquid side is considered negligible.

iii. Heat capacity of ice is negligible in comparison to its latent heat of melting.

iv. Thermal properties of ice are assumed constant.

v. T_a and h_a are constant.

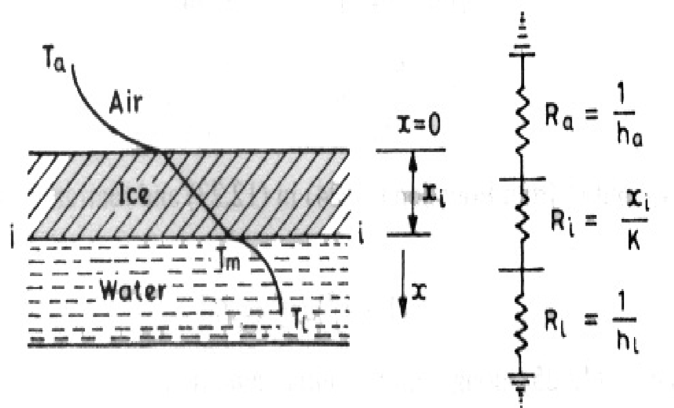


Figure 2.9: Diagram of pond.

2.4.3 Analysis of phase change material

Let us consider a PCM slab which is subjected to solar intensity I(t). The energy balances at different boundaries are:

$$\alpha\tau\bar{I}(t) = -K_1 \frac{\partial T_1}{\partial x}\bigg|_{x=-L_1} + U_t(T|_{x=-L_1} - T_s)$$

$$T_1(x=0) = T_s(x=0) = T_0$$

$$-K_1 \frac{\partial T_1}{\partial x}\bigg|_{x=0} = -K_s \frac{\partial T_s}{\partial x}\bigg|_{x=0} + \dot{q}$$

$$-K_s \frac{\partial T_s}{\partial x}\bigg|_{x=L_2} = h_2(T_s|_{x=L_2} - T_s)$$

Here $\quad T_1 = A_1 x + B_1 \quad$ and $\quad T_s = A_2 x + B_2$

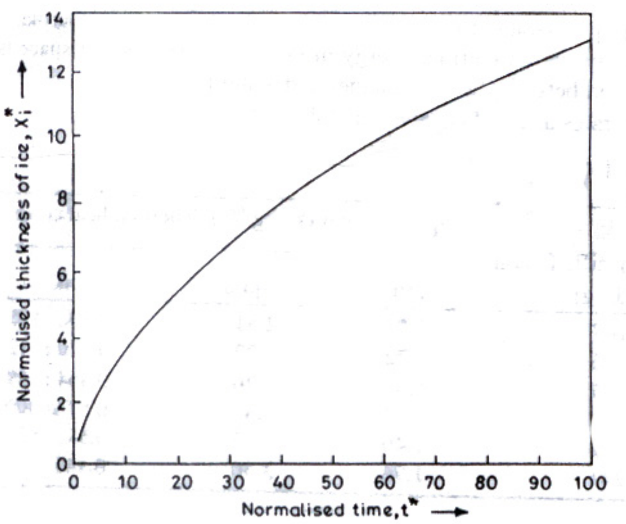


Figure 2.10: Variation x_i with t.

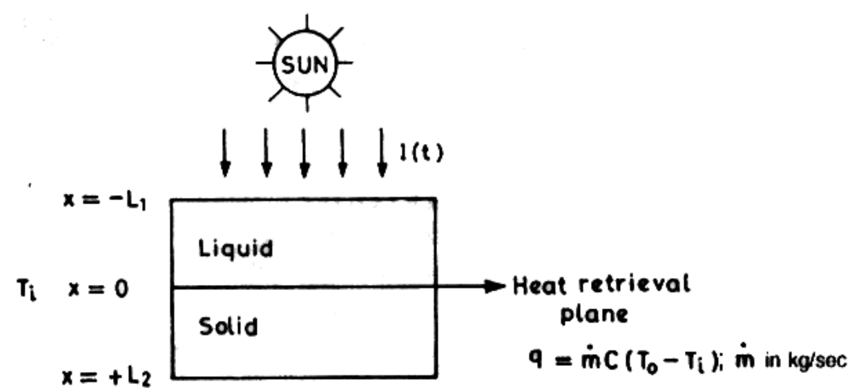


Figure 2.11: Phase change material system.

Substituting the values of T_1 and T_s

$$A_1(K_1+U_tB_l) - U_tB_l = -\alpha\tau I(t) - U_tT_a$$

$$B_1=B_2=T_0$$

$$-K_1A_1 - mCB_1+K_sA_2= - mCT_i$$

$$A_2(K_s+h_2L_2)+h_2B_2=h_2T_a$$

Equations can be solved for A_1, B_1, A_2 and B_2. After knowing these constant, an average temperature of PCM can be obtained as

$$\bar{T} = \frac{1}{L}\left[\int_{-L_1}^{0} T_1(x)dx + \int_{0}^{L_2} T_s(x)dx\right]$$

Then the effective thermal properties of PCM can be expressed as;

$$C_{eff} = C_s + (H_0/(\bar{T} - T_a))(L_1/L)$$

The air-based solar heating system with phase change energy storage (PCES) has been shown in Figure 2.12. The system can be used for domestic hot water as well as space heating. There is **a** provision of direct space heating by byepassing PCES system. The collectors are connected in series. There is a co-axial counter current heat exchanger. The heat exchanger is connected to water tank and phase change energy system as shown in Figure. There are three pumps. One pump (P_1) operates for water heating.

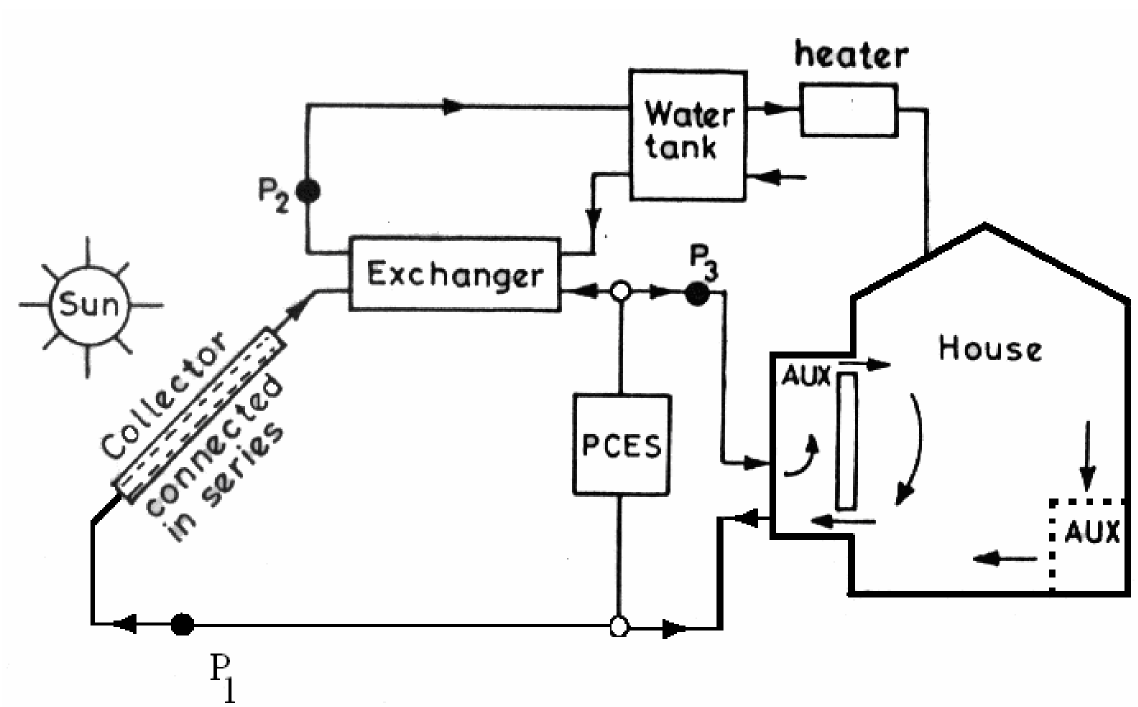


Figure 2.12: Phase change energy storage (PCES) system for space heating.

Pump (P_1) operates for collector loop through PCES for thermal energy storage. In the absence of solar energy, stored thermal energy in PCES can be used for space heating through pump (P_3). Pump (P_3) is used between heat exchanger and water tank. Properties of some of the salt hydrates as PCMs are given in Table 2.1.

Table 2.1 Properties of salt-hydrates as PCMs

Material	**Melting heat point (°C)**	**Specific fusion (kJ/kg)**	**Specific heat (kJ/kg °C)**		**Thermal heat conductivity W/mk**
			Solid	**Liquid**	
$Mg(NO_3)_2 \cdot 6H_2O$	**89.9**	**167**	**1.84**	**2.51**	**0.490 at 95°C**
$MgCl_2 \cdot 6H2O$	**115.0**	**165**	**1.72**	**2.82**	**0.570 at 120°C**
$Zn(NO_3)_2 \cdot 6H2O$	**36.1**	**147**	**1.34**	**2.26**	**0.464 at 39.9°C**
$Na_2S_2O_3 \cdot 5H2O$	**48.5**	**210**	**1.46**	**2.38**	**0.57 at 40°C**
$CaCl_2 \cdot 6H2O$	**29.7**	**170**	**1.46**	**2.13**	**0.540 at 38.7°C**
$Na_2So_4 \cdot 10H2O$	**32.4**	**241**	**1.76**	**3.30**	**0.544**

2.5 Chemical Storage

In this concept the energy is stored in the form of heat of chemical reactions which are often of larger magnitude than the latent heat storage. The idea of storing solar energy by the utilization of chemical reactions is not new. Nature has been storing energy by the use of chemical reactions in photosynthesis. Chemical energy storage is a two step process:

i. Storage or endothermic mode in which energy is absorbed to either break or rearrange the chemical bonds, producing in the process more energetic species which are stored.
ii. Discharge or exothermic mode in which the reaction is reversed producing thermal energy and regenerating the starting material.

Chemical energy storage is very attractive due to high energy storage densities, high reaction temperature attainable by present solar concentrators suitable for power production, last reaction rate**,** low energy losses, in principle, an unlimited life and easy transportability. In addition to these advantages, chemical energy storage also has certain demerits. The underlying technology is much more complex than the other two energy storage systems. At times, these may have hazardous impact on the environment.

Chapter 3
Photovoltaic system

3.1. Photovoltaic

Photovoltaic is the direct conversion of light into electricity. Some materials exhibit a property, known as the photoelectric effect, which causes them to absorb photons of light and release electrons. When these free electrons are captured, electric current can be used as electricity.

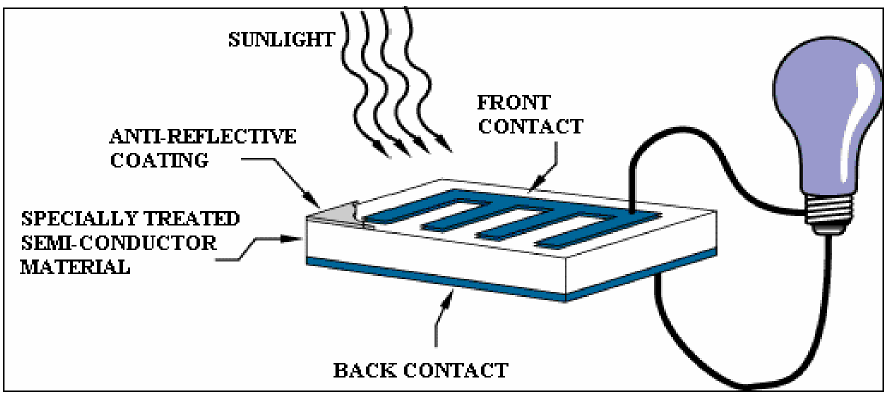


Figure 3.1: Operation of basic photovoltaic system.

The diagram above illustrates the operation of a basic photovoltaic cell, also called a solar cell. Solar cells are made of the same kinds of semiconductor materials, such as silicon, used in the microelectronics industry. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current that is, electricity. This electricity can then be used to power a load, such as a light or a tool.

A number of solar cells electrically connected to each other and mounted in a support structure or frame is called a photovoltaic module. Modules are designed to supply electricity at a certain voltage, such as a common 12 volts system. The current produced is directly dependent on how much light strikes the module.

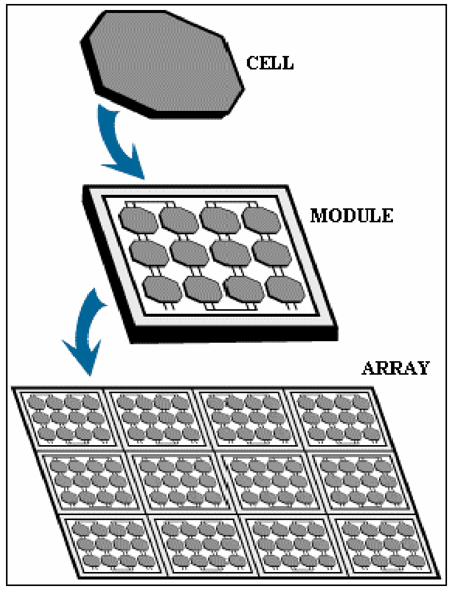


Figure 3.2: Multiple modules can be wired together to form an array

Multiple modules can be wired together to form an array. In general the larger area of a module or array, the more electricity that will be produced. Photovoltaic modules and arrays produce direct-current (dc) electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination. Today's most common PV devices use a single junction, or interface, to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to or greater than the band gap of the cell material can free an electron for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used. One way to get around this limitation is to use two (or more) different cells, with more than one band gap and more than one junction, to generate a voltage. These are referred to as "Multijunction" cells (also called "cascade" or "tandem" cells). Multijunction devices can achieve higher total conversion efficiency because they can convert more of the energy spectrum of light to electricity.

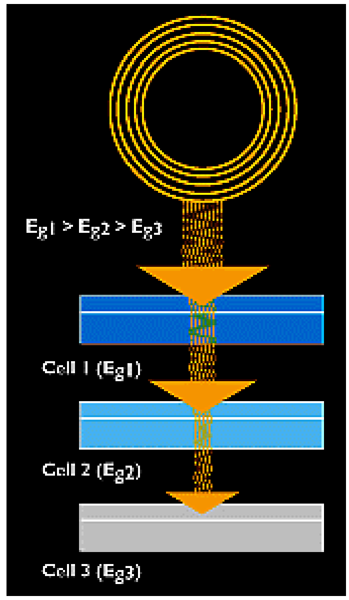


Figure 3.3.multijungtion cell

As shown below, a Multijunction device is a stack of individual single-junction cells in descending order of band gap (Eg). The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells.

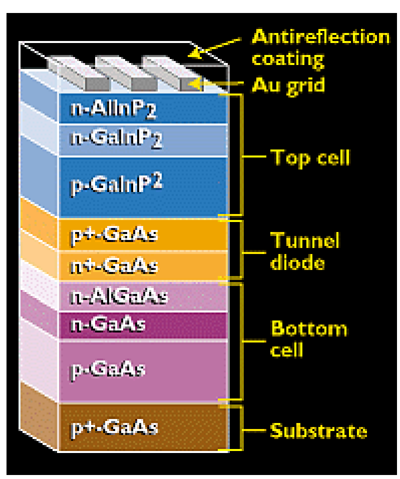


Figure 3.4.multijungtion cell showing different band gap

Much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells. Such cells have reached efficiencies of around 35% under concentrate sunlight. Other materials studied for multijunction devices have been amorphous silicon and copper indium diselenide. As an example, the multijunction device below uses a top cell of gallium indium phosphate, "a tunnel junction," to aid the flow of electrons between the cells, and a bottom cell of gallium arsenide.

3.2 Basic Principles of Photovoltaic

As the heading is telling, this section will focus on basic function of photovoltaic. This includes how the solar resource works, types of solar energy converters, the principle of detailed balance, work available from a PV cell and its efficiency.

3.2.1 Solar Radiation

To a good approximation, the Sun acts as a perfect emitter of radiation at a temperature close to 5800 K, and thus considered as a black body. The Sun emits electromagnetic light in various wavelengths:

- UV (<400 nm)
- Visible (400-800 nm)
- Infrared (>800 nm)

Figure 3.5 shows the solar irradiance outside the earth's atmosphere, denoted by AM0, and at sea level, denoted by AM1.5.

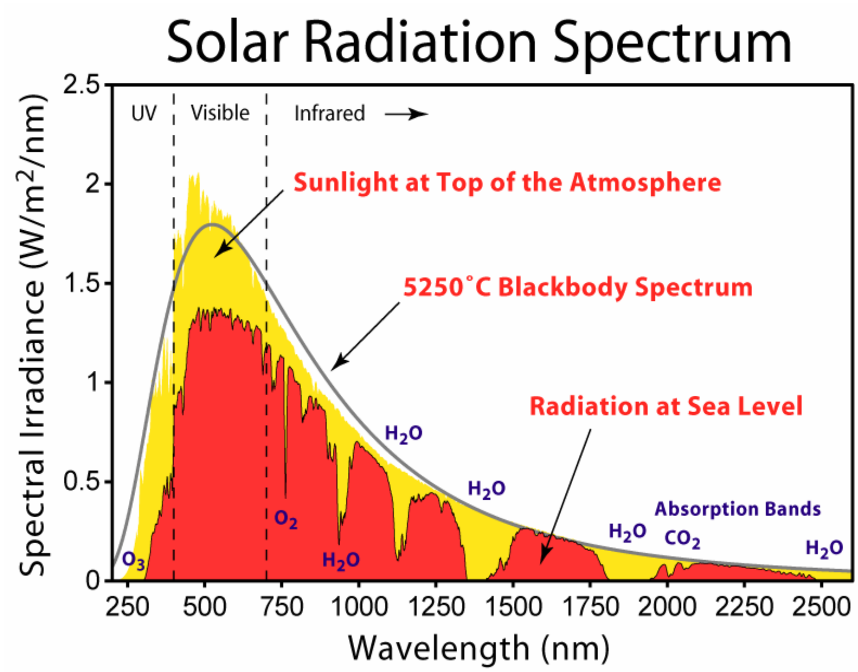


Figure 3.5: The solar spectrum.

As the solar radiation passes the atmosphere, a part of the incident energy is removed by absorption or scattering by molecules, clouds and aerosols. Wavelengths less than 300 nm is filtered out by molecules like ozone, nitrogen and oxygen. Dips in the infrared area are caused by water and CO_2.

If the surface temperature on a black body is the same everywhere, the spectral photon flux normal to the surface is

$$2F \quad (\quad E^2 \quad)$$

On the earth F_s is reduced by a factor of $\mathbf{4.6 \cdot 10^4}$, to $\mathbf{2.16 \cdot 10^{-5}}$ **p:**

The total emitted power density is

$$\sigma_s T_s \qquad \textbf{... (3.3)}$$

Where sØis Stefan's constant:

$$\sigma_s = \frac{2\pi^5 k^4}{15c^2 h^3} \qquad \textbf{.. (3.4)}$$

At the sun's surface this power density is **62 MW/m^2**, and at a point just outside the atmosphere the power density has shrunk to **1353 W/m^2** because of the reduced angular range of the sun.

3.2.2 Solar Energy Converters

There are mainly three kinds of solar energy converters

- The photovoltaic converter
- The solar thermal converter
- The photochemical converter

3.2.2.1 The Photovoltaic Converter

The photovoltaic converter transforms the photon energy into electrochemical potential energy. To prevent the excited electrons from falling back into their ground state, there is some built-in asymmetry that pulls the excited electrons away before they can relax. The extra energy of the excited electrons generates a potential difference, ?µ, and it is this force that drives the electrons into the external circuit and exerts work. The excited state (conduction band) and ground state (valence band) are separated by an energy gap, also called band gap. The band gap's function is to maintain the excited electrons at the high energy for a long time compared to the thermal relaxation time, so that they can be collected. Note that electrons in each of the different bands relax to form a QTE with a different QFL.

For a two band system, the Gibbs free energy represents the increase in electrochemical potential energy:

[illegible]

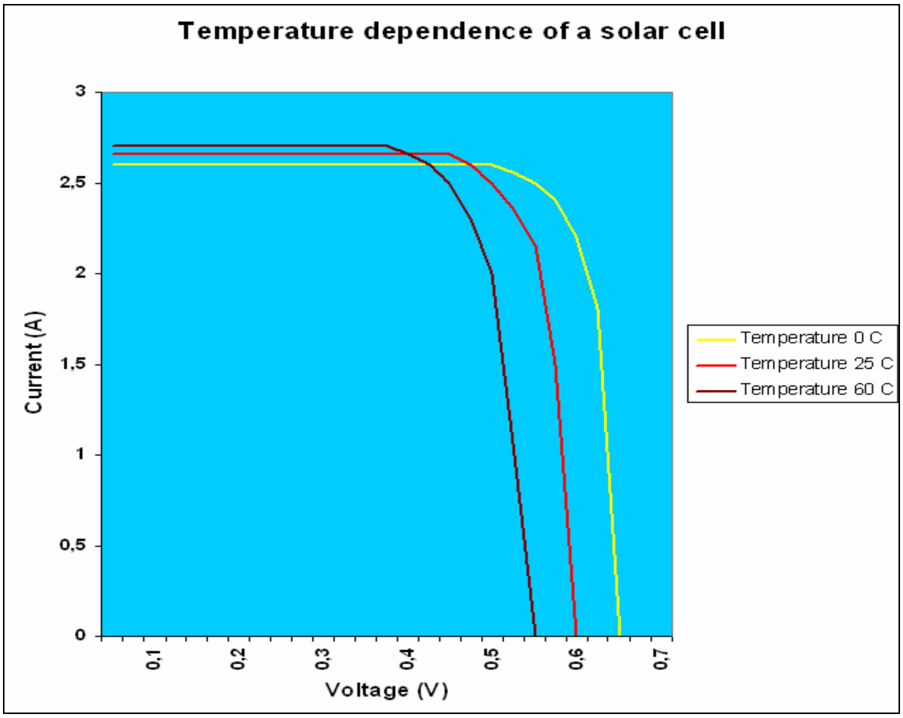


Figure 3.6: temperature dependence of solar cell

3.2.2.2 The solar thermal converter

In a solar thermal converter, radiation absorbed is converted into internal energy and the temperature of the cell is raised. Because of the difference in temperature between the cell and the surroundings, the cell can now act as a heat engine and do work. In order to maximize the working temperature difference, the cell is thermally insulated from the ambient.

3.2.2.3 Photochemical energy converter

A photochemical energy converter works almost exactly like a photovoltaic energy converter, the only difference is that instead of converting the energy directly into electricity, the energy results in a permanent increase in chemical potential.

3.3 Performances of a PV cell

The principle of detailed balance is utilized when describing the performance of a photovoltaic cell. As the solar energy converter absorbs the radiant energy, it also emits thermal radiation to its surroundings. The ratio between absorption and emission must be equal so that in the steady state the concentration of electrons in the cell remains constant.

3.3.1 In equilibrium

Consider a cell in the dark and in thermal equilibrium with the ambient, which radiates like a black body, then the equivalent current density absorbed from the ambient is

$$j_{abs}(E) = q(1 - R(E))a(E)b_a(E) \quad \textbf{(3.6)}$$

Where a (E) is the probability of absorption, the absorptive, of a photon of energy E, and R (E) is the probability of photon reflection.

Let us take a look at some collectors of area A:

If the rear surface of the cell is in contact with air, the total equivalent current is

$$2qA(1 - R(E))a(E)b_a(E) \quad \textbf{(3.7)}$$

If the rear surface of a cell is in contact with a material of higher refractive index, n_s, the total equivalent current is

$$q(1 + n_s^2)A(1 - R(E))a(E)b_a(E) \quad \textbf{(3.8)}$$

If the rear surface acts as a perfect reflector (capable of reflecting thermal photons), the total equivalent current for absorbed thermal photons is

In the last case the device efficiency is greatest.

Emission of thermal photons by spontaneous emission is necessary to maintain a steady state. If ε is the emissive, the equivalent current density for photon emission through the surface of the cell is

$$b_e(E, \Delta\mu) = F_e \frac{2}{h^3 c^2} \frac{E^2}{e^{\frac{(E-\Delta\mu)}{k_B T_a}} - 1} \quad \text{(3.12)}$$

Where

$$F_e = \pi \sin^2 \theta_c = \pi \frac{n_0^2}{n_s^2} \quad \text{(3.13)}$$

n_0 is the refractive index of the ambient. If ε again is the probability of photon emission, the equivalent current density for photon emission is

$$j_{rad}(E) = q(1 - R(E))\epsilon(E) b_e(E, \Delta\mu) \quad \text{(3.14)}$$

The net equivalent current density is then

As V increases (larger E_g), the emitted flux, which is concentrated on photon energies near E_g, will increase and thus result in a decrease of the net current. Note that, under open circuit, when J(V) = 0, all the light-generated current passes through the diode. Under short circuit (V = 0), all this current passes through the external load. The upper limit on the voltage is $\mathbf{V = E_g/q}$. This means that V_{oc} must always be less than this in order to avoid being a light emitting device.

3.4.2 The photovoltaic effect

Photovoltaic is a term in solar technology that describes a solar cells ability to convert light from the sun directly into electric power. When photons in the sun light collide with the silicon solar cell, one of three things can happen:

- The photon can be reflected at the surface of the silicon
- The photon can be absorbed by the silicon
- The photon can pass right through the silicon

As the photons hits the atoms in the silicon, the energy is absorbed by the electrons and excited into a higher state of energy. When these free electrons flow through the material, electricity arises.

Every metal has its own band gap that describes how strong the electrons are bonded to the atoms. For semiconductors, such as silicon, the band gap refers to the energy difference between the valence band and the conduction band. When a negative electron is excited, it leaves behind a void which is called a positive hole. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to jump into the hole, leaving another hole behind. Because of this, holes also move through the lattice. When photons are absorbed in the semiconductor, it can be said they create mobile electron-hole pairs.

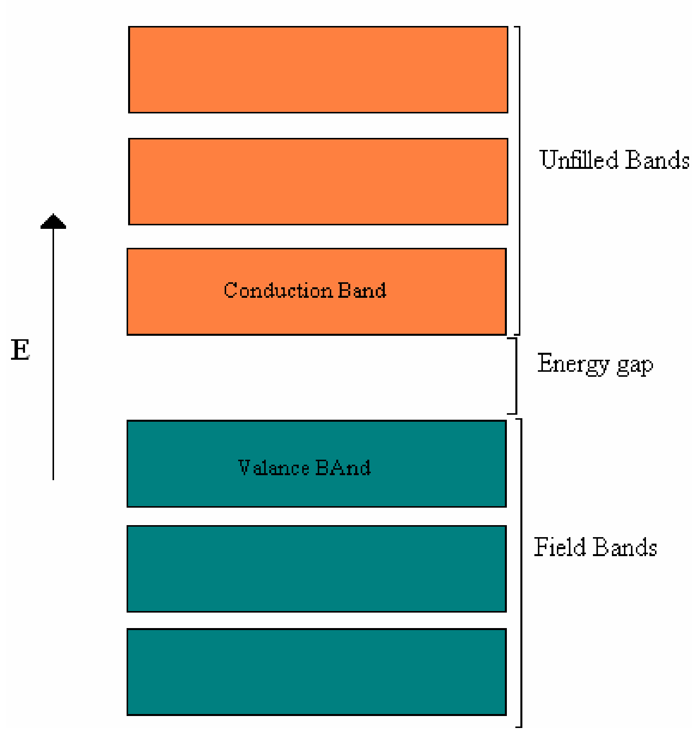


Figure 3.7: Band gap of metal

The holes move to the negative layer of the cell, and the negative excited electrons move to the positive layer. This will be described by the p-n junction technique later. When placing a circuit between the two layers, a path of continuous flow of electrons is established. Due to the concept conservation of energy, the excited electrons cannot have greater nor less energy than that of the incident rays from the sun. Photons with less energy than the energy gap will go straight through the semiconductor and no electrons will be excited. Photons with greater energy than the energy gap will be absorbed, but the difference in energy between the photons and the energy gap is converted into heat by lattice vibration.

3.4.3 Limiting efficiency

If it is assumed that no potential is lost through resistance anywhere in the circuit, all collected electrons should have ?ÂµÂ of electrical potential energy and deliver ?ÂµÂ of work to the external circuit. Since ?µ = q V, the power conversion, based on P = V J (V) and J(V), is

$$\eta = \frac{V J(V)}{P_s} \quad \text{.......................................} \quad \mathbf{(3.18)}$$

and with maximum efficiency when…

…………………………… **(3.19)**

3.5 Effects of band gap and spectrum

Given the earlier assumptions, and with a fixed incident spectrum, ? depends only on the band gap. If the band gap is very small, the working value of V would be too small. If it is very large, the photocurrent would be too small. For the standard AM1.5 solar spectrum, the maximum ?; is around **33%** at an E_g about 1.4eV.

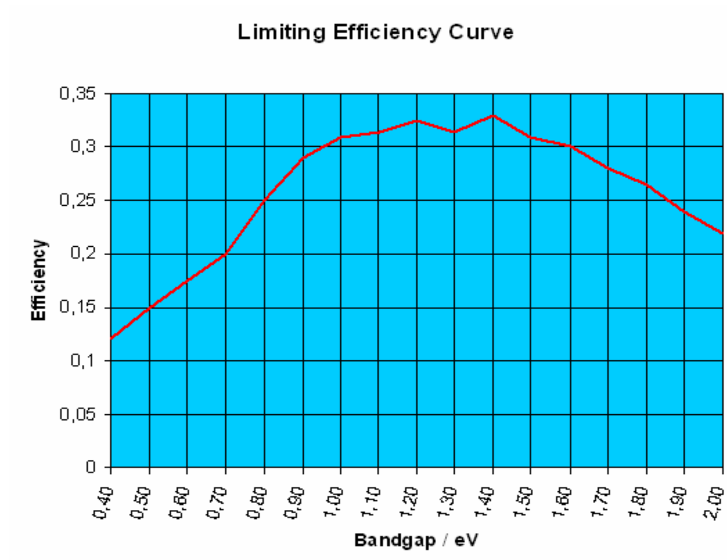


Figure 3.8: Limiting efficiency for a single band gap solar cell in AM 1.5

Table 3.1:List of band gaps

Material	Band gap (eV)
crystalline Si	1.12
amorphous Si	~1.75
CdTe	1.45
GaAs	1.42
CdS	2.4

The spectrum of a 5760 K black body shows a limiting efficiency around **31%** at an E_g about 1.3eV outside the Earth's atmosphere (AM0).By reducing the temperature of the radiant source (more reddish), the optimal energy gap and efficiency decreased. Similarly, by increasing the temperature of the source, optimal energy gap and efficiency both are increased. In the case where T_a (ambient temperature) is zero and the black body temperature is 6000K, the optimum V is **E_g/q**, which gives a maximum efficiency around 44% at a band gap of 2.2eV.
Another way of improving the efficiency through the spectrum is by concentrating the light, so that absorbed flux will increase relative to the emitted flux. For light concentrated by a factor of 1000, a limiting efficiency around 37% at E_g about 1.1eV is predicted. And as for a concentration up to $4.6 \cdot 10^4$ (the maximum), ? is over 40%. But these estimates ignore the fact that under high concentration the cell will be heated, and emit more strongly.

3.6 Photovoltaic Modules

For almost all applications, the one-half volt produced by a single cell is inadequate. Therefore, cells are connected together in series to increase the voltage. Several of these series strings of cells may be connected together in parallel to increase the current as well.

These interconnected cells and their electrical connections are then sandwiched between a top layer of glass or clear plastic and a lower level of plastic or plastic and metal. An outer frame is attached to increase mechanical strength, and to provide a way to mount the unit. This package is called a "module" or "panel". Typically, a module is the basic building block of photovoltaic systems.

Groups of modules can be interconnected in series and/or parallel to form an "array." By adding "balance of system" (BOS) components such as storage batteries, charge controllers, and power conditioning devices, we have a complete photovoltaic system.

3.6.1 Describing Photovoltaic Module Performance

To insure compatibility with storage batteries or loads, it is necessary to know the electrical characteristics of photovoltaic modules.

As a reminder, "I" is the abbreviation for current, expressed in amps. "V" is used for voltage in volts, and "R" is used for resistance in ohms.

A photovoltaic module will produce its maximum current when there is essentially no resistance in the circuit. This would be a short circuit between its positive and negative terminals.

This maximum current is called the short circuit current, abbreviated I(sc). When the module is shorted, the voltage in the circuit is zero.

Conversely, the maximum voltage is produced when there is a break in the circuit. This is called the open circuit voltage, abbreviated V (oc). Under this condition the resistance is infinitely high and there is no current, since the circuit is incomplete.

These two extremes in load resistance, and the whole range of conditions in between them, are depicted on a graph called a I-V (current-voltage) curve. Current, expressed in amps, is on the vertical Y-axis. Voltage, in volts, is on the horizontal X-axis (Figure-3.9).

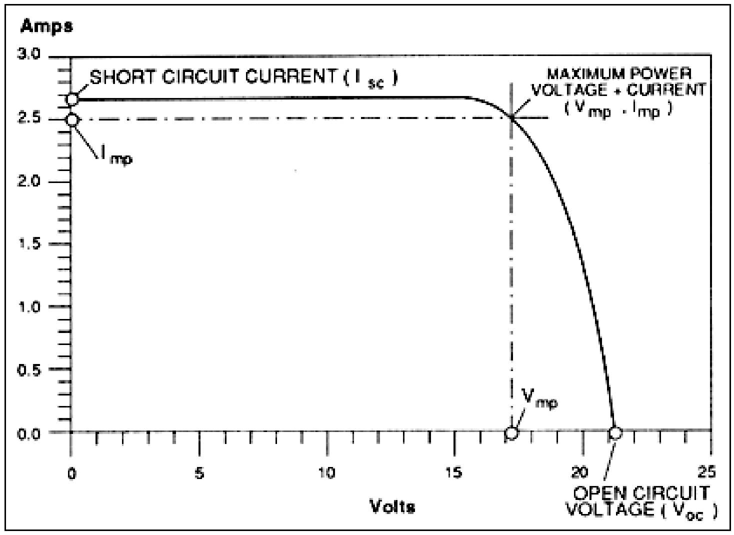


Figure-3.9. A Typical Current-Voltage Curve.

As seen in Figure 3.9, the short circuit current occurs on a point on the curve where the voltage is zero. The open circuit voltage occurs where the current is zero.

The power available from a photovoltaic module at any point along the curve is expressed in watts. Watts are calculated by multiplying the voltage times the current (watts = volts x amps, or W = VA).

At the short circuit current point, the power output is zero, since the voltage is zero.

At the open circuit voltage point, the power output is also zero, but this time it is because the current is zero. There is a point on the "knee" of the curve where the maximum power output is located. This point on our example curve is where the voltage is 17 volts, and the current is 2.5 amps. Therefore the maximum power in watts is 17 volts times 2.5 amps, equaling 42.5 watts. The power, expressed in watts, at the maximum power point is described as peak, maximum, or ideal, among other terms. Maximum power is generally abbreviated as "I (mp)." Various manufacturers call it maximum output power, output, peak power, rated power, or other terms. The current-voltage (I-V) curve is based on the module being under standard conditions of sunlight and module temperature. It assumes there is no shading on the module. Standard sunlight conditions on a clear day are assumed to be 1000 watts of solar energy per square meter (1000 W/m^2 or lkW/m^2). This is sometimes called "one sun," or a "peak sun." Less than one sun will reduce the current output of the module by a proportional amount. For example, if only one-half sun (500 W/m2) is available, the amount of output current is roughly cut in half.

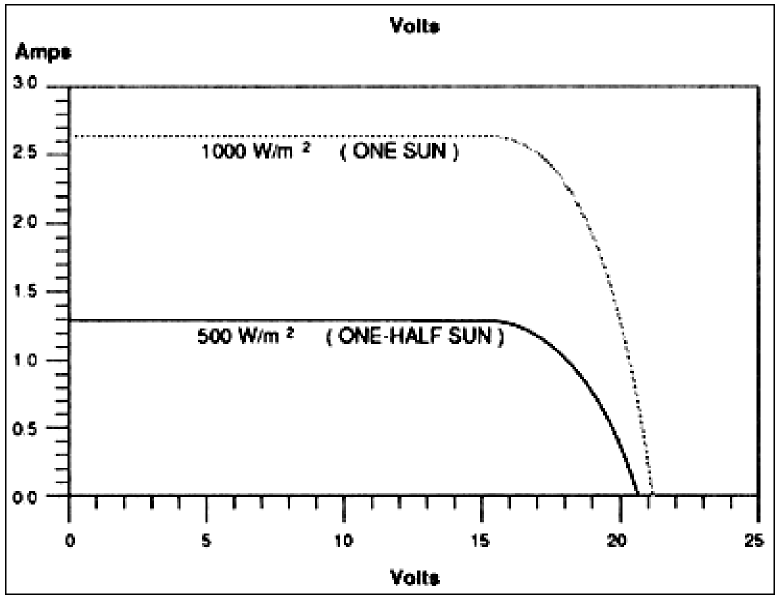


Figure-3.10: Typical Current-Voltage Curve at One Sun and One-half Sun

For maximum output, the face of the photovoltaic modules should be pointed as straight toward the sun as possible. Photovoltaic cells are electrical semiconductors; partial shading of the module will cause the shaded cells to heat up. They are now acting as inefficient conductors instead of electrical generators. Partial shading may ruin shaded cells.

Partial module shading has a serious effect on module power output. For a typical module, completely shading only one cell can reduce the module output by as much as 80% (Figure-3.11). One or more damaged cells in a module can have the same effect as shading.

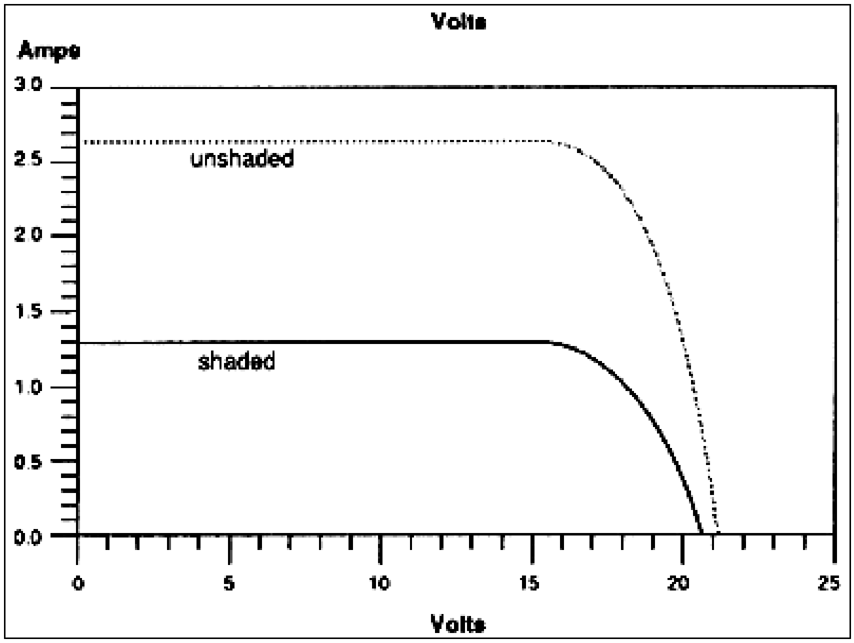


Figure 3.11: Typical Current-Voltage Curve for an Un-shaded Module and for a Module with One Shaded Cell

This is why modules should be completely un-shaded during operation. A shadow across a module can almost stop electricity production. Thin film modules are not as affected by this problem, but they should still be un-shaded.

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04 to 0.1 volts for every one Celsius degree rise in temperature (0.04V/0C to 0.1V/0C). In Fahrenheit degrees, the voltage loss is from 0.022 to 0.056 volts per degree of temperature rise (Figure-3.12).

This is why modules should not be installed flush against a surface. Air should be allowed to circulate behind the back of each module so its temperature does not rise and reducing its output. An air space of 4-6 inches is usually required to provide proper ventilation.

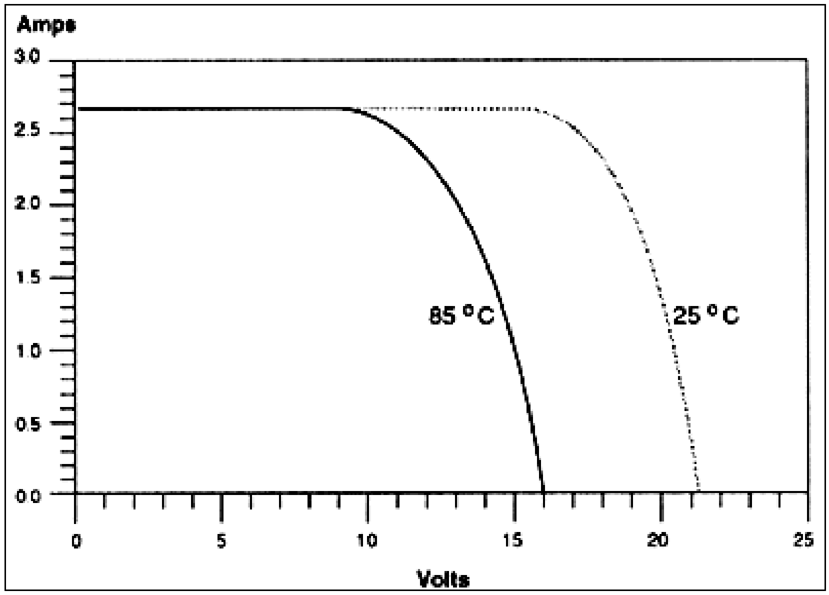


Figure 3.12: A Typical Current-Voltage Curve for a Module at 25°C (77°F) and 85°C (185°F)

The last significant factor which determines the power output of a module is the resistance of the system to which it is connected. If the module is charging a battery, it must supply a higher voltage than that of the battery.

If the battery is deeply discharged, the battery voltage is fairly low. The photovoltaic module can charge the battery with a low voltage, shown as 0.1 in Figure 3.13. As the battery reaches a full charge; the module is forced to deliver a higher voltage, shown as 0.2. The battery voltage drives module voltage.

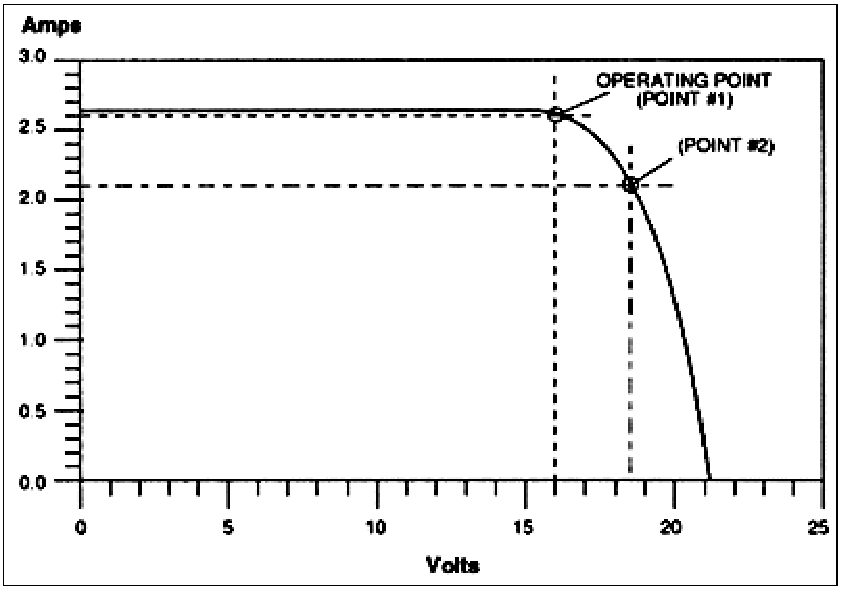


Figure 3.13: Operating Voltages during a Battery Charging Cycle

Eventually, the required voltage is higher than the voltage at the module's maximum power point. At this operating point, the current production is lower than the current at the maximum power point. The module's power output is also lower.

To a lesser degree, when the operating voltage is lower than that of the maximum power point, the output power is lower than the maximum. Since the ability of the module to produce electricity is not being completely used whenever it is operating at a point fairly far from the maximum power point, photovoltaic modules should be carefully matched to the system load and storage.

Using a module with a maximum voltage which is too high should be avoided nearly as much as using one with a maximum voltage which is too low.

The output voltage of a module depends on the number of cells connected in series. Typical modules use 30, 32, 33, 36, or 44 cells wired in series.

The modules with 30-32 cells are considered self regulating modules. 36 cell modules are the most common in the photovoltaic industry. Their slightly higher voltage rating, 16.7 volts, allows the modules to overcome the reduction in output voltage when the modules are operating at high temperatures.

Modules with 33 - 36 cells also have enough surplus voltage to effectively charge high antimony content deep cycle batteries. However, since these modules can overcharge batteries, they usually require a charge controller.

Finally, 44 cell modules are available with a rated output voltage of 20.3 volts. These modules are typically used only when a substantially higher voltage is required.

As an example, if the module is sometimes forced to operate at high temperatures, it can still supply enough voltage to charge 1 2 volt batteries.

Another application for 44 cell modules is a system with an extremely long wire run between the modules and the batteries or load. If the wire is not large enough, it will cause a significant voltage drop. Higher module voltage can overcome this problem. It should be noted that this approach is similar to putting a larger engine in a car with locked brakes to make it move faster. It is almost always more cost effective to use an adequate wire size, rather than to overcome voltage drop problems with more costly 44 cell modules. It's discusses maximum power point trackers. These devices are used to bring the module to a point as close as possible to the maximum power point. They are used mostly in direct DC systems, particularly with DC motors for pumping.

3.7 Types of Photovoltaic Systems

3.7.1 Small Stand-Alone DC or AC System

The small stand-alone system is an excellent replacement for propane or kerosene lights in a remote cabin, a recreational vehicle or a boat. The size of the photovoltaic (PV) array and battery will depend upon individual requirements. The actual sizing methods are discussed elsewhere. The PV array charges the battery during daylight hours and the battery supplies power to the loads as needed. The charge regulator terminates the charging when the battery reaches full charge. The load center may contain meters to monitor system operation and fuses to protect wiring in the event of malfunction or short circuit in the house. You can add more panels and an inverter to make this an AC Stand-Alone System.

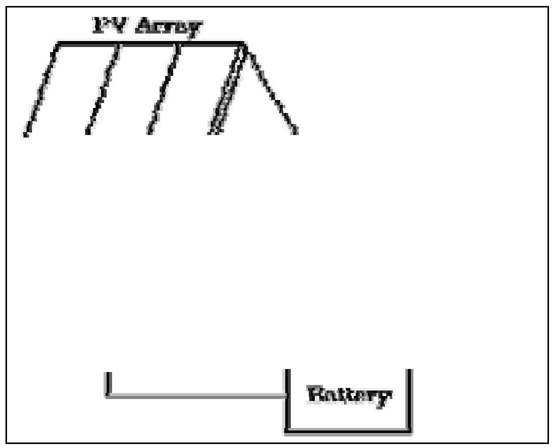
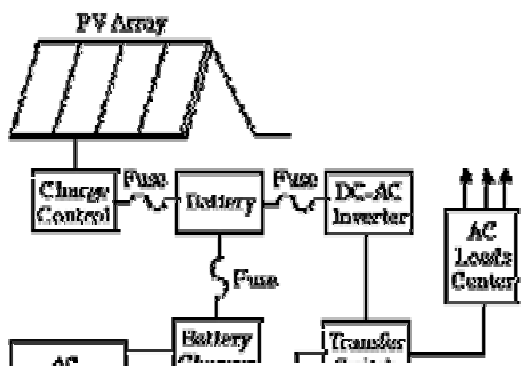


Figure 3.14: PV - Generator Combination

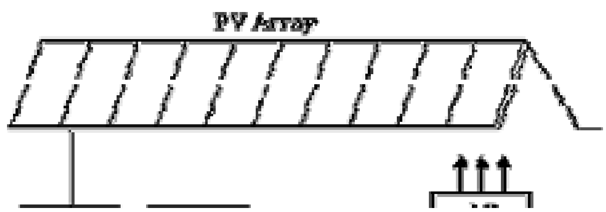
The PV - Generator Combination system may be an economical alternative to a large stand-alone PV system, because the PV array does not have to be sized large enough for worst case weather conditions. A gasoline, propane, diesel, wind, or micro-hydro generator combined with a battery charger can supply power when the PV array falls short. If the PV array is sized for average conditions, then during extended overcast situations or periods of increased load, the generator can be started. When batteries are low, the generator will power the AC loads in the house as well as a battery charger to help recharge the batteries. If the PV array is sized much smaller than needed for normal use, the generator can power peak loads such as doing laundry or pumping water and simultaneously run the battery charger to charge the battery bank. In addition to allowing for a smaller PV array, a back-up charging system may also allow use of a smaller battery bank. Generator and battery bank size must be chosen carefully for reliable system operation. See the system sizing section for more details on equipment choice.

3.7.2 Utility Integrated System (Alternating Current Solar System (not grid Intertie))

For areas that don't have utility Intertie easily available or if you want backup power. Same as the Utility Intertie system, it's given below, but with battery storage. If your PV array is large enough you will only need the Utility (Grid) for backup power; i.e. extended cloudy periods. Any of the systems above can be made into a hybrid system with the addition of a gas, wind, steam or micro-hydro generator.



optimum configuration from an economic viewpoint because all the electricity is utilized by the owner during the day and any surplus is exported to the grid. Meanwhile, the cost of storage to meet night-time needs is avoided, because the owner simply draws on the grid in the usual way. Also, with access to the grid, the system does not need to be sized to meet peak loads.



3.8 Low-voltage adaptor

A voltage adaptor is an electronic unit that steps down the voltage. It does this by 'losing' the extra voltage as heat. Voltage adaptors are sold for use in cars and are designed to plug into the cigarette lighter socket. The output wire usually has a multi-way plug on the end to suit a wide range of D.C. input sockets. The adaptor has one switch to select the output voltage according to the number of batteries used by the appliance. Another switch sets the polarity of the connections on the plug.

When using the adaptor in a solar system, connections need to be made to the contacts on the side of the plug. This is done by opening up the plastic box and connecting a cable to the spring contacts. The side contact is negative and the end one is positive.

3.9 D.C—D.C. converters

A d.c.-d.c. converter is an electronic unit which can step a d.c. voltage down or up. Examples are shown in Figure 3.17. They are more complicated than a voltage adaptor and work by a method called pulse width modulation. The input to a d.c.-d.c. converter is switched on and off very quickly. The relative length of on and off times is adjusted so that after smoothing the required D.C. output voltage is obtained.

A good application for a d.c.-d.c. converter is in systems operating at 24 V where the converter can reduce the voltage down to 12 V for a number of appliances. D.c.-d.c. converters are more expensive and less common than voltage adaptors but they have the advantage of a higher power efficiency. A typical power efficiency is 85 percent while a voltage adaptor doing the same job of having the voltage can be no better than 50 percent efficient.

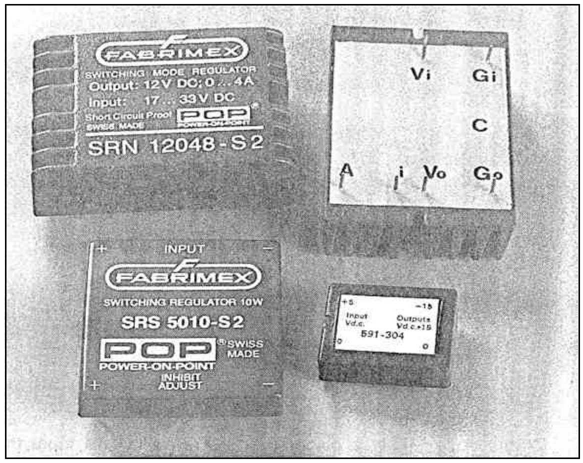


Figure 3.17: Examples of d.c.-d.c. converters for reducing or increasing a d.c. voltage.

3.10 Power inverters

A power inverter or transverter-is used in a solar electric system to convert low-voltage D.C. to mains voltage a.c. This is needed when using appliances that only work from a mains voltage a.c. supply.

A power inverter may seem to be the best solution of running all the appliances at mains voltage but it has several disadvantages. Good-quality power inverters are expensive and difficult to obtain in many countries. Also they make the solar system more complicated by adding another unit that can fail and be difficult to repair.

Therefore it is strongly recommended that an attempt is first made to find a supply of low-voltage D.C. appliances. If these appliances turn out not to be available, then resort to using mains voltage appliances with a power inverter.

Another use for a power inverter is in a large system covering a wide area. The size of long-distance cables is reduced by operating at a high voltage. Bearing in mind the disadvantages of using a power inverter, there must be a large reduction in the cost from using small cables at high voltage to make this approach worth while.

Figure 3.18: Example of a solid-state power inverter. From a 24V d.c. input, this inverter provides 240 V sinusoidal a.c. output with a rating of 100 W. The weight of the u nit is 37.3 kg (17 lb). (Source Valradio Power Ltd.)

3.10.1 Types of inverter

There are basically two ways that an inverter can operate. In the solid-state electronic type, transistors switch the d.c. input on and off many times per second. The current is now changing so it can be transformed to other voltages by a transformer. The output from the transformer is a.c. An example of a solid-state power inverter is shown in Figure 3.18.

The older type of inverter is mechanical instead of solid-state. It is called a rotary inverter ox motor generator and consists of a d.c. motor and an a.c. dynamo connected directly in one unit. The motor runs at low-voltage d.c. and drives the dynamo. The output from the dynamo is high-voltage a.c. Rotary inverters are lighter than solid-state inverters for the same power output but the moving parts require regular maintenance. They are also less efficient.

3.11 Waveform of a.c. output

In mains a.c, the current change is sinusoidal This means that whenever the current alternates direction, it decreases gradually to zero current and increases gradually up to the full negative current. As the current varies with time, it follows a sine curve and so is sinusoidal (see Figure 3.19(a)).

The a.c. output from a rotary inverter is a pure sine wave so it is just like mains a.c. In contrast, the simplest way for a solid-state electronic inverter to work is by switching the D.C. on and off. This produces a square wave type of a.c. at the output (see Figure 3.19(b)).

Lamps and heaters work equally well on sinusoidal and square wave a.c. This is not so for most appliances containing electronics such as televisions and computers. There is a rapid change in voltage as the current alternates, which can damage these appliances. Motors can be powered by square wave a.c. but are less efficient than with sinusoidal a.c.

More expensive electronic inverters produce a modified or quasi sine wave output (see Figure 3.19(c)). They work by switching the d.c. input using pulse width modulation, as for D.C.-D.C. converters. A modified or pure sine wave output is required for most appliances that contain electronic circuits.

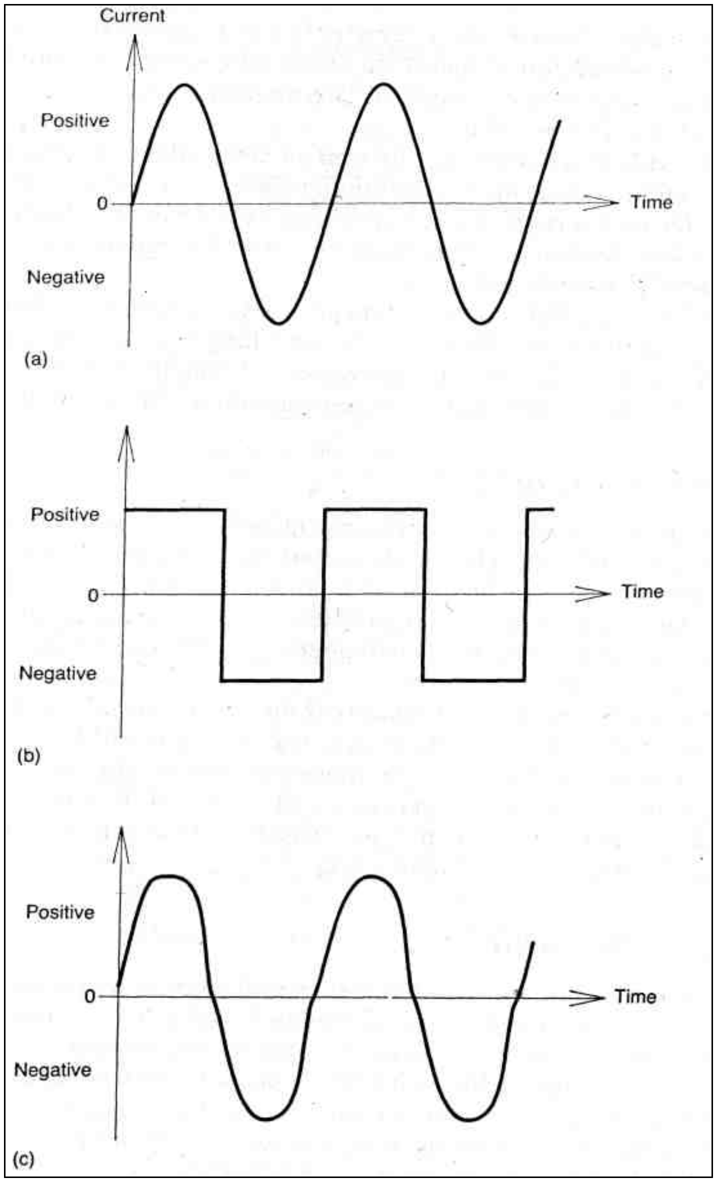


Figure 3.19: Waveforms of a.c. (alternating current).

(a) Sinusoidal wave.

(b) Square wave.

(c) Modified sine wave.

3.12 Frequency of a.c. output

The frequency of a.c. is given by how many times it alternates every second. It is measured in units of hertz (Hz) which is short for cycles per second.

There are two systems of mains frequency around the world which are 50 and 60 Hz. Appliances are marked with the frequency they should be run at. When ordering a power inverter, the frequency must be checked to make sure it will suit the appliances.

Cassette and record players that are run directly from mains voltage a.c. use the frequency of the a.c. to feed the tape or turn the record at the correct speed. For proper control of the speed in these appliances, the variation in a.c. frequency should be less then 1%, and some inverters feature accurate control of the frequency for this purpose. This feature is called internal crystal control using a crystal-controlled oscillator.

3.13 Efficiency of inverters

Some electrical power is used by an inverter itself so more power must be put in than is available as high-voltage a.c. Therefore the efficiency is always less than 100 per cent and varies a lot between different makes and types of power inverter. Efficiencies are in the range 50-90 per cent with square wave power inverters being the best value for money.

The efficiency of many power inverters tends to be lower when they are operating well below their maximum rated power. For the best operating efficiency, choose a power rating that is just a little higher than the total power required by the appliances.

Inverters have a standby consumption of electricity when the appliances are switched off. Therefore a good feature to include in a power inverter is automatic switching off when appliances are not in use. This avoids wasting electricity while the inverter is on standby.

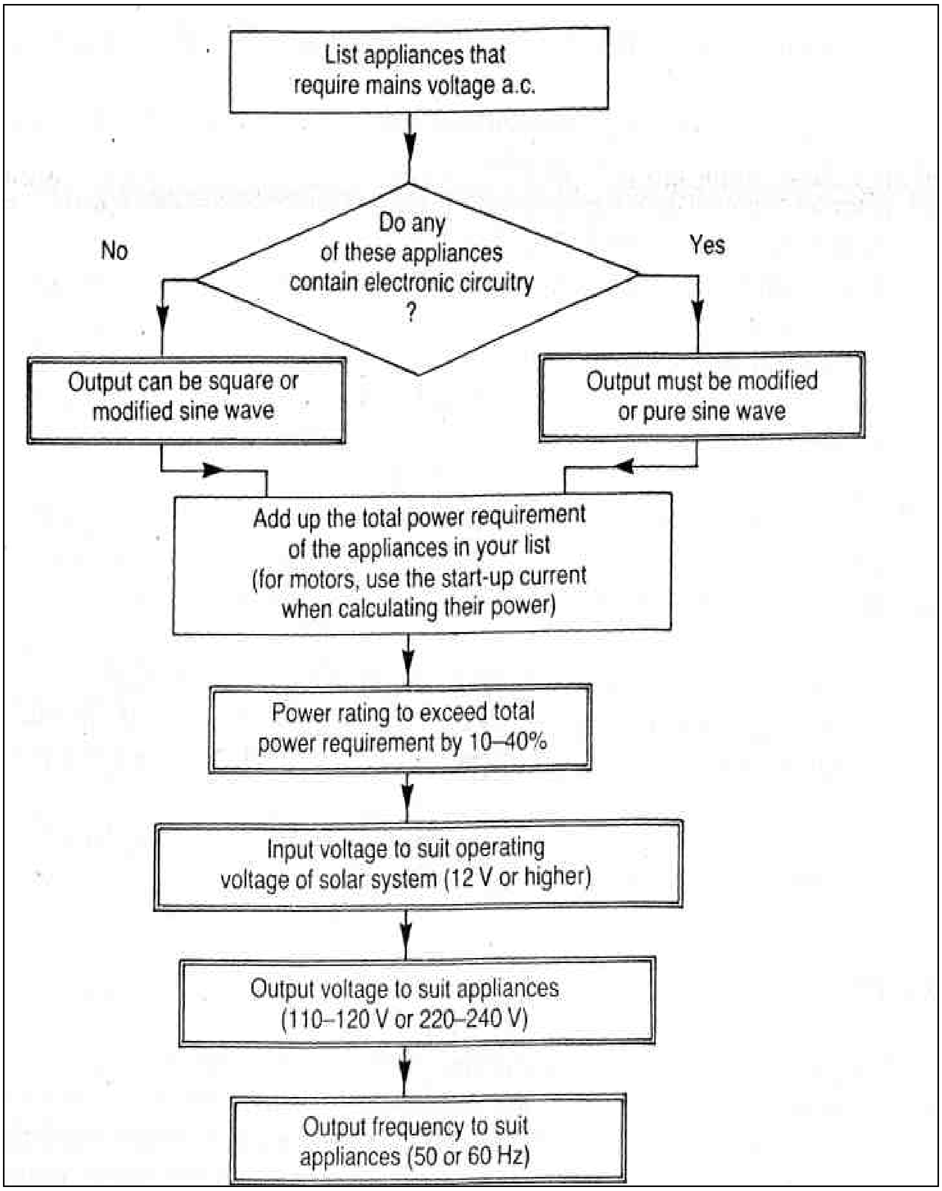


Figure 3.20: Procedure for preparing the specifications of a power inverter for a solar electric system:

?‘ steps involved

?‘ decisions

?‘ specifications of power inverter

3.14 Cell temperature:

The temperature of operation of a PV module can be determined by an energy balance. The solar energy absorbed by a module is converted partly into thermal energy and partly into electrical energy. The electrical energy is removed from the cell through the external circuit. Thermal energy is dissipated by a combination of heat transfer mechanisms. An energy balance on a unit area of module, cooled by losses to the surroundings can be written as,

täãI $_T$ = ?ä$_c$ I T + U_L (T_c - T_a)................................(3.20)

Where t™is the transmittance of any cover that may be over the cells, a™is the fraction of the radiation incident of the cells, that is absorbed, and ?ĉ is the efficiency of the module of conversion of incident radiation into electrical energy. The efficiency will vary from zero to a maximum; depending on how close to the maximum, depending on how close to the maximum power point, the module is operating. The loss coefficient, U_L, will include losses by convection and radiation from top and bottom and by conduction through any mounting framework that may be present, to the ambient temperature $T_{a.}$

The nominal operating cell temperature (NOCT) is defined as the cell or module temperature which is reached when the cells are mounted in their normal way at a solar radiation level.

Chapter 4
Solar Cell and its Efficiency

4.1 History

The story of photovoltaic and how it all began in 1839 as a coincidence, just like many other discoveries in the past, such as penicillin, is a very interesting reading. The story will take you through some facts, persons and events, which have marked the history of photovoltaic.

"Being desirous of obtaining a more suitable high resistance for use at the Shore Station in connection with my system of testing and signaling during the submersion of long submarine cables, I was induced to experiment with bars of selenium - a known metal of very high resistance. I obtained several bars, varying in length from 5 cm to 10 cm, and of a diameter from 1.0 mm to 1.5 mm. Each bar was hermetically sealed in a glass tube, and a platinum wire projected from each end for the purpose of connection..."

4.1.1 Discovery of photovoltaic effect

A physical phenomenon allowing light-electricity conversion - photovoltaic effect, was discovered in 1839 by the French physicist Alexander Edmond Becquerel. Experimenting with metal electrodes and electrolyte he discovered that conductance rises with illumination.

4.1.2 First solar cells

Willoughby Smith discovered photovoltaic effect in selenium in 1873. In 1876, with his student R. E. Day, William G. Adams discovered that illuminating a junction between selenium and platinum also has a photovoltaic effect. These two discoveries were a foundation for the first selenium solar cell construction, which was built in 1877. Charles Fritts first described them in detail in 1883.

4.1.3 The first solar modules

In 1963, Sharp Corporation developed the first usable photovoltaic module from silicon solar cells. The biggest photovoltaic system at the time, the 242 W module field was set up in Japan. A year later, in 1964, Americans applied a 470 W photovoltaic field in the Nimbus space project.

4.2 Theory

The basic idea of a solar cell is to convert light energy into electrical energy. The energy of light is transmitted by photons, small packets or quanta of light. Electrical energy is stored in electromagnetic fields, which in turn can make a current of electrons flow. Thus a solar cell converts light, a flow of photons, to electric current, a flow of electrons. When photons are absorbed by matter in the solar cell, their energy excites electrons higher energy states where the electrons can move more freely. The perhaps most well-known example of this is the photoelectric effect, where photons give electrons in a metal enough energy to escape the surface. In an ordinary material, if the electrons are not given enough energy to escape, they would soon relax back to their ground states. In a solar cell however, the way it is put together prevents this from happening. The electrons are instead forced to one side of the solar cell, where the build-up of negative charge makes a current flow through an external circuit. The current ends up at the other side (or terminal) of the solar cell, where the electrons once again enter the ground state, as they have lost energy in the external circuit.

4.2.1 The p-n Junction

In order to understand how a solar cell works, it is necessary to understand p-n junctions. A p-n junction is formed when an n-type semiconductor is put together with a p-type semiconductor. See Figure 4.1 The n-type semiconductor is doped with donor atoms that have more electrons than the surrounding material, and the p-type semiconductor is doped with acceptor atoms that have fewer electrons than the surrounding material. Atoms in the p-type semiconductor with fewer electrons than the surrounding material are said to have holes. These holes are thought of as positive entities much like electrons in that they can move throughout the material and contribute to the current. When a hole and an electron meet, they essentially annihilate each other; this is called recombination.

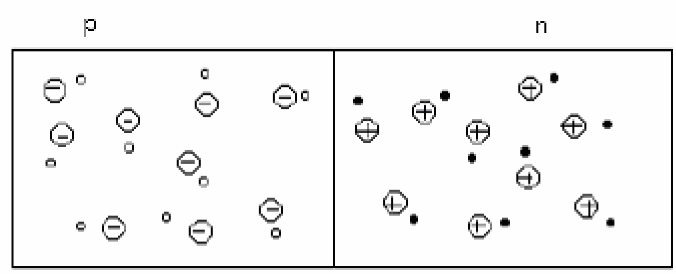


Figure 4.1: p-n junctions

(Electrons are depicted as filled circles; holes are depicted as empty circles, negatively charged donor atoms in the p-side and positively charged acceptor atoms in the n-side are also shown.)

Putting an n-type semiconductor together with a p-type semiconductor creates an Electron/hole concentration gradient. This concentration gradient causes diffusion current with electrons diffusing to the p-side and holes diffusing to the n-side. The area in which this diffusion takes place is called the depletion region. When electrons from the n-side diffuse to the p-side they meet with holes and recombine leaving negatively charged donor atoms on the p-side. The holes from the p-side diffusing to the n-side create positively charged donors on the n-side. The ionized donors create an internal electric field in the depletion region. See Figure 4.2. The Electric field in the region works as a barrier preventing more electrons from diffusing from the n-side to the p-side. Only those electrons with a high enough energy to overcome the field can make the transition. In equilibrium there is no net current so the diffusion current and the drift current (due to the internal electric field) cancel each other.

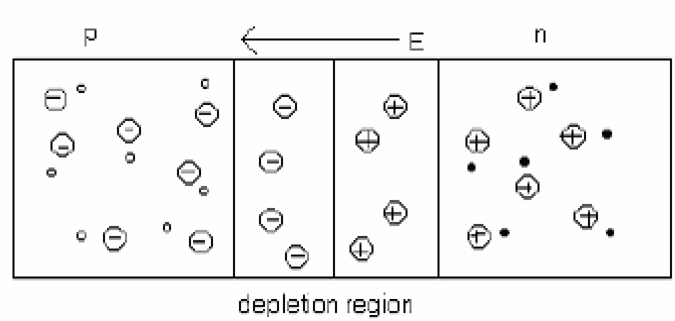


Figure 4.2: Creation of internal Electric field

4.2.2 The p-n Junction under an Applied Bias

When a potential is applied across a p-n junction, it can either increase or decrease the internal electric field. If the negative side of the potential is connected to the p-side, then the electric field is increased. This is called a reverse bias. Alternately, a forward bias, where the positive side of the potential is connected to the p-side, results in the reduction of the internal field. When the internal field is decreased by a forward bias the number of electrons on the n-side that have enough energy to cross the depletion region to the p-side increases by a factor of $\exp(eV / kT)$. Here e is the charge of the electron, V the applied voltage, k the Boltzmann coefficient, and T absolute temperature. The resulting electron current from the n-side to the p-side is $I_{e0} \exp(eV/kT)$. There is a small electron current I_{e0} from the p-side to the n-side. This is due to the very few electrons (minority carriers) in the p-side. Thus the total electron current is:

$$\mathbf{I_e = I_{e0} (e^{eV/kT}-1)} \qquad \textbf{(4.1)}$$

The same relation holds for the hole current from the p-side to the n-side. A forward bias results in a hole current:

$$\mathbf{I_h = I_{h0} (e^{eV/kT}-1)} \qquad \textbf{(4.2)}$$

Where I_{h0} is the equilibrium hole current. Putting equations 1 and 2 together gives the total current, also known as the diode current:

$$\mathbf{I = I_e + I_h = I_0 (e^{eV/kT}-1)} \qquad \textbf{(4.3)}$$

Where

$$\mathbf{I_0 = I_{e0}+I_h} \qquad \textbf{(4.4)}$$

I_0 is sometimes called the dark current.

4.3 Solar Cell Principles

When photons of a high enough energy are incident on a semiconductor, they create an electron-hole pair. This can be understood by looking at the energy band diagram of a semiconductor. Figure-4.3 shows the three distinct energy bands of electrons in a semiconductor. Valence band states are fully occupied by electrons and the first empty band (conduction band) is separated by a band gap. Electrons in the valence band can not be involved in conduction. This is due to the Pauli Exclusion Principle, since there are no low lying empty energy states for the electrons in the valence band to move to under and electric field. When electrons acquire a sufficient amount of energy, they can enter the conduction band. When a photon with energy greater than the band gap is incident on a semiconductor, it gives an electron in the valence band enough energy to move to the conduction band. Both the electron in the conduction band and the hole that has been created in the valence band can be involved in the conduction of a current under an electric field.

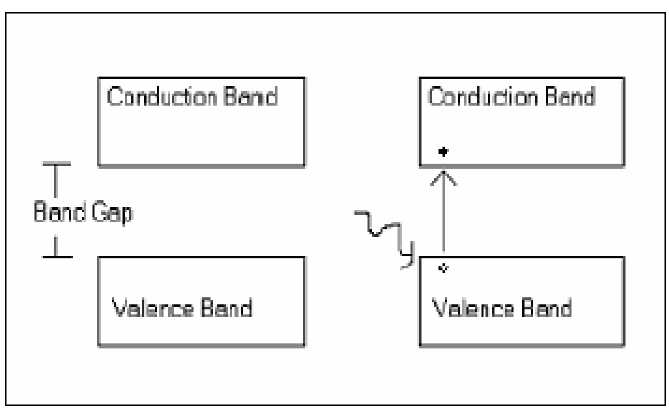


Figure 4.3: Band diagram and electron-hole pair production

A solar cell can be constructed by putting a very thin, heavily doped n-type layer on top of a thicker p-type layer. As can be seen in Figure-4.4, the depletion region is mostly on the p-side. Light is absorbed through the n-type layer. Because the n layer is so thin, most photons penetrate into the depletion region or the p-side before creating an electron-hole pair. When an electron-hole pair is created in the depletion region the electric field moves the electron into the n-side and the hole into the p-side. This gives the previously neutral n-side a negative charge and the previously neutral p-side a positive charge. When a load is connected to the cell, the electron can travel through the circuit, do work, and recombine with the hole.

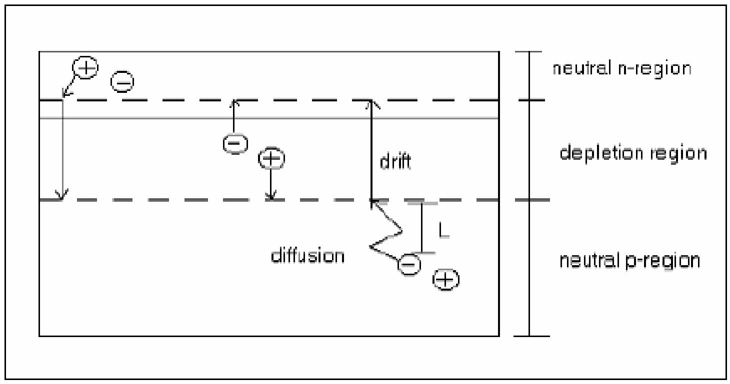


Figure 4.4: Electron-Hole Pair Behavior in Solar Cell

If the light penetrates into the neutral p-side, then there is no electric field to separate the electron-hole pair. Instead the electron and the hole diffuse at random through the material and recombine if they meet. The average time between pair production and recombination for an electron is t'_e. In this time, the electron diffuses a mean distance of $L_e=\sqrt{(2 D_e t'_e)}$ where D_e is the diffusion coefficient in the p-side. If the electron-hole pair is created within L_e of the depletion region, then the electron can diffuse to the depletion region and be moved by the electric field over to the n-side. For this reason it is important for the diffusion length L_e to be as long as possible. The same process takes place for electron-hole pairs created in the n-side. In silicon, the diffusion length is longer for electrons than it is for holes. This is why the thin top region is n-type and the thicker region is p-type. When an illuminated solar cell is short-circuited, a current flows through the circuit in the opposite direction of the diode current. This current is a result of electron hole production in the solar cell and is called the photocurrent I_{ph} . The photocurrent is directly proportional to the intensity of light. If the cell is in a circuit with some resistance, then there is a voltage across the junction. This voltage acts like a forward bias and as a result in a diode current through the cell. The total current is then:

$$I_{ph}=I_0\,(e^{eV/KT}-1)\text{...}\;(4.5)$$

A typical IV curve for a solar cell can be seen in Figure 4.5.
The Fill Factor (ff) of a solar cell is a measure of the quality of the cell. It is defined as:

$$ff=\frac{I_{mpp}V_{mpp}}{I_{SC}V_{OC}}\text{..}\;(4.6)$$

Where I_{mpp} and V_{mpp} are the current and the voltage at the maximum power point on the IV curve, I_{sc} is the short circuit current, and V_{oc} is the open circuit voltage.

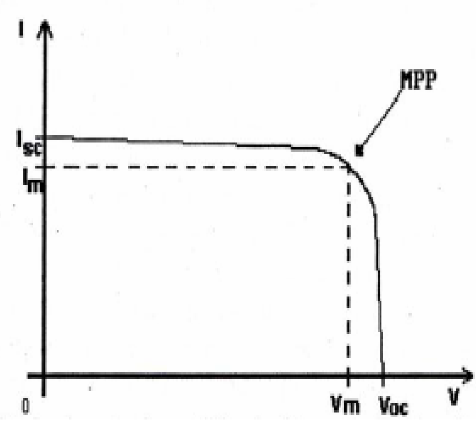


Figure 4.5: A typical IV curve for a solar cell under illumination. MPP is the maximum power point of the cell.

The efficiency of a cell is the ratio of the maximum converted power P_C to the input power P_I :

$$\eta = \frac{P_C}{P_I} \qquad \text{.. (4.7)}$$

Converted power is the product of the current and voltage at the maximum power point so equation can be rewritten as:

$$\eta = \frac{ff \cdot I_{SC} V_{OC}}{P_I} \qquad \text{………………………………….... (4.8)}$$

4.4 Voltage and current

Two important quantities to characterize a solar cell are

Open circuit voltage (V_{oc}): The voltage between the terminals when no current is drawn (infinite load resistance)

Short circuit current (I_{sc}): The current when the terminals are connected to each other (zero load resistance)

The short circuit current increase with light intensity, as higher intensity means more photons, which in turn means more electrons. Since the short circuit current I_{sc} is roughly proportional to the area of the solar cell, the short circuit current density, $J_{sc} = I_{sc}/A$, is often used to compare solar cells.

When a load is connected to the solar cell, the current decreases and a voltage develops as charge builds up at the terminals. The resulting current can be viewed as a superposition of the short circuit current, caused by the absorption of photons, and a dark current, which is caused by the potential built up over the load and flows in the opposite direction. As a solar cell contains a PN-junction (LINK), just as a diode, it may be treated as a diode. For an ideal diode, the dark current density is given by

$$J_{dark}(V) = J_0(e^{qV/k_BT} - 1) \quad \text{... (4.9)}$$

Here J_0 is a constant, q is the electron charge and V is the voltage between the terminals. The resulting current can be approximated as a superposition of the short circuit current and the dark current:

$$J = J_{sc} - J_0(e^{qV/k_BT} - 1)$$

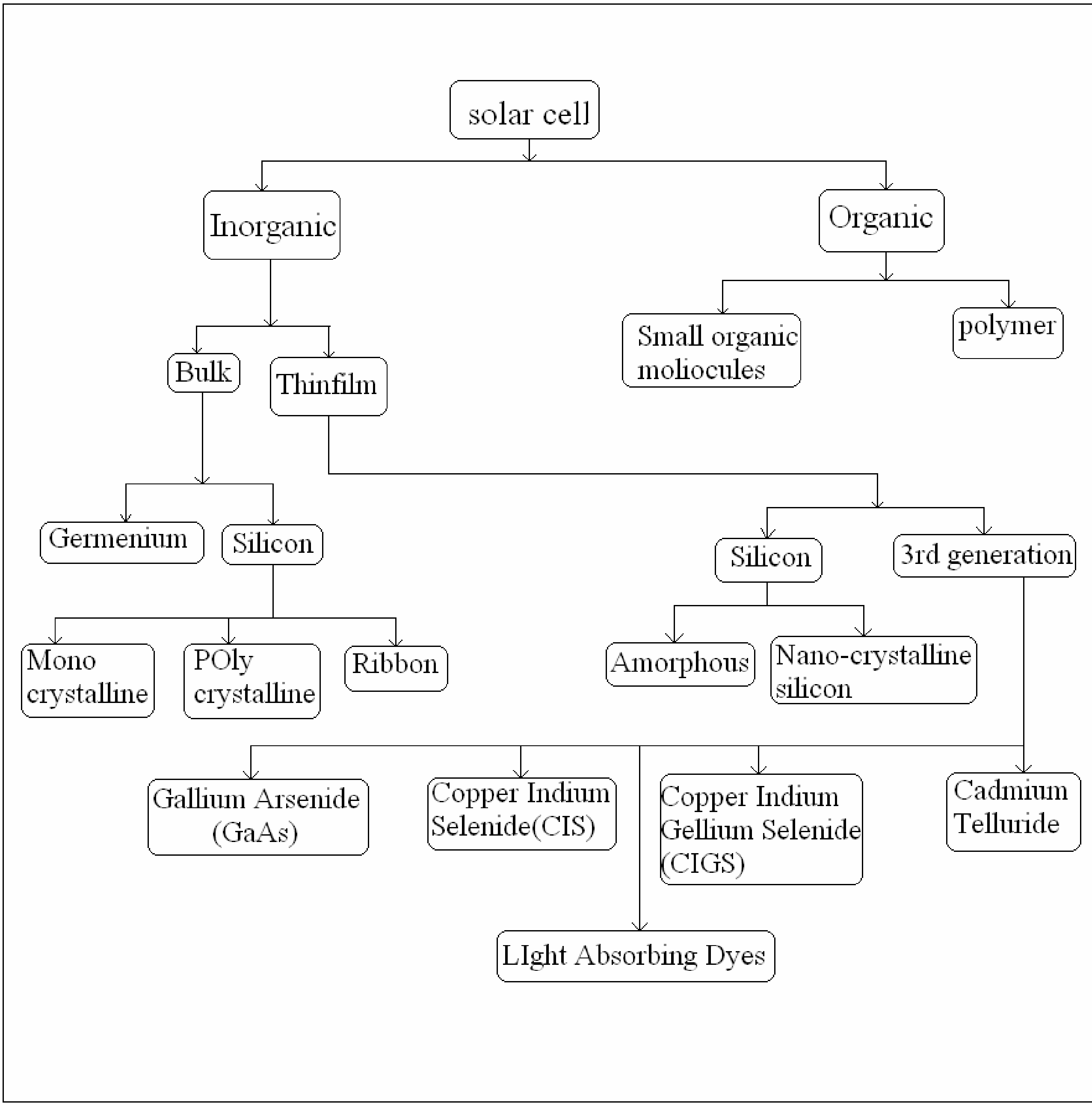


Figure 4.6: Basic types of solar cell

4.5.1 Monocrystalline or Single crystal solar cell

The most common material used in solar cells is single crystal silicon. Solar cells made from single crystal silicon are currently limited to about 25% efficiency because they are most sensitive to infrared light, and radiation in this region of the electromagnetic spectrum is relatively low in energy. But single crystal silicon isn't the only material used to build solar cells.

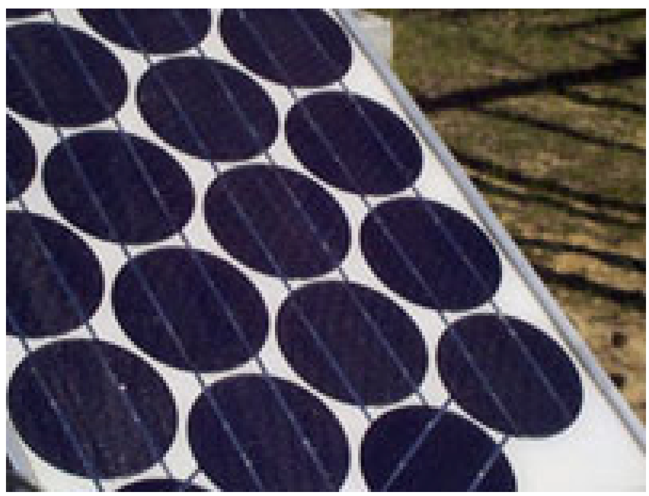


Figure 4.7: Single crystal solar cells.

4.5.2 Polycrystalline

Polycrystalline ("many crystals") solar cells are made by a casting process in which molten silicon is poured into a mould and allowed to cool, then sliced into wafers. This process results in cells that are significantly cheaper to produce than single crystal cells, but whose efficiency is limited to less than 20% due to internal resistance at the boundaries of the silicon crystals.

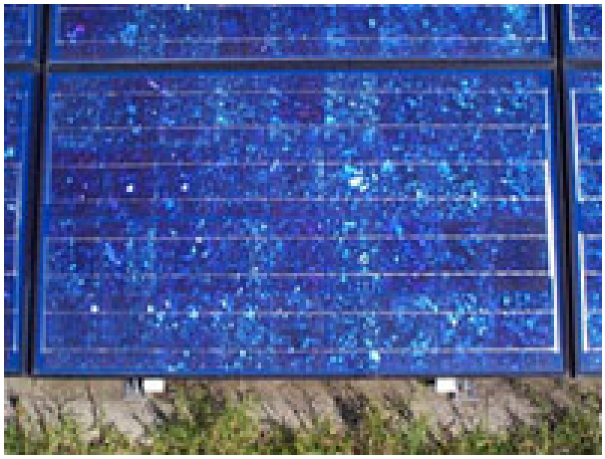


Figure 4.8: Polycrystalline solar cell

4.5.3 Amorphous solar cell

Amorphous cells are made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH_4). This type of solar cell can be applied as a thin film to low cost substrates such as glass or plastic. Thin film cells have a number of advantages, including easier deposition and assembly, the ability to be deposited on inexpensive substrates, the ease of mass production, and the high suitability to large applications. Since amorphous silicon cells have no crystal structure at all, their efficiencies are presently only about 10% due to significant internal energy losses.

Figure 4.9: Amorphous solar cells

4.5.4 Organic photovoltaic

Organic photovoltaic cells are solar cells made mostly of organic molecules. Specifically, the active layer of the device is made of organic material.

Many scientists and engineers believe organic solar cells will provide a cheaper alternative to traditional inorganic cells, since it is thought that economies of scale due to large-scale production of organic polymers will turn out to be less expensive than the current costs for fabrication of silicon or other inorganic materials. However, organic solar cells have much lower efficiencies than traditional technologies. Organic solar cells are considered to be a third generation technology.

There are three main types of organic photovoltaic technologies:

- Molecular OPV,
- Polymer OPV, and
- Hybrid OPV.

The main differences between these three technologies are the fabrication methods employed and the types of materials that are used.

4.5.4.1 Molecular OPV

Molecular photovoltaic devices are typically fabricated by sublimating successive layers of electron and hole transporting materials under vacuum. Common materials include PTCBI, PTCDA, Me-PTCDI, Pe-PTCDI, H2Pc, MPc where M stands for (Zn, Cu), TPyP, TPD, CBP, C60, and PCBM.

4.5.4.2 Polymer OPV

Polymer OPV photovoltaic devices are typically made by solution processing blends of two conjugated polymers or a conjugated polymer with a molecular sensitizer.The most common materials are PPV - Poly (p-phenylene vinylene), polyfluorenes, or polythiophenes.

Polymer solar cells are the most heavily researched of all OPV technologies because they are the most promising when it comes to low cost. In general, it is thought that solution processing will be the most cost effective way to fabricate solar cells.

4.5.4.3 Hybrid OPV

Hybrid photovoltaic devices make use of both organic and inorganic materials. For example, research has been done on polymer-nano-crystal blended active layers, including the use of quantum dots. Research has also been done on the use of metals such as TiO_2. These technologies have not yet surpassed the best polymer OPV technology, but they are promising.

4.5.5 Multijunction photovoltaic cells

These are a sub-class of solar cell or photovoltaic cell developed for higher efficiency. These multijunction cells consist of multiple thin films produced using molecular beam epitaxy and / or Metal organic vapor phase epitaxy. Each type of semiconductor will have a characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain color, or more precisely, to absorb electromagnetic radiation over a portion of the spectrum. The semiconductors are carefully chosen to absorb nearly the entire solar spectrum, thus generating electricity from as much of the solar energy as possible. In short, in the multijunction structure, several layers each capture part of the sunlight passing through the cell. These layers allow the cell to capture more of the solar spectrum and convert it into electricity.

4.5.6 Nano-crystal solar cells

It is also known as quantum dot solar cells, are solar cells based on a silicon substrate with a coating of nano-crystals. While previous methods of quantum dot creation relied on expensive molecular beam epitaxy processes, fabrication using colloidal synthesis allows for a more cost-effective manufacture. A thin film of nanocrystals is obtained by a process known as “spin-coating”. This involves placing an amount of the quantum dot solution onto a flat substrate, which is then rotated very quickly. The solution spreads out uniformly, and the substrate is spun until the required thickness is achieved. Quantum dot based photovoltaic cells based around dye-sensitized colloidal TiO_2 films were investigated in 1991 and were found to exhibit promising efficiency of converting incident light energy to electrical energy, and were found to be incredibly encouraging due to the low cost of materials in the search for more commercially viable/affordable renewable energy sources. A single-nano-crystal (channel) architecture in which an array of single particles between the electrodes, each separated by ~1 excitation diffusion length, was proposed to improve the device efficiency.

4.5.7 Dye-sensitized solar cell

(DSSc, DSC or DYSC): It is a relatively new class of low-cost solar cell that belongs to the group of thin film solar cells. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photo electrochemical system. This cell was invented by Michael Grätzel and Brian O'Regan at the École Polytechnique Fédérale de Lausanne in 1991and is also known as Grätzel cells. This cell is extremely promising because it is made of low-cost materials and does not need elaborate apparatus to manufacture. In bulk it should be significantly less expensive than older solid-state cell designs. It can be engineered into flexible sheets and is mechanically robust, requiring no protection from minor events like hail or tree strikes. Although its conversion efficiency is less than the best thin-film cells, its price-performance ratio (kWh/m^2/annum/dollar) should be high enough to allow them to compete with fossil fuel electrical generation (grid parity). Commercial applications, which were held up due to chemical stability problems, are now forecast in the European Union Photovoltaic Roadmap to be a potentially significant contributor to renewable electricity generation by 2020.

4.5.8 Hybrid photovoltaic cells

It's a combine advantage of both organic and inorganic semiconductors. Hybrid photovoltaics have organic materials that consist of conjugated polymers that absorb light as the donor and transport holes. Inorganic materials in hybrid cell are used as the acceptor and electron transporter in the structure. The hybrid photovoltaic devices have a significant potential for not only low-cost by roll-to-roll processing but also scalable solar power conversion.

4.6 Efficiency

In general, the power delivered from a power source is P = IV, i.e. the product of voltage and current. If we instead use the current density J, we get the power density:

The fill factor, FF, is another quantity which is used to characterize a solar cell. It is defined as

$$FF = \frac{J_m V_m}{J_{sc} V_{oc}} \quad \text{.. (4.14)}$$

It gives a measure of how much of the open circuit voltage and short circuit current is "utilized" at maximum power. Using FF we can express the efficiency as

$$\eta = \frac{J_{sc} V_{oc} FF}{P_s} \quad \text{...................................... (4.15)}$$

The four quantities J_{sc}, V_{oc}, FF and ?U are frequently used to characterize the performance of a solar cell. They are often measured under standard lighting conditions, which implies Air Mass 1.5 spectrum, light flux of $1000 W/m^2$ and temperature of 25°C.

4.6.1 Efficiency Progress

Photovoltaic, though old in concept is still a relatively new technology. There is still much room for improvement. The chart shown in Figure 4.11 depicts the improvement of solar panels over 40 years.

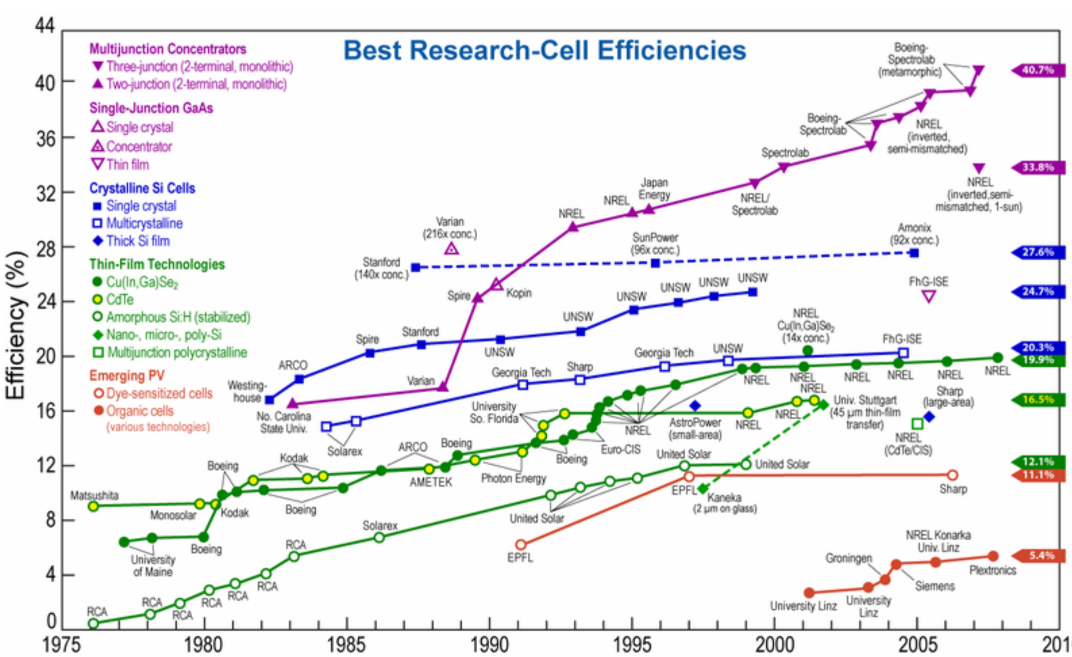


Figure 4.11: Efficiency progress over 40 years.

In this graph there are many types of solar cell such as, multyjunction solar cell, single junction solar cell, crystalline Si cells, thin-film solar cell and emerging solar cell. Here we can see when amorphous Si cell starts at 1975 that time its efficiency was nearly about zero. Day by day the technology is improved and after 24 years at 1999 the efficiency is improved at 12.1%. On the other hand when the multyjunction solar cell starts at 1983 that time its efficiency was 17% and now its efficiency is improved at 40.7%. But for some demerits this cell is not highly used.

We can use the information depicted in Figure 4.11 in order to project the photovoltaic efficiencies in the future. Figure 4.13 illustrates a linear extrapolation of the efficiencies data shown in Figure 4.12.

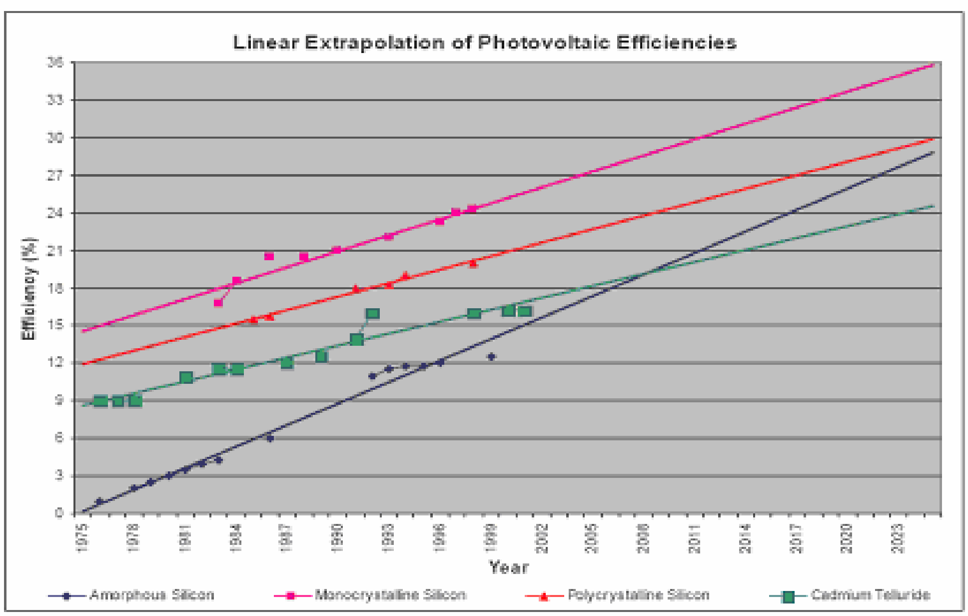


Figure 4.12: Linear extrapolation of efficiency data.

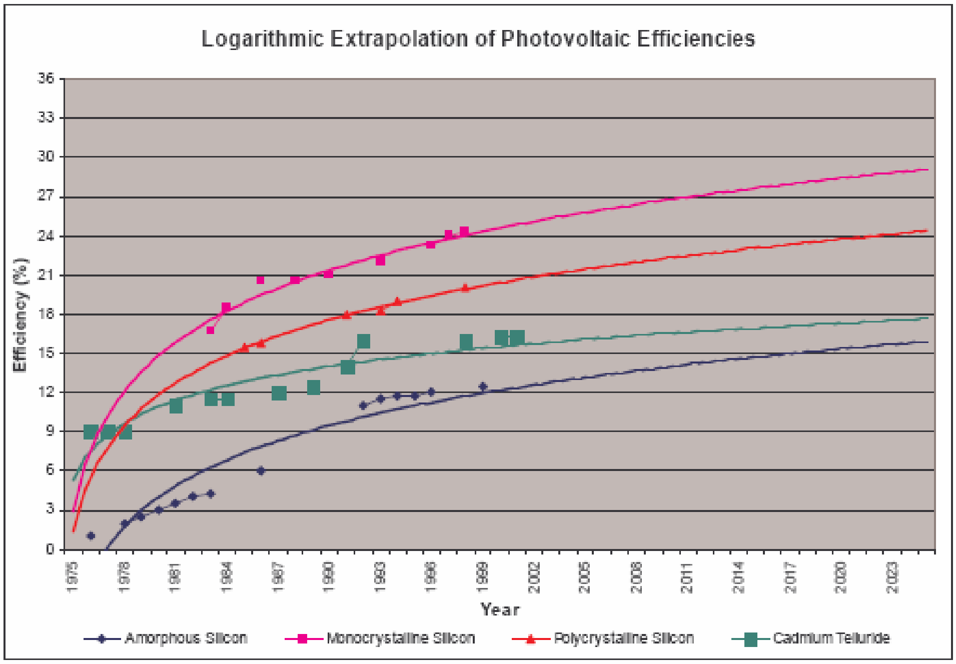


Figure 4.13: Logarithmic extrapolation of efficiency data.

4.7 Equivalent circuit of a solar cell

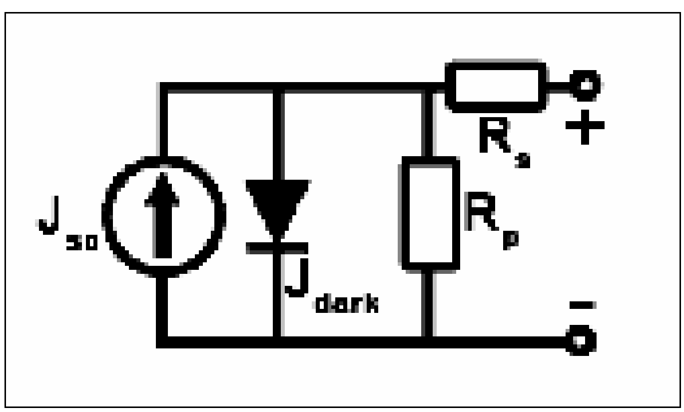


Figure 4.14: Simple equivalent circuit for a solar cell

The solar cell can be seen as a current generator which generates the current (density) J_{sc}. The dark current flows in the opposite direction and is caused by a potential between the + and - terminals. In addition there would have two resistances; one in series (R_s) and one in parallel (R_p). The series resistance is caused by the fact that a solar cell is not a perfect conductor. The parallel resistance is caused by leakage of current from one terminal to the other due to poor insulation, for example on the edges of the cell. In an ideal solar cell, you would have $R_s = 0$ and $R_p = 80$

When these so called parasitic resistances are included, the current expression (4.10) becomes

$$I = I \quad e^{q(V+JAR_s)/kT} \quad 1) \quad V + JAR_s$$

A diode is used to stop this reverse current flow. Diodes are electrical devices which only allow current to flow in one direction (Figure -4.16). A blocking diode is shown in the array in (Figure-4.17).

Diodes with the least amount of voltage drop are called schottky diodes, typically dropping .3 volts instead of .7 volts as in silicon diodes.

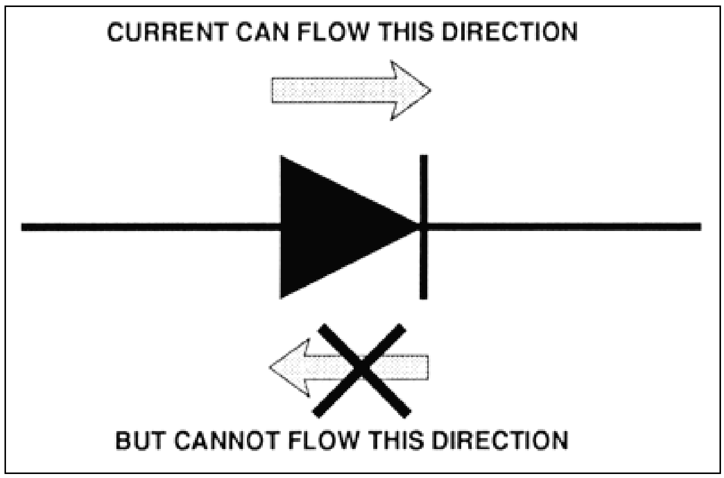


Figure 4.16: Basic Operation of a Diode

Because diodes create a voltage drop, some systems use a controller which opens the circuit instead of using a blocking diode.

If the same three modules are connected in series, the output voltage will be 45 volts, and the current will be 3 amps. If one module in a series string fails, it provides so much resistance that other modules in the string may not be able to operate either. A bypass path around the disabled module will eliminate this problem. The bypass diode allows the current from the other modules to flow through in the "right" direction.

Many modules are supplied with a bypass diode right at their electrical terminals. Larger modules may consist of three groups of cells, each with its own bypass diode. Built in bypass diodes are usually adequate unless the series string produces 48 volts or higher or serious shading occurs regularly. Combinations of series and parallel connections are also used in arrays. If parallel groups of modules are connected in a series string, large bypass diodes are usually required.

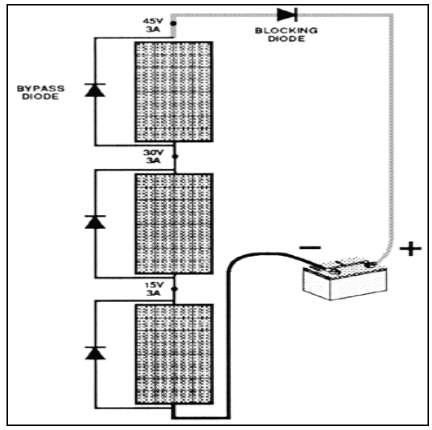


Figure 4.17: Three Modules Connected in Series with a Blocking Diode and Bypass Diodes

Isolation diodes are used to prevent the power from the rest of an array from flowing through a damaged series string of modules. They operate like a blocking diode. They are normally required when the array produces 48 volts or more. If isolation diodes are used on every series string, a blocking diode is normally not required.

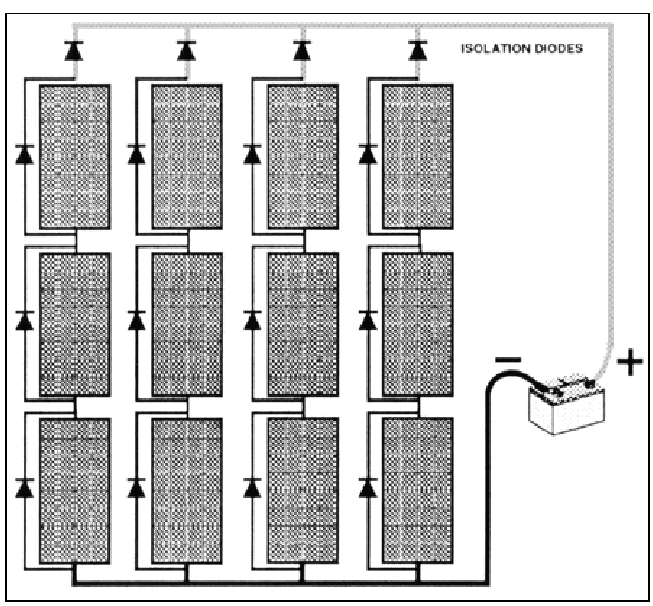


Figure 4.18: Twelve Modules in a Parallel-Series Array with Bypass Diodes and Isolation Diodes

4.8.1 Flat-plate stationary arrays

Stationary arrays are the most common. Some allow adjustments in their tilt angle from the horizontal. These changes can be made any number of times throughout the year, although they are normally changed only twice a year. The modules in the array do not move throughout the day.

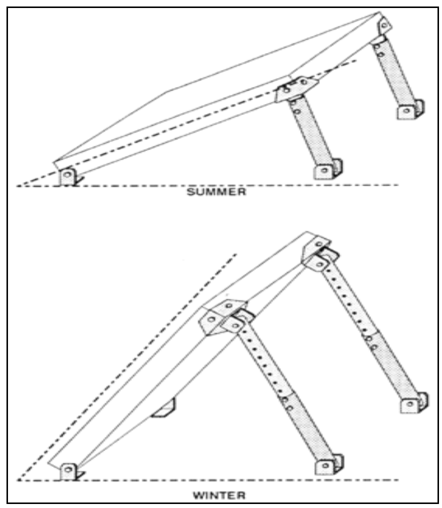


Figure 4.19: Adjustable Array Tilted for Summer and Winter Solar Angles

Although a stationary array does not capture as much energy as a tracking array that follows the sun across the sky, and more modules may be required, there are no moving parts to fail. This reliability is why a stationary array is often used for remote or dangerous locations. This Section contains information on determining the correct tilt angle and orientation for different photovoltaic applications.

4.8.2 Portable arrays

A portable array may be as small as a one square foot module easily carried by one person to recharge batteries for communications or flashlights. They can be mounted on vehicles to maintain the engine battery during long periods of inactivity. Larger ones can be installed on trailers or truck beds to provide a portable power supply for field operations (Figures-4.20and 4.21)

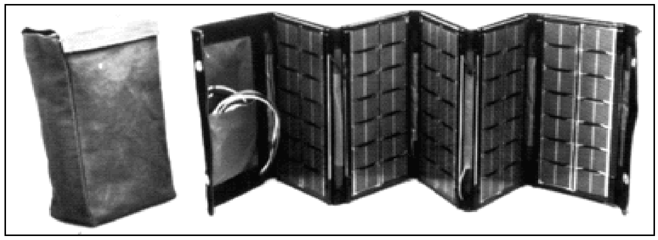


Figure-4.20: Personal Photovoltaic Array

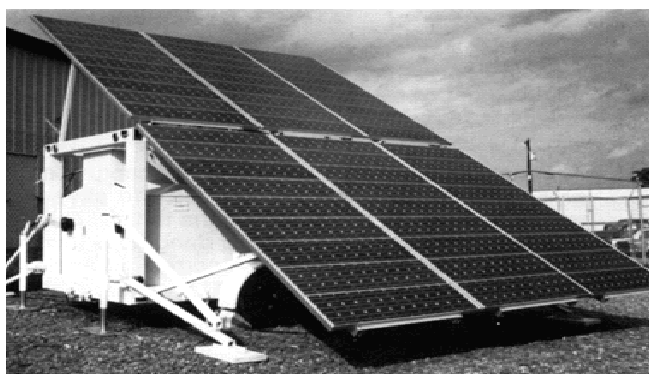


Figure-4.21: Portable Power Supply

4.8.3 Tracking arrays

Arrays that track, or follow the sun across the sky, can follow the sun in one axis or in two. Tracking arrays perform best in areas with very clear climates. This is because following the sun yields significantly greater amounts of energy when the sun's energy is predominantly direct. Direct radiation comes straight from the sun, rather than the entire sky. Normally, one axis trackers follow the sun from the east to the west throughout the day. The angle between the modules and the ground does not change. The modules face in the "compass" direction of the sun, but may not point exactly up at the sun at all times. Two axis trackers change both their east-west direction and the angle from the ground during the day. The modules face straight at the sun all through the day. Two axis trackers are considerably more complicated than one axis types.

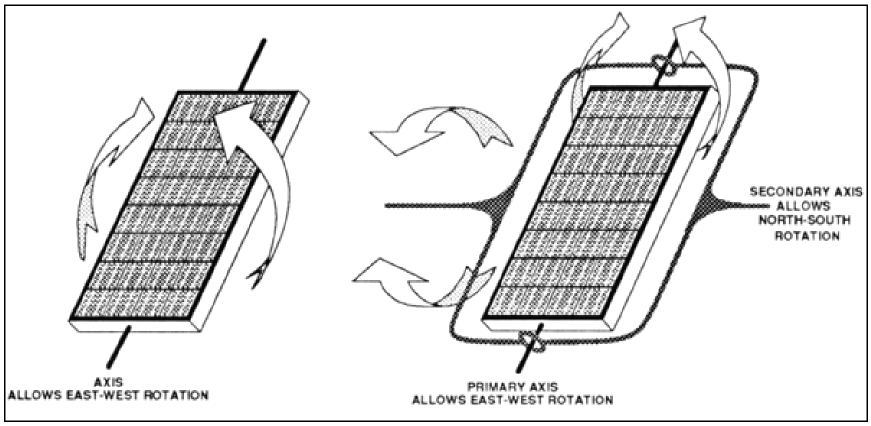


Figure 4.22: One Axis and Two Axis Tracking Arrays

Three basic tracking methods are used. The first uses simple motor, gear, and chain systems to move the array. The system is designed to mechanically point the modules in the direction the sun should be. No sensors or devices actually confirm that the modules are facing the right way.

The second method uses photovoltaic cells as sensors to orient the larger modules in the array. This can be done by placing a cell on each side of a small divider, and mounting the package so it is facing the same way as the modules (Figure 4.23).

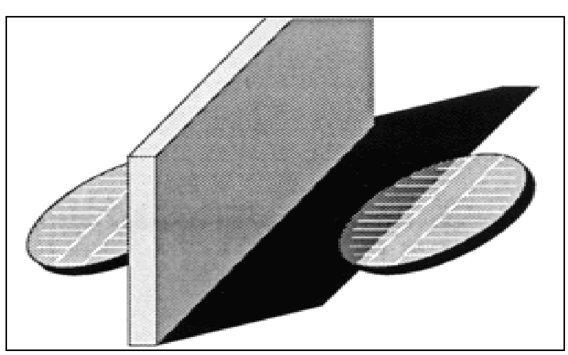


Figure 4.23: Photovoltaic Cells Used as Solar Orientation Sensor

An electronic device constantly compares the small current flow from both cells. If one is shaded, the device triggers a motor to move the array until both cells are exposed to equal amounts of sunlight.

At night or during cloudy weather, the output of both sensor cells is equally low, so no adjustments are made. When the sun comes back up in the morning, the array will move back to the east to follow the sun again.

Although both methods of tracking with motors are quite accurate, there is “parasitic” power consumption. The motors take up some of the energy the photovoltaic system produces. A method which has no parasitic consumption uses two small photovoltaic modules to power a reversible gear motor directly. If both modules are in equal sunlight, as shown in Figure 4.24 current flows through the modules and none flows through the motor.

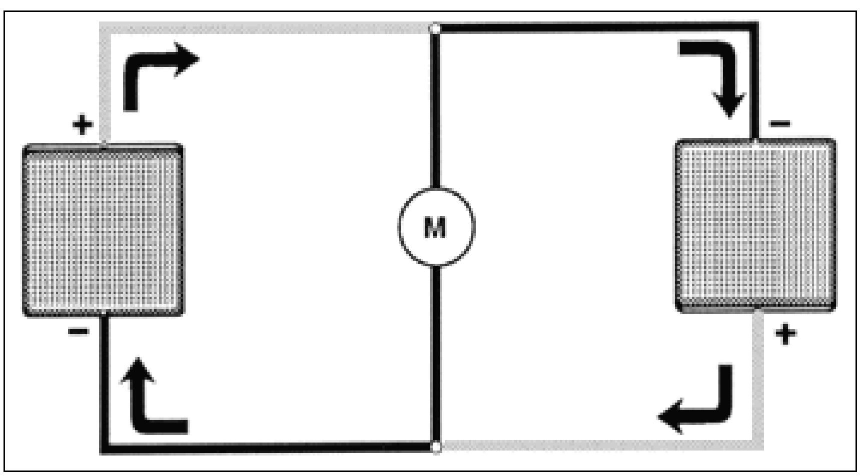


Figure-4.24: Current Flow with Both Modules in Equal Sunlight

If the right module is shaded, it acts as a resistor (Figure 4.25). Now the current will flow through the motor, turning it in one direction.

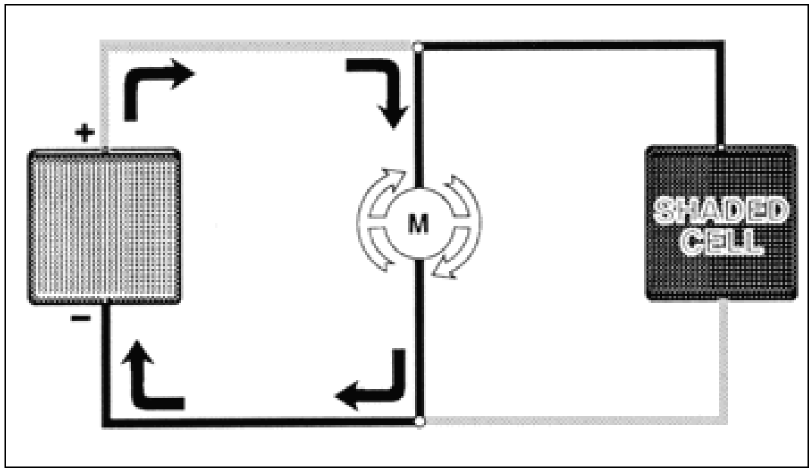


Figure 4.25: Current Flow with One Module Shaded

If the other module, shown in Figure 4.26 on the left, is shaded, the current from the right module flows in the opposite direction. The motor will turn in the opposite direction as well.

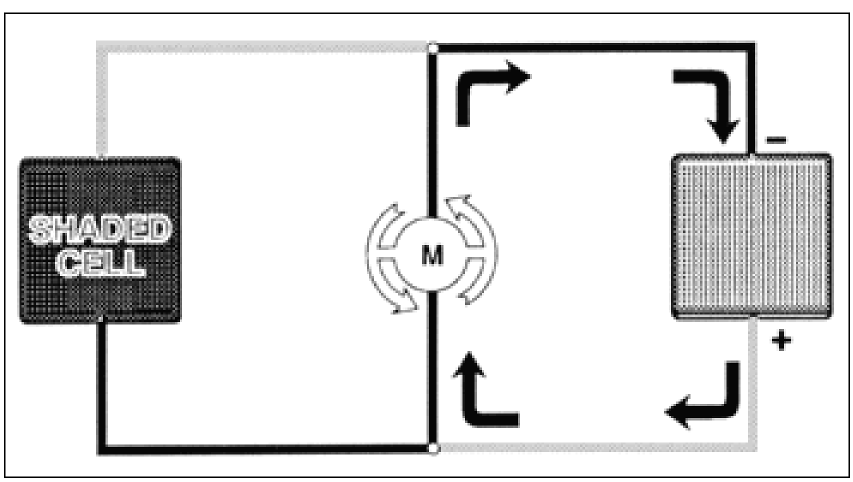


Figure 4.26 Current Flow with the Other Module Shaded

The motor must be able to turn in both directions. A third tracking method uses the expansion and contraction of fluids to move the array. Generally, a container is filled with a fluid that vaporizes and expands considerably whenever it is in the sun. It condenses and contracts similarly when in the shade. These "passive" tracking methods have proven to be reliable and durable, even in high wind situations.

One system, the 9'SUN SEEKER" TM from Robbins Engineering, uses the pressure of the expansion and contraction to operate a hydraulic cylinder. Flexible piping from two containers filled with Freon goes to opposite sides of a piston in the cylinder.

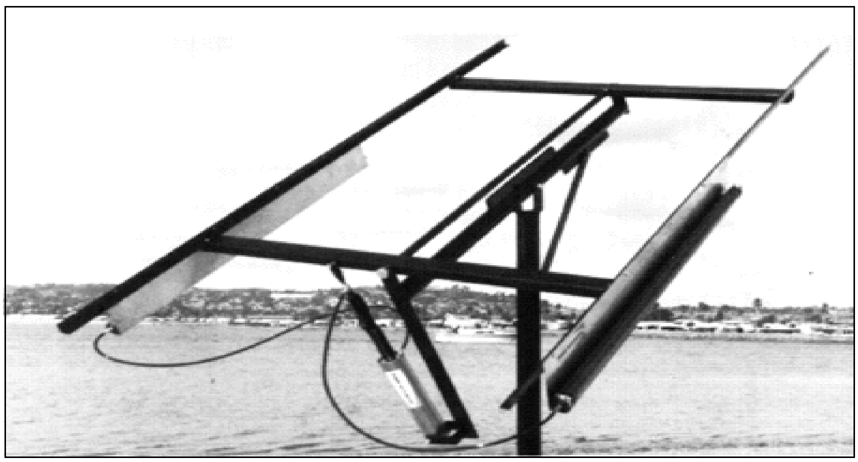


Figure 4.27: Sun Seeker System without Modules.

If the array is facing the sun, the pressure in both containers stays the same, and the piston will not move in the cylinder. However, when the sun moves the shading on the containers changes the placing of them under different pressures.

The pressure difference, brought to the cylinder by the piping, will move the piston. The shaft from the piston will move the array. When the array is pointed back to the sun, the pressure stops increasing the cylinder and the piston and rod are stop moving.

Another way to move the array with an expansive fluid is to use the change in fluid weight when it vaporizes. The Solar Track Rack TM by Zomeworks uses this method.

The fluid-filled containers are integrated into the sides of the array mounting structure. They are connected together flexible piping, which is protected in the mounting structure. As long as the array is facing directly at the sun, the shades cover each container equally.

When the array is no longer facing directly at the sun, one container is exposed to more heat from the sun. This causes the fluid in that container to boil out of that container into the other one. Now the shaded container has more fluid in it and is heavier. The array will drop down like a "teeter-totter" in the direction of the shaded container until the shading equalizes on the two containers again.

Since this method is more sensitive, wind can move the array. A shock absorber is included in the system to absorb such rapidly applied forces.

4.9 Reflectors

Reflectors are sometimes used to increase the amount of solar energy striking the modules. Since reflectors cost less than photovoltaic modules, this method may be used for some applications. There are several problems with reflectors, however. Not all photovoltaic modules are designed for the higher temperatures reflectors cause. The performance and physical structure of many modules will suffer if reflectors are used with them. Remember that higher module temperatures mean lower output voltages.

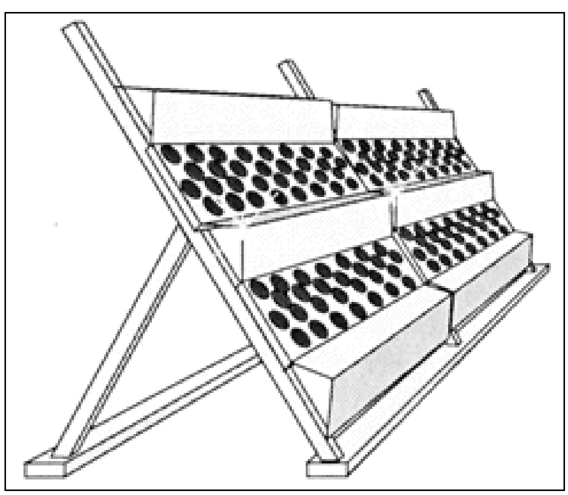


Figure 4.28: Reflectors on a Fixed Photovoltaic Array

Another problem is that reflectors work mostly with sunlight coming directly from the sun. Since a great deal of the sun's energy in cloudy climates comes to the earth's surface from all parts of the sky, reflectors are most effective in clear climates.

In all but the clearest of climates, the amount of direct solar energy is rarely high enough to justify the use of reflectors all year.

By increasing the overall surface area of the array, reflectors also increase the array's wind loading characteristics.

Finally, some type of tracking system may be required. This increases the system cost, may add a parasitic power loss, and can reduce the system reliability. Poorly designed or improperly installed reflectors have been known to shade modules.

4.10 Mounting

There are four types of mounting. They are;

- Bracket mounting
- Pole mounting
- Ground mounting
- Structure mounting

4.10.1 Bracket mounting

Small arrays of one or two modules can use simple brackets to secure the modules individually to a secure surface. The surface may be a roof, wall, post, pole, or vehicle. Brackets can include some method to adjust the tilt angle of the module. The brackets are usually aluminum. If steel is used, it should be painted or treated to prevent corrosion. Galvanized steel is normally avoided, because the continuous grounding used on arrays aggravates the galvanic corrosion that occurs between galvanized steel and almost all other metals. Fastener hardware should be stainless steel or cadmium plated to prevent corrosion. Identical metals should be used for components and fasteners whenever possible.

4.10.2 Pole mounting

Typically, up to four modules can be connected together and mounted on a pole. Typically, 2 1/2" nominal steel pipe (O.D. of 3") is used.

Black iron or steel pipe can be used, if painted. Galvanized pipe, rarely available in this size, can be used if compatible fasteners are used. Larger arrays can be pole mounted, if hardware sizes are appropriately increased.

The same types of materials used for bracket mounting should be used for pole mounting.

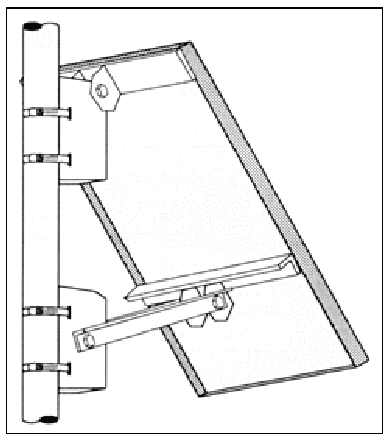


Figure 4.29: Pole Mount of Photovoltaic Array

4.10.3 Ground mounting

For arrays of eight or more modules, ground mounting is usually the most appropriate technique. The greatest concern is often the uplifting force of wind on the array. This is why most ground mounted arrays are on some kind of sturdy base, usually concrete.

Concrete bases are either piers, a slab with thicker edges, or footings at the front and rear of the array. All three usually include a steel reinforcement bar.

In some remote sites it may be more desirable to use concrete block instead of poured concrete. The best way to do this is to use two-web bond-beam block, reinforce it with steel, and fill the space between the webs with concrete or mortar. Pressure-treated wood of adequate size is sometimes used for ground mounting. This can work well in fairly dry climates, but only if the beams are securely anchored to the ground, and regular inspection and maintenance is provided.

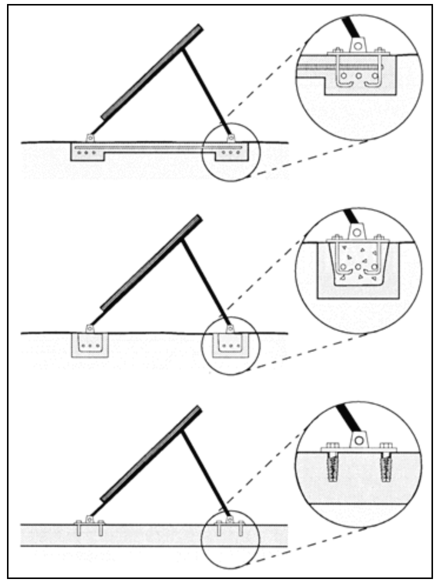


Figure 4.30: Concrete Bases

The array's mounting hardware can be bolted to an existing slab. With extensive shimming, some mountaintop arrays are bolted to exposed rock. In either case, adequately sized expansion-type anchor bolts are used. The heads of the bolts should be covered with some type of weatherproof sealant. Silicone sealant is the best choice.

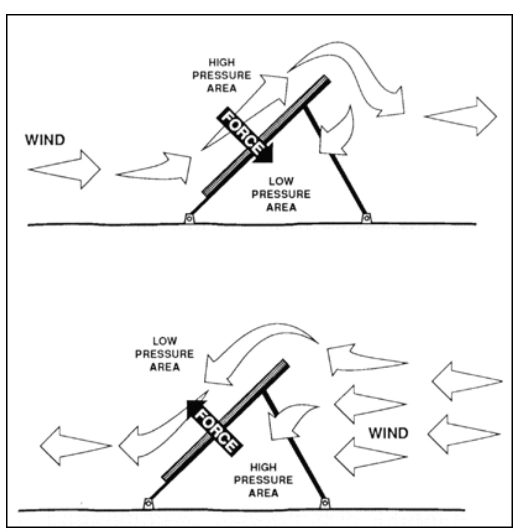


Figure 4.31: Forces on a Photovoltaic Array

4.10.4 Structure mounting

Photovoltaic modules mounted on buildings or other structures are subjected to downward force when the wind hits their front surfaces. When the wind strikes the back of the modules, upward force is generated.

For this reason, the attachment to the building of modules with exposed backs is designed to resist both directions of force.

Another consideration when modules are mounted to a structure is the trapped heat between the module and the structure. Remember that module voltage drops with increased temperature.

Generally, photovoltaic arrays are mounted on structures in such a way that air can maturely circulate under the modules. This keeps the modules operating at the lowest possible temperature and highest possible output voltage. Access to the back of the modules also simplifies service operations.

4.11 Modulation Tilt and its Orientation

Permanently mounted modules should be tilted up from the horizontal. The correct tilt angle varies with the times of year the system is used, and the latitude of the site. The tilt angle is measured from the horizontal, not from a pitched roof or hillside. The tilt should be within 10 degrees of the listed angle. For example, a system used throughout the year at latitude of 350 can have a tilt angle of 250 to 450 without a noticeable decrease in annual performance

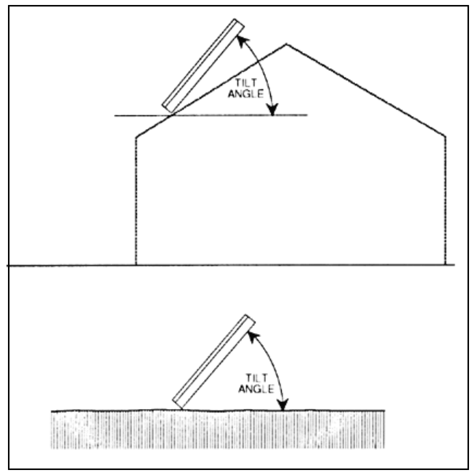


Figure 4.32: Module Tilt Measured form the Horizontal on Level and Tilted Surfaces

For proper operation, the modules must be oriented as close as possible toward the equator. In the Northern Hemisphere, this direction is true south. In most areas, this varies from the magnetic south given by a compass. A simple correction must be made. First, find the magnetic variation from an isogonic's map. This is given in degrees east or west from magnetic south.

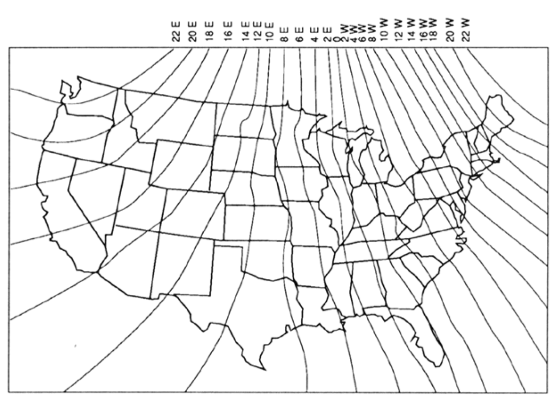


Figure 4.33: Isogonic's Map of the United States

For example, a site in Montana has a magnetic variation of 200 east. This means that tern south is 200 east of magnetic south. On a compass oriented so the north needle is at 3600, true south is in the direction indicated by 1600.

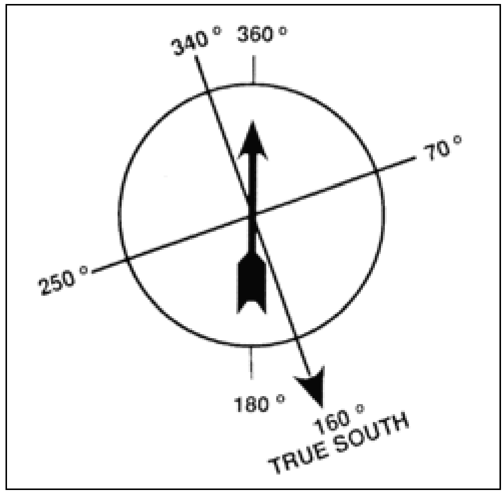


Figure 4.34: Directions on a Compass at 20° East Magnetic Variation

The modules should be installed within 200 of true south. In areas with morning fog, the array can be oriented up to 200 toward the west to compensate. Conversely, arrays in areas with a high incidence of afternoon storms can be oriented toward the east. If he array is located in the Southern Hemisphere, the array must face true north. Small portable arrays are usually just pointed at the sun, and moved every hour or so to follow the sun across the sky.

Chapter 4

Solar Concentrators

5.1 Introduction

Solar concentrator is a device which concentrates the solar energy incident over a large surface onto a smaller surface. The concentration is achieved by the use of suitable reflecting or refracting elements, which results in an increased flux density on the absorber surface as compared to that existing on the concentrator aperture. In order to get a maximum concentration, an arrangement for tracking the sun's virtual motion is required.

The knowledge of concentrator dates back even to the time of Archimedes, whose book "On Burning Mirrors" is an evidence of this fact. Many uses of concentrators were reported in the eighteenth and nineteenth centuries, particularly in heat engines and steam production. The advantages concentrators are as follows:

i. It increases the intensity by concentrating the energy available over a large surface onto a smaller surface (absorber).
ii. Due to the concentration on a smaller area, the heat-loss area is reduced. Further, the thermal mass is much smaller than that of a flat plate collector and hence transient effects are small.
iii. The delivery temperatures being high, a thermodynamic match between the temperature level and the task occurs.
iv. It helps in reducing the cost by replacing an expensive large receiver by a less expensive reflecting or refracting area.

However, concentrator is an optical system and hence the optical loss terms become significant. Further, it operates only on the beam component of solar radiation, resulting in the loss of diffuse component.

5.2 Classification

Solar concentrators may be classified as

1. Tracking type and
2. Non-tracking type.

Tracking may be continuous or intermittent and may be one-axis or two-axes. As the sun may be followed by moving either the focusing part or the receiver or both; concentrators can be classified accordingly. Further, the system may have distributed receiver or central receiver.

The concentrators may also be classified on the basis of optical components. They may be

(i) Reflecting or refracting type,

(ii) Imaging or non-imaging type, and

(iii) Line focusing or point focusing type.

The reflecting or refracting surface may be one piece or a composite surface; it may be a single stage or two stage type system and may be symmetric or asymmetric. In practice, however, hybrid and multistage systems, incorporating various levels of the features, occur frequently.

5.3 Types of Concentrators

There are a number of methods by which the flux of radiation on receivers can be increased. Some of them have been discussed in this section.

5.3.1. Fixed mirror solar concentrator (FMSC)

This concentrator consists of a fixed mirror with a tracking receiver system (Fig. 5.1). The fixed mirror is composed of long, narrow flat strips of mirror arranged on a reference circular cylinder of a chosen radius R.

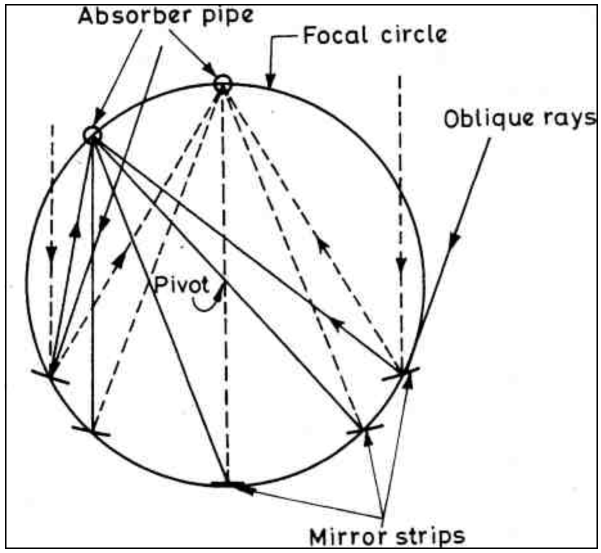


Figure 5.1: Fixed mirror solar concentrator

The width of mirror strip is compatible with the diameter of the absorber pipe to be used. The angle of each element is so chosen that the focal distance of the array is twice the radius of the reference cylinder. The array produces a narrow focal line that lies along the same circular path with the diurnal motion of the sun. The focal line can be easily tracked by the movable receiver pipe that is made to rotate about the centre of curvature of the reflector module. Thus the delicate part (the mirrors) of the system can be rigidly fixed. The image width at the absorber is ideally the same as the projected width of the mirror element. Thus, the concentration ratio is approximately the same as the number of mirror elements, ignoring the solar beam spread. As the aperture is fixed and concave in shape, the mirror strips result in shading with very high or very low sun altitude angles. Also, due to the strips, edge losses occur during reflection. However, mirrors can be suitably designed to have less than 10% of the total energy lost over a year’s time. Some (Fixed Mirror Solar Concentrator) models have shown overall efficiencies in the range of 40-50%.

5.3.2 Cylindrical parabolic concentrator

A cylindrical parabolic trough is a conventional optical imaging device used as a solar concentrator. It consists of a cylindrical parabolic reflector and a metal tube receiver at its focal plane (Fig. 5.2). The receiver is blackened at the outside surface and is covered by concentrator and rotated about one axis to track the sun's diurnal motion. The heat transfer fluid flows through the absorber tube, gets heated and thus carries heat. Such concentrators have been in use for many years. The aperture diameter, rim angle and absorber size and shape may be used to define the concentrator. The absorber tube may be made of mild steel or copper and is coated with a heat resistant black paint. Selective coatings may be used for better performance.

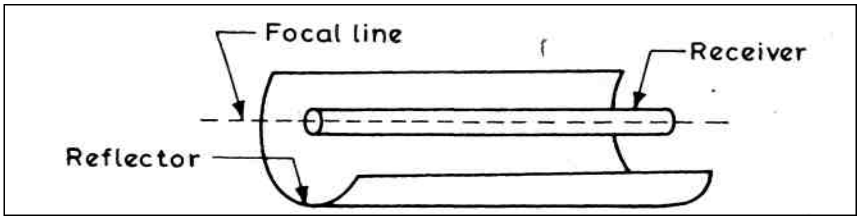


Fig-5.2 cylindrical parabolic concentrator

Depending on the temperature requirement different heat transfer liquids may be used. Reflectors may be of anodized aluminum sheet, aluminized Mylar or curved silvered glass. Since it is difficult to curve a very large glass, mirror strips are sometimes used in the shape of parabolic cylinder. The reflecting part is fixed on a light weight structure. The concentration ratio for a cylindrical absorber varies from 5 to 30.

The major energy losses from a concentrator-receiver assembly for normal incidence are the losses during reflection from reflecting surface and convection loss from the receiver to surroundings. Efforts are made to use high reflecting materials and to reduce convection. Twisted tapes are used in the absorber tube to cause large heat transfer from the absorber to working fluid.

A cylindrical parabolic trough may be oriented in any of the three directions: East-West, North-South or polar. The first two orientations, although simple to assemble, have higher incidence angle cosine losses. The polar configuration intercepts more solar radiation per unit area as compared to other modes and thus gives the best performance.

5.3.3 Linear Fresnel lens/reflector

A linear Fresnel lens solar concentrator is shown in Figure 5.3. It consists of linear grooves on one surface of the refracting material. The groove angles are chosen with reference to a particular wavelength of incident beam so that the lens acts as a converging one for the light which is incident normally.

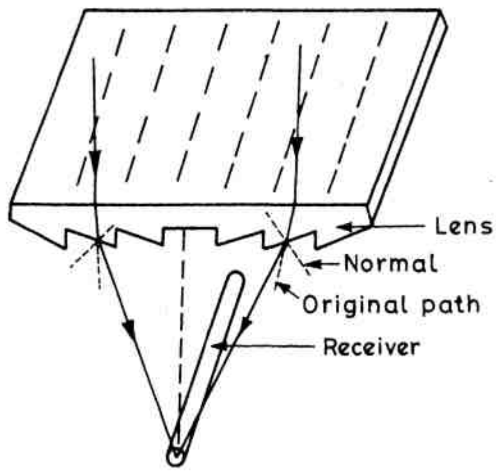


Figure 5.3 Schematic view of Fresnel lens concentrator.

Although, both glass and plastic can be used as refracting materials for fabricating Fresnel lenses, glass is seldom used because it is difficult to mould, and has large surface tension. Plastic lenses, on the other hand, are economical and the mould last for an appreciable time. Plastic Fresnel lenses with 20 grooves per mm have been molded.

The Fresnel lens may be installed with either the grooves facing the sun or the grooves facing downward. In the first case, the ineffective facts of the grooves prevent a part of the input light from being transmitted to the focus (According to Snell's law the refracted light is deviated away from the normal on moving from a denser to a rarer medium). Also dust is accumulated in these grooves resulting in a reduced performance. In the second case, the concentrator has a high surface reflection loss and large off-axis aberrations. While reflection loss causes low efficiency, the aberrations result in a low concentration ratio. The fact that the beam is not incident normally also affects. The focal length of the lens varies rapidly with the change of angle of incidence. So, for a better performance, the optical system needs to track the path of the sun.

Fresnel reflectors can also be used as concentrating devices. Figure 5.4 shows such a configuration, which is made up of smaller flat or curved components. It consists of a number of mirror elements mounted suitably, so that all incident parallel rays of light, after reflection, are focused at a common point. Ideally, mirror elements must be parabolic in shape, but to simplify the manufacturing and assembling problems, flat mirrors are generally used.

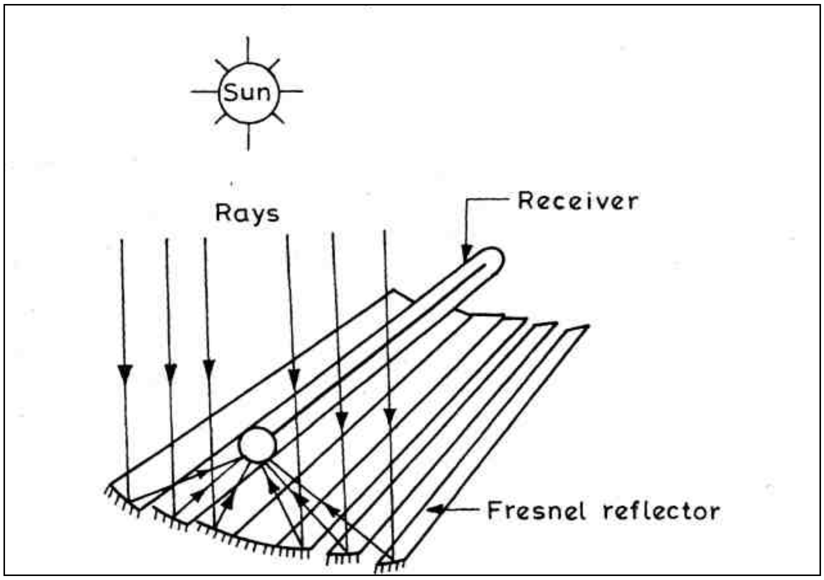


Figure 5.4 Fresnel reflectors.

5.4 Two-axes tracking concentrators

In order to achieve a high concentration for high temperature solar processes, concentrators with double curvatures are used. These require two axes tracking of the sun. Some of these have been described below:

5.4.1 Paraboloidal dish concentrator

A paraboloid is produced when a parabola rotates about its optic axis (Fig. 5.5). When it is used to concentrate solar radiation, a high concentration ratio is achieved.

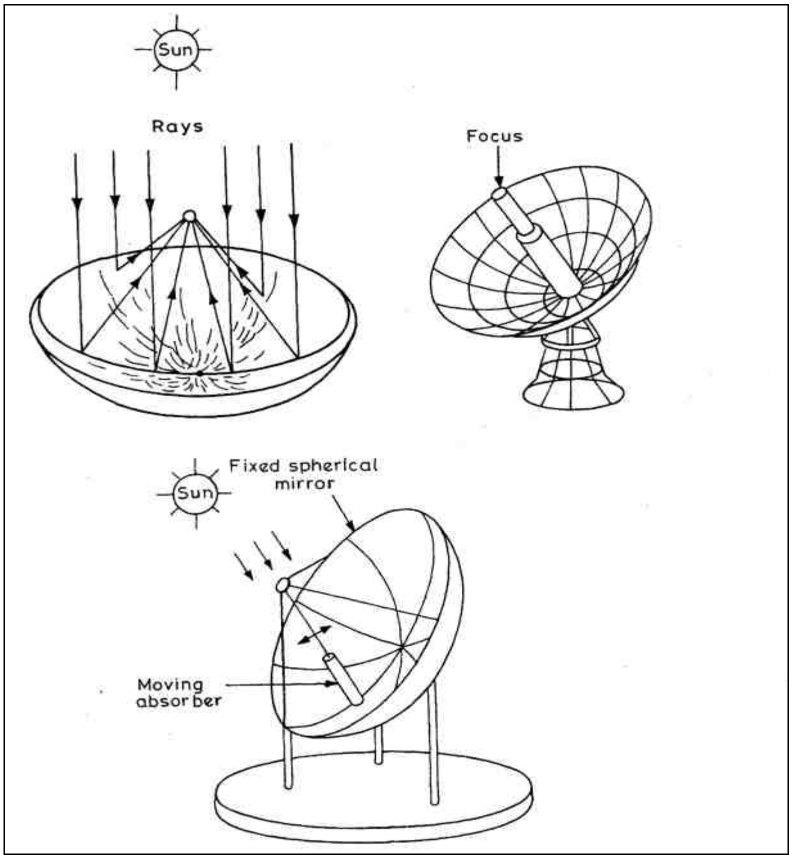


Figure 5.5 Schematic view of a paraboloid concentrator.

Due to the compound curvature with perfect optics and a point source of light, theoretically, lights focused at a point in a paraboloid. However, an image is produced due to the finite angular subtense of the sun. Also, the surface may not be strictly parabolic so that the image will be enlarged due to misdirection of the light rays by misaligned surface elements. A degraded image is obtained if the object is off-axis. The rays from the central region of the paraboloid travel a shorter distance in arriving at the focus, whereas, the rays from the edges travel a larger distance, resulting in a spread of the image. Thus a three dimensional image of the sun in the shape of an ellipsoid is formed (Fig. 5.6).

The thermal losses from a paraboloid are primarily radiative and can be reduced by decreasing the absorber aperture area. This, however, results in a smaller intercept factor.

The optimum intercept factor is about 0.95-0.98. The larger the surface errors, the larger must be the absorber size to achieve the optimum beam intercept.

High collection efficiency and high quality thermal energy are the features of paraboloid or parabolic dish type of concentrator. The delivery temperatures being very high, these devices can be used as sources for a variety of purposes.

Figure 5.6 Illustration of formation of ellipsoid image in paraboloid

5.4.2 Central tower receiver

The system consists of a central stationary receiver to which the solar radiation is reflected by heliostats (Fig. 5.7). A heliostat is composed of a large array of mirrors fixed to a supporting frame. This frame can be used to track the sun, as desired.

The heliostats are installed in the open space and together they act like a dilute paraboloid. They focus solar radiation on a central receiver, which is stationary. Concentration ratios are as high as 3000 can be achieved. The absorbed energy can be extracted from the receiver and delivered at a temperature and pressure suitable for driving turbines for power generation.

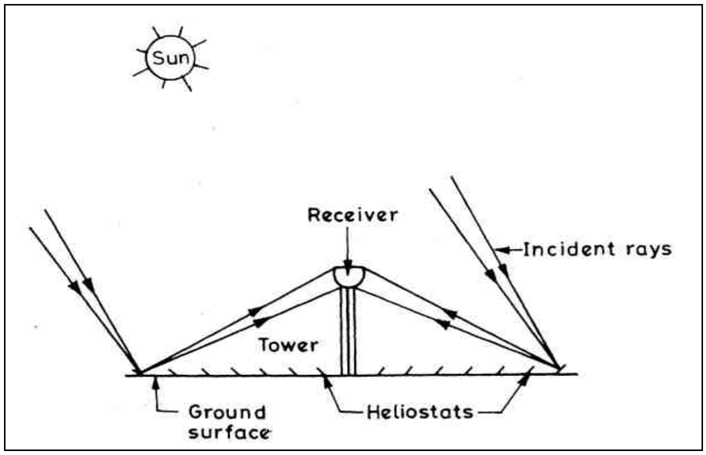


Figure 5.7: Schematic view of central receiver-heliostat system.

The advantage of this system is that it eliminates the treed for carrying the working fluid over large distances. As a result, the heat losses are reduced significantly thus eliminating the need for insulation there are, however, many other problems associated with this system. A majority of them are due to heliostats and receiver. A large number of heliostats are required to focus solar radiation requiring large free space. The heliostats may be provided with proper tracking arrangement and may be arranged such that self shading is avoided; at the same time achieving reasonable concentration. In addition to the cost, the cleaning of mirrors to remove dust and dirt poses another problem. Further, the heliostat arrangement must be strong enough to withstand extreme weather conditions. The receiver must be able to effectively intercept the focused radiation, absorb it as heat and transfer this energy to the working fluid with minimum heat loss. Several designs have been proposed for the receiver. Heat transfer fluids like steam, hi-tech and liquid metals are suggested for use. Some problems arise due to reflection and transmission losses and thermal stress in the receiver.

5.4.3 Circular Fresnel lens

Lenses are usually not used in solar energy applications due to cost and weight. However, these are used where high temperature is required, as in solar furnace. Figure 8.10 shows the principle of this lens optically, the lens is equivalent to a thin-lens approximation. It is divided into a number of zones which are spaced at a few tenths of a millimeter; the space can also be few centimeters. Within each aperture zone, the tilt of the lens surface is so adjusted that its optical behavior resembles that of a conventional spherical lens of the same focal length. The focus of the annulus need not be curved, but is required to have the correct tilt so as to refract the light to the focus. This is because; the absorbing surface is usually much larger than the width of a Fresnel zone on the lens. Meinel (1977) has given the equation for the tilt of the facet as a function of the aperture zone and focal length.

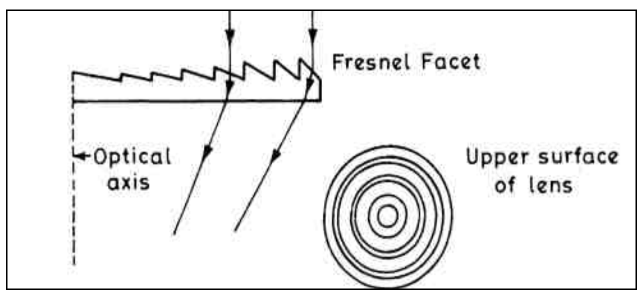


Figure 5.8: Schematic diagram of circular Fresnel lens.

The circular Fresnel lens provides very good concentration. For a precise plastic lens, the brightness concentration is as high as 2000. Hence, such concentrators are usually used with silicon and gallium arsenide solar cells for high flux. In solar cell applications, the lens has to track the sun since it is required to keep the small solar image centered on the receiver. It may be noted that the brightness concentration in this case is smaller than that in case of parabolic mirrors.

The transmitting system has an advantage over the reflecting system in that it absorbs certain wavelength of incident beam, which may result in heating of the focus.

5.4.4 Hemispherical bowl mirror

Figure 5.9 shows another type of fixed mirror and moveable receiver type concentrator, independently proposed by Steward (1973) and Meinel (1973). The major components of this concentrator are a fixed hemispherical mirror, a tracking linear absorber and a supporting structure. The hemisphere produces a highly aberrated optical image. However, because of its symmetry all rays entering into the hemisphere after reflection cross the paraxial line at some point between the focus and the mirror surface.

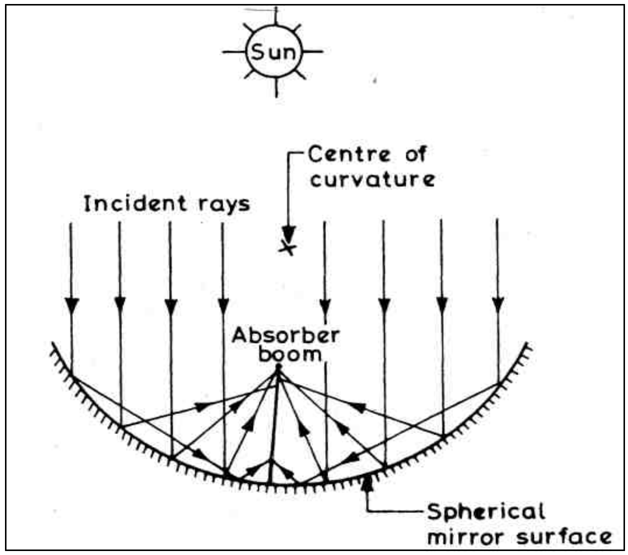


Figure 5.9: Cross-section view of hemispherical mirror concentrator.

Therefore, an absorber pivoted about the center of curvature of the hemisphere intercepts all reflected rays. The absorber is to be moved so that its axis is always aligned with solar rays passing through the center of the sphere. This requires two axes tracking. Though this motion can be set in a number of ways, the simplest one is to adopt equatorial mount in which the absorber is driven around a polar axis, during the day, at a constant angular speed of 15 degree/hour. Through a slow continuous motion or a periodic adjustment about an axis normal to polar axis, correct declination can be maintained. It may be noted that this type of concentrator gives a lesser concentration, owing to spherical aberration, than that in paraboloids.

5.5 Non-tracking Concentrators

Tracking concentrators provide high delivery temperatures but require accurate tracking device and fine surface accuracies and hence are expensive. However, for medium temperature operation, less expensive concentrators have been designed, without the tracking requirement. The description of some of these concentrators is given below:

5.5.1 Flat receiver with booster mirror

Figure 5.10 shows a flat receiver with plane reflectors at the edges to reflect additional radiation into the receiver. Mirrors are also called booster mirrors. The concentration ratio of these concentrators is relatively low, with a maximum value less than four. As the solar incidence angle increases, the mirrors become less effective. For a single collector, booster mirrors can be used on all the four sides. When the sun angle exceeds the semi angle of booster mirrors, the mirror actually starts casting shadow on the absorber. In case of an array of collectors, booster mirrors can be used only on two sides.

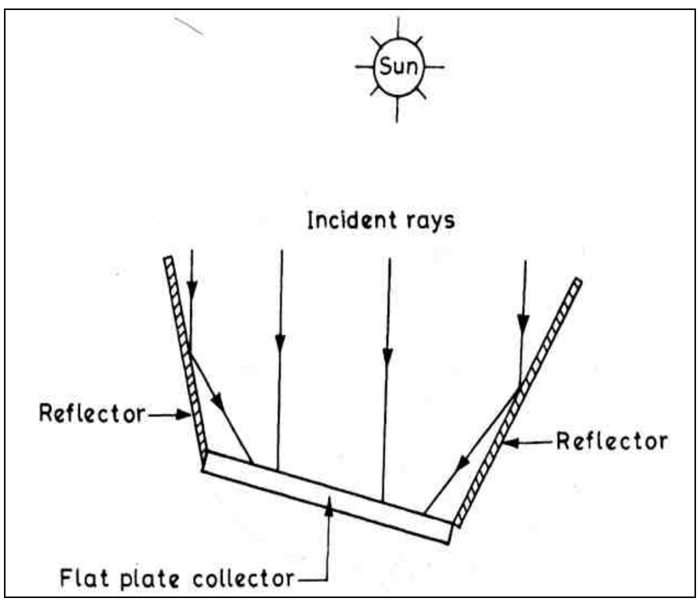


Figure 5.10: Flat plate collector with booster mirrors.

The efficiency of a boosted flat plate system can be increased if the angle of the flat mirrors can be changed several times during the year. The advantage of such a system is that it makes use of the diffuse radiation in addition to the beam radiation. The attainable temperature and collection efficiency will be higher than that of a flat plate collector of the same collection area.

5.5.2 Tabor-Zeimer circular cylinder

Figure 5.11 shows such a concentrator. It is a very simple cylindrical optical system which consists of an inflated plastic cylinder with a triangular pipe receiver. The cylinder has a clear portion on the top to permit radiation to enter and fall on its rear portion which is aluminized to act as a mirror. The incident radiation is reflected by the mirror and is focused on the absorber near the bottom of the cylinder.

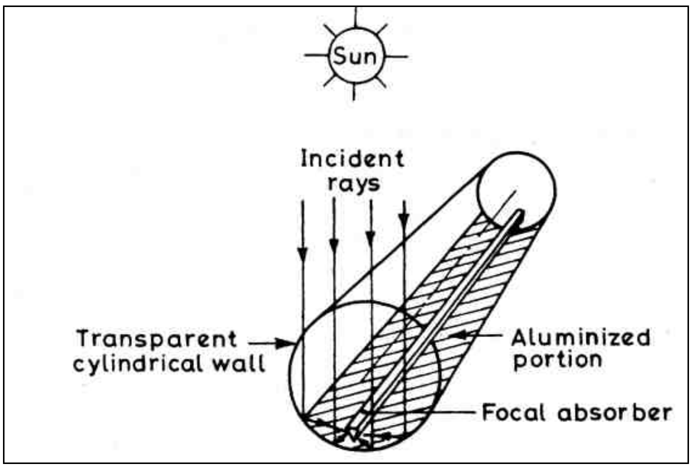


Figure 5.11: Schematic of Tabor-Zeimer cylindrical concentrator.

A concentration of about 3 can be achieved without tracking. It can be placed along East-West axis and requires only seasonal tracking. The concentrator uses, in addition to beam component, some diffuse radiation. The delivery temperatures and collection efficiencies are higher than that possible with an ordinary flat plate collector.

5.5.3 Compound parabolic concentrator

This concentrator is a non-imaging one and belongs to a family of concentrator which has highest possible concentration permissible by thermodynamic limit for a given acceptance angle. Further, it has a large acceptance angle and needs to be intermittently turned towards the sun. The first design of a compound parabolic concentrator (CPC) was found Rays incident in the central region of the aperture undergo no reflection whereas those near the edges undergo one or more reflections. The number of reflections depends on the incident angle, collector depth and concentration ratio (Rabl, 1976). To reduce cost of the unit, the CPC can be truncated in height to half, without any significant change in concentration.

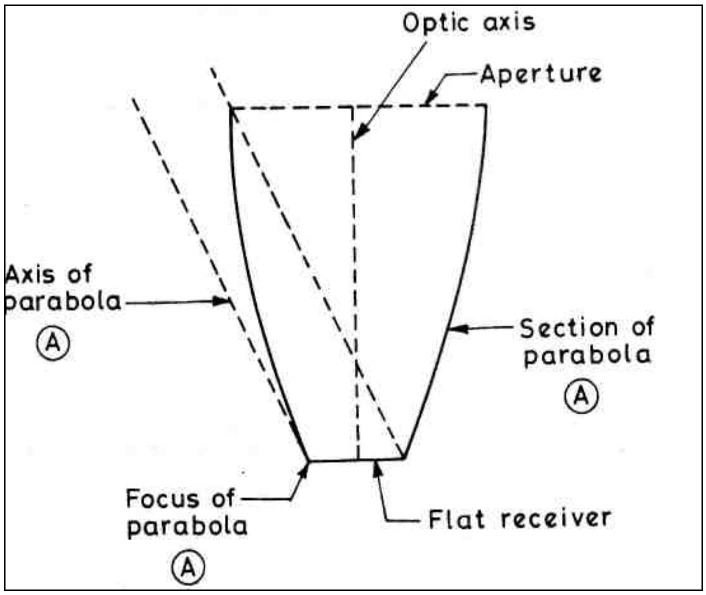


Figure 5.12: Schematic cross-section of a CPC

Extensive investigations on this concentrator have led to several modified designs of the ideal CPC. The salient modifications can be listed as follows:

i. The use of receiver shapes such as fins, circular pipes for better optical and thermal performance.

ii. Truncation of CPC height to reduce the physical size and cost.

iii. Asymmetric orientation of source and aperture to deliver seasonal varying outputs.

iv. Design of CPC as a second stage concentrator.

In view of the above modification, the reflecting surface of all resulting concentrators may not be parabolic, but these still belong to non-imaging group of concentrators.

The CPC can be used in a non-tracking mode for concentration ratios of about 6. However, for higher ratios, the reflector surface area becomes very large and hence cannot be used.

5.5.4 V-trough

Figure 5.13 shows schematically such a concentrator. It consists of highly reflecting side walls which reflect solar rays to a receiver plate placed at the base of the trough. The trough is aligned in East-West direction, so as to avoid diurnal tracking. These concentrators provide higher concentration (of the order of 3 in straight wall case) than flat plate collectors with booster mirrors, because in the latter case the acceptance angle is very large and so the concentration is low. Different combinations of depth to base-width ratios and cone angle are possible for optimum performance depending on the frequency of seasonal tilt adjustments.

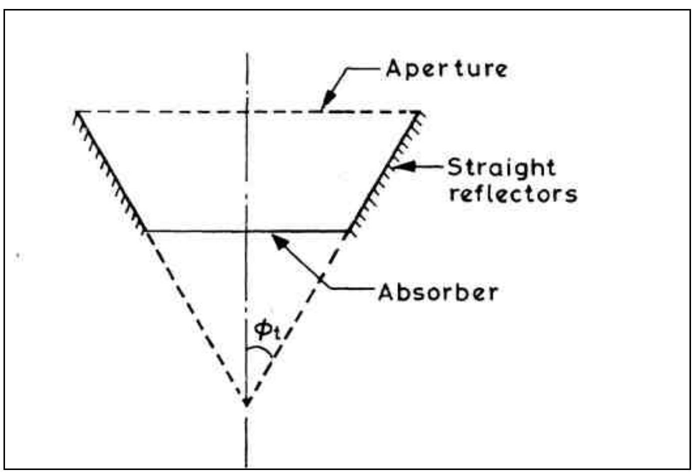


Figure 5.13: Schematic cross-section of a V-length concentrator.

The average number of reflections in a V-trough is more or less the same as that in a CPC. For low concentrations, performance of both is comparable. For high concentrations, these appear impractical. The performance of these can be improved by using more than one mirror element in each side wall at suitable angle thus resulting in polygonal troughs.

Chapter 6
Solar Insolation

6.1 Introduction

The amount of sunshine reaching the solar cells at any moment is referred as solar insolation or irradiance.

The irradiance reaching the ground varies throughout the day with the movement of the sun and the clouds. The total amount of irradiance received over a period of time is a different measurement. Over one day, it is usually called daily insolation.

Irradiance is often measured in units of watts per square meter (W/m^2) and milli watts per square centimeter (mW/cm^2).

6.2 Resources for All Solar Energy System

The basic resource for all solar energy systems is the sun. Knowledge of the quantity and quality of solar energy available at a specific location is of prime importance for the design of any solar energy system. Although the solar insolation is relatively constant outside the earth's atmosphere, local climate influences can cause wide variations in available insolation on the earth’s surface from site to site. In addition, the relative motion of the sun with respect to the earth will allow surfaces with different orientations to intercept different amounts of solar energy.

Figure 6.1 shows regions of high insolation where solar energy conversion systems will produce the maximum amount of energy from a specific collector field size. However, solar energy is available over the entire globe, and only the size of the collector field needs to be increased to provide the same amount of heat or electricity as in the shaded areas. It is the primary task of the solar energy system designer to determine the amount, quality and timing of the solar energy available at the site selected for installing a solar energy conversion system.

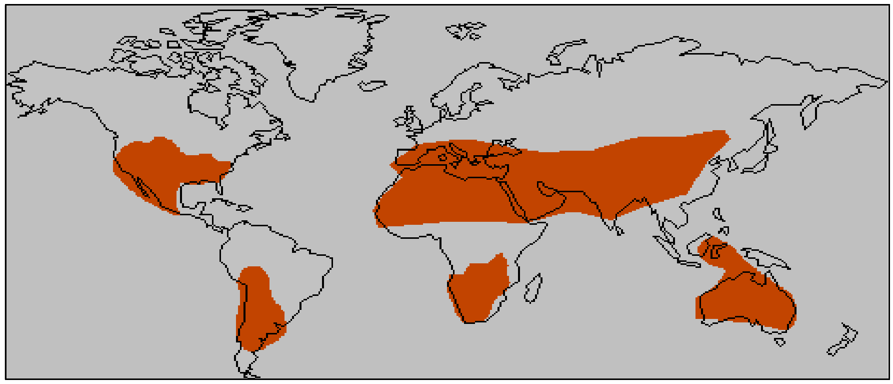


Figure 6.1: Areas of the world with high insolation.

Just outside the earth's atmosphere, the sun's energy is continuously available at the rate of 1,367 Watts on every square meter facing the sun. Due to the earth's rotation, asymmetric orbit about the sun, and the contents of its atmosphere, a large fraction of this energy does not reach the ground.

Figure 6.2 shows the variation of insolation over a full, clear day in March at Daggett, California, a meteorological measurement site close to the Kramer Junction solar power plant described previously. The outer curve, representing the greatest rate of incident energy, shows the energy coming directly from the sun (beam normal insolation) and falling on a square meter of surface area which is pointed toward the sun. The peak rate of incident solar energy occurs around 12:00 noon and is 1,030 Watts per square meter. Over the full day, 10.6 kilowatt-hours of energy has fallen on every square meter of surface area as represented by the area under this curve.

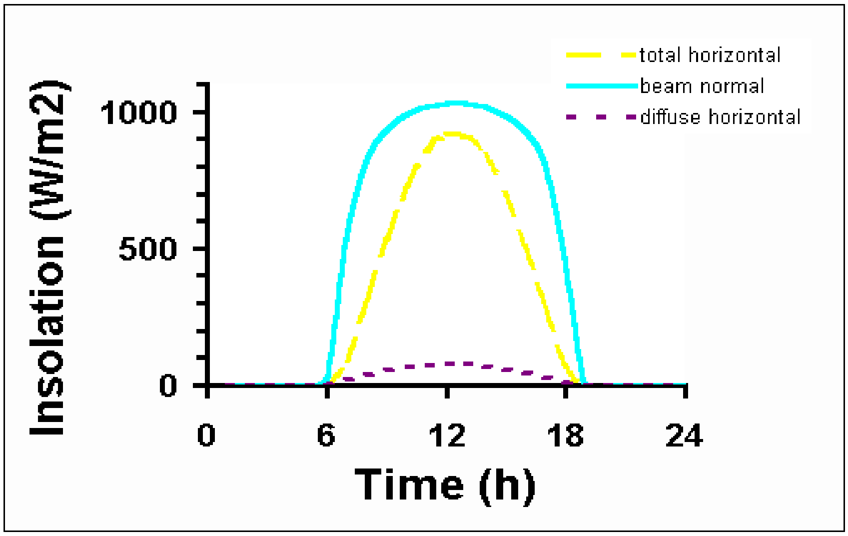
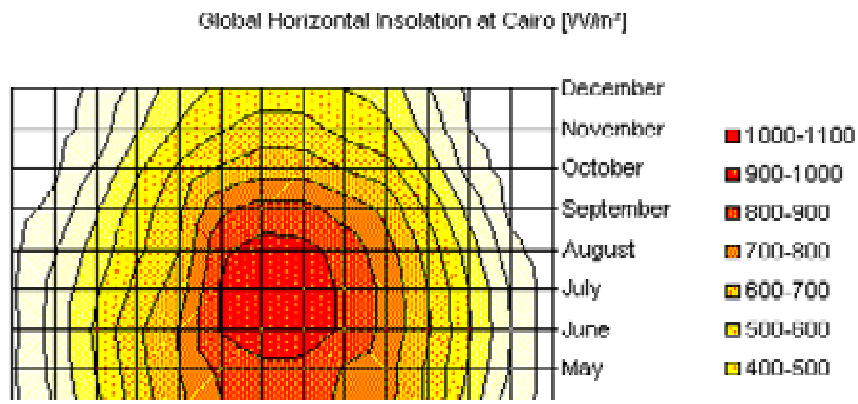


Figure 6.2: Insolation data from Daggett, California on a clear March day.

The middle curve represents the rate of solar energy falling on a horizontal surface at the same location. For reasons to be discussed later this curve includes both the energy coming directly from the sun's disc, and also that scattered by the molecules and particles in the atmosphere (total horizontal insolation). This scattered energy is shown as the bottom curve (diffuse insolation). Over the entire day, 6.7 kilowatt-hours of solar energy fall on every square meter of horizontal surface, of which 0.7 kilowatt-hours comes from all directions other than directly from the sun.

An example of a complete set of beam normal insolation data for a given location is shown in Figure 6.3. Here we see hourly insolation data, summarized over a day, for each month of a year. With this type of data for a specific site, it is possible to predict accurately the output of a solar energy conversion system, whether it is a low temperature thermal system, a high temperature thermal system or a photovoltaic system.



Global Horizontal Insolation at Cairo [W/m²]
December
November
October
September
August
July
June
May
1000-1100
900-1000
800-900
700-800
600-700
500-600
400-500

Using a formula developed elsewhere for the zenith angle of the Sun at each hour of the day the insolations (Watts per square meter per day) at the solstices and equinoxes were computed. All refinements such as the varying path lengths and average cloud cover were ignored. The computation does take into account the fact that the Earth is closer to the Sun at the Northern Hemisphere's winter solstice (December 21) than at its summer solstice (June 21). This means that the summer solstice for the Southern Hemisphere gets more intense solar radiation than the Northern Hemisphere gets for its summer solstice.

The insolation per day is measured in kilowatt-hours of energy per square meter (kW-hr/m²). The rate of energy input varies from 1.412 kW/m² at the closest approach to the Sun to 1.321 kW/m² at the furthest. If an area is receiving energy at a rate of 1.4 kW/m² for one hour that is 1.4 kW-hr/m² of energy input. If its energy input falls from 1.4 kW/m² to 1.3 kW/m² for an hour then the combined energy received is 2.7 kW-hrs/m²

In the following latitudes in degrees north are given as positive figures; latitudes in degrees south are given as negative figures.

The rate of energy input per unit area depends upon the angle of the Sun. The solar constant is multiplied by the cosine of the zenith angle of the Sun, the angle between the Sun's rays and the vertical.

Table 6.1: Amount of Solar Energy Received Per Day Per Unit Area by Season and Latitude (Kilowatt-hours/meter²)

Solar constant	1.321 kW/m²	1.366 kW/m²	1.412 kW/m²	
Latitude(deg)	NH Summer Solstice	Equinoxes	NH Winter Solstice	Average of these four
90	12.64	0	0	3.1600
80	12.45	1.8	0	4.0125
70	11.88	3.55	0	4.7450
60	11.49	5.19	0.58	5.6125
50	11.59	6.67	2.04	6.7425
40	11.65	7.95	3.76	7.8275
30	11.39	8.99	5.42	8.6975
20	10.99	9.75	7.12	9.4025
10	10.25	10.22	8.61	9.8250

0	9.20	10.38	9.84	9.9500
-10	8.06	10.22	10.96	9.8650
-20	6.67	9.75	11.75	9.4800
-30	5.07	8.99	12.18	8.8075
-40	3.25	7.95	12.45	7.9675
-50	1.91	6.67	12.39	6.9100
-60	0.54	5.19	12.28	5.8000
-70	0	3.55	12.70	4.9500
-80	0	1.80	13.31	4.2275
-90	0	0	13.51	3.3775

Here is the graph of the values for the solstices and equinoxes.

effectively at latitude of 23.5° south. The point on Earth that gets the highest one-day energy input from the Sun is the South Pole. One-day energy inputs do not count for much in terms of annual climate. Here is the graph of the averages of the energy inputs for the solstices and the equinoxes. This average is a reasonable approximation of the annual average daily energy inputs.

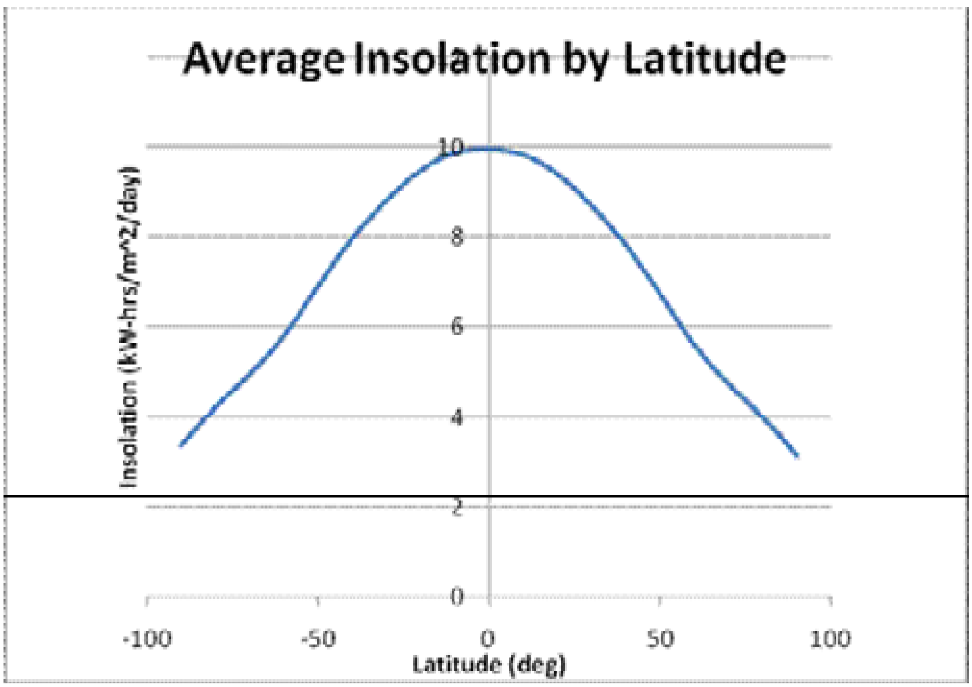


Figure 6.5: Average Insolation by Latitude

6.4 Daily insolation

Measurements of sunshine and cloud cover are taken as part of the meteorological records kept by weather stations all over the world. Two types of measurement to do with sunshine are daily sunshine measured in hours and daily insolation which has various units. Daily insolation is the measurement used to estimate the output from a solar module. It takes into account variations in angle between the sun and a horizontal surface together with the reduction of irradiance owing to cloud cover.

The measurement of daily insolation is also referred to by many other names, such as daily radiation, insolence, solar irradiation, and global horizontal irradiation. ('Insolation' is a shortened version of the words Incoming Solar Radiation.)

6.4.1 Units of daily insolation

At any moment in time, the light intensity or irradiance reaching the front of a module or any surface can be measured in units of watts per square meter (W/m^2). A different unit is used when measuring the total amount of light or insolation reaching the ground over a period of time.

The units used in this chapter for calculating the daily output of a solar module are peak-hours per day. Peak-hours are the equivalent number of hours of sunlight at an irradiance of 1000 W/m^2. This value of irradiance is chosen because it is the same value as in the standard test conditions under which the electrical specifications of solar modules are measured. The value of 1000 W/m^2 also happens to be about the highest irradiance that can be received on a surface facing the sun directly and when the sun is more than 45° above the horizon.

Peak-hours per day can also be given as kWh/m^2 per day which is the same size. Details and conversion factors of other units are listed in Table 6.2.

The daily insolation figures from meteorological records are often measured in units of Langley's. One Langley is another name for one calorie per square centimeter (cal/cm^2) of sunshine energy reaching the ground. Other units also used for this measurement are listed in Table 6.2.

Table 6.2: Conversion factors for use in formula 6.1

Units of daily insolation		Conversion factor to peak hours at
Abbreviation	Name in full	1000 W/m^2
Peak hour	Peak-hour at an irradiance of 100 W/m^2	1
Langley	Calorie per square centimeter	0.0116
Cal/cm^2	Calorie per square centimeter	0.0116
Wh/m^2	Watt hour per square meter	0.001
Wh/m^2	Kilo-watt hour per square meter	1
W/m^2 averaged over 24 hours	Watt per square meter averaged over 24 hours	0.024
kJ/m^2	Kilo-Joule per square meter	0.000278
MJ/m^2	Mega joule per square meter	0.278
Btu/ft^2	British thermal unit per square foot	0.0428

Conversion of measurements in other units to peak-hours is done using the appropriate conversion factor from Table 6.2 in the following formula:

Daily insolation (various units per day)	×	**Conversion factor from table 6.2 for unit of measurement**	=	**Daily insolation (peak hours per day)**	**… … … 6.1**

6.4.2 Module tilt

A solar module is always mounted at a certain angle of tilt from horizontal (see Figure 6.6). The tilt angle should be 15° or more to ensure that rain-water drains off easily, washing dust away with it.

The value of tilt angle is chosen to optimize irradiance on the module throughout the year. A simple way to choose the tilt angle is to set it at the latitude angle of the site. The direction of tilt should be set towards the Equator, which is due south for countries north of the Equator and due north for countries south of the Equator.

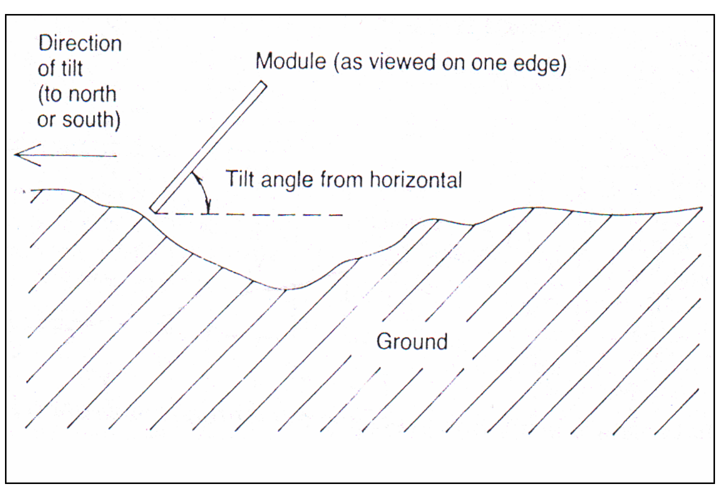


Figure 6.6: How to define the tilt angle of a module.

For sites at higher latitudes than 30°, the tilt angle can be set at the latitude angle plus 15°. This helps to even out the daily electrical output over the year by optimizing the tilt angle for the winter months.

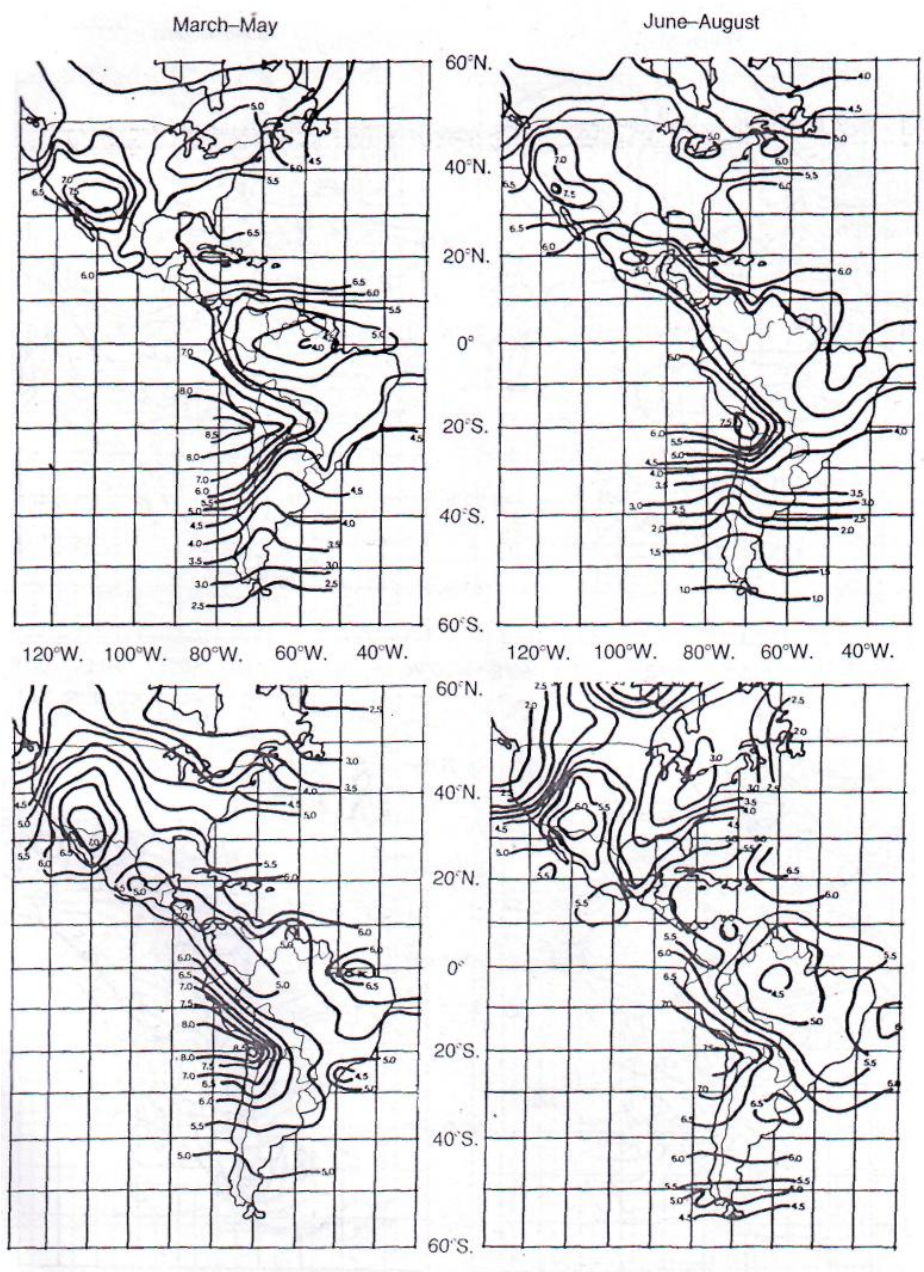
For sites at latitudes between 15°S. and 15°N., a tilt angle of 15° is used. The direction of tilt depends on which half of the year has the cloudiest month. For example, if July is the cloudiest month, modules just north or just south of the Equator should both face north. Alternatively, facing west or east should be considered if mornings or afternoons tend to be cloudy.

6.4.3 Daily output from one module

The maps in Figure 6.7 have sets of curves of average daily insolation for most countries of the world. The averages are over three-month periods and apply to modules tilted at the same angle as their angle of latitude.

For some sites, the country can be found directly on the maps. Otherwise draw pencil lines for the angles of latitude and longitude of the site so that the site is located where the lines cross. For each quarter of the year, choose the nearest curve of daily insolation and follow along this curve to the value of peak-hours per day. A more accurate estimate of daily insolation can be made by judging the position of the site between two curves.

The daily electrical output from one module in units of Wh per day at 12 V is calculated using the following formula:



September-November December-February

Figure 6.7 (a): North and South America (longitudes 130° W. to 30° W.).

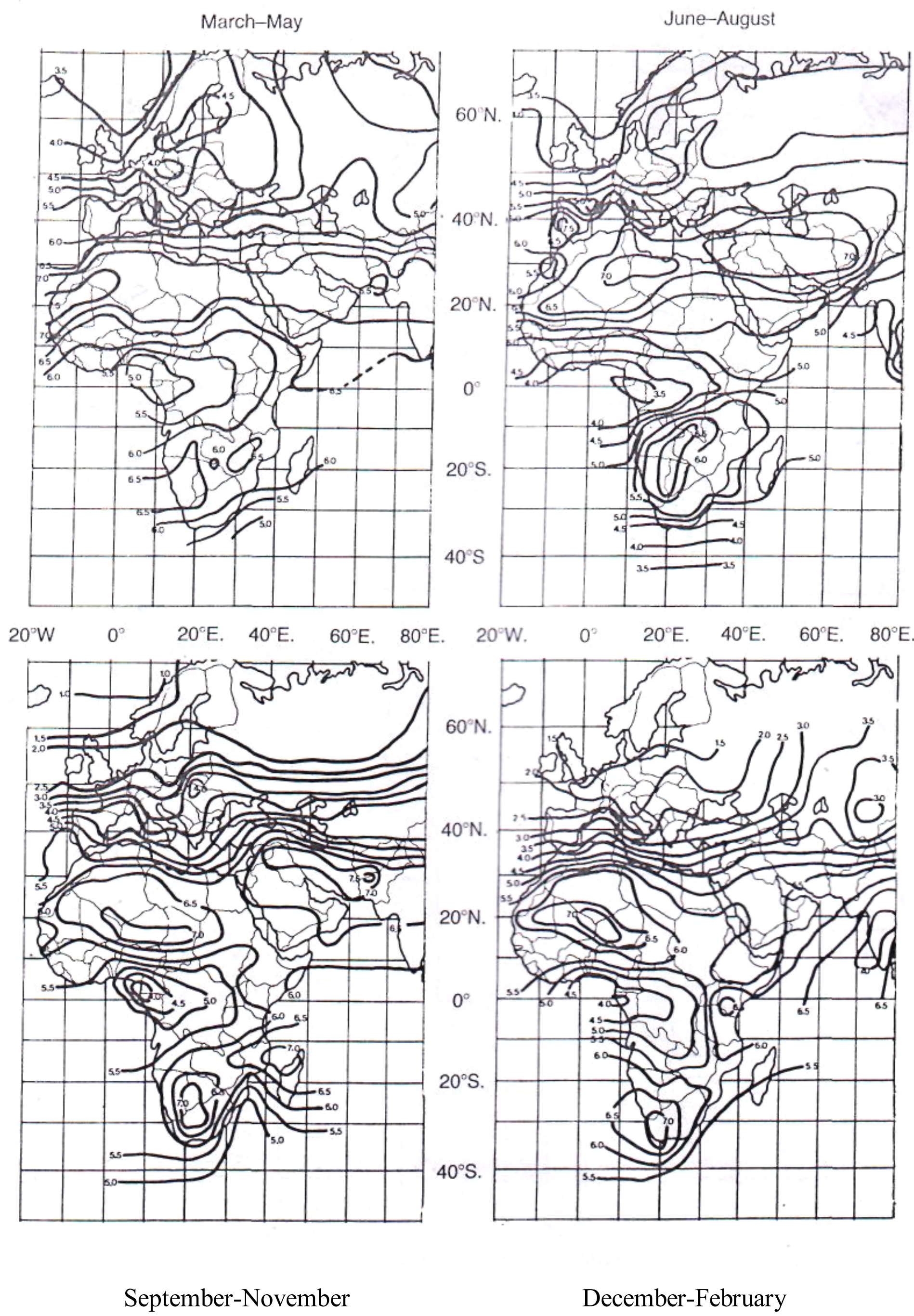


Figure 6.7 (b): Europe, Middle East, and Africa (longitudes 20°W. to 80°E.).

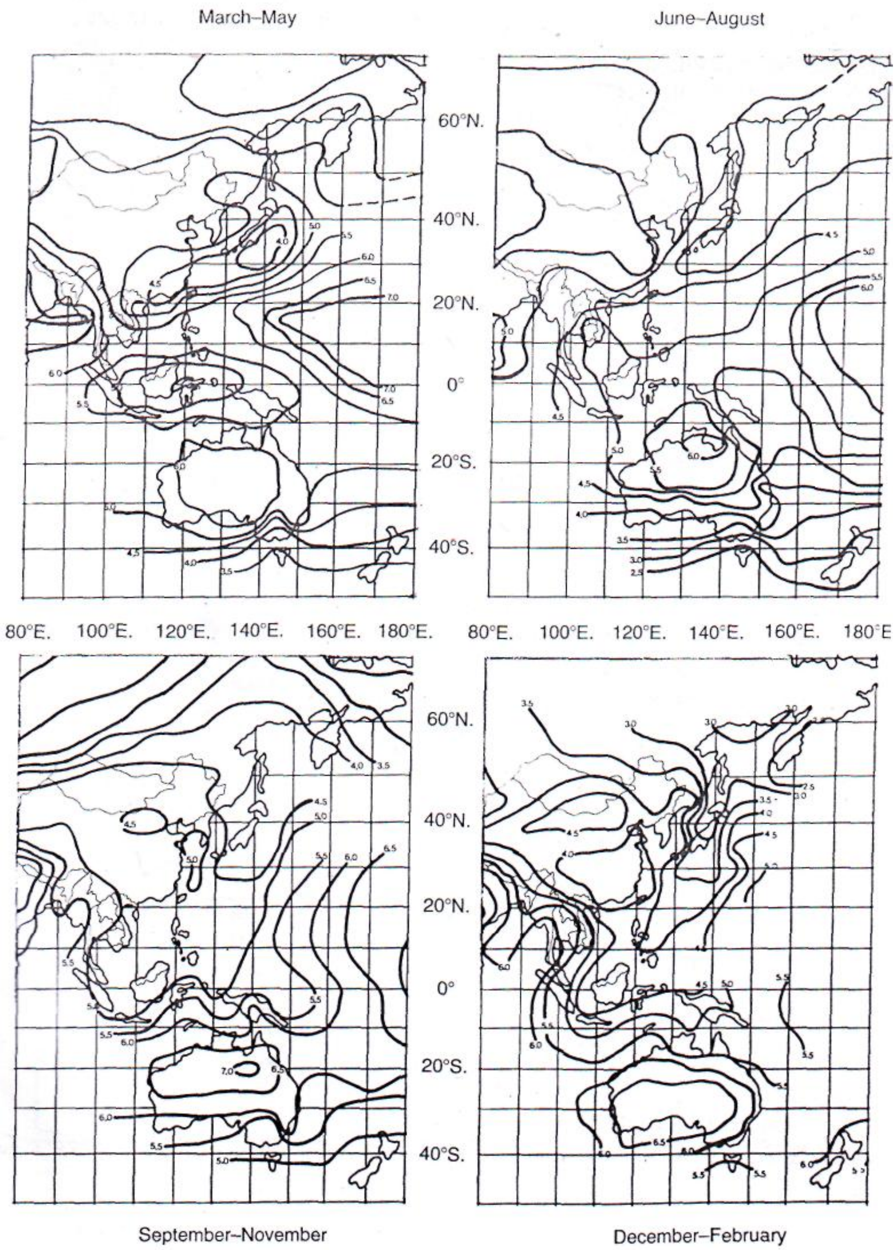


Figure 6.7 (c): Far East, Australia, and New Zealand (longitudes 80° E. to 180° E.)

The use of 12 V in this formula might be surprising since the output at a module varies from 12 V to over 15 V as a battery is charged up. The value of 12 V is chosen because it is the voltage at which the electricity is actually used by the appliances. For 24 V systems, 12 is still used because allowance for the higher voltage is made later when sizing the number of modules.

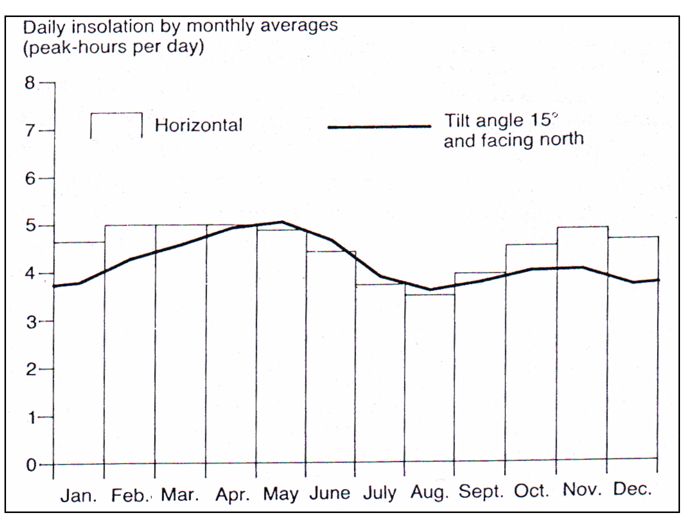
6.4.4 Limitations of using daily insolation maps

The information in Figure 6.7 gives only an approximate indication of daily insolation. The values on the curves are averaged over three-month periods. There is no indication of how low the daily electrical output might get for one month. Setting the tilt angle of the module at the same angle as the latitude of the site may not be the optimum. On the small scale of the maps, they cannot take into account local variations which can be significant for some sites.

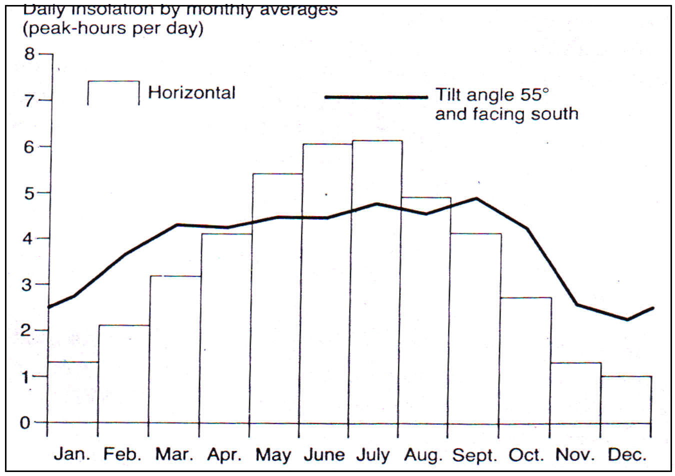
Examples of daily insolation by monthly averages are given in Figure 6.8 for two places at different latitudes. The daily insolation averages are for a horizontal surface and the effect of correcting for tilt angle is shown by the lines.

Ibadan in Figure 6.8(a) is at latitude of 7°N. But the modules should be tilted at no less than 15°. Since the lowest month is August, the tilt is to the north. Belgrade in Figure 6.8(b) is at latitude of 45°N. And a tilt angle of 55° is used to maximize output between November and February. This tilt angle means that a potentially high output for May to July is reduced but this is desirable for self-regulated systems to minimize over-charging.

If meteorological records are available for your area of interest, they can be used to give a better estimate of daily electrical output expected from a module. Meteorological measurements are always for a horizontal detector so they need to be corrected for other angles before they can be used for sizing.



(a)



(b)

Figure 6.8: Examples of daily insolation for two sites. Daily insolation as monthly averages on a horizontal surface is shown as bar charts. The dashed lines show the result of correcting for a particular tilt angle (using the procedure and tables in Appendix B). These tilt angles are chosen to raise the lowest monthly average and smooth out variations for the whole year.
(a) Ibadan in Nigeria at a latitude 7°N. and longitude 4°E., as an example of a site near the Equator.
(b) Belgrade in Yugoslavia at a latitude 45°N. and longitude 20°E., as an example of a site at a high latitude.

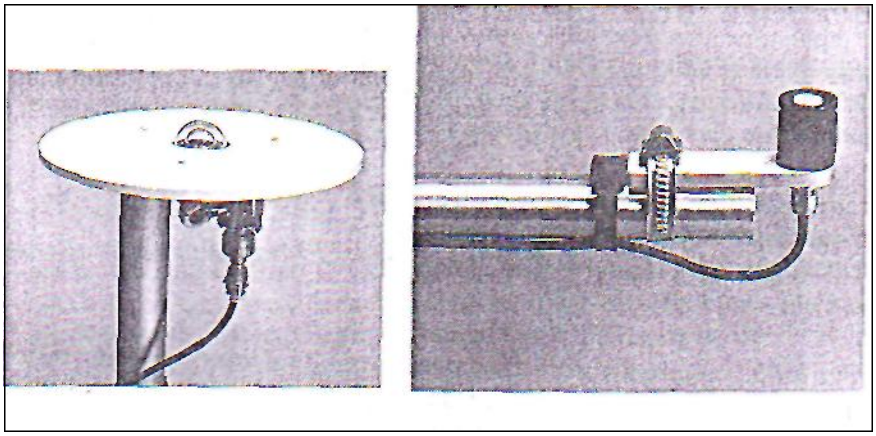
6.4.5 Instruments for measuring daily insolation

The general name for an instrument used to measure irradiance is a solarimeter. Two well-known types are,

(1) The Eppley pyranometer (in the United States)

(2) The Kipp and Zonen pyranometer (in Europe)

The detecting part of a pyranometer is a metal disc with thermocouples attached underneath and a black surface on top. The detector is fixed in a horizontal position facing directly upwards and protected by two glass domes (see Figure 6.9(a)).



(a) (b)

Figure 6.9: Two types of solarimeter used by meteorologists to measure daily insolation. Both types measure the total of direct and diffuse radiation combined. (Source Didcot Instruments Co. Ltd.)
(a) Pyranometer.
(b) Photovoltaic solarimeter.

The back surface of the detector warms up as it absorbs radiation from all parts of the sky. The rise in temperature is sensed by the thermocouples and this gives a measure of the light intensity or irradiance at that particular moment. As the sun passes overhead, measurements are recorded through the day and added up to give a value of total insolation for the day.

Chapter 7

Storage and Control unit

7.1 An Introduction on battery:

Batteries are used in solar electric to store electricity generated during daylight hours for later use. The main ones used in solar electric systems are lead acids batteries and nickel-cadmium batteries. These batteries are available in a variety of different types whose suitability for solar systems varies a lot. The choice of which types to use is a matter of balancing a num of factor, because the most suitable types may be unavailable or too expensive.

7.2 Battery Size

The size of the battery bank required will depend on the storage capacity required, the maximum discharge rate, the maximum charge rate, and the minimum temperature at which the batteries will be used. When designing a power system, all of these factors are looked at, and the one requiring the largest capacity will dictate battery size. Our System Sizing work forms take many of these factors into account.

One of the biggest mistakes made by those just starting out does not understand the relationship between amps and amp-hour requirements of 120 volt AC items versus the effects on their DC low voltage batteries. For example, say you have a 24 volt nominal system powering a load of 3 amps, 120VAC, which has a duty cycle of 4 hours per day. You would have a 12 amp hour load (3A X 4 hrs=12 ah). However, in order to determine the true drain on your batteries you have to divide your nominal battery voltage (24v) into the voltage of the load (120v), which is 5, and then multiply this times your amp hours (12 ah). So in this case the calculation would be 60 amp hours drained from your batteries - not the 12 ah. The easiest way to quickly determine the total battery amp hours required is to first determine total watt-hours required by all loads, and then divide by the nominal DC system voltage. This resulting number will indicate the amount of amp hours needed to operate all loads for a given period. However, additional amp hour capacity would typically be added for more "reserve" capacity or to prevent complete discharge.

Using the above example, 3 amps x 120 VAC x 4 hours = 1440 watt-hours divided by 24 VDC battery environment equals 60 amp-hours; the same answer as before, but another way to get it.

There are other factors for determining the full extent of the battery drain, such as temperature, start-up factors, etc., but this should help you get a more complete picture on how to size your low DC voltage batteries when powering 120/240 volt loads using an inverter. Our System Sizing work forms take many of these factors into account.

The storage capacity of a battery, the amount of electrical energy it can hold, is usually expressed in amp hours. If one amp is used for 100 hours, then 100 amp-hours have been used. A battery in a solar power system should have sufficient amp hour capacity to supply needed power during the longest expected period "no sun" or extremely cloudy conditions. In wind systems allowance for "no wind" days should be included. A lead-battery should be sized at least 20% larger than this amount. If there is a source of back-up power, such as a standby generator along with a battery charger, the battery bank does not have to be sized for worst-case weather conditions.

7.2.1 Series Wiring

Series wiring refers to connecting batteries to increase volts, but not amps. If you have two 6 volt batteries like the Trojan L16 rated at 350 amp hours, for example, by connecting the positive terminal of one battery to the negative terminal of the other, then you have series wired the two together. In this case, you now have a 12 volt battery and the rated 350 amps do not change. If you were to series wire four L16's you'd have 24 volts at 350 amps, and so on.

7.2.2 Parallel Wiring

Parallel wiring refers to connecting batteries to increase amps, but not volts. If you have two 6 volt batteries like the Trojan L16 rated at 350 amp hours, for example, by connecting the positive terminal of one battery to the positive terminal of the other, and the same with the negative terminal, then you have parallel wired the two together. In this case, you now have a 6 volt battery and the rated 350 amps increases to 700 amp hours. If you were to series wire four L16's you'd have 24 volts at 350 amps, and then parallel wire these four to the four other that are in series, then you'd have a 24 volt battery at 700 amps.

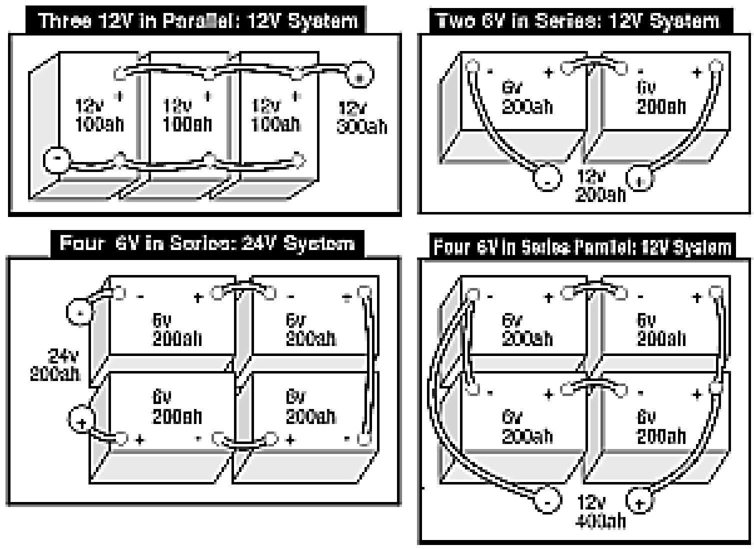


Figure-7.1.Five basic wiring types using these wiring examples a complete battery bank might have any number of total batteries to achieve required reserve capacity.

7.3 Lead-Acid Batteries

Lead-acid batteries are the most common in PV systems because their initial cost is lower and because they are readily available nearly everywhere in the world. There are many different sizes and designs of lead-acid batteries, but the most important designation is whether they are deep cycle batteries or shallow cycle batteries.

Shallow cycle batteries, like the type used as starting batteries in automobiles, are designed to supply a large amount of current for a short time and stand mild overcharge without losing electrolyte. Unfortunately, they cannot tolerate being deeply discharged. If they are repeatedly discharged more than 20 percent, their life will be very short. These batteries are not a good choice for a PV system.

Deep cycle batteries are designed to be repeatedly discharged by as much as 80 percent of their capacity so they are a good choice for power systems. Even though they are designed to withstand deep cycling, these batteries will have a longer life if the cycles are shallower. All lead-acid batteries will fail prematurely if they are not recharged completely after each cycle. Letting a lead-acid battery stay in a discharged condition for many days at a time will cause sulfation of the positive plate and a permanent loss of capacity.

7.3.1 Sealed deep-cycle lead-acid batteries

These are maintenance free. They never need watering or an equalization charge. They cannot freeze or spill, so they can be mounted in any position. We especially recommend sealed batteries for remote, unattended power systems, but also for any client who wants the maintenance free feature and doesn't mind the extra cost associated with these batteries. The Concorde PVX series (Sun-Extender) is an excellent choice.

7.3.2 Sealed Gel Cell (gelled-electrolyte) batteries

These are relatively maintenance free, however unlike a high quality sealed lead-acid battery like the Concorde PVX extra care must be taken to insure a Gel Cell battery is not charged above 14.1 volts for a 12 volt battery, for example. Over charging a Gel Cell even once for a sustained period can really shorten its life and even ruin it. Any charge source or charge regulator used must have user adjustable settings for sealed Gel Cell batteries to insure charge voltage does not exceed a safe limit. If your application dictates a sealed, gelled battery the Deka-East Penn MK series is an excellent choice.

7.3.3 Caring For Wet Cell Lead-Acid Batteries

Wet cell lead acid batteries like the high quality Surrette require periodic watering and equalization. Always use extreme caution when handling batteries and electrolyte. Wear gloves, goggles and old clothes. "Battery acid" will burn skin and eyes and destroy cotton and wool clothing.

The quickest way to ruin lead-acid batteries is to discharge them deeply and leave them stand "dead" for an extended period of time. When they discharge, there is a chemical change in the positive plates of the battery. They change from lead oxide when charged to lead sulfate when discharged. If they remain in the lead sulfate state for a few days, some part of the plate does not return to lead oxide when the battery is recharged. If the battery remains discharged longer, a greater amount of the positive plate will remain lead sulfate.

The parts of the plates that become "sulfated" no longer store energy. Batteries that are deeply discharged, and then charged partially on a regular basis can fail in less than one year.

Check your batteries on a regular basis to be sure they are getting charged. Use a hydrometer to check the specific gravity of your lead acid batteries. If batteries are cycled very deeply and then recharged quickly, the specific gravity reading will be lower than it should because the electrolyte at the top of the battery may not have mixed with the "charged" electrolyte. Check the electrolyte level in wet-cell batteries at least four times a year and top each cell off with distilled water. Do not add water to discharged batteries. Electrolyte is absorbed when batteries are much discharged. If you add water at this time, and then recharge the battery, electrolyte will overflow and make a mess.

Keep the tops of your batteries clean and check that cables are tight. Do not tighten or remove cables while charging or discharging. Any spark around batteries can cause a hydrogen explosion inside and ruin one of the cells, and possibly you too.

It is a good idea to do an equalizing charge when some cells show a variation 0.05 specific gravity from each other. This is a long steady overcharge, bringing the battery to a gassing or bubbling state. Typically, we'll recommend an equalization charge at least once a month. Do not equalize sealed or gel type batteries. With proper care, lead-acid batteries will have a long service life and work very well in almost any power system.

7.4 Measuring battery condition

Connect a voltmeter and measure the voltage across the battery terminals with the battery at rest (no input, no output) for at least three hours. These readings are best taken in the early morning, at or before sunrise, or in late evening. Take the reading while all loads are off and no charging sources are producing power.

The following table will allow conversion of the voltage readings obtained to an estimate of state of charge. The table is good for batteries at 77·F that have been at rest for 3 hours or more. If the batteries are at a lower temperature you can expect lower voltage readings.

We can see that when voltage reading is about equal to the battery "nominal voltage" your battery is about 60% discharged.

Table 7.1 Battery State of Charge Voltage

Percent of Full Charge	12 Volt DC System	24 Volt DC System	48 Volts DC System
100%	12.7	25.4	50.8
90%	12.6	25.2	50.4
80%	12.5	25	50
70%	12.3	24.6	49.2
60%	12.2	24.4	48.8
50%	12.1	24.2	48.4
40%	12.0	24	48
30%	11.8	23.6	47.2
20%	11.7	23.4	46.8
10%	11.6	23.2	46.4
0%	<11.6	<23.2	<46.4

The following Table-7.2 reflects state of charge vs. specific gravity of the electrolyte in each cell. A hydrometer is used to determine specific gravity.

State of Charge	Specific Gravity
100% Charged	1.265
75% Charged	1.239
50% Charged	1.200
25% Charged	1.170
Fully Discharged	1.110
These readings are correct at 75°F	

7.5 Nickel-cadmium battery

The nickel-cadmium battery (commonly abbreviated NiCd and pronounced NYE-kad) is a type of rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes.

The abbreviation NiCad is a registered trademark of SAFT Corporation and should not be used to refer generically to nickel-cadmium batteries, although this brand name is commonly used to describe all nickel-cadmium batteries. On the other hand, the abbreviation NiCd is derived from the chemical symbols of nickel (Ni) and cadmium (Cd), though it is not to be confused with a chemical formula.

There are two types of NiCd batteries: sealed and vented.

7.5.1 Vented cell (wet cell, flooded cell)

It is a type of nickel-cadmium battery that is used when large capacities and discharge rates are required. The term vented refers to a difference to common NiCd batteries which are sealed.

They are used in aviation, rail and mass transit, backup power for telecoms, engine starting for backup turbines etc. Using vented cell NiCd batteries results in reduction in size, weight and maintenance requirements over other types of batteries. Vented cell NiCd batteries have long lives (up to 20 years or more, depending on type) and operate at extreme temperatures (from -40°C to +70°C).

7.5.2 Sealed nickel-cadmium cells

This is another type of nickel-cadmium battery. Sealed nickel-cadmium batteries are available in the same size as zinc dry cells. An example is the D-0size cell of diameter 32mm and length 57mm.although the voltage of the nickel-cadmium cells at 1.25 V is less than the voltage of zinc dry cells at 1.4V, they can be used in the same appliances.

7.6 Problem with NiCd

- **Overcharging:**
- **Cell reversal:**
- **Memory and lazy battery effects:**
- **Dendritic shorting:**
- **Environmental consequences of Cadmium**
- **Safety**

7.6.1 Overcharging

Overcharging must be considered in the design of most rechargeable batteries. In the case of NiCds, there are two possible results of overcharging:

If the negative electrode is overcharged, hydrogen gas is produced.

If the positive electrode is overcharged, oxygen gas is produced.

For this reason, the anode (negative) is always designed for a higher capacity than the cathode, to avoid releasing hydrogen gas. There is still the problem of eliminating oxygen gas, to avoid rupture of the cell casing. NiCd cells are vented, with seals that fail at high internal gas pressures. The sealing mechanism must allow gas to escape from inside the cell, and seal again properly when the gas is expelled. This complex mechanism, unnecessary in alkaline batteries, contributes to their higher cost.
NiCd cells dealt with in this article are of the sealed type. Cells of this type consist of a pressure vessel that is supposed to contain any generation of oxygen and hydrogen gasses until they can recombine back to water. Such generation typically occurs during rapid charge and discharge and exceedingly at overcharge condition. If the pressure exceeds the limit of the safety valve, water in the form of gas is lost. Since the vessel is designed to contain an exact amount of electrolyte this loss will rapidly affect the capacity of the cell and its ability to receive and deliver current. To detect all conditions of overcharge demands great sophistication from the charging circuit and a cheap charger will eventually damage even the best quality cells.

7.6.2 Cell reversal

Another potential problem is reverse charging. This can occur due to an error by the user, or more commonly, when a battery of several cells is fully discharged. Because there is a slight variation in the capacity of cells in a battery, one of the cells will usually be fully discharged before the others, at which point reverse charging begins seriously damaging that cell, reducing battery life. The by-product of reverse charging is hydrogen gas, which can be dangerous. Some commentators advise that one should never discharge multi-cell nickel-cadmium batteries to zero voltage; for example, torches (BrE)/flashlights (AmE) should be turned off when they are yellow; before they go out completely.
A common form of this deprecation occurs when cells connected in series develop unequal voltages and discharge near zero voltage. The first cell that reaches zero is pushed beyond to negative voltage and gasses generated open the seal and dry the cell.
In modern cells, an excess of anti-polar material (basically active material ballast at positive electrode) is inserted to allow for moderate negative charge without damage to the cell. This excess material slows down the start of oxygen generation at the negative

plate. This means a cell can survive a negative voltage of about -0.2 to -0.4 volts. However if discharge is continued even further, this excess ballast is used up and both electrodes change polarity, causing destructive gassing (gas generation).

Battery packs with multiple cells in series should be operated well above 1 volt per cell to avoid placing the lowest capacity cell in danger of going negative. Battery packs that can be disassembled into cells should be periodically zeroed and charged individually to equalize the voltages. However, this does not help if old and new cells are mixed, since their different capacities will result in different discharge times and voltages.

7.6.3 Memory and lazy battery effects

NiCd batteries suffer from a "memory effect" if they are discharged and recharged to the same state of charge hundreds of times. The apparent symptom is that the battery "remembers" the point in its charge cycle where recharging began and during subsequent use suffers a sudden drop in voltage at that point, as if the battery had been discharged. The capacity of the battery is not actually reduced substantially. Some electronics designed to be powered by NiCds are able to withstand this reduced voltage long enough for the voltage to return to normal. However, if the device is unable to operate through this period of decreased voltage, the device will be unable to get as much energy out of the battery, and for all practical purposes, the battery has a reduced capacity.

There is controversy about whether the memory effect actually exists, or whether it is as serious a problem as is sometimes believed. Some critics claim it is used to promote competing NiMH batteries, which apparently do not suffer from it. Many NiCd battery manufacturers either deny the effect exists or are silent on the matter.

There is much evidence that the memory effect story originated from orbiting satellites, where they were typically charging for twelve hours out of twenty-four for several years. After this time, it was found that the capacities of the batteries had declined significantly, but were still perfectly fit for use. It is unlikely that this precise repetitive charging (e.g., 1000 charges / discharges with less than 2% variability) could ever be reproduced by consumers using electrical goods.

An effect with similar symptoms to the memory effect is the so-called voltage depression or lazy battery effect. (Some people use this term as a synonym for "memory effect".) This results from repeated overcharging; the symptom is that the battery appears to be fully charged but discharges quickly after only a brief period of operation. Larger cells may benefit from refilling with distilled water, or a complete electrolyte replacement. In rare cases, much of the lost capacity can be recovered by a few deep-discharge cycles, a function often provided by automatic NiCd battery chargers. However, this process may reduce the shelf life of the battery. If treated well, a NiCd battery can last for 1000 cycles or more before its capacity drops below half its original capacity.

7.6.4 Dendritic shorting

NiCd batteries, when not used regularly, tend to develop dendrites which are thin, conductive crystals which may penetrate the separator membrane between electrodes. This leads to internal short circuits and premature failure, long before the 800–1000 charge/discharge cycle life claimed by most vendors. Sometimes, applying a brief, high-current charging pulse to individual cells can clear these dendrites, but they will typically reform within a few days or even hours. Cells in this state have reached the end of their useful life and should be replaced. Many battery guides, circulating on the Internet and online auctions, promise to restore dead cells using the above principle, but achieve very short-term results at best.

7.6.5 Environmental consequences of Cadmium

NiCd batteries contain cadmium, which is a toxic heavy metal and therefore requires special care during battery disposal. In the United States, part of the price of a NiCd battery is a fee for its proper disposal at the end of its service lifetime. In the European Union, the Restriction of Hazardous Substances Directive (RoHS) bans the use of cadmium in electrical and electronic equipment products since July 2006. The sale of nickel-cadmium batteries has now been banned within the European Union except for medical use; alarm systems; emergency lighting and portable power tools. This last category is to be reviewed after 4 years.

Cadmium, being a heavy metal, can cause substantial pollution when landfilled or incinerated. Because of this, many countries now operate recycling programs to capture and reprocess old NiCd batteries.

7.6.6 Safety

- Rayovac Safety Data Sheet
- Never short-circuit the battery because this may cause the battery to explode. (A short-circuit is a direct electrical connection between the + and – battery terminals, such as with a wire. Batteries should never be short circuited.)
- Never incinerate NiCd batteries; along with the possibility of an explosion, incinerating a NiCd battery will result in the release of a toxic gas containing cadmium. Recycle the battery instead.
- Avoid dropping, hitting, or denting the battery because this may cause internal damage including (internal) short-circuiting of the cell.
- Avoid rapid overcharging of the battery; this may cause leakage of the electrolyte, out gassing, or possibly an explosion.

The charge efficiency of the nickel-cadmium cell is found to be 100% up to the state of charge where oxygen evolution begins to take place. Inefficiencies at lower states of charge are due to poor utilization of capacity on discharge rather than to any inefficiency in recharge ability. The dependence of the utilization efficiency on charge and discharge rates is reported. The results are consistent with the hypothesis that the utilization of capacity in the nickel electrode is limited by the formation of a depletion layer at the current collector-active material interface

7.7 Choosing battery and comparing prices

The first step in choosing a battery is to find out which ones are available. Then their details, specifications, and price should be listed in a copy. The price should includes the cost of delivery to the site and all other incidental costs for each battery.

The choice of battery from the list is done by comparing their cost and relative advantages. Comparing batteries by value for money based on usable capacity and total usable capacity over life.

The voltage supplied by a battery depends on the number and types of cells from which it is made. Batteries should be compared at the same voltage of 12v.

The nominal capacity is covered using the following formula with the cost for a 12v battery.

(Total cost of one battery)x(12v)/(nominal voltage of one battery)=cost for a 12v battery

……………….7.1

Lead-acid batteries should not be cycled over their full nominal capacity otherwise their cycle life is too short. The usable capacity is calculated as follows:

[Nominal capacity(Ah)] x [Usable depth(%)] / [100%] = [Usable capacity(Ah)]

…………………….7.2

Another useful specification relates to the capacity used over the cycle life of a battery. This is calculated as follows:

[Usable capacity] x [Cycle life at usable depth] = [Total usable capacity over cycle life]
(Ah) (cycle) (Ah)

…………………….7.3

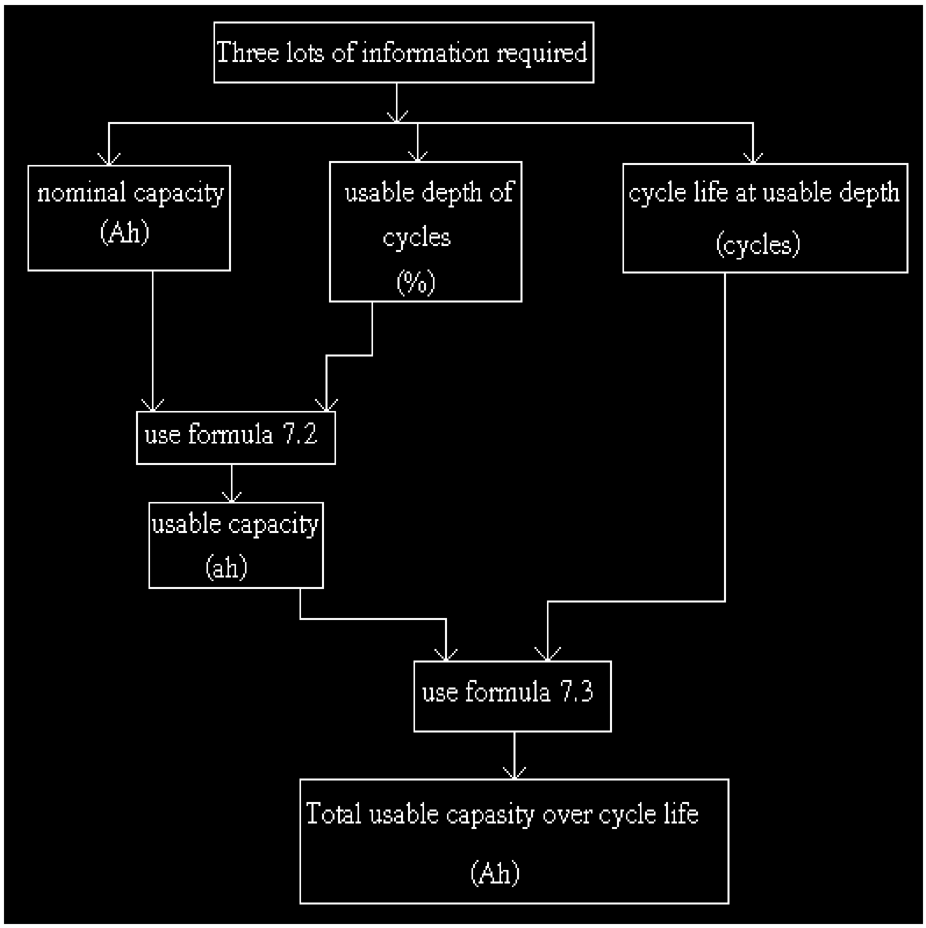


Figure-7.2: Summery of procedure for calculating different types of capacity for a battery

7.8 Control Unit

For solar electric system with rechargeable batteries, protection is required against the following problems:

- Risk of cable damage and fire from short circuits.
- Over-discharge Of lead-acid batteries.
- Excessive charging of batteries.

A control unit is used to provide this protection. Other functions are to indicate performance of the whole system and to provide switching for separate circuits

7.8.1 Safety requirements

Safety is an important concern when dealing with any electrical system. The first concern in mains wiring is to avoid giving people electric shocks. For solar systems operating at 12 or 24 V, there is no danger of electrocution because these voltages are low."

7.8.2 Short circuit protection

The most essential part in a control system is a fuse fitted near the battery. This is required to protect the wiring and thus avoid the risk of fire. The connections between the modules, Battery, fuse, and appliances are shown in figure-7.3.

7.8.2.1 Miniature circuit-breaker (MCB)

This can be used in place of a fuse. This is an automatic switch which opens when the current exceeds a certain value. The protection it provides against excess currents is said to be 'close' because it opens in a shorter time than a fuse of the same rating takes to melt. Resetting an MCB is easier and quicker than replacing a fuse but MCBs are an expensive option.

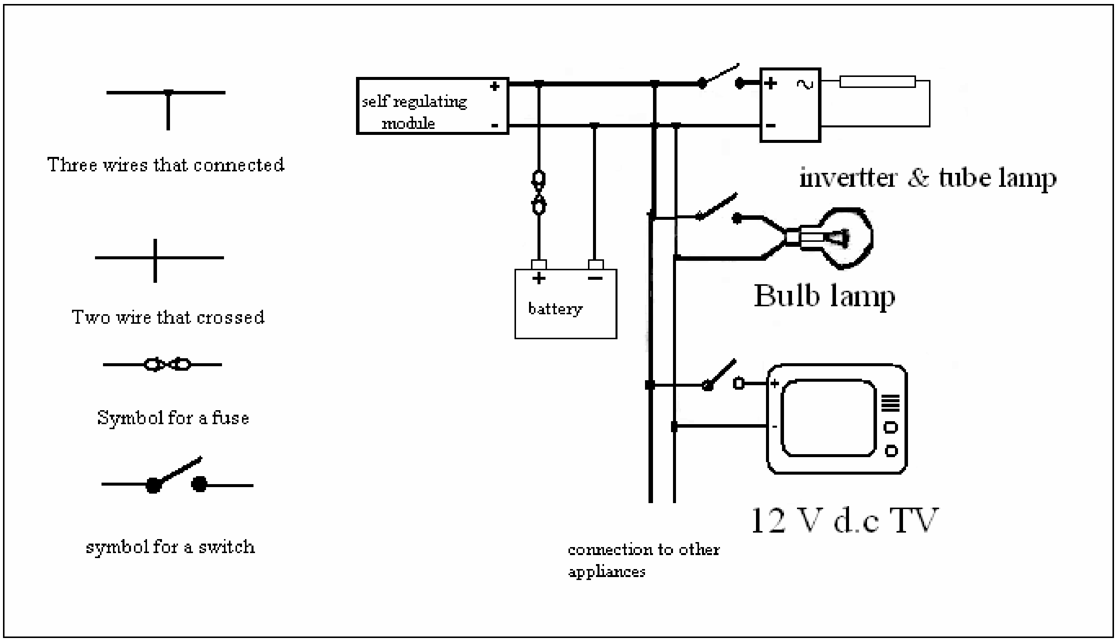


Figure 7.3: The minimum requirement for control in a solar electric system with battery storage is a fuse connected close to one of the battery terminal.

7.8.2.2 Residual current circuit-breakers

These are recommended in mains systems that are earthed to provide better protection for users. They work by breaking the circuit when a short circuit to earth causes a difference in the current between of the two conductors.

7.8.2.3 Protecting appliances and module

Some appliances might require their own protection against an internal short circuit. If a fuse holder is not provided in the appliance, a fuse can be fitted in a fusible plug or by an in-line fuse in the cable. Note that fuses introduce an additional voltage drop in the distribution system. Extra fuses should only be used for individual appliances if there is a high risk of a short circuit. An example is apparatus used by pupils in a school science laboratory

A blocking diode provides extra safety for modules. If a short circuit develops in a module, the diode prevents the battery supplying a high current and causing more damage.

7.9 Protection against lightning

Lightning strikes can cause damage in solar electric systems. The strike itself is unlikely to hit the module support structure directly, especially if there are tall buildings and trees nearby. However, a close strike induces high voltages in the wiring which can destroy the electronic circuits in control units and inverters for tube lamps.

Circuits should be protected against current surges caused by indirect lightning strikes by using a metal oxide varistor (MOV). This is an essential feature for control units used at sites which are known for frequent lightning.

7.10 Importance of correct polarity

Even though neither the positive nor the negative is as dangerous as a high-voltage live conductor, polarity of wiring should always be correct when wiring a solar system. This means that the positive is connected to red insulated wires, the negative is connected to terminals marked 'N', and so on

If the polarity is reversed (positive and negative connected the wrong way around), some D.C. appliances will not work, others will be damaged, and the solar modules will not charge the batteries.

7.11 Protecting against over-discharge of lead-acid batteries

Most batteries used in small- and medium-size solar systems are the lead-acid type because of availability and reasonable cost. To obtain the best life from them, it is essential to avoid over-discharge. An indicator for state of charge informs users when the batteries are low and should not be used any further. A more reliable approach requiring less involvement by the users is to use a control unit which automatically disconnects the appliances. Over-discharge is not a problem for nickel-cadmium batteries which can be totally discharged and left discharged with no ill effects. If nickel-cadmium cells are available, they should be seriously considered as an alternative to lead-acid batteries because of their reliability. It is possible to avoid the current drain in either condition by using a latching relay.

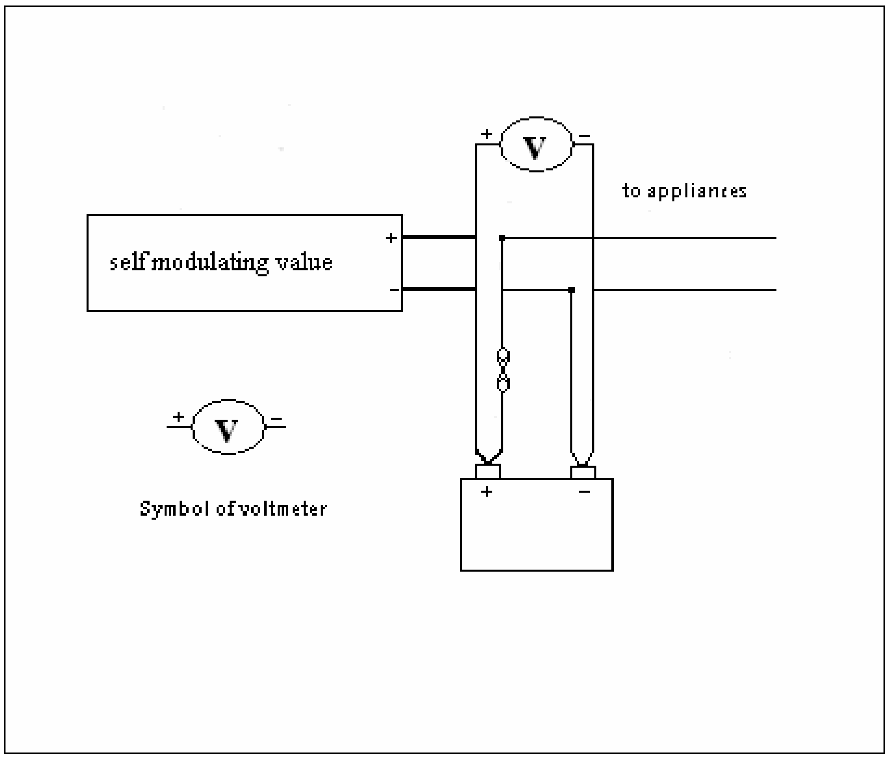


Figure-7.4.Circuit diagram for connecting a voltmeter

7.12 Dark-current leakage

The total loss of electricity by dark current leakage through a number of modules with other current specifications can be calculated from the following formula:

[number of modules in array] x [current output of each module under STC] x [length of night] = [total loss of electricity by dark current(WH/day)]

…………………… (7.4)

The answer is in units of W h per day so that it can be directly compared to the requirement for electricity by the appliances, as calculated in the following table.

Appliances	Appliance power (W)	Expected daily use (Hours per day)	Electrical requirement (W h per day)
Tube lamp for living room	8	4	32
Tube lamp for kitchen	8	3	24
Filament bulb for wash room	10	0.5	5
Filament bulb for bed room 1	10	0.5	5
Filament bulb for bed room 2	15	0.5	5
Small BIW TV	5	3	45
Cassette player		4	20
Total daily requirement of electricity (W h per day)			= 136

Table-7.3. Example of the electrical requirements of a simple solar electric system for a home

7.13 Low-voltage disconnects

In a home system, the owner can appreciate that over-discharging the battery will result in having to replace it within two years rather than after three or more year. A more reliable method of protecting against over-discharging is to use a control unit which automatically disconnects the appliance when the state of charge is too low. This feature is known as "low-voltage disconnect" since it works by disconnecting the appliance circuits when a low state of charge makes the battery voltage low. A control unit with this feature is particularly recommended for small institutions where the users are not really involved in the day-to-day operation of the solar system. There are two parts to a low-voltage disconnect mechanism, as shown in Figure -7.5.

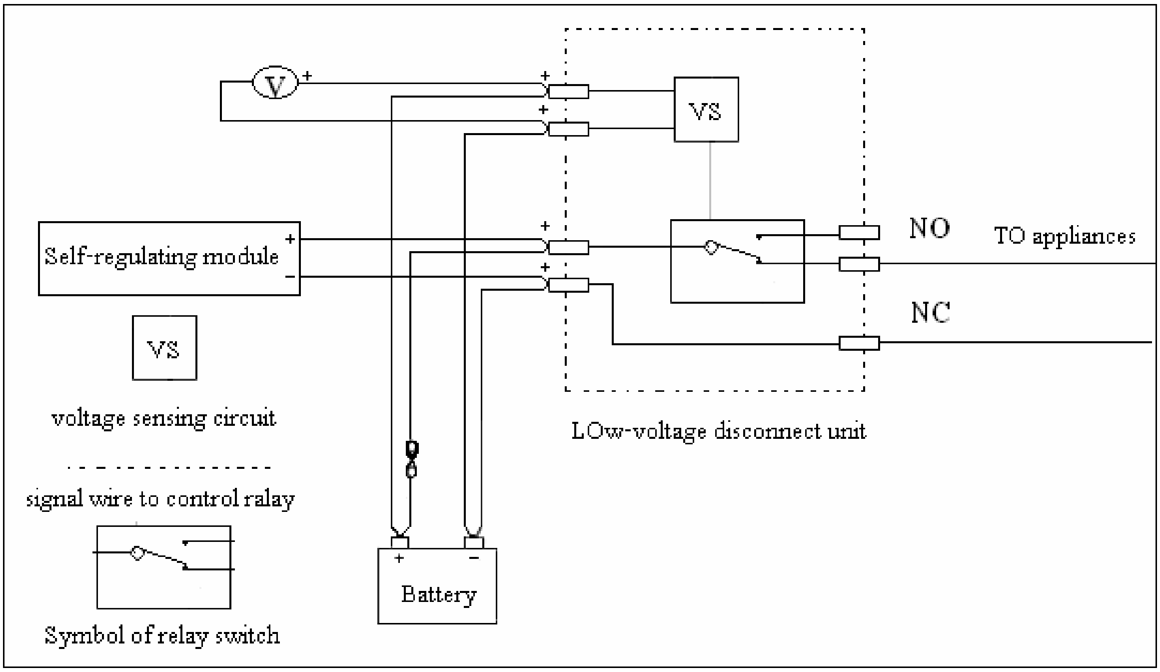


Figure7.5: Circuit for connecting a control unit with low-voltage disconnect

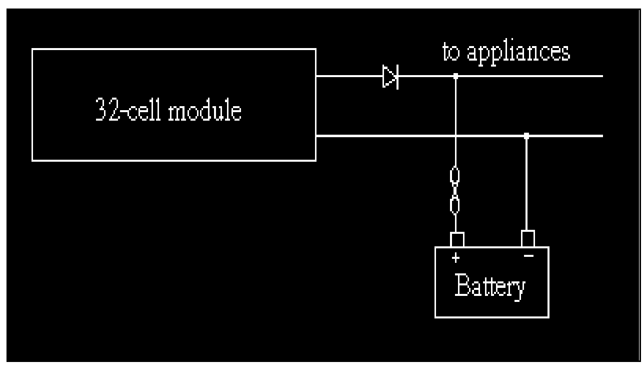
7.14 Charge regulators

Two disadvantages of self-regulating modules are that the batteries are not charged as quickly as possible and the charging current is low in cloudy weather. Modules with more cells produce a higher voltage. This gives them the advantage that they have sufficient voltage to supply their maximum current at all states of charge of the batteries.

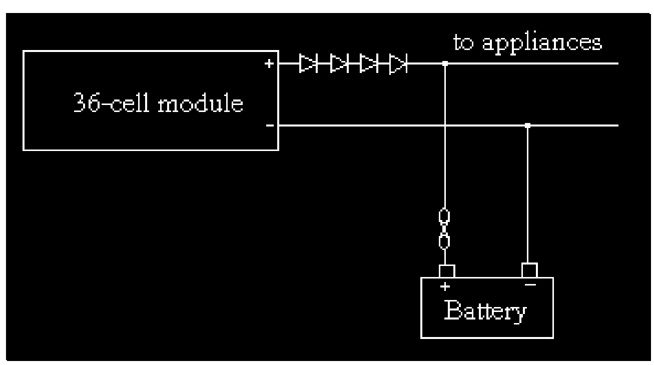
On approaching full charge, the voltage at the battery terminals rises. If it is allowed to go above about 15 V, gassing becomes excessive. In batteries with vented cells, this results in damage to the plates, loss of water from the electrolyte, and acid spray or mist leaving the vents. In sealed cells, excessive gassing causes a build-up of gas pressure and over-heating. Also appliances used during charging may be damaged by a voltage higher than 15 V. To limit the voltage, there is a variety of charge regulators available for use with solar modules.

For nickel-cadmium cells, the vented type can be charged in the same way as for lead-acid batteries. Different voltage settings are required in the regulator, so check with the supplier first. The charging of sealed cells is different because they are limited to maximum charging current. Some regulators are given below;

- **Over-voltage shunt for charge regulator.**
- **Pulsing regulators**
- **Dual-voltage regulators**



(a)



(b)

Figure 7.6: preventing dark current leakage of electricity when a self-regulating module is directly connected to a battery.(a)-blocking diode;(b)-use of four blocking diodes to convert a module with thirty-six cells to one with thirty-two cells that a self regulating with just one blocking diode. This system could be used while waiting for a regulating control unit to be delivered or repaired.

7.14.1 Over-voltage shunts for charge regulator

An over-voltage shunt is a regulator that prevents the battery voltage going above 15v. The regulating part contains a high power transistor as shunt which means that the transistor is connected in parallel with a battery as shown in Figure 7.7.

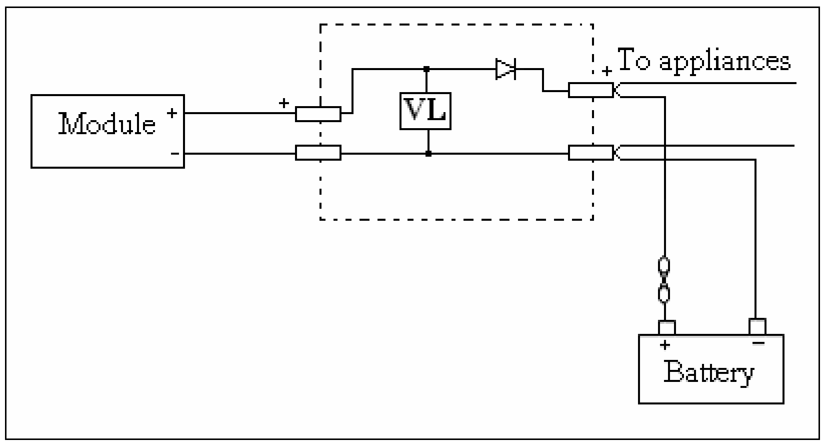
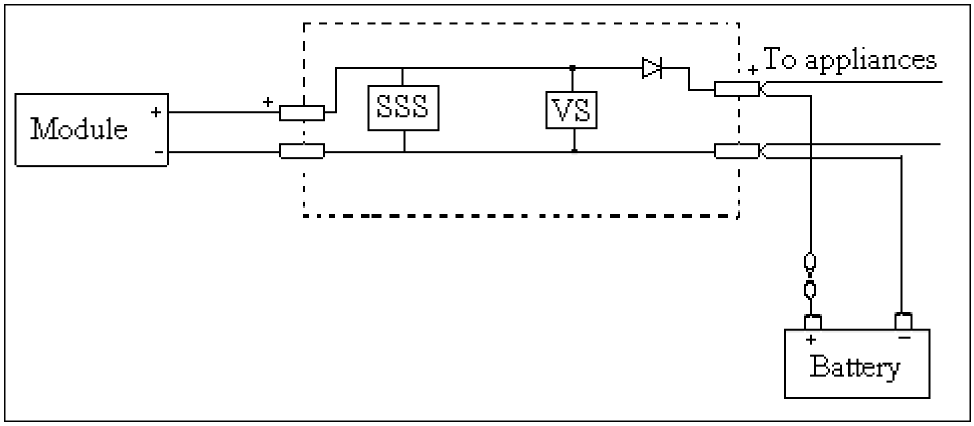


Figure 7.7: Charge regulation using an over voltage shunt to limit the battery voltage

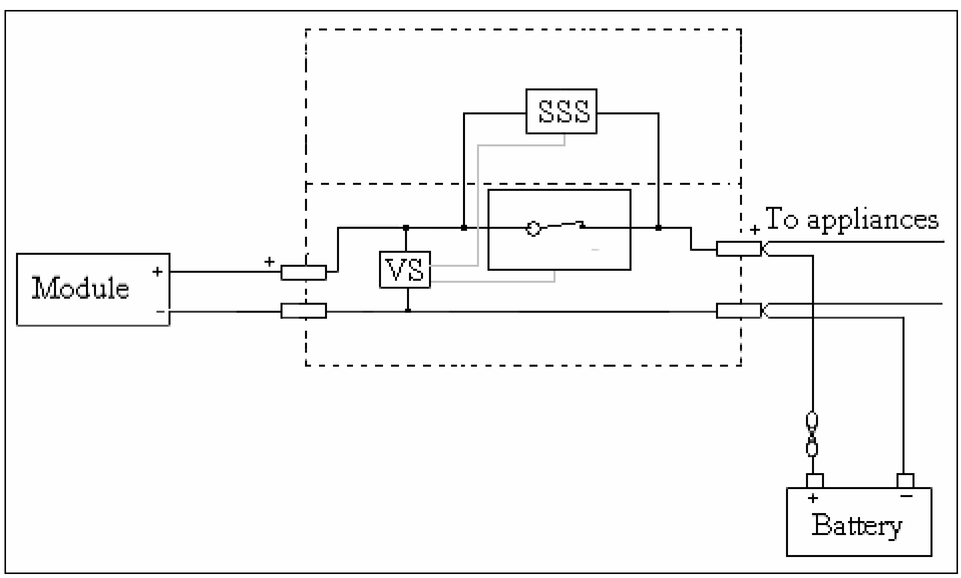
The disadvantage of this connection is that maintaining 15v still causes some unnecessary gassing. Also lead-acid batteries only reach their fullest charge when the final stage of charging involves reducing or pulsing the current on and off repeatedly.

7.14.2 Pulsing regulators

Two types of pulsing regulators are shown in Figure 7.8. Both have small electronic circuits for monitoring the voltage of the battery, like the one for the low voltage disconnect. This circuit controls a switch for turning the charging current on and off.



(a)



(b)

Figure 7.8: two types of pulsing regulator

(a) When the battery voltage reaches about 15v, the shunt switch is closed by the VS circuit to stop charging.

(b) When the battery voltage reaches to 15v, the series switches of a relay and a solid switch are opened by the VS (voltage sensing) circuit to stop charging.

7.14.3 Dual voltage regulator

Two step or dual voltage regulators control charging in two stages. As shown in figure-7.9., there is a relay switch connecting the module directly to the battery. When the battery voltage reaches 15V, the voltage sensing circuit opens the switch. The battery is now maintained at a float voltage of about 13.5B by a series regulator so that a low charging current flows. Compared to the parallel arrangement in figure-7.6., the voltage drop across a series regulator is small so less heat is reduced. This gives the option of using “surplus” current from the module to charge the reserved battery or to run a non-essential appliance such as a cooling fan.

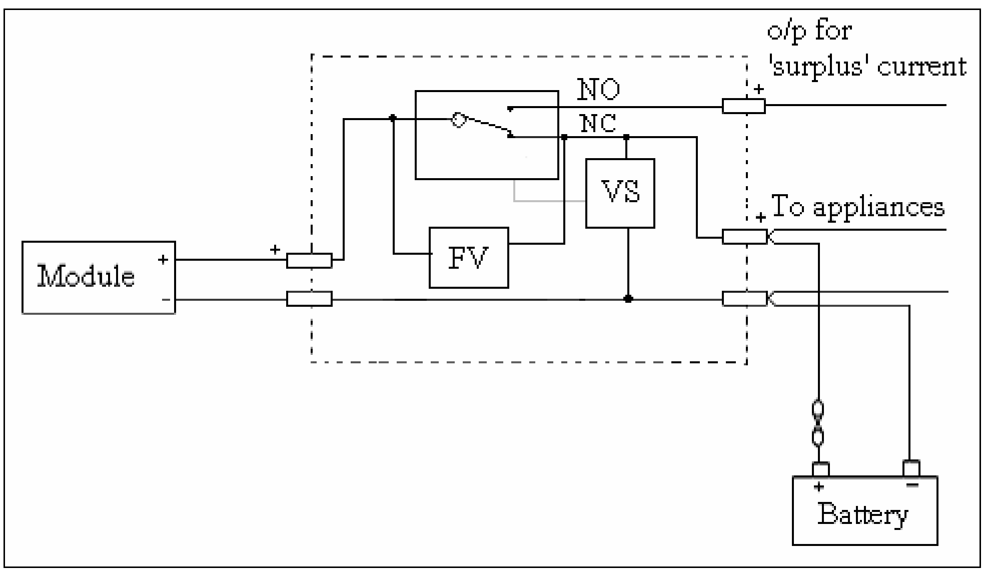


Figure 7.9: Two-step or dual-voltage regulator

7.15 Commercially available control unit

The Figure-7.10 shows an example of a controller that combines several features into one unit. It has lightning protection, a charging LED, charge regulation, a blocking diode, and low-voltage disconnect.

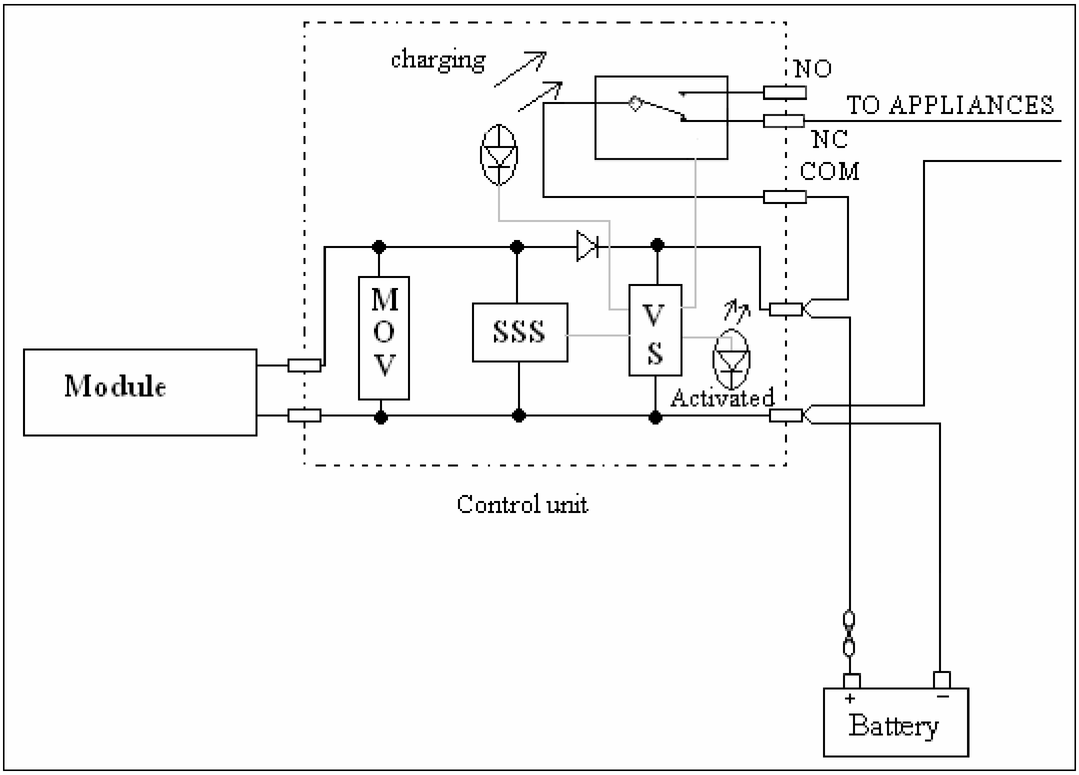


Figure 7.10: Commercially available control unit

7.16 Conclusion

This chapter is based on storage and control unit. In storage section we have learnt about battery, its size, properties, materials, types, wiring, measuring conditions of batteries, choosing battery and its cost.

In control unit section we've learnt about safety requirements i.e. how to protect the system (from lightening, lead acid battery), safety requirements, low-voltage disconnect, charge regulators and commercially available control unit.

Chapter 8
System Planning & Installation

8.1 Introduction

Planning a solar electric system involves designing the layout and ordering the parts. The modules, control unit, and batteries should all be as close together on the site as is convenient. Installation should only be performed or supervised by personnel who have experience of electricity.

8.2 System planning

8.2.1 Solar modules

The place and method of mounting a module or array of modules must be chosen carefully. There are several points to be considered for both aspects.

8.2.1.1 General position of solar modules

The modules should be close to the control unit and batteries to minimize voltage drop along the cables.
The modules should be upwind from kitchen fires and dusty roads to minimize build-up on the glass of ashes and other dirt carried by the wind.

Modules should not be mounted in a place where shadows of big trees or other tall objects can prevent the maximum amount of sunlight reaching them. Even a small shadow on just one cell can affect the performance of the whole module.

8.2.1.2 Procedure for checking shadows

One way to check for shadows is to stand at the position proposed for the modules. Look at all parts of the sky that the sun passes across over a year. Table 8.1 lists a number of angles that may be helpful in finding the positions of the sun at various times. While looking at these positions, check that no objects appear between you and the sun that could cast a shadow on the modules.

This is the procedure for using Table 8.1:

i. Stand at the proposed place for the modules.
ii. Mark a line on the ground starting at your feet and leading in the direction of north. A compass is needed for this.
iii. Select the row in Table 10.1 with the right range of latitude for the site and note the six angles for bearings and angle above the horizon at midday.
iv. Use a protractor to find bearing angles from north. Draw lines or place straight objects on the ground for marking the four bearings for sunrise and sunset.
v. Hold one arm out straight and slightly raised so that the tips of your fingers are at about 20 cm (8 in) above eye level. By looking over your finger tips, you are looking at the height of the sun above the horizon at about one hour after dawn.
vi. For sunrise, swing your arm between the bearing angles for 21 June and 21 December. Check for objects above your fingers that might cause shadows.
vii. Repeat step 6 for the sunset angles.
viii. For the position of the sun at midday, use the angles from the middle pair of columns in table 8.1.

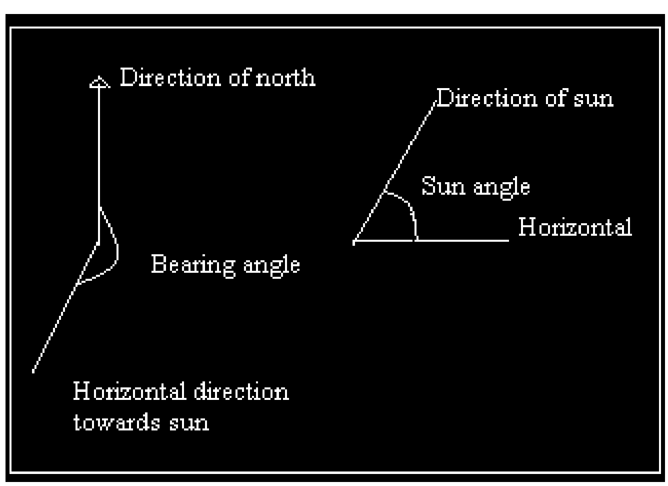


Table 8.1 Angles of the sun above the horizon at different times of the day and year. These are used for checking that obstacles will not form shadows over the modules. The sunrise bearings are for one hour after the sun has risen above the horizon (horizontal skyline). The sunset bearings are for one hour before the sun reaches the horizon.

Latitude	Bearing one hour After sunrise		Angle above Horizon at midday		Bearing one hour Before sunset	
	21 June	21 Dec.	21 June	31 Dec.	21 Jun	21 Dec.
60°-50° S	35°	120°	10° N	60° N	325°	240°
50°-40° S	45°	115°	20° N	70° N	315°	245°
40°-30° S	50°	110°	30° N	80° N	310°	250°
30°-20° S	55°	110°	40° N	90°	305°	250°
20°-10° S	60°	110°	50°N	80° S	300°	250°
10°S-0°	65°	115°	60° N	70° S	295°	245°
0°-10° N	65°	115°	70° N	60° N	295°	245°
10°-20° N	70°	120°	80° N	50° S	290°	240°
20°-30° N	70°	125°	90°	40° S	290°	235°
30°-40° N	70°	130°	80° S	30° S	290°	230°
40°-50° N	65°	135°	70° S	20° S	295°	225°
50°-60° N	60°	145°	60° S	10° S	300°	215°

8.2.1.3 Mounting arrangement

There are several aspects to remember for the mounting arrangement:

- Rigid and secure.
- Accessible for cleaning.
- Kept cool.
- Tilt angle.
- Tilt direction.

- Tracking option

Modules can be mounted on a frame at ground level set in concrete and an example is shown in Figure 8.1(a).

The alternative to mounting at ground level is on a pole or a roof (see Figure 8.1(b)). The direction of tilt should be to the north or south to within 20°, which may restrict the choice of roof.

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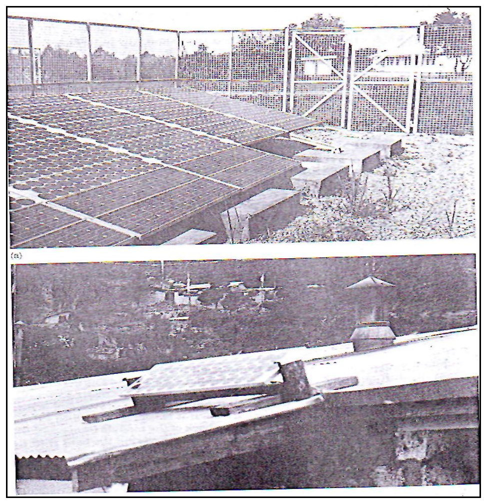


Upper one (a), lower one (b)

Figure 8.1 Examples of methods for mounting modules.
(a) Large array of modules mounted on an aluminium frame. The array is surrounded by a high fence to keep unauthorized people and animals away.
(b) Module mounted on a roof using a wooden frame.

Solar cells produce less electricity when they are hot. The mounting should be positioned where the wind can help to cool the module. Mounting directly on a roof made of iron sheets is not recommended because the sheets become very hot in direct sunlight.

Modules generate most electricity when facing the sun directly but the position of the sun in the sky changes through the day. The mounts shown in Figure 8.1 are the stationary type where the modules only face the sun directly a few times a year. To improve the positioning of the modules, their angle can be changed to follow the sun across the sky and this is called tracking.

8.2.2 Batteries

There are several points that must be considered when choosing a place to put the batteries:

- Moderate temperature.
- Ventilation.
- Security.
- Protection.
- Access.

8.2.2.1 Temperature

It is important to keep the batteries at a moderate temperature. The optimum range is 15-25 °C (60-80 °F) while the maximum is 10-35 °C (50-95 °F).

In hot climates, the batteries should be away from direct sunlight and as cool as possible. In cold climates, low temperatures are not as serious but the batteries should be kept close to living-quarters to avoid the lowest temperatures.

To prevent temperature differences developing across a battery, avoid both direct sunlight and positions next to heaters and pipes for radiators or steam. Batteries can be partially buried or insulated if temperature differences might be a problem.

8.2.2.2 Ventilation

During the charging of vented batteries, small amounts of hydrogen gas are produced. If there is no space above the batteries for the hydrogen to escape, it may collect there and create a danger of explosion. Therefore vented batteries must be in a place that is well ventilated.

A single battery in a small system serving a home releases very small amounts of hydrogen and can be positioned in living quarters quite safely. Sealed batteries do not release any gases under normal operation so they do not have any special requirements for ventilation. A large bank of vented batteries should be positioned away from living quarters, and gases from them should not be allowed to enter air vents to the living-quarters or heating and cooling systems.

8.2.2.3 Security

Batteries are expensive items of equipment and useful for other purposes. Therefore their position must be secure so that they are safe from theft. Also batteries should be secure from tampering by unauthorized people and children. Theft of batteries which look suitable for vehicles can be a problem. One solution is to use a battery bank made up from separate 2 V cells in groups of six instead of 12 V batteries. This makes transfer to a vehicle less tempting.

8.2.2.4 Protection

The batteries should be covered. If the batteries are not in a box, a strong wooden stand or other support should be used. This keeps each battery off the floor and a lid protects the terminals and connecting wires. The tops of the batteries should be easily accessible for routine cleaning and for measuring the state of charge. Also, the batteries should be kept horizontal.

The box and floor should be resistant to spillage of electrolyte (acid for lead-acid batteries and alkali for vented nickel-cadmium batteries). A strong plastic tray can be put under each battery to contain spillages from damaging other equipment. This is especially important if there is a risk of contaminating a water supply. For a wooden stand, the wood can be protected by two coats of epoxy paint.

8.2.2.5 Access

Clear access must be available to install the batteries and carry out maintenance. If batteries are heavy, provision for handling equipment should be provided. The place should have good illumination. A lamp may need to be installed on a separate circuit so that the batteries can be inspected if there is a problem at night.

8.2.3 Control unit

The control unit acts as the main junction point between the modules, batteries, and appliances. It contains the main switches, fuses, indicator lights, and sometimes meters to show how well the system is operating. There may also be a timer that is set each day for the lighting circuits.

Easy access is required to the control unit for adjustment of the controls and for inspecting the indicators. Therefore the unit should be mounted on a wall in an accessible place. However, in a system for an institution, access to switches may need to be restricted to prevent tampering.

Control units contain manual and automatic (relay operated) switches. These produce a small spark when opened. Manufacturers of the control units recommend that the units are not mounted too close to vented batteries unless the ventilation is very good. If the battery is in a box, the control unit should certainly not be mounted inside the same box.

8.2.4 Power inverter

For a large power inverter of more than 100 W capacities, a large current is drawn from the batteries. Therefore the inverter should be sited as close as convenient to the batteries to keep the cable short. Also a thick cable should be used to make sure the voltage drop is less than about 1 V. The smallest size of cable for a voltage drop of 1 V is calculated from the following formula:

$$\begin{array}{c}\text{Change}\\ \text{length}\\ \text{(m)}\end{array} \times \begin{array}{c}\text{Output}\\ \text{power}\\ \text{(W)}\end{array} \times \begin{array}{c}100\\ (\%)\end{array} \times \begin{array}{c}0.04\\ \left(\dfrac{V\,mm^2}{A\,m}\right)\end{array} \div \begin{array}{c}\text{Input}\\ \text{voltage}\\ \text{(V d.c.)}\end{array} \div \begin{array}{c}\text{Inverter}\\ \text{efficiency}\\ (\%)\end{array} = \begin{array}{c}\text{Smallest cable}\\ \text{to 1 v drop}\\ \text{(mm-square)}\end{array} \quad \ldots 8.1$$

From the output of the inverter, wiring must comply with standards and regulations for mains voltage. This means using fittings intended for mains voltage and an earthing system. Refer to electrical installation manuals for full details.

If the system includes a circuit with socket outlets for low-voltage d.c. appliances, a different style of socket outlet and plug is essential to avoid confusion with connections to circuits at mains voltage.

8.3 Installation

8.3.1 Mounting parts

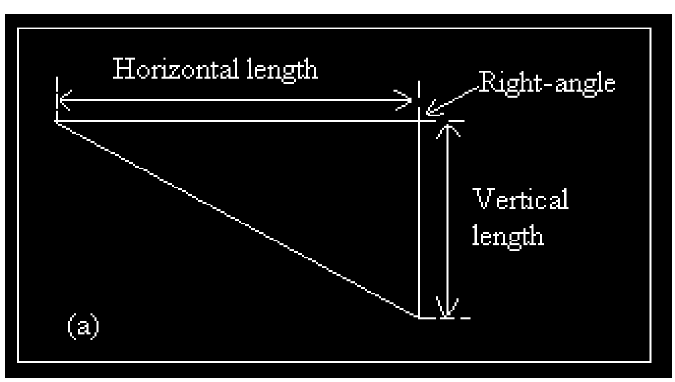
8.3.1.1 Solar modules

It is often easiest to make the electrical connections to modules when the modules are flat on the ground rather than mounted on the support structure. If this is the case, the modules and support structure are only prepared at this stage ready for permanent mounting of the modules during the wiring stage.

Setting the direction of tilt to north or south has to be accurate only to within 20° of the right direction. If the modules are mounted on a roof, adjustment of the direction may not be possible.

The direction of tilt can be checked using a compass to show the direction of north. Another method is to use the direction of the shadow from a vertical pole.

Ensure that the support structure sets the modules at the correct tilt angle. The tilt angle can be checked using a template with a spirit level or a plumb line. The template is a triangle with the shape shown in Figure 8.2(a).



(a)

Tilt angle	Lengths of sides			
	Dimensions (mm)		Dimensions (in)	
	Horizontal	Vertical	Horizontal	Vertical
15	500	135	20.0	5.4
20	500	180	20.0	7.3
25	500	235	20.0	9.3
30	500	290	20.0	11.5
35	500	350	20.0	14.0
40	500	420	20.0	16.8
45	500	500	20.0	20.0
50	420	500	16.8	20.0
55	350	500	14.0	20.0
60	290	500	11.5	20.0
65	235	500	9.3	20.0
70	180	500	7.3	20.0
75	135	500	5.4	20.0
80	90	500	3.5	20.0
85	45	500	1.7	20.0

(b)

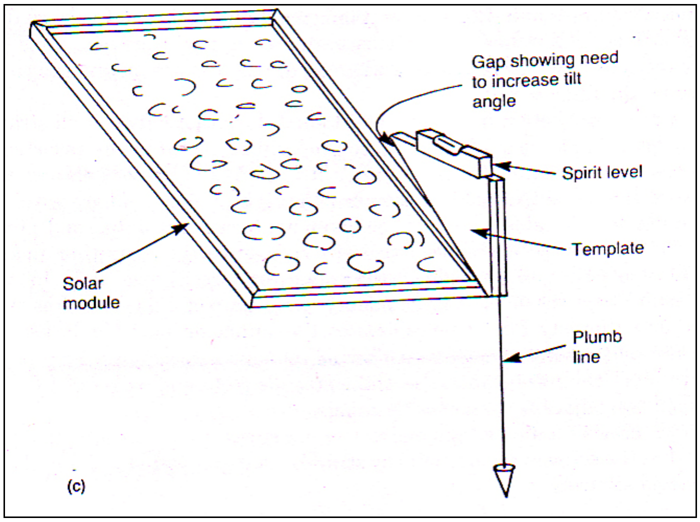


Figure 8.2: Template for setting and checking the tilt angle of modules.

(a) Outline of template.

(b) Table of dimensions for a range of tilt angles.

(c) Method of using template with a spirit level or plumb line on a module. In this example, the tilt angle of the module needs to be increased.

Using 500 mm (20 in) for the length of one side, the length of the other side is given in Figure 8.2(b) for a number of tilt angles. Cut the template from a stiff material, such as cardboard or wood, that will not scratch the glass.

Figure 8.2(c) shows a spirit level or a plumb line being used to set the template in the correct position. The gap between the module and the long side of the template indicates the amount of adjustment required to the tilt angle.

8.3.1.2 Control unit

Control units should be securely attached to a wall at eye level. One method is to attach them to a wooden sub-board with the connections taken behind the hinged panel of the sub-board. Otherwise attach the unit directly to a wall with screws into plastic or wooden rawl plugs. If the wall is not hard enough for rawl plugs, use threaded rods through the whole thickness and put nuts on both sides of the wall. Mark, where the holes have to be drilled by putting the regulator on the wall and checking its position with a spirit level.

8.3.1.3 Wiring the system

The first stage of wiring can be done by an electrician or any other person who has experience of wiring mains-type systems. It involves connecting all the circuits for the appliances and laying the wires ready for connection to the solar modules, batteries, and control box. The final connections are made in a particular order to prevent damage to equipment.

8.3.2 Connections to the solar modules

No wires should be connected to the modules at this stage but the wires can be prepared. Connections to modules are either to screw terminals injunction boxes or to a pair of wires that are already sealed into the back. Junction boxes have a gland fitting which seals onto the cable or conduit to prevent water leaking into the box.

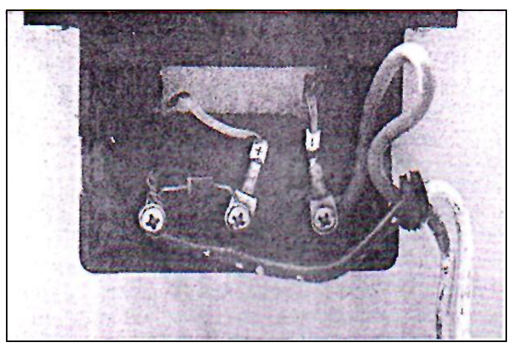


Figure 8.3: Example of a junction box with the cover removed on a module. This box contains a blocking diode connected to the positive output of the module. If the blocking diode is not required at the module, the wire is connected directly to the' + ' screw terminal instead.

Some modules have diodes fitted in the junction box (see Figure 8.3). Check their identity with the module instructions before preparing the connections. Bypass diodes should always be left in place. If the control unit already contains a blocking diode or has some means of preventing discharge at night, any blocking diode on the module should be removed.

8.3.3 Series and parallel connections of modules

When there is more than one module, connections between the modules are necessary to put them either in series, in parallel, or a combination of series and parallel. Examples of these connections are shown in Figure 8.4. It is very important to understand the connections and to avoid the risk of making the wrong series connections by mistake.

Parallel connections are used to increase the current output of the array of modules. They are made by connecting like terminals (negatives connect to negatives and positives connect to positives). For modules with separate junction boxes for positive and negative, all the positives should be at one end for ease of connection (see Figure 8.4(a)). Figure 8.4(b) shows the arrangement for modules with single junction boxes. It also shows use of a single diode if blocking diodes are not provided in each module or a control unit. Make sure that the end of the diode with the stripe is connected towards the control unit.

Modules are connected in series to increase the system voltage. The positive of one module is connected to the negative of the next module. When grouping modules with series connections, modules are in the same group that must have the same current output and be mounted next to each other on the support structure. They should also be of the same type so that their outputs are exactly matched when generating electricity.

Figure 8.4(c) shows the arrangement for 24 V operation using modules with separate junction boxes. The modules alternate in direction to keep the wires short. For modules with single junction boxes, the parallel connections between series groups of modules should be made in a separate junction box to avoid mistakes (see Figure 8.4(d)).

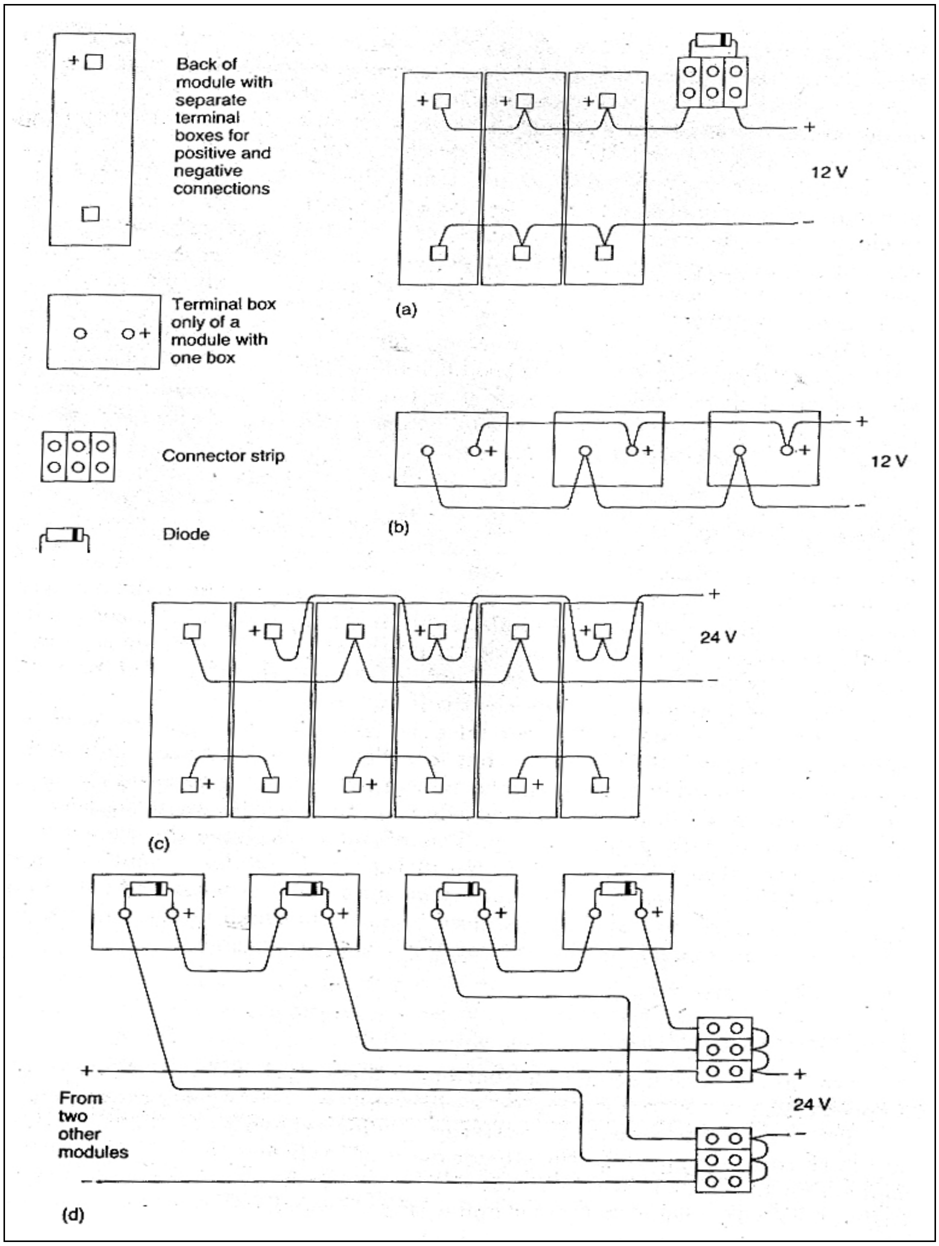


Figure 8.4: Connecting arrays of modules.

(a) For a system voltage of 12 V and modules with separate terminal boxes for positive and negative. Connection of a blocking diode, if required, is shown using a connector strip. (The current rating of the diode must be greater than the total short circuit currents of the modules.)
(b) For a system voltage of 12 V and modules with a single terminal box each.
(c) For a system voltage of 24 V and modules with separate terminal boxes for positive and negative.

(d) For system voltage of 24 V and modules with a single terminal box each. If bypass diodes are not already fitted in the modules, the positions are shown. (The current rating of the diode must be greater than the short circuit current of the module in which it is used.)

8.3.4 Bypass diodes

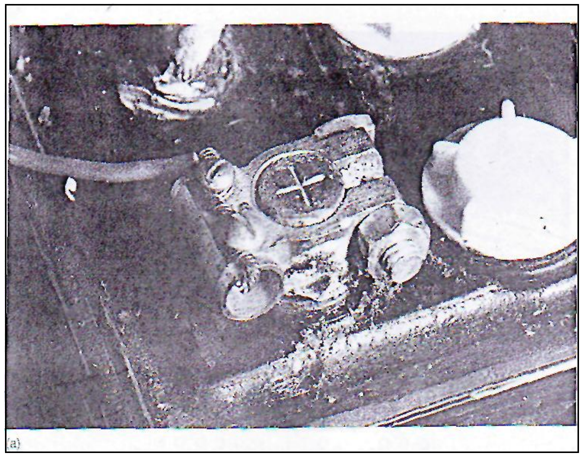
For systems operating at 24 V or higher, bypass diodes are required for each module. If bypass diodes are not already fitted in modules by the manufacturer, they can be added across the terminals as shown in Figure 8.4(d). Silicon diodes should be used with a higher current rating than the maximum short circuit current of the other series-connected module. Make sure that the end of the diode with the stripe is connected to the positive.

When the voltage of the modules is less than the system voltage, Figures 8.4(c) and 8.4(d) show that parallel connections are made after modules are grouped in series up to the system voltage. If it is necessary to have parallel modules within series strings, add an extra diode between the positive and negative of each parallel group. This diode should have the capacity to conduct the total current of the whole parallel group of modules. A heat sink may be necessary to ensure that the diode does not over-heat when in use. This large extra diode is required because the small internal diodes in each module may not share current equally in this arrangement.

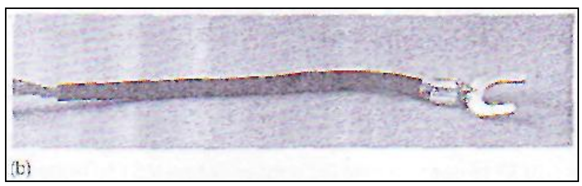
8.3.5 Battery connections

No wires should be connected to the battery at this stage but the connections can be prepared.

The brass terminals used for batteries in vehicles have a large hole to accept the thick cable that leads to the starter motor. This hole is too large for a good connection to be made with the sizes of wire used in solar electric systems. Instead the wires should be twisted and wrapped around the screw heads on the terminal, as shown in Figure 8.5(a). This is necessary to ensure maximum contact with the terminals when the screws are tightened.



(a)



(b)

Figure 8.5 Connections to batteries.
(a) Wires twisted around screws on a brass terminal clamp.
(b) Spade connector crimped on to wire.

Another method of connection is by spade connectors, as shown in Figure 8.5(b). They are often used for wiring in vehicles because the connections are quick to make, neat, and reliable. Joining the spade connector to the end of a wire requires the correct crimping tool. The joint can be made by squeezing with pliers and soldering but it is not as strong. If tools are not available at the installation or are inconvenient to carry there, the wires could be prepared before hand elsewhere.

8.3.6 Connections to the control unit

No wires should be connected to the control unit at this stage but the wires can be prepared.

There is a great variety of different control units with their own system of connections. The instructions supplied with the unit should be read carefully before any wires are prepared.

The usual system of connections is pairs of terminals for cables to the modules, batteries, and load circuits. Terminals for the charging current from the solar modules may be marked 'array'. This name describes the way a group of modules is neatly arranged on the mounting structure to face the sun.

For the batteries, there may be two pairs of terminals marked 'battery' and 'battery sense'. The battery sense pair is required so that the control unit can accurately measure or 'sense' the voltage across the battery terminals. The battery voltage is used for regulating the charging current and triggering the low-voltage disconnect (for control units fitted with these features).

When the cable to the batteries is more than a few meters long or connecting several batteries, there will be a significant voltage drop along the cable when it carries a high current. This means that the voltage measured at the control unit will be less than the voltage- across the battery terminals. A separate cable should link the battery terminals directly to ‘battery sense’. The cable can be as small as the test leads used for a voltmeter since it carries a very small current.

One advantage of having sense wires is that the true voltage of the battery is checked even if connections carrying the current have deteriorated.

In small systems, the 'battery sense' terminals can be linked directly to the 'battery' terminals at the control unit. This is when there are only one or two batteries at less than 2 m (6 ft) from the control unit.

There is usually one pair of terminals marked 'load' to supply the appliances. If there are several pairs of terminals, they can be used for separate circuits serving different groups of lamps and power outlet points. A relay may be included for a low-voltage disconnect of the loads or alarm circuits. The relay connections are called voltage free and can be used just like any other switch.

8.3.7 Final connections

The final connections should be done carefully. Follow instructions from suppliers where given and the guidance in this section. If possible, get help from someone who has some experience in installing solar systems successfully. Before starting the final connections, the following jobs should be complete:

- Modules ready for mounting on their support structure.
- Batteries charged and in place.
- Fixed appliances and socket outlet points wired up to the control box but not connected to it.
- All cables cut and fixed in position but no connections made to batteries, control unit, or modules.

The order of final connections is as follows:

1. Measuring electrical output of modules (open circuit voltage, short circuit current) and completing installation of the solar array.
2. Connecting batteries.
3. Connecting the solar array to the control unit.
4. Connecting circuits for the appliances.

8.3.7.1 Installation and wiring of solar array

The exact order of steps for completing the wiring to the modules and attaching the modules to the support structure is not definite. It varies with the type of connections, number of modules in the solar array, and ease of working on the support structure.

Making the connections to the back of the modules is usually easiest with the modules laid glass side down on level ground. Use the packing material as protection to avoid damage to the glass. The modules are then attached to the support structure before completing the wiring to the control unit and batteries.

Here are some points to note:

- Ensure that the ends of the wires in the main cable to the control unit are covered so that they cannot touch each other or any other connections and bare wires.
- When working on the electrical connections of a module that is installed, try to work early in the morning or late in the evening when modules generate low currents. If work must be done around midday, cover the front of the module with a thick sheet or cloth.
- If series connections are required between modules, make these bringing each series group of modules up to the system voltage. Measure the voltage of each series group (If covers are being used, remove these for the measurement and then replace.). If the measurement is not above the system voltage, check the connections.
- Once the wiring is complete, measure the voltage of the whole solar array. (If covers are being used, remove these for the measurement and then replace.) If the measurement is not above the system voltage, check the connections.

For small systems with just one module, it is not essential to measure the electrical output of the module during installation. However, making measurements is recommended, especially for a solar array which has several modules.These measurements help check that the wiring is correct and help in solving problems that might arise when one part of the solar system fails to work properly.

8.3.7.2 Connecting batteries

1. If series connections are required, make these, bringing each series group of batteries up to the system voltage.
2. Measure the voltage of each series group. If it is not at the system voltage, check the connections. If any individual battery has too low a voltage, it must

be replaced.

3. If "battery sense' wires are being used, connect these to one battery or series group of batteries and at the control unit. The control unit should now indicate full charge. Disconnect these wires.
4. Make the main positive and negative connections for the battery wires at the control unit.
5. Ensure that the bare ends of the positive cables are well clear of the positive terminals of the batteries.
6. Fit the negative cables to each series group of batteries first. Tighten each clamp just enough to hold it on to the terminal.
7. Take one positive cable and briefly touch it against the positive terminal on one battery. There may be some small sparks or no sparks at all. Any sign of a large spark suggests a problem in the wiring to the control unit or in the control unit itself. Check these parts.
8. If there are no sparks from the test in step 7, proceed to fit all the positive cables to the positive terminals. Reconnect the sense connections from step 3.

8.3.7.3 Connecting the solar array to the control unit

Try to work early in the morning or late in the evening when the solar array only generates a low current. If work must be done around midday, cover the front of the solar array with a thick sheet or cloth. Make sure that the array is completely covered, taking care not to scratch the surface of the glass fronts as the cover is pulled across.

1. Make the negative connection for the solar array cable at the control unit.
2. Briefly touch the positive wire of the solar array cable against the positive terminal on the control unit. There should be no sparking. Any sign of a large spark suggests a problem in the wiring to the control unit or in the control unit itself. Check these parts.
3. If there are no sparks from the test in step 2, proceed to connect the positive wires securely.

4. If a cover was used, remove it.
5. If there is a charging indicator on the control unit, it should now show charging. (Some control units have a slight delay in operation when they are first connected so the charging indicator may not light up immediately.) Measure the voltage at the control unit. It should be above the system voltage.

8.3.7.4 Connecting circuits for appliances

1. Turn off all lighting switches.
2. Fit tubes and bulbs in all lamps.
3. Unplug any appliances from socket outlet points.
4. Turn off circuit switches or remove main fuses.
5. Complete the negative connections for the appliance circuits.
6. Touch one positive wire for the appliance circuits against the positive terminal on the control or junction box. Watch for sparks. If there are any, check that all appliances are off. Repeat the touching test. If there are still sparks, inspect all the wiring to the appliances for mistakes.
7. When the touching test does not give sparks, complete the positive connection. .
8. Turn on the load circuits by switches and fuses in the control box.
9. In each room, turn on the lamps. If the lamp does not light, turn off immediately and leave for later examination. Leave on lamps that do work.

8.3.8 Finishing off

- Check that all lamps, power outlet points, and appliances work as expected.
- Turn on all the lamps and appliances. At the main switch on the control unit, turn the appliance circuits off and back on. This ensures that the rating of the main fuses is not too low.

- Switch all the appliances off. Then remove each clamp from the battery terminals in turn. Coat each clamp with petroleum jelly or some other available grease. Wipe away excess from the contact surfaces. Refit to the battery terminal, twisting slightly to ensure metal-to-metal contact between the clamp and the terminal. Tighten up the clamp. Do not over-tighten since the clamp needs only to be firm enough to prevent movement.
- Replace the lids of the junction boxes on the modules and elsewhere. If a rubber gasket is used, make sure it is properly located. Do not over-tighten the screws holding each lid on. Seal any holes that may let in rain-water with silicone mastic or pitch.
- Cover all bare wires.
- Paint any exposed parts that require protection from the weather.
- Mark each battery with a different letter (A, B, C ...) for ease of record keeping.
- If a ladder is used to reach the modules, make sure that it is locked away to prevent unauthorized access to the modules and theft.
- Complete documentation (see below).
- Plan for the first service after one month and then at twelve-month intervals.

Chapter 9

Maintenance and Cost of PV System

9.1 Introduction

Photovoltaic (PV) is an important energy technology for many reasons. As a solar energy technology, it has numerous environmental benefits. As a domestic source of electricity, it contributes to the nation's energy security. As a relatively young, high-tech industry, it helps to create jobs and strengthen the economy. As it costs increasingly less to produce and use, it becomes more affordable and available.

It's highly reliable and needs little maintenance. It costs little to build and operate. It has virtually no environmental impact. It's produced domestically, strengthening our economy and reducing our trade deficit. It's modular and thus flexible in terms of size and applications.

9.2 PV System Maintenance

PV systems require very little maintenance. Grid inter-tied PV systems without battery back-up require virtually no maintenance at all. If the PV racks require manual adjustments each season, this task must be carried out according to the appropriate schedule. If a tracking rack is used some minimal maintenance will be needed to keep moving parts in working order. Installation documentation for Wattsun active tracking racks, Zomeworks passive tracking racks, and other systems cover maintenance for their equipment. Typically, various parts are greased and the tightness of nuts is checked once a year. Most stand-alone battery-based systems are wired at a lower voltage than grid-intertied systems. For this reason ensure that all low voltage DC wire connections in a battery based system are clean and tight. This is particularly important for connections at the battery and the contacts on the inverter, especially if the inverter has a large output. A system monitor is a necessity for stand-alone battery based systems of all sizes, except perhaps very small systems, such as sign lights, fence chargers, etc.

Scheduled maintenance is needed twice a year. Around noon on a sunny day is an ideal time to perform maintenance. A homeowner with neither the necessary instrumentation nor the electrical knowledge might consider contracting with an electrician to perform maintenance and inspection of the PV system.

9.3 Maintenance Steps

9.3.1 Step 1: At the Inverter

Use a voltmeter and a DC ammeter to check and record the inverter's operating DC input voltage and current level and on the AC side, and the inverter's output voltage and current levels. Check that the appropriate LEDs are lit up to indicate proper operation of the inverter. If the inverter can display the total kWh produced since it first started up, record the amount. Use this number to compare the PV system's production since the last inspection.

9.3.2 Step 2: On the Roof

Note and record the condition of the modules. Look for signs of degradation (for example, color changes, fogged glazing, de-lamination, warping, or water leaks), cracked glazing, and bent frames on the modules. Tighten all loose nuts and bolts, holding the modules to the mounting rack and to the mounting clips. Secure any loose wiring under the modules. Check the wiring for signs of chewing by squirrels, and look for cuts, gashes, or worn spots in the wiring's insulation. Replace any damaged wire runs. Check the frame ground connections between modules and from the modules to the junction box(es). Check to see that the sealants around all building penetrations are in good condition and repair if necessary. Open the junction box(es) and look for and correct any dirty, loose, or broken connections. Test the tightness of each connection and tighten all loose ones. Note any problems that can be corrected at a later time or at the next scheduled inspection time. Close the junctions box(es) and check that all conduit connections are tight.

Remove all sources of shade on the array and rinse the array to remove the accumulated dust, dirt, and other debris. Some debris, such as bird droppings, may need to soak a bit to fully remove it.

9.3.3 Step 3: At the Combiner Box

Open the combiner box and look for any dirty, loose, or broken connections, and correct as necessary. Use a voltmeter and DC ammeter to measure and record the array's operating voltage and current level on the output side of the combiner box. Note the relative sun conditions at the time (i.e., full sun, partly cloudy, heavy overcast). Remove the fuses and then check and record each string's open circuit voltage and current levels. Note any deviation between strings for future correction. You can also use the open circuit measurements to determine if the array's output is degrading over time. Return the fuses and close the combiner box.

9.3.4 Step 4: Inside

Open all disconnect switches. Use the ohmmeter section of the voltmeter to check the grounding system connections. Greater than 25 ohms indicates that corrosion or a poor connection is present, which must be located and corrected. If opening the disconnect switch breaks the ground, you need to rewire the switch to correct the problem. Check each of the disconnected sections for a ground-fault condition any that are found.

9.3.5 Step 5: Back at the Inverter

turning the inverter off and check for dirty, loose, or broken wires and connections. Check for and repair any ground faults. Power the system up. Check for normal start up operation and that the inverter produces AC electricity.

9.4 Battery Maintenance

Of all the components in a solar electric system, the battery bank requires the most maintenance in order to ensure a long life. The greatest problems with batteries occur when more electricity is consistently withdrawn than is put back into them. This usually occurs during the winter months when batteries may go weeks without being fully recharged. Standard liquid electrolyte deep cycle lead acid batteries should be brought up to a complete charge at least every three weeks. Leaving them discharged over long periods of time will cause a coating of sulfate to crystallize on the surface of the internal plates. This impedes the normal charging process of the battery, and the battery will start to behave like a smaller battery. To remedy such a situation the batteries must be overcharged in a controlled fashion to drive off the sulfate coating.

When batteries are left discharged for extended lengths of time, unequal cell charge levels can also result. It is wise to test all cells every three months with a hydrometer, which measures the specific gravity of the electrolyte in the battery. Hydrometers can be bought from solar dealers and auto parts stores. Most batteries are full at a specific gravity of 1.265 and are overly-discharged if below 1.175. Batteries have multiple cells. If the cell measurements are unequal by a difference of more than 0.02, manually overcharge the batteries through an equalization charge which will cause the lesser cells to come up to the specific gravity of the rest of the battery pack. An equalization charge is a controlled overcharge, which is often accomplished by pressing a switch on the charge controller that allows the charger to slightly overcharge the batteries for a set length of time. Some charge controllers will even do this automatically on a regular schedule. In non-automatic systems, a manual charge control bypass switch can be used to equalize the batteries, but this requires careful monitoring and an understanding of the process. When using a hydrometer (or doing anything else around batteries), always follow battery and hydrometer manufacturers' cautions regarding safety. Battery acid is dangerous, especially to eyes.

The electrolyte level for each cell in a battery will have to be checked at least every three months. This is especially important during summer months. Only distilled water should be used to bring the electrolyte up to its proper level. This should be done when the batteries are near full, but not while being charged heavily. Often when distilled water is added to a discharged battery, the electrolyte will be overfilled and spill out of the battery when it becomes fully charged.

Keep battery tops clean and dry by wiping them occasionally with a rag. Wet, acidy tops provide a conductive path between terminals resulting in energy loss and more corrosion. If evidence of cruddy green buildup appears on the tops of batteries they should be wiped off with distilled water, then wiped dry. If there is heavy corrosion you might consider diluting a small amount of baking soda in the cleaning water. Be aware that this runs the risk of getting some of the baking soda solution into the battery cells, which is not good for them. Do without the baking soda for cleaning purposes if you can. However, it is a very good idea to keep a box or two of baking soda near the battery bank in case a spill ever occurs. The baking soda can be dumped on the spill to neutralize it. In an enclosed space batteries should be vented to the outside. An enclosed box with a 1" pipe venting above the battery tops to the outdoors will suffice.

Batteries are the nasty part of a PV system and usually warrant being located outside of living spaces (but still indoors). Be careful around batteries. They contain strong acids. Rubber gloves and safety glasses are minimum safety measures when working with them.

9.5 System Troubleshooting:

Troubleshooting in a PV system usually means:

- A load does not operate properly or not at all;
- The inverter does not operate properly or not at all; or
- The array has low or no voltage or current.

A qualified electrician should check and correct electrical problems in a PV system, since homeowners are unlikely to be qualified to perform such work.

9.5.1 Load Problem

The first step is to check all switches. Are they turned off, or in the wrong position? If so, turn them on or put them in the correct position. Also check to see that the load is plugged in. With a voltmeter check to see that the proper voltage is present at the load's connection. Next check the fuses and circuit breakers. Are there blown fuses or tripped breakers? If so, locate the cause and fix or replace the faulty component. If there are no blown fuses or tripped breakers and the load is a motor, an internal thermal breaker may be tripped or there may be an open circuit in the motor. Plug in another load and note its operation.

Check for broken wires and any loose connections. Clean all dirty connections and replace all bad wiring. With the power off, check for and repair any ground faults. Replace the fuses and reset the switches. If they blow or trip again, there is a problem short, which must be located and repaired.

If the load does not operate properly, check the system's voltage at the load's connection. Low voltage could mean that the wire feeding the circuit is too small and too long and needs to be upgraded to reduce the voltage drop. The load also could be too large for the wire size in the circuit. Reduce the load on the circuit or run larger wire that is sized for the current load.

9.5.2 Inverter Problem

A lack of power output from the inverter could be caused by a blown fuse, tripped breaker, a broken wire, a ground fault, or any of the inverter's internal disconnects (high and low voltage and current). The load on the inverter may have too high of a current demand. Reduce the loads or replace the inverter with one with a larger output.

With the power off, check for and repair any ground faults before starting the inverter again.

The utility's voltage and frequency are sensed by the inverter, which normally produces AC electricity at the same voltage and frequency. The AC current output from the inverter fluctuates with the level of solar insolation on the array. Low or high utility voltage sensed by the internal disconnects will cause the inverter to shut down. Contact the utility to correct the problem on its side.

Inverter problems could also be caused by a problem on the array side of inverter that trips one of the internal disconnects.

9.5.3 Array Problem

Prior to getting on the roof, check and record the inverter's input voltage and current level from the array. If the array is not producing DC electricity, check all switches, fuses, and circuit breakers. Replace blown fuses and reset the breakers and switches. A spurious surge may have passed through, tripping or blowing the protective devices.

Check for broken wires and loose or dirty connections in the inverter. Replace all damaged wires and clean and tighten all connections.

Visually check the array for obvious damage to the modules and wiring. Repair as needed and replace all damaged wiring.

Having a fused combiner box can save a lot of time when checking each module or sub-array string. Remove the fuses and then check and record the open-circuit voltage and current reading for each circuit string.

If the output voltage is low, it could indicate that some modules in the series string are defective or disconnected and need to be replaced. Defective blocking or bypass diodes in the modules may need to be replaced. Low voltage also could be caused by the wrong wiring connecting the modules in the string to the junction box or combiner box or the inverter. The wiring could be either sized too small or the wire run is too long for the string's output current level. Upgrading the wire size for the current level should correct this problem.

Low current output could be caused by cloudy conditions, a defective blocking or bypass diode, a damaged module, one or more parallel connection between modules in the string is broken, loose, or dirty, or some parallel connections the module are broken, loose, or dirty. Replace a damaged module or one with internal parallel connection problems. Replace defective diodes and clean and tighten all connections. Some of the array may be shaded, significantly reducing the array's current output. Remove the shade source to regain the string's full current output.

Dirty modules also could cause reduced current output. Wash the modules to restore the array's current output.

9.6 Photovoltaic Costs:

For many applications, especially remote site and small power applications, PV power is the most cost-effective option available, not to mention its environmental benefits. New PV modules generally retail for about \$5 per peak watt, depending on quantities purchased. Batteries, inverters, and other balance of system components can raise the overall price of a PV system to over \$10 - \$15 per installed Watt. PV modules on the market today are guaranteed by manufacturers from 10 to 20 years, while many of these should provide over 30 years of useful life. It is important when designing PV systems to be realistic and flexible, and not to over design the system or overestimate energy requirements (e.g., overestimating water-pumping requirements) so as not to have to spend more money than needed. PV conversion efficiencies and manufacturing processes will continue to improve, causing prices to gradually decrease.

PV conversion efficiencies have increased with commercially available modules that are from 12 to 17 percent efficient, and research laboratory cells demonstrate efficiencies above 34 percent. A well-designed PV system will operate unattended and requires minimum periodic maintenance, which can result in significant labor savings. PV modules on the market today are guaranteed by the manufacturer from 10 to 25 years and should last well over 30 years. PV conversion efficiencies and manufacturing processes will continue to improve, causing prices to gradually decrease, however no dramatic overnight price breakthroughs are expected.

9.6.1 Estimating PV System Size and Cost:

The worksheet presented here will help you estimate the size and cost of a PV system. The analysis is conducted in two sections. In the first section, we derive the system specifications by determining the load, available sunlight, and the size of the PV array and battery bank needed. In the second section, we convert the system specification into a cost for the PV system. Let’s walk through the analysis, step by step.

9.6.1.1 Step-1: Determine Load, Available Sunlight, PV Array Size, and Battery Bank Size

1.a Determine Load:

The preferred method for determining PV system loads is a “bottom-up” approach in which every daily load is anticipated and summed to yield an average daily total. For PV systems designed to power simple loads, such as a single water pump, electric light or other appliance, this method is easy. Simply look at the nameplate power rating on the appliance to calculate its power consumption in watts (some labels show amperage and voltage only; to obtain watts, just multiply amps by the voltage). Then multiply by the number of hours it is expected to operate on an average day to obtain watt-hours (Wh). For more complex loads, such as powering a whole house, you will need to estimate all the different loads in the house on a typical day and sum them.

Appliance	AC or DC Watts		Hours Used/ Day		Watt Hours/ Day
Ceiling Fan	100	x	6.0	=	600
Coffee Maker	800	x	0.3	=	150
Clothes Dryer	4,856	x	0.8	=	3,885
Computer	75	x	2.0	=	150
Computer Monitor	150	x	2.0	=	300
Dishwasher	1,200	x	0.5	=	600
Lights, 4 Compact Fluorescents	4x15	x	5.0	=	300
Microwave Oven	1,300	x	0.5	=	650
Radio	80	x	4.0	=	320
Refrigerator	600	x	9.0	=	5,400
Television	300	x	8.0	=	2,400
Vacuum Cleaner	600	x	0.2	=	120
VCR	25	x	8.0	=	200
Washing Machine	375	x	0.5	=	188
Total					15,483

Table 9.1: Typical household electrical appliances and run times

Table 9.1 provides an example calculation for a household using this method. For complex loads like households, it is sometimes difficult to anticipate every electric load. Electric clocks, TVs, stereos and other appliances sometimes draw small amounts of power even when they are turned off. For this reason, we recommend multiplying your estimated daily load by a "fudge factor" of 1.5. Some other elements accounted for by this factor are all the system efficiencies, including wiring and interconnection losses, as well as the efficiency of the battery charging and discharging cycles. Of course, for grid-connected systems, you can simply review your monthly utility bills to get an accurate idea of monthly energy consumption.

1.b. Determine Available Sunlight:

The amount of useful sunshine available for the panels on an average day during the worst month of the year is called the "insolation value." (We use the worst month for analysis to ensure the system will operate year-round.) In most of Texas, average solar insolation values range from about 3.3 to 5.0 hours per day in December, with the lowest values in east Texas and the highest values in the Panhandle and far west Texas. The insolation value also can be interpreted as the kilowatt-hours per day of sunlight energy that fall on each square meter of solar panels at latitude tilt.

1.c. Determine PV Array Size: For a PV system powering loads that will be used every day, the size of the array is determined by the daily energy requirement (1.a.) divided by the sun-hours per day (1.b.). For systems designed for non-continuous use (such as weekend cabins), multiply the result by the days per week the loads will be active divided by the total number of days in the week. For example, for a weekend cabin, multiply by 2/7. Generally, grid connected systems are designed to provide from 10 to 60% of the energy needs with the difference being supplied by utility power.

1.d. Determine Battery Bank Size: Most batteries will last longer if they are shallow cycled–discharged only by about 20% of their capacity–rather than being deep-cycled daily. A conservative design will save the deep cycling for occasional duty, and the daily discharge should be about 20% of capacity. This implies that the capacity of the battery bank should be about five times the daily load. It also suggests that your system will be able to provide power continuously for five days without recharging (such as during a winter storm). Multiply the daily load (1.a.) by 5, and then divide the result by the voltage of the battery bank you will use (typically 12 volts). The result is the recommended amp-hour rating of the battery bank. If you wish to be more secure and design for more days of cloudy weather multiply by a number greater than 5. However, it is generally not recommended to design for more than 12 days of cloudy weather unless it is a highly critical load. Of course, you can skip this step entirely if your system does no incorporate a battery bank such as a water pump, or is grid-connected since the availability of grid power obviates the need for storage.

9.6.1.2 Step-2: Calculate PV System Costs

2.a Estimate PV Array Cost:

Many PV modules can be purchased at retail for about $5 per watt for most small systems in the 150 – 8,000 watt range. Of course, there are opportunities to purchase modules for a lower price, especially when your system is larger and you can buy in bulk. When purchasing modules are looking for a UL listing (which certifies that the modules meet electrical safety standards) and long-term warranties, some manufacturers offer modules with 10-20 year warranties.

2.b Estimate Battery Bank Cost (if needed):

Many flooded lead acid batteries designed for use with PV systems can be purchased at retail for under $1 per amp-hour.

2.c Estimate Inverter Cost (if needed):

An inverter will be needed for systems that output AC power. For stand-alone systems the inverter should be sized to provide 125% of the maximum loads you wish to run simultaneously at any one moment. For example, if the total loads you wish to run will be 1,600 watts (a dishwasher, television and ceiling fan from Table 1) choose an inverter with a rated continuous power output of 2,000 watts. For grid-connected systems the maximum continuous input rating of the inverter should be about 10% higher than the PV array size to allow for safe and efficient operation. The input rating of the inverter should never be lower than the PV array rating.

2.d Estimate Balance of System Cost:

Besides PV modules and batteries, complete PV systems also use wire, switches, fuses, connectors and other miscellaneous parts. We use a factor of 20% to cover balance of system costs.

9.7 Economic and Environmental Considerations

The most important factor driving the solar energy system design process is whether the energy it produces is economical. Although there are factors other than economics that enter into a decision of when to use solar energy; i.e. no pollution, no greenhouse gas generation, security of the energy resource etc., design decisions are almost exclusively dominated by the 'levelized energy cost'. This or some similar economic parameter, gives the expected cost of the energy produced by the solar energy system, averaged over the lifetime of the system. In the following chapters, we will provide tools to aid in evaluating the factors that go into this calculation.

Commercial applications from a few kilowatts to hundreds of megawatts are now feasible, and plants totaling 354 MW have been in operation in California since the 1980s. Plants can function in dispatchable, grid-connected markets or in distributed, stand-alone applications. They are suitable for fossil-hybrid operation or can include cost-effective storage to meet dispatch ability requirements. They can operate worldwide in regions having high beam-normal insolation, including large areas of the southwestern United States, and Central and South America, Africa, Australia, China, India, the Mediterranean region, and the Middle East, . Commercial solar plants have achieved levelized energy costs of about 12-15¢/kWh, and the potential for cost reduction are expected to ultimately lead to costs as low as 5¢/kWh.

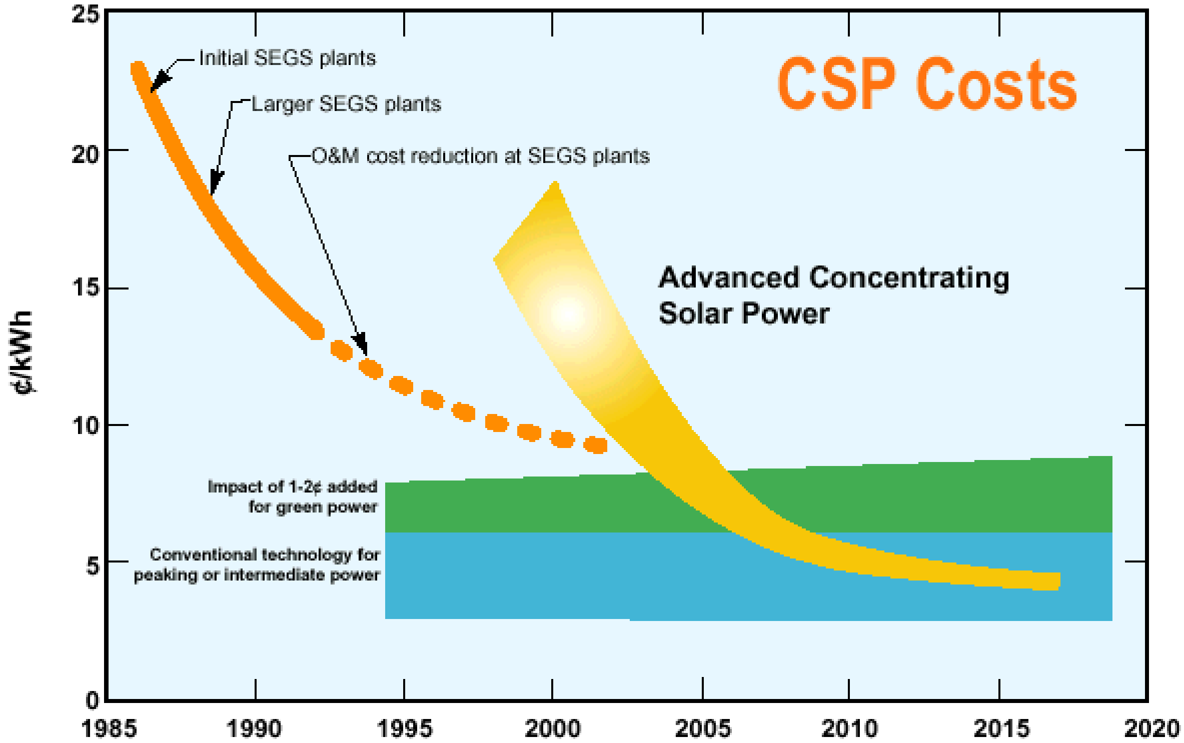


Figure 9.1 Projections of levelized electricity cost predictions for large scale solar thermal power plants. Current costs are shown in blue with a 1-2 cent/kWh addition for 'green' power shown in green.

Chapter 10

Conclusion & PV System in Bangladesh

10.1 Solar PV Electrification Programme in Bangladesh:

Bangladesh is situated between 20.30 - 26.38 degrees north latitude and 88.04 - 92.44 degrees east which is an ideal location for solar energy utilization. Daily average solar radiation varies between 4 to 6.5 kWh per square meter. Maximum amount of radiation is available on the month of March-April and minimum on December-January.

There is a good prospect of harnessing solar power in Bangladesh. In a recent study conducted by Renewable Energy Research Centre, it is found that average solar radiation varies between 4 to 6.5 kWhm-2day-1. Maximum amounts of radiation are available in the month of March-April and minimum in December-January. Solar energy resource study map has illustrated prospect of solar radiation in Bangladesh. There are different organizations, entrepreneurs implementing solar energy program in Bangladesh.

So far in Bangladesh 15 Mw power being produced form Solar PV panels. By the 2012 one million house holds will be powered form solar PV panel and targeted to produce 50Mw power.

10.1.1 Description of Solar PV Electrification Programme in Bangladesh:

The largest Solar PV project in Bangladesh: 20 kWp Solar Production and Training Centre in Khulna, Bangladesh.

Overall objective(s): The general objective is to introduce Renewable Energy (RE) as an alternative solution for power generation to overcome regular shortages in power supply for urban areas in KHULNA division, Bangladesh through transferring European technology and know-how as well as through forming regional partnership between local governments, enterprises, industrial bodies and financing institutions.

Figure 10.1: Solar Production and Training Centre in Khulna, Bangladesh.

Specific objective: The specific objective is to transfer and implant the European technical and technological know-how on mechanism of producing energy on the basis of photo voltaic solar cells to Small and Medium-sized Enterprises (SME) in KHULNA division through practice and product-oriented training for their own use to overcome the shortage in power supply as well as to make this group competent as potential vendors for marketing this RE-based technological solution to other consumers.

Solar Energy Programme supported by,

Infrastructure Development Company Ltd. (IDCOL):

IDCOL promotes solar home systems (SHSs) under the Rural Electrification and Renewable Energy Development Project (REREDP). REREDP is being jointly financed by the IDA, Global Environment Facility (GEF), KfW, and GTZ over 2002 to 2009. IDCOL's initial target was to finance 50,000 SHSs with financial assistance from the World Bank and GEF by the end of June 2008. The target has already been achieved in September 2005, 3 years ahead of schedule and US $ 2.0 million below estimated project cost with additional assistance from the World Bank, KfW and GTZ. IDCOL's Solar Energy Programme is one of the fastest growing renewable energy programs in the world and is expected to change lives in remote rural areas of Bangladesh through providing access to electricity.

IDCOL promotes Solar Home Systems (SHSs) under REREDP through 15 partner organizations (POs) namely Grameen Shakti, BRAC Foundation, Srizony Bangladesh, COAST Trust, Thengamara Mahila Shabuj Shangha, Integrated Development Foundation, Centre For Mass Education in Science, Upokulio Bidyuatayon O Mohila Unnayan Shamity, Shubashati, Bangladesh Rural Integrated Development For Grub-Street Economy, Padakhep Manbik Unnayan Kendra, Palli Daridra Bimochan Foundation, Hilful Fuzul Samaj Kalyan Sangstha, Mukti Cox's Bazar, and Rural Services Foundation.

SHSs are sold (mostly through micro-credit) by POs to the households and business entities in the remote and rural areas of Bangladesh. IDCOL provides refinancing facility to the POs and channel grants to reduce the SHSs costs as well as support the institutional development of the POs. In addition, IDCOL also provides technical, logistic, promotional and training assistance to the POs.

Table 10.1: Price of typical Solar Home Lighting System (SHLS) (Determined by IDCOL with finance from donor agencies);

System Capacity	Appliances/Load used	Price (Taka)
21Wp(Watt Peak)	* Lamp 2	15,000
30Wp(Watt Peak)	* Lamp 2	17,000
40Wp(Watt Peak)	* Lamp 2 * TV 1	22,500
50Wp(Watt Peak)	* Lamp 4 * TV 1	27,000
65Wp(Watt Peak)	* Lamp 5 * TV 1	35,000
75Wp(Watt	* Lamp 6	38,000

Peak)	* TV 1		
85Wp(Watt	* Lamp	7	41,650
Peak)	* TV 1		
120Wp(Watt	* Lamp	10	65,000
Peak)	* TV 1		
130Wp(Watt	* Lamp	11	68,000
Peak)	* TV 1		

Over 290,000 households brought under Infrastructure Development Company Ltd (IDCOL)'s Solar Programme.

Beginning from January 2003, Infrastructure Development Company Ltd. (IDCOL) has brought more than 290,000 (May 2009) rural households under the solar power system. IDCOL is implementing this programme with financial assistance from the World Bank, GEF, GTZ and KfW. A total of 15 Partner Organizations are disseminating solar home systems in the remote rural areas of Bangladesh under IDCOL's renewable energy programme.

10.2 Solar Home System in Bangladesh

The only type of modern renewable energy technology that has had some success in Bangladesh is solar PV. From the limited demonstration and institutional uses of a decade ago, solar PV is now being taken directly to ordinary rural households and communities. This success has been possible because of the direct implementation of solar systems in rural households by NGOs that have received financial backing from donors. With the help of soft loans and grant facilities of donors, almost 100,000 SHSs have been installed in different parts of Bangladesh. Table 3 shows the number of SHSs installed by NGOs.

Table 10.2: SHSs Installed by NGOs (As of May 2006)

Name of NGO or institute	Number of SHSs installed	Capacity of installed solar system (Wp*)
Rural Electrification Board	5,000	250,000
Grameen Shakti	65,000	3,250,000
Bangladesh Rural Advancement Committee	15,456	770,000
Centre for Mass Education in Science (CMES)	1,025	51,250
Thangamara Mohila Sobuj Shangha	1,003	50,150
Coast Trust	805	40,250
Srizony Bangladesh	2,384	119,200
Shubushati	796	40,000
Integrated Development Foundation	818	40,900

*Wp = Watt peak.

The dissemination of almost 100,000 SHSs has been made possible in part by the Rural Electrification and Renewable Energy Development Project, which is coordinated by the Infrastructure Development Company Ltd. and financed by the World Bank. The soft loan, a grant from the Global Environment Facility, and technical support facilities have attracted partner organizations, mostly NGOs, to implement SHSs in remote areas of Bangladesh (Figure 10.2).

The Centre for Mass Education in Science (CMES), a national NGO in Bangladesh, conducted a cost analysis of the SHS, examining the price of each system, possible repairs, replacements, maintenance, and depreciation. The analysis suggested that several possible marketing strategies could be piloted by the program. Table 3 indicates the pricing and financing options of the SHS.

A socioeconomic survey of 79 customers of SHSs was conducted in the district of Dinajpur and Rangpur (northern Bangladesh). According to the survey, most of the customers of SHSs were engaged in both agriculture and business (33%), followed by only business (29%). Approximately 48% of customers' annual income level was between 51,000 BDT and 100,000 BDT. Approximately 84% of customers of SHSs indicated that they had no other sources of electricity except solar energy. Most of the customers were using solar energy to power domestic lighting appliances and black-and-white televisions (69%). About 90% of customers were satisfied with the performance of the technology.

Figure 10.2 Areas of solar home systems in Bangladesh.

Table 10.3: Pricing Options of SHS

Scale of SHS (Wp)	Cash package price (BDT*)	Down payment (BDT)	Loan amount (BDT)	Monthly installment amount (36 installments)	Monthly installment amount (24 installments)	Monthly installment amount (12 installments)
75	34,500	5,865	28,635	1,034	1,432	2,625
50	22,000	3,740	18,260	660	913	1674
40	17,300	2,941	14,359	519	718	1317
30	12,500	2,125	10,375	375	519	951

10.3 Introduction of Electric Vehicles in Dhaka City

Dhaka, the capital and the largest city of Bangladesh, has population of 10 million who use both motorized and non-motorized vehicles for transportation. The city has both private and public transport facilities. However, the majority of the city dwellers and outside commuters depend on public transport system. Bus, minibus, rail and small passenger vehicles operate in different routes within the city. Small passenger vehicles, among others, play a major role in the city transport system.

The vehicles are using diesel, gasoline and lube oil as energy. Electric Vehicle (EV) is a new addition to the city transport system showing potential to reduce local pollution load as well as greenhouse gases. In order to provide pollution free passenger services in Dhaka City, three thousand new electric vehicles are being planned to introduce under the proposed project over five years. Estimated lifetime of the electric vehicles is about 10 years and will be operated in five routes in the city. The EVs will use 72 volts of electric power consisting of 12 acid leaded batteries each of which has 6 volts capacity with 190 ampere-hour (Ah). In term of electricity each battery stores 1.14 kilowatt-hour (KWh) of electricity and therefore the total stored electricity in 12 batteries is 1.14 x 12 = 13.68 KWh. Charging station will be set up with microchips based charger to recharge the batteries with grid electricity generated from natural gas.

10.4 Discussion and Conclusion

Photovoltaic (PV) systems convert sunlight into electricity. The photovoltaic effect is the basic physical process through which this happens. Sunlight is composed of photons, or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a PV cell, they may be reflected or absorbed, or they may pass right through. Only the absorbed photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the cell (which is actually a semiconductor). With its newfound energy, the electron is able to escape from its normal position associated with that atom to become part of the current in an electrical circuit. By leaving this position, the electron causes a "hole" to form. Special electrical properties of the PV cell provide the voltage needed to drive the current through an external load (such as a light bulb).

A PV system comprises several components. The basic building block of a PV panel is the PV cell, which is a solid state, or non-mechanical, device. A solar system uses a number of PV panels, each made of silicon, plus boron and phosphorous. The output of a single cell under direct sunlight is about one watt. To increase their effectiveness, dozens of individual cells are interconnected together in a sealed, weatherproof glass package called a module. Modules come in a range of wattages, and their nature allows for great flexibility in designing systems that meet a variety of electrical needs.

Since PV modules are only capable of producing direct current (DC) electricity, an inverter is required to convert the direct current (DC) output produced by the PV array into alternating current (AC) power. AC electricity is needed to run computers, refrigerators and other appliances, and lighting.

A utility PV system, such as those installed under the Sun4Schools project, generate electricity which is supplemented by the energy provided by the existing utility grid. A PV system requires neither battery storage nor an emergency back-up system since it is connected directly to the utility grid, which is used as the storage medium. Systems that

are not connected to the utility grid use batteries to store energy for use when the sun is not shining.
A well-designed and properly installed PV system with a consistent maintenance schedule will operate for more than 20 years. The PV module, which has no moving parts, has an expected lifetime of more than 30 years.

In the past 30 years, the photovoltaic industry maintained a growth rate of 20 percent on the average, while in the last five years, with an average annual growth rate of as high as 35 percent. As of 2007, the global PV power installed capacity is 9.1 million kilowatts, the growth rate goes up to 33 % in 2007, capacity of 2.2 million kilowatts is installed, and the growth rate is 40%.

On the optimistic view, in the next 30 years, the photovoltaic industry will maintain a growth rate of more than 25 percent, while the pessimistic view is that this opinion is not based on reality.

Optimistic faction believes that as the technological progress and industrial expansion, photovoltaic power generation costs will be quickly reduced, thereby it bring a fundamental demand for the expansion, the process will run through the entire century. The latter part of the growth rate will decline because the base PV will be huge.

Pessimistic view is base on the biggest obstacles for photovoltaic industry is the high cost. In the Western developed countries, they mainly go through various kinds of financial subsidies to support the development of the industry, such as United States allow advance photovoltaic project with the financial and tax incentives, and support the Internet price of photovoltaic for 21.29 cents / unit.

According to our opinion, base on the cost of photovoltaic, the next three to five years, in some time and some areas, photovoltaic will have cost advantage. U.S. Environmental Co-op non-profit organization says, the cost of solar power will be equal with the traditional fossil energy for power generation costs. With the decline of the cost for solar power, while coal, natural gas and the rising cost of nuclear power, United States will come to the intersection by 2015.From Comprehensive opinion, the photovoltaic industry will have a high growth period.

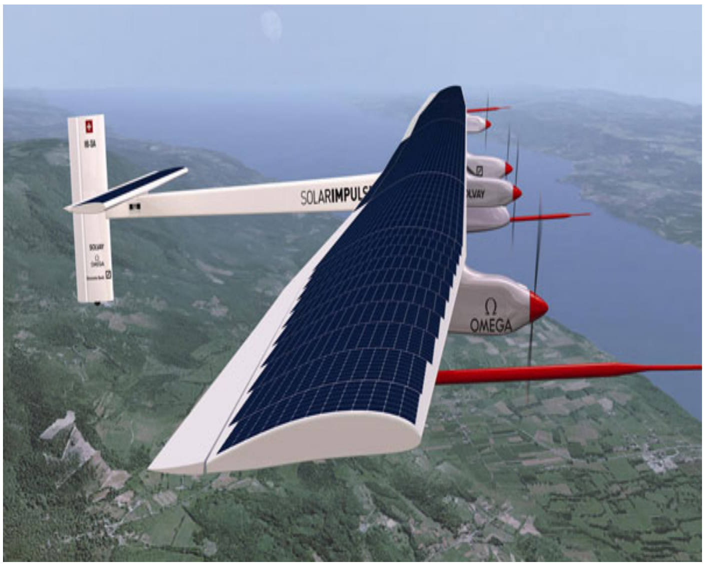
Solar Photo-voltaic (PV) technology is the way of the future, for generating and supplying electric power for homes and businesses in the US and across the world. Despite the great potential of Solar PV, current cost and efficiency of solar panels makes them a green, yet expensive alternative to conventional ways of generating electricity, such as Coal, Gas and Oil fired power plants as well as Nuclear and Hydro electricity.

Main obstacle that is holding the wide-spread of solar PV is the long ROI (return on investment) that in some situations may exceed 10 years. Fortunately, US federal government and local and state governments have a multitude of incentives and rebate programs for solar and other renewable energy projects.

Purpose of this Solar PV system is to help you squeeze the most efficiency out of you home solar system, making it collect as much sun light as is available throughout the year.

Appendix

Solar aircraft:

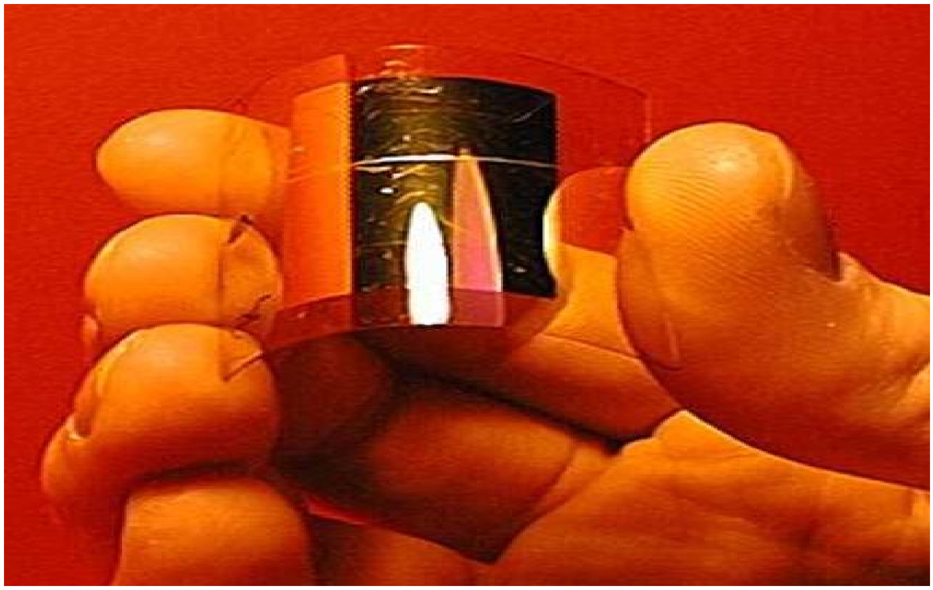


One hopes that professional adventurer Bertrand Piccard, son of the bathysphere inventor and grandson of the first stratospheric balloon skipper, gets the money to build his Solar Impulse. It is to be a delicate, enormous airplane with four electric propellers and a slew of solar cells across its slender wings that he plans to captain around the world (it is a system pioneered by the late engineer Paul MacCready, but for automated aircraft). Piccard is raising money, has gotten an endorsement from the aviation industry that wants to look as green as possible, and garnered himself some publicity with a news conference at an air show in Singapore this week.

Whether such a craft will help pave the way for profitable, passenger-carrying no-carbon-contrail-print solar airplanes is anybody's guess. Nonetheless, a few outlets picked up on the news. Again, hope it happens if only for the spectacle of such a delicate, technically sweet feat.

Solar Car:

Honda dream, the winning car in the 1996 World Solar Challenge. The custom made cells for the car are greater than 20% efficient. (Photograph PVSRC)



Plastic solar cell

World largest solar park (Spain)

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