# CHAPTER 2

# THEORETICAL BACKGROUND

## 2.1 INTRODUCTION

One of the promising options is to make more extensive use of renewable sources of energy derived from the Sun. Solar energy can be used both directly and indirectly. It can be used directly in a variety of thermal applications like heating water or air, drying, distillation and cooking. The heated fluids can in turn be used for applications like power generation or refrigeration. A second way in which solar energy can be used directly is through the photovoltaic effect in which it is converted to electrical energy.

The study of photoeffects in electrochemical systems can be traced back to Becquerel's [1], investigations of the effect of solar illumination on metal electrodes in 1839.

Number of review articles on semiconductor electrochemistry and photoelectrochemical conversion have been appeared in the literature [2-13].

In this chapter photovoltaic effect, types of solar cells, semiconductor-liquid junction solar cells, semiconductor septum solar cells are discussed in brief.

Modelling of solar cells has been discussed at the last of the chapter.

## 2.2 PHOTOVOLTAIC EFFECT

Solar cell is the semiconductor device which converts the radiant energy into the form of electrical energy. The radiant energy is given by the relation $E = h\nu$. The electrical energy device consists of the source of electrons and the sink of electrons [14]. When source and sink are connected together through external circuit, there flows the current. So the requirement is to produce sources of electrons and holes at the consumption of radiant energy. This can be done with a semiconductor. When photon of energy, $h\nu$ greater than the band gap energy, Eg of a semiconductor, is absorbed, a pair of electron and hole is generated. However, the electron with negative and hole with positive charge attract and annihiate immediately. As a result, though the electrons and holes are generated within a single piece of semiconductor by the absorption of radient energy one cannot get externally the electrons to flow. However, if one creates a situation, wherein the electrons and holes are immediately separated, produces an electricity. This is done with junction device.

When the semiconductor junction is formed, due to the transport of charges across the junction to set the equilibrium i.e. to make the Fermi levels at equal energy level, the donors are ionized at the interface within the n-type semiconductor and acceptors are ionized at the interface within p-type semiconductor. This gives rise to a local field, also called as built in potential $V_D$. When the light of energy $h\nu > Eg$ is made to incident within this interfacial layer the pairs of electron and hole are generated and are separated due to the influence of local electric field as shown in Fig. 2.1.

The n-type side of a junction acts as a source of electrons while the p-type, as a sink of electrons and when these two sides are connected through external circuit, the current flows through the external circuit.

## 2.3 TYPES OF SOLAR CELLS

The key parameter involved in the principle operation of solar cell is the existence of the local field or the built in potential needed to separate the electrons and holes generated due to incidence of photons on a semiconductor. This built in potential can be generated by making the junctions and by the virtue of the nature of the junction. The solar cells can be grouped mainly into the following four categories namely :

1) Semiconductor - Semiconductor junction cells
2) Semiconductor - metal junction cells

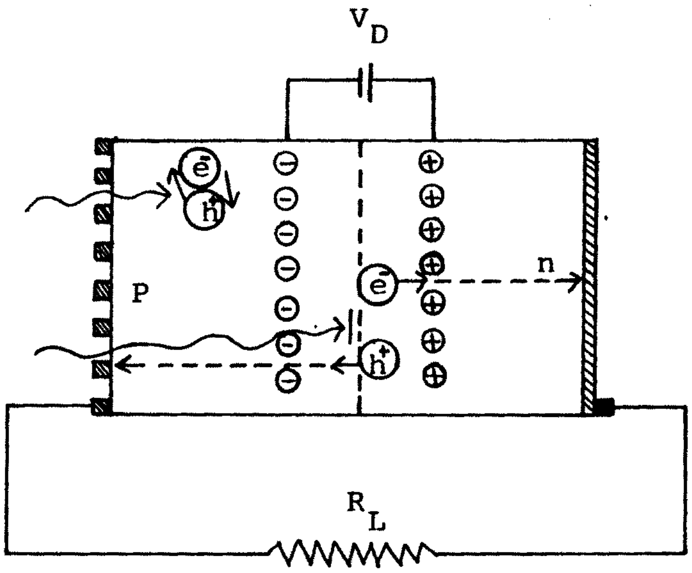

Fig.2.1. P-n junction with influence of local electric field.

3) MIS and SIS solar cells

4) Semiconductor - liquid junction cells

### 2.3.1 Semiconductor-Semiconductor Junction Cells

There are two types of S-S junction cells namely homojunction and heterojunction cells.

The homojunction cell normally consists of a shallow p-n junction formed either by diffusion of a dopant into a mono-crystalline semiconductor substrate or by growth of an epitaxial layer onto the substrate. Silicon and gallium arsenide [15] are two common materials used, with the diffused silicon cell, being the most popular. Figure 2.2(a) and 2.2(b) shows the structure and energy band diagram of a typical p-n homojunction cell. The cell is illuminated from the thin surface layer side.

A hetrojunction cell consist of the interface between tow dissimilar semiconductors. Depending on the nature of interface, the heterojunction cells can further be classified as abrupt or graded according to the distances during which the transition from one semiconductor to the other is completed near the interface. For example, in the former case the transition occurs within a few atomic distances (< 1 μm), while in the latter it takes place over distances of the order of several diffusion lengths. Hetrojunctions are fabricated by the growth or deposition of one

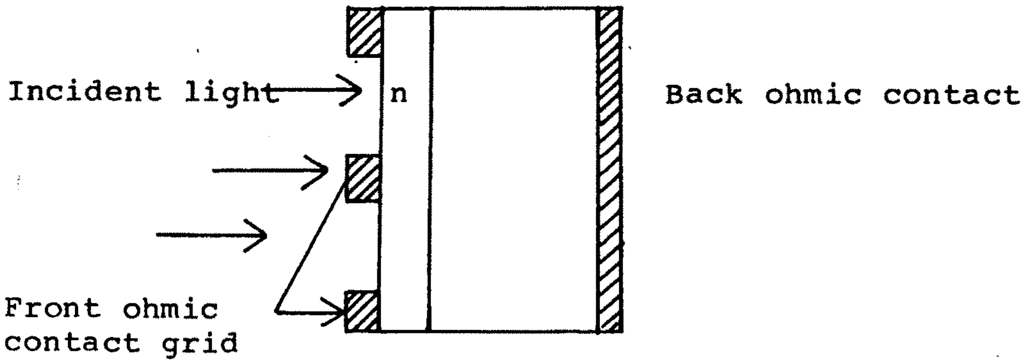

Fig.2.2(a). A structure of p-n Homojunction solar cell.

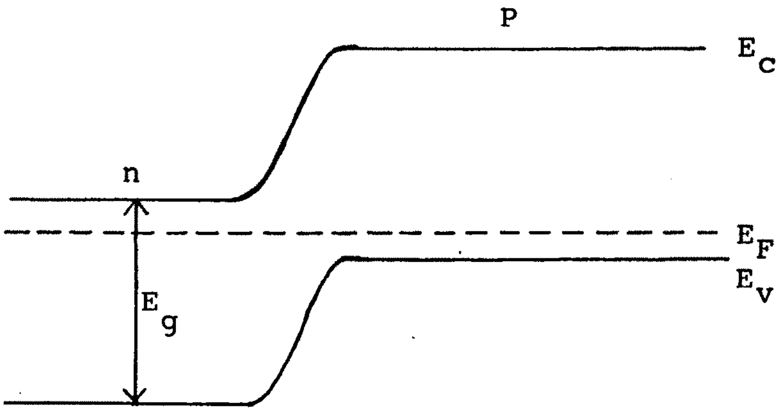

Fig.2.2(b). Energy band diagram of p-n Homojunction solar cell.

semiconductor onto the other.

The energy band profile of n-CdS/p-CdTe heterojunction at thermal equilibrium and at zero bias is shown in Fig. 2.3(a) and (b), before and after the formation an abrupt heterojunction [14]. Each semiconductor is characterised by its electron affinity $\chi$, energy band gap Eg and work function $\Phi$. At zero bias, the Fermi level on both sides coinside at the junction.

When the cell is illuminated from the side of larger gap semiconductor (CdS), this layer serves as a "window" for photons with energies below $Eg_1$. The major portion of photons with energies between $Eg_1$ and $Eg_2$ would excite carriers in the transition region at the substrate side of the hetrojunction where collection efficiency is unity due to the presence of the built in field. This is in contrast to the case of homojunction cells where the photons are absorbed in the surface layer where carrier recombination is significant. Thus, the "window effect" in heterojunction cells can improve collection efficiency.

When the cell is illuminated from the side of the smaller band gap semiconductor, most absorption will occur in this smaller gap layer and excited carriers have to diffuse to the junction before they can be collected. The

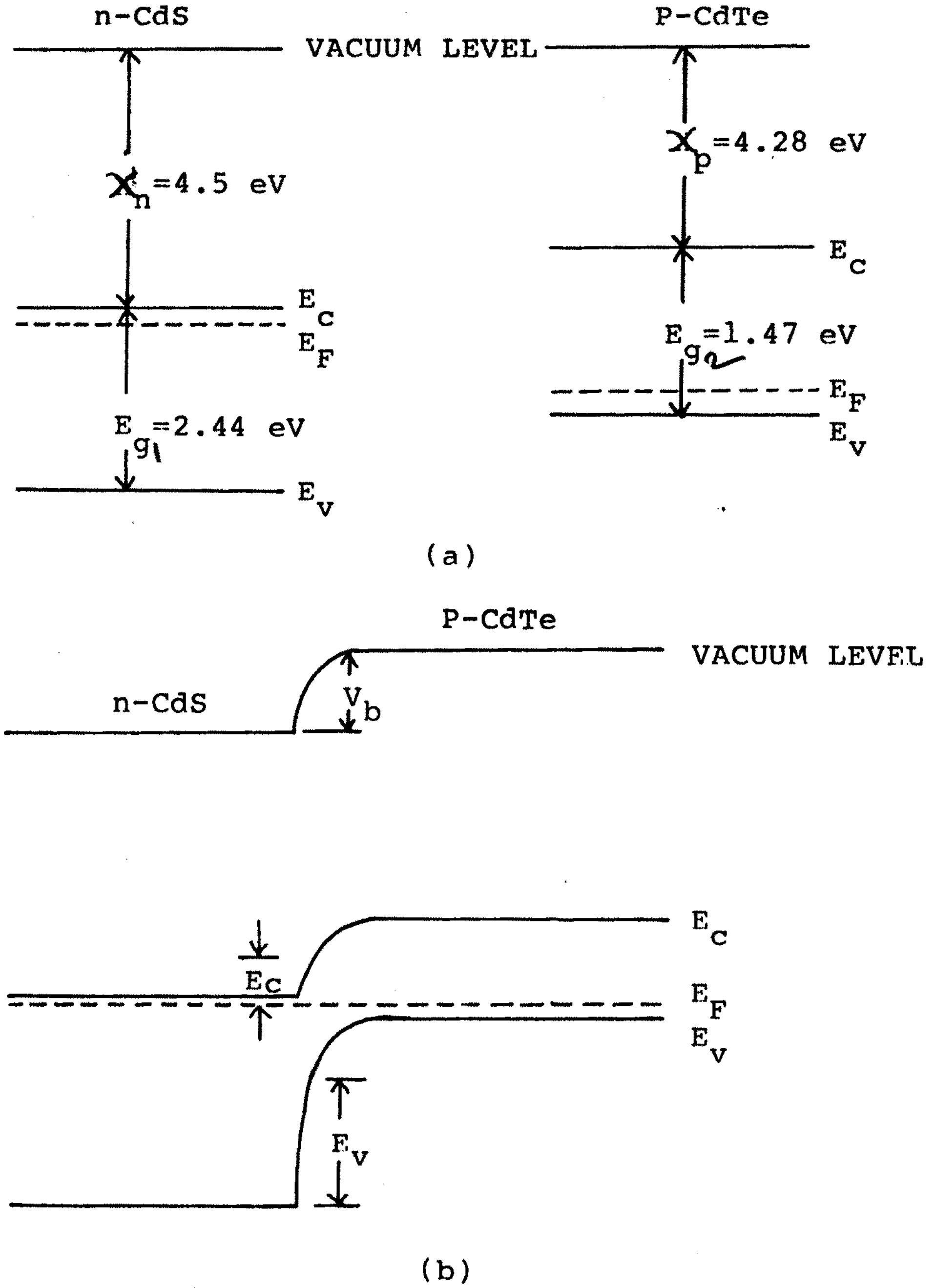

Fig.2.3. Energy band profile of n-CdS/P-CdTe heterojunction at thermal equilibrium and zero bias (a) before and (b) after the formation of an abrupt heterojunction.

larger band gap semiconductor serves simply as a junction forming and contact layer. The $Cu_2S/CdS$ cell is a common example of this type of cell.

### 2.3.2 Semiconductor-Metal Junction Cells (Schottky Barrier Cells)

Semiconductor-Metal junction cells are probably the simplest of all types to fabricate, requiring only an ohmic contact at the back and semi-transparent metal at the front, along with the usual contact grid pattern to lower the series resistance. The transparent metal films is normally evaporated onto the carefully prepared semiconductor surface and films of about 100 A° thickness yield transmission of about 60% with sheet resistivity of 5-50 ohms/square cm [14]. Fig. 2.4 shows structure and band diagram of metal-semiconductor junction cell. The thin semi-transparent metal layer permits passage of solar photons and forms the transition region in the semiconductor for collection of generated carriers. Because of the presence of the built in field, the collection efficiency for carriers excited in the barrier transition region will be 100%. A major loss of photons is due to incomplete transmission of barrier metal layer which is required to be thick enough for low series resistance. Large barrier voltage $\Phi_B = \Phi_M - \chi_S$ and high doping level in the semiconductor are desirable for large buit in voltage.

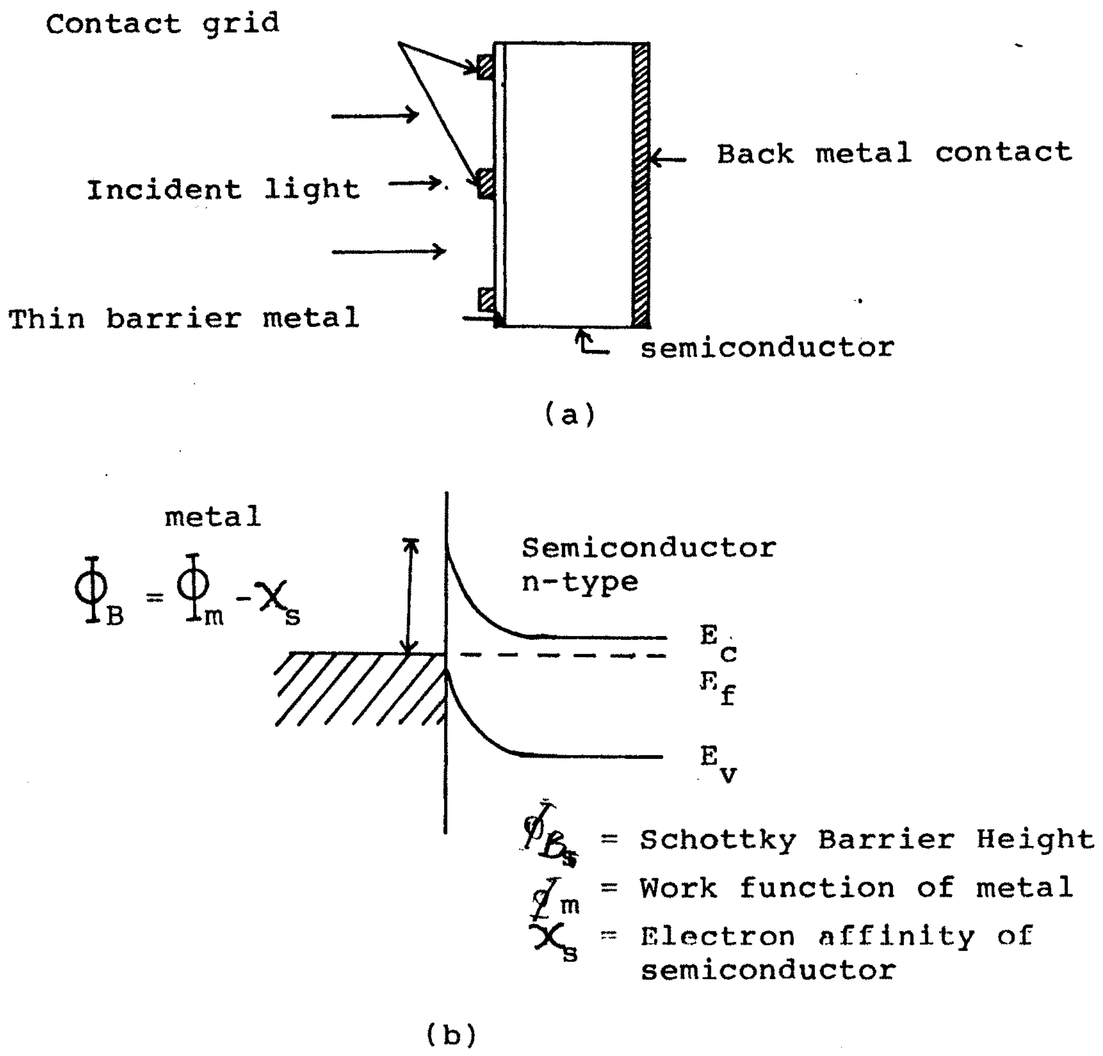

Fig.2.4. (a) Structure of Schottky Barrier solar cell.

(b) Band diagram of Schottky Barrier solar cell.

### 2.3.3 MIS and SIS Solar Cells

Such cells have thin interfacial layer (10-30 A°) between the top "inducing" contact (metal or conducting semiconductor) and the base semiconductor. This interfacial layer is generally an oxide or some other compound which is normally an insulator in its bulk form. This configuration is illustrated in Fig. 2.5.

### 2.3.4 Semiconductor-Liquid Junction Cells

It essentially consists of a semiconductor photoelectrode and metallic counter electrode dipped into an electrolyte. Charge transfer at the semiconductor electrolyte interface produces a band bending $V_B$ as a result of formation of space charge region, establishing a potential barrier. The direction of the field is such that for n-type semiconductor, holes generated in space charge region move towards the interface and the excess electrons move towards the bulk. The width of space charge region is given by the relation [14].

$$W = \left[ \frac{2\ \varepsilon\ \varepsilon_o\ V_B}{eN_D} \right] \qquad \ldots. \ (2.3.1)$$

Where $N_D$ - donor charge density in semiconductor electrode
$\varepsilon$ - dielectric constant of semiconductor electrode
$\varepsilon_o$ - permitivity of free space
e - electronic charge

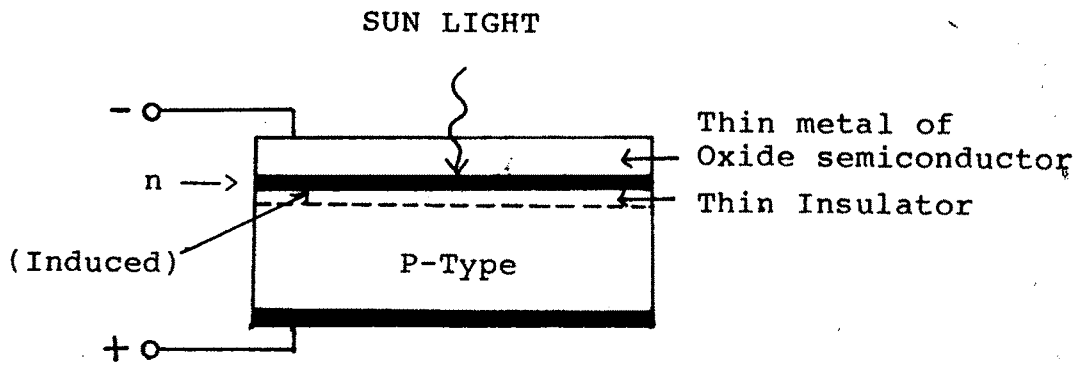

Fig.2.5. Structure of MIS or SIS solar cell with thin interfacial layer.

Basic theory of S-L junction cells is discussed in the section 2.4.

## 2.4 ELECTRICAL CHARACTERISTICS OF SOLAR CELLS

### 2.4.1 Equivalent Circuit

By connecting a load across the terminals of a solar cell a current $I_L$ can flow through the load and develop a voltage $V_L$ across it. The values of $V_L$ and $I_L$, besides depending on the nature of the load, will be related to the photogenerated current $I_{ph}$ and the properties of the diode. These relationships can be established by reference to the simple equivalent circuit as shown in Fig. 2.6.

The photocurrent $I_{ph}$ is represented by a current generator and its magnitude depends on the wavelength and intensity of the incident light, optical absorption co-efficient of the solar cell material, the junction depth, the width of the depletion region and the lifetime and the mobilities of the carriers on both sides of the junction. The polarity of the output photo-voltage $V_L$ is such that the diode is in forward bias condition. The current flowing through the diode is represented by $I_d$ and is given by

$$I_d = I_o \left[ \exp \frac{eV_L}{nKT} - 1 \right] \qquad \ldots\ldots (2.4.1)$$

Where $I_o$ is the reverse saturation current

$K$ is the Boltzman constant and

$n$ is the junction ideality or perfection factor

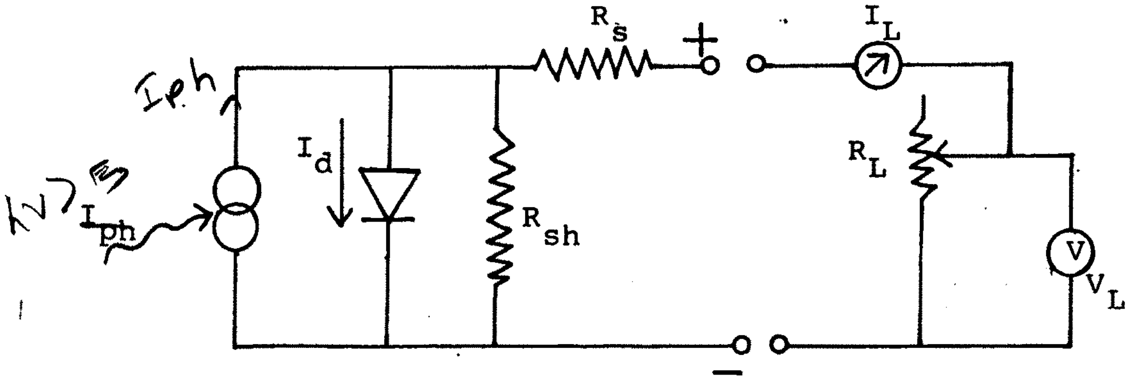

Fig.2.6. Equivalent circuit of a solar cell including series and shunt resistances.

Shunt resistance paths are represented by' $R_{sh}$; they can be caused by surface leakage along the edges of the cell, by diffusing spikes along dislocations or grain boundaries, or possibly by fine metallic bridges along microcraks, grain boundaries or crystal defects such as stacking faults after the contact metallization has been applied. The series resistance, Rs, can arise from contact resistances to the front and back, the resistance of the base region itself, and the sheet resistance of the thin diffused or grown layer. The load resistance is represented by $R_L$ and it is desirable to choose its magnitude such that the maximum power is extracted from the solar cell.

From the equivalent circuit of Fig. 2.6, a relation, can be written, between output photocurrent $I_L$ and the output photovoltage $V_L$ as

$$I_L \left( 1 + \frac{R_S}{R_{sh}} \right) = I_{ph} - \frac{V_L}{R_{sh}} - I_d \quad .... (2.4.2)$$

### 2.4.2 Solar Cell Output Parameters

In general, the phtotovoltaic output properties are studied with the help of experimental circuit diagram shown in Fig. 2.6..

In the short circuited condition, the load resistance $R_L$ is zero, and hence $V_L$ is zero. The current flowing the external circuit is the short circuit current denoted by

$I_{sc}$ and given by

$$I_{sc} = I_{ph} \qquad \text{.... (2.4.3)}$$

In the open circuit condition, the $R_L$ is infinite, the current flowing through the external circuit is zero and $V_L$ becomes maximum called the open circuit voltage $V_{oc}$ and is given by

$$V_{oc} = \frac{nKT}{e} \ln \left( 1 + \frac{I_{sc}}{I_o} \right) \qquad \text{.... (2.4.4)}$$

The product of $I_{sc}$ and $V_{oc}$ is the ideal power of the cell. The maximum useful power is the area of the largest rectangle that can be formed under the I-V curve. If the current and voltage corresponding to this situation are denoted by $I_m$ and $V_m$, then the maximum useful power is given by

$$P_{max} = I_m V_m \qquad \text{.... (2.4.5)}$$

The fill factor (FF) of a solar cell is defined as

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \qquad \text{.... (2.4.6)}$$

The energy conversion efficiency, $\eta$, is given by

$$\eta = \frac{I_m V_m}{P_{in}} = \frac{I_{sc} V_{oc} FF}{P_{in}} \qquad \text{.... (2.4.7)}$$

Where $P_{in}$ is the total power in the light incident on the cell.

## 2.5 SEMICONDUCTOR - LIQUID JUNCTION SOLAR CELLS (BASIC THEORY)

Photoelectrochemical processes can be both photoelectrical and photochemical in nature. When a semiconductor is dipped in a redox solution, its chemical potential is different from the redox potential ($E_{redox}$). A new equilibrium is established between the semiconductor and electrolyte solution by rearrangement of charges. This results in a strong field near the junction. This is shown by the bending of bands for a n-type semiconductor as illustrated in Fig. 2.7. When the semiconductor electrolyte junction is illuminated with light having energy greater than the band gap energy, electron-hole pairs are produced in the depletion layer. Charge separation takes place due to the local field present at the interface. The probability of annihilation of a hole with an electron is reduced by this field. This condition will be optimum when the light penetration depth is equal to the depletion layer width so that all the light is absorbed in the depletion layer and maximum number of electron-hole pairs are produced in it. These separated charges produce a counter charge and under open circuit condition this counter field is maximum. This is the open circuit photovoltage. The conduction band and valence band get shifted due to the counter voltage. The photovoltage is given by the change in the Fermi level as shown in Fig.

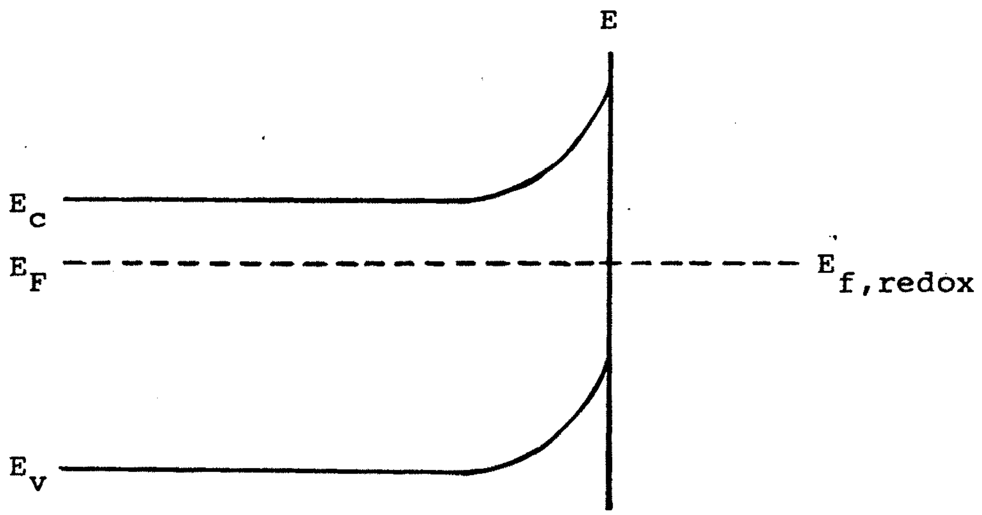

Fig.2.7. Bending of bands for a n-type semiconductor.

2.8(a). When a counter electrode is immersed in the electrolyte and connected externally to the semiconductor the photogenerated electron moves into the bulk of semiconductor and through the external circuit it reaches the counter electrode to reduce an oxidized species in the electrolyte. The hole is pushed to the electrode surface where it oxidizes a species in the electrolyte as shown in Fig. 2.8(b). Fig. 2.9(a) illustrates the flow of photocurrent in short circuit condition of semiconductor-electrolyte junction cell for the redox couple $A/A^+$. Fig. 2.9(b) shows the photoelectrochemical cell with an external load resistance in the circuit.

The oxidation and reduction reactions in the photoelectrochemical cell are illustrated as follows.

A process in which the substance gains an electron is called a reduction reaction [16].

$$O_x + e^- \longrightarrow \text{Red.},\ E^o \qquad \ldots.\ (2.5.1)$$

Where, $O_x$, and Red. are the oxidised and reduced species and $E^o$ is the standard electrochemical potential, measured with respect to standard electrode. The reverse process of losing an electron is called an oxidation reaction. A system in which one species loses an electron and the other species gains an electron is called redox system. $E^o$, is the measure of the tendency of the reaction to proceed in a particular

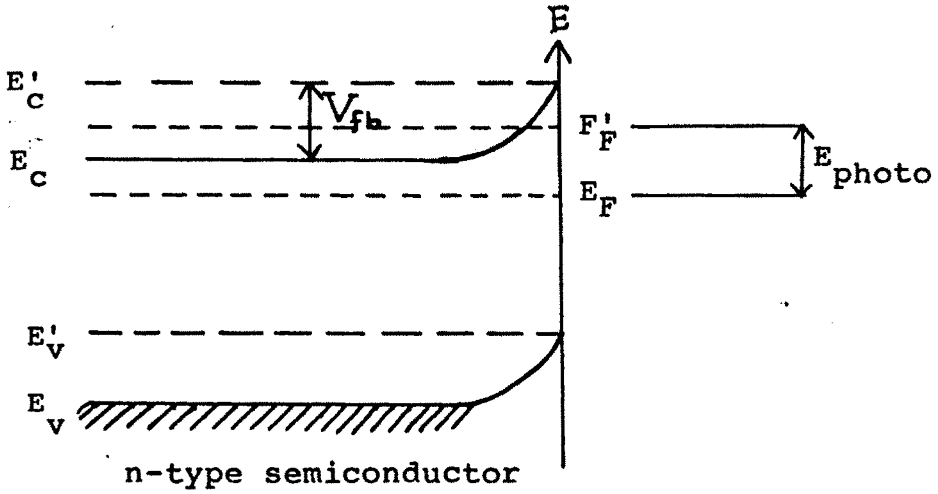

Fig.2.8(a). Shifting of bands as a result of illumination.

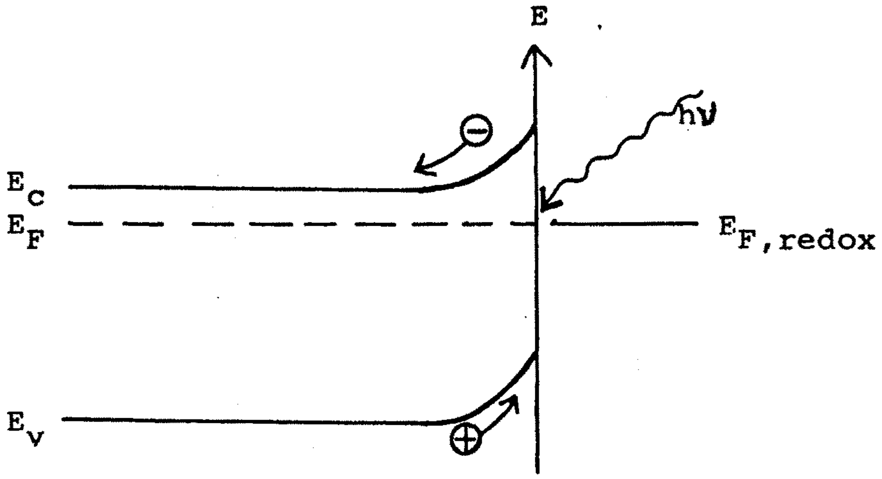

Fig.2.8(b). Transfer of holes and electrons.

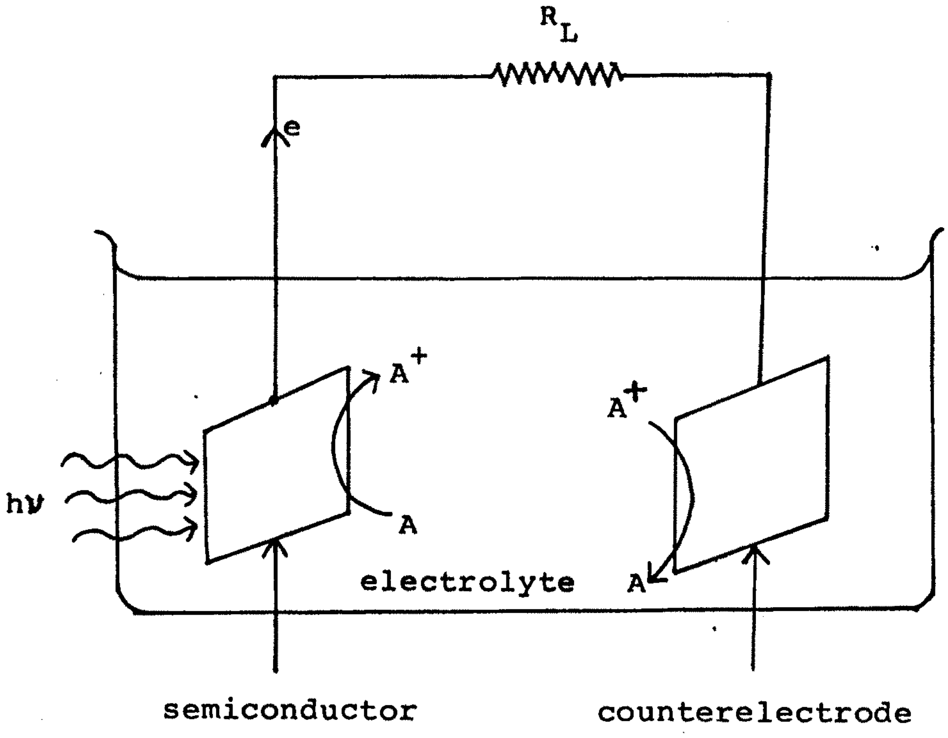

Fig.2.9(a). Photocurrent at short circuit condition.

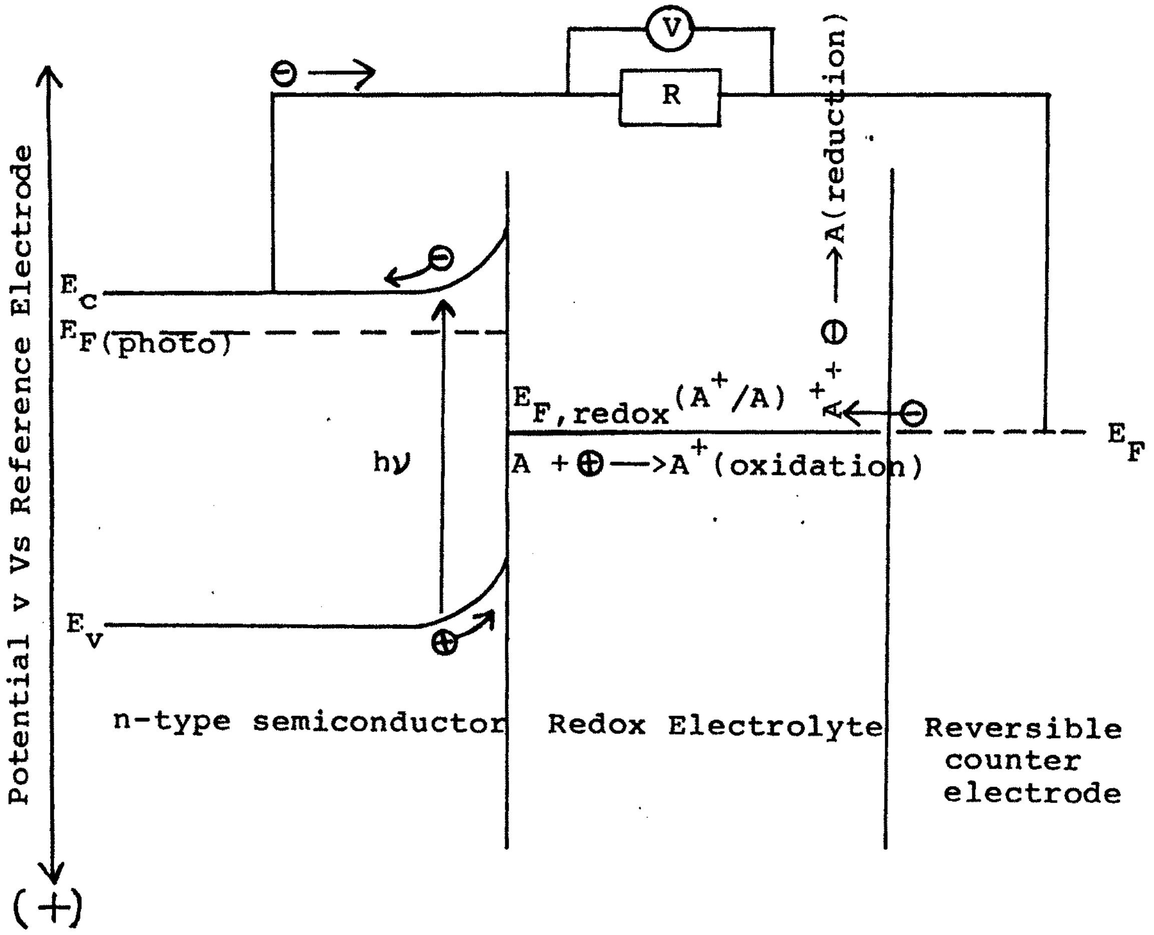

Fig.2.9(b). A regenerative PEC cell. The interface energetics are illustrated.

direction and is a measure of free energy available. If $E^o$ is positive the reaction proceeds from left to right and when it is negative the reaction proceeds from right to left.

Gerischer, while deriving an anology with semiconductor physics, has suggested that the oxidised and reduced species may be linked with the conduction band (i.e. an unoccupied electron state) and valence band (i.e. an occupied electron state) respectively [17-19]. A term similar to Fermi level $E_f$ of a semiconductor can be defined for a redox couple also and can be abbreviated as $E_{f,redox}$. The energy necessary to transfer an electron from the reduced species to the oxidised species is analogous to the band gap of a semiconductor. The redox potential is defined as the potential required to transfer an electron from redox species to the vacuum level or vice-versa [20].

The electron energy state in the redox electrolyte is in analogy with the concept of energy states in a solid. One can define the electron energy state in the redox electrolyte by energy change in the reaction.

$$(O_x^{+}\ \mathrm{Solv.}) + e_{\infty}^{-} \rightleftharpoons (\mathrm{Red\ Solv.}) \qquad \ldots.\ (2.5.2)$$

This means that we introduce a free electron from infinity into the solution and let it occupy the lowest electron state in an oxidised species without change of solvation structure. This gives the energy of the unoccupied state. The reverse process gives the energy of the occupied state. Because the solvation structure of redox ions can be changed to a great extent by thermal fluctuation, we get a thermal distribution of energy states in the redox electrolyte.

The probability function for electron states in redox electrolyte as the sum of occupied and unoccupied states is given by [21].

$$D_{redox}(E) = D_{red}(E) + D_{ox}(E) \quad \text{....} \quad (2.5.3)$$

Which is equivalent to the density of states function in solid.

$D_{red}(E)$ and $D_{ox}(E)$ are represented by

$$D_{red}(E) = C_{red}\, W_{red}(E) \quad \text{....} \quad (2.5.4)$$

and

$$Dox(E) = C_{ox}\, W_{ox}(E) \quad \text{....} \quad (2.5.5)$$

Where $W_{red}$ and $W_{ox}$ are given by the thermal distribution functions of ionic configurations, and $C_{red}$ and $C_{ox}$ are the concentrations of reduced and oxidised species. These distribution functions have a maximum at the electron level for the most probable configuration of the reduced and oxidised component of the redox couple.

At equilibrium the occupation of these energy states in redox electrolyte is given by the Fermi distribution function.

$$D_{red}\ (E) = D_{redox}(E).F\ (E-E_{f,redox}) \quad .... \ (2.5.6)$$

and

$$D_{ox}\ (E) = D_{redox}(E).F\ (E_{f,redox}-E) \quad .... \ (2.5.7)$$

$E_{f,redox}$ is equivalent to the chemical potential of electrons in the redox electrolyte and is related to the mean free energy change, $\Delta\mu$ per mole electrons in the redox reaction as,

$$E_{f,redox} = E^{0}_{f,redox} + KT \ln \frac{C_{red}}{C_{ox}} \quad .... \ (2.5.8)$$

## 2.6 SEMICONDUCTOR SEPTUM SOLAR CELLS

In recent years, much efforts have been directed towards developing new and better solar energy conversion devices. A high degree of sophistication has already been achieved in the fabrication of p-n junction solar cells. However, one of the challenging problems in solar energy research is solar energy storage. Recently an alternative strategy has been suggested in which a solid-liquid junction has been used. Here, instead of the solid-solid junction of conventional solar cells, a semiconductor electrode dipped in a liquid electrolyte provided the necessary charge transfer of a redox ionic species which being used to obtain photovoltage/photocurrent. This offers the possibility of both solar energy conversion and storage and these cells are called as photoelectrochemical (PEC) solar cells.

Recently some groups have attempted the use of a membrane based PEC system for solar energy storage devices [22-24]. The objective of most of the research carried out in this area is to optimize the efficiency and life time of these cells. Economic conditions are also important for these devices.

The solar energy storage cells can be classiffied as

(a) Redox Storage Electrode
(b) Redox Storage Electrolyte
(c) Semiconductor Septum Solar Energy Storage Cell

The origin of the semiconductor septum electrochemical photovoltaic cell is traceable to early studies of the membrane biophysics aspects of photosynthesis, for redox reactions.

The solar energy storage with the help of semiconductor septum cells is most promising due to its inherent properties. In this cell under illumination, on one side of the membrane solution interface reduction occurs while on the other side oxidation takes place. Thus the basic concept in all the systems is light induced charge separation in the form of electrons and holes which causes reduction on one side and oxidation on the other side. Two different redox couples having standard potentials sufficiently wide apart from each other should be used in order to achieve large photovoltage. Under illumination these chemical species can be charged and then electrochemically discharged for the production of electricity.

The semiconductor septum cell can be used as an efficient storage cell if the semiconductor septum electrode and elecgtrolytes have properties, listed in Table I and II respectively [25].

**Table I : Semiconductor Septum Electrode**

SEMICONDUCTOR PHOTOELECTRODES

1. $h\nu > Eg$ i.e. the energy of the incident light should be greater than the band gap of the semiconductor.
2. The absorption coefficient of a semiconductor must posses a large value.
3. In order to utilize the incident light to generate electricity, the reflection and transmission coefficients must be small.
4. The local field generated after the formation of the junction should be strong enough to separate electron-hole pairs effectively.
5. Recombination states must be minimum.
6. The thickness of the bulk of the semiconductor must be optimum.

Table II : Electrolyte Properties Requisite for the ECPV Cells

| PROPERTY | ROLE |
|---|---|
| 1) Reduction-oxidation potential | Redox reaction to be positioned appropriate to the semiconductor band edges. Electrolyte decomposition limits suitability. |
| 2) Electron-Transfer rates of OX and red species | Ideally rapid (reversible) at both semiconductor and counter electrodes suitable mass transport conditions. |
| 3) Photo and Thermal stabilites | OX, red and solvent components to have photo and thermal stability throughout usable solar spectrum and operational temperature range. |
| 4) Surface compatibility | Non corrosive to electrode and containment materials. Semiconductors corrosion inhibited if necessary and undesirable surface reactions absent e.g absorption dissociation,passivation etc. |

| | |
|---|---|
| 5) Optical transparency | Minimum absorption losses for solar energy spectrum. |
| 6) Fluidity | Liquidious range and viscosity to allow convective mixing within temperature extremes. |
| 7) Solubility | OX, red and supporting electrolyte concentration in solvent or liquid matrix to be adequate to reach required current densities. |
| 8) Conductance | Ionic conductance of electrolyte should permit negligible ohmic losses. |
| 9) Toxicity and reactivity to environment, cost | Perferably low dependent on application. |

The concept of using semiconductor septum cell as an energy storage is based on modeling of natural photosynthetic systems with a pigmented bilayer lipid membrane [26-29]. The chemical reactions taking place in the two compartments must be reversible, hence different metallic counter electrodes like Cd, Cu Ag etc. are used in electrolytic solutions like $Cd(NO_3)_2$, $CuCl_2$, $Cu(NO_3)_2$, $AgNO_3$ etc. Such a cell can store energy above some threshold, the highest value of which depends on the difference between the $E_{redox}$

potentials and on the position of the band edges of the septum relative to the Fermi levels of the redox systems [25].

## 2.7 MODELLING OF SC-SEP SOLAR CELLLS FOR ELECTRICITY GENERATION

### 2.7.1 Photovoltaic Power Systems

The individual photovoltaic cell has a theoretical limit on voltage and current. For e.g. a 4 inch diameter Si solar cell will give the maximum voltage of order of 0.7 volts and current 500 mA. This single P.V. cell will not sufficient to run transistor, T.V. or taperecorder. To run the electronic appliances there requires certain voltage and currents. Such type of supply can be designed using solar cells. Total set up is called "photovoltaic system" depending on nature of power requirement.

The best efficiency data for a single crystal silicon cell now exceed 22%. However, such data have been achieved only in laboratories on small cell, using the highest-quality silicon, and experimentally made in very complicated ways. The efficiencies of the commercially available layer size cells are much less than that, namely about 15%. A number of such cells are assembled to make a so-called module. For practical applications, several such modules are mounted on a stack and connected with wire to form the final output. This final setup is called an array. The efficiency of a module is inevitably smaller than that of a cell, and the efficiency of an array is still less than that. With silicon cells it is the order of 10%.

There are three types of power systems.

1. Residential Photovoltaic System
2. Central Power Station
3. Space System

A typical stand-alone photovoltaic (SAPV) system (i.e. without utility backup) is described here [30]. In all the power systems the basic structure is similar as shown in Fig.2.10. Figure 2.10 shows a stand-alone photovoltaic (SAPV) power system in block diagram form [31, 32]. Photovoltaic power system mainly consists of five parts namely,

1. Photovoltaic panel (or Solar Array)
2. Energy Storage
3. Power Conditioning Subsystem
4. Load
5. System Controls

Photovoltaic panel consists number of photovoltaic cells connected in series and parallel. When cells are connected in series, one gets additional voltage while the cells connected in parallel there is additional current. The design of photovoltaic panel depends on characteristic of photovoltaic cell and requirement of supply. For example, if we have a cell with 0.5 volts and current 100 mA, then in order to get power supply 12 volts, 1 Amp capacity we require 240 cells in series and parallel combination.

Solar array is the most important component of a PV system. It is composed of modules which are weatherproof units composed of many solar cells which are interconnected in series and parallel configurations. By means of the photovoltaic phenamenon, the array produces DC electric power, thus acting as the generator.

Batteries provide the energy storage for the needs of a stand-alone PV system. They give to the system the following advantages.

* Ability to provide energy for sunless periods and night-time.
* Ability to meet momentary peak power demands.
* Stabile system voltage.
* Ability to store energy, thus reducing energy loss.

Batteries, though, do have their disadvantages :

* Add to system complexity.
* Add to system cost.

- Increase the maintenance activity and resulting cost.
- May reduce system reliability.

Despite these disadvantages, batteries are required in practically every stand-alone application.

Another important element of a SAPV system is the power conditioning subsystem. It is comprised of the array control system, voltage regulators, inverters and distribution system (including cables, protection devices, grounding system, etc.).

The fourth important component of a SAPV system is the load. The size and cost of a PV system depends strongly upon the energy requirements of the loads to be served. The power and energy demand must be estimated as well as possible in order to avoid oversizing the system and adding to its cost.

Load control should be incorporated into the PV system in order to make the system more reliable and reduce the need for storage. Classification of the loads into controllable and uncontrollable is necessary for the implementation of an effective load management algorithm [32]. Also load properties have to be set for reasonable energy distribution.

Another very important component of a SAPV system are the system controls. This include over a undervoltage protection, auto-start or shutdown of the system and data gathering.

### 2.7.2 Solar Array and Battery Sizing

One of the most critical steps in designing SAPV systems is the sizing of the solar array and the battery capacity in order to supply the required power and energy. Two major features are considered : the life-cycle cost of the system should be as small as possible and an acceptable performance figure for loss-of-load probability (LOLP) should be determined [31].

The array area required for each month is determined by,

$$A = DL/[\eta(I - M \times S)] \qquad \ldots. \ (2.7.1)$$

A is area ($m^2$)

DL (kWh/day) is the estimated daily demand for that month.

$\eta$ is the system efficiency

I is the average insolation (kWh/$m^2$ per day) during the month.

S is the standard deviation in the daily insolation (kWh/$m^2$ per day) for each month.

M is the fractional monthly average insolation difference and is equal to,

$$M = (I - I_D)/S \qquad \text{....(2.7.2)}$$

where, $I_D$ is the insolation which is required to exactly meet the load demand. M is a balancing parameter in the sizing of the solar array and the battery, the two main components of a SAPV system.

The battery sizing problem is a slightly more complicated task and its role has not yet been fully investigated for SAPV systems. A SAPV power supply must always maintain a continuous power supply at night and on cloudy days when there is little or no solar energy. The amount of battery capacity Q (kWh) needed will depend on the load demand, parameter characteristics of components and on weather patterns at the site. Clearly for applications where energy is required throughout a 24 hour period, the need cannot be met through the PV array power output alone as can be seen from Figure 2.11. In addition, there is a need for energy storage to meet energy needs which go beyond the daily energy requirements.

Indeed, the nominal battery capacity Q (kWh) consists of two quantities, the long-term battery capacity $Q_1$ and the short-term battery capacity $Q_2$. The first represents the amount of energy needed to satisfy the load during the cloudy days of the month. The second corresponds to the daily peak demand which cannot be met by the daily

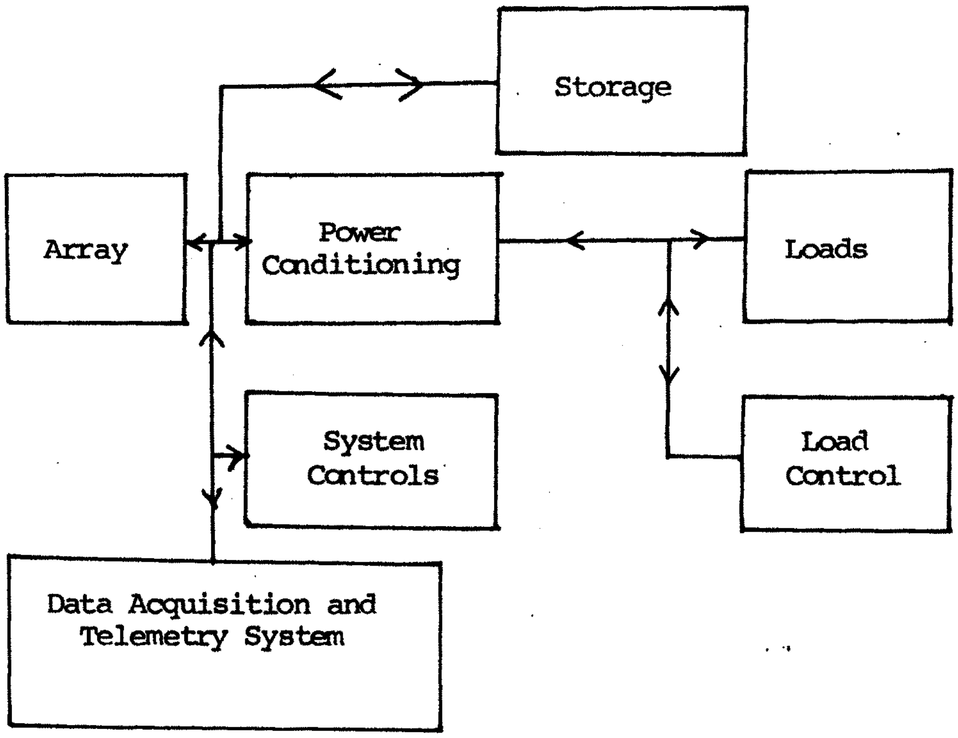

Fig.2.10. Stand-alone photovoltaic (SAPV) power system.

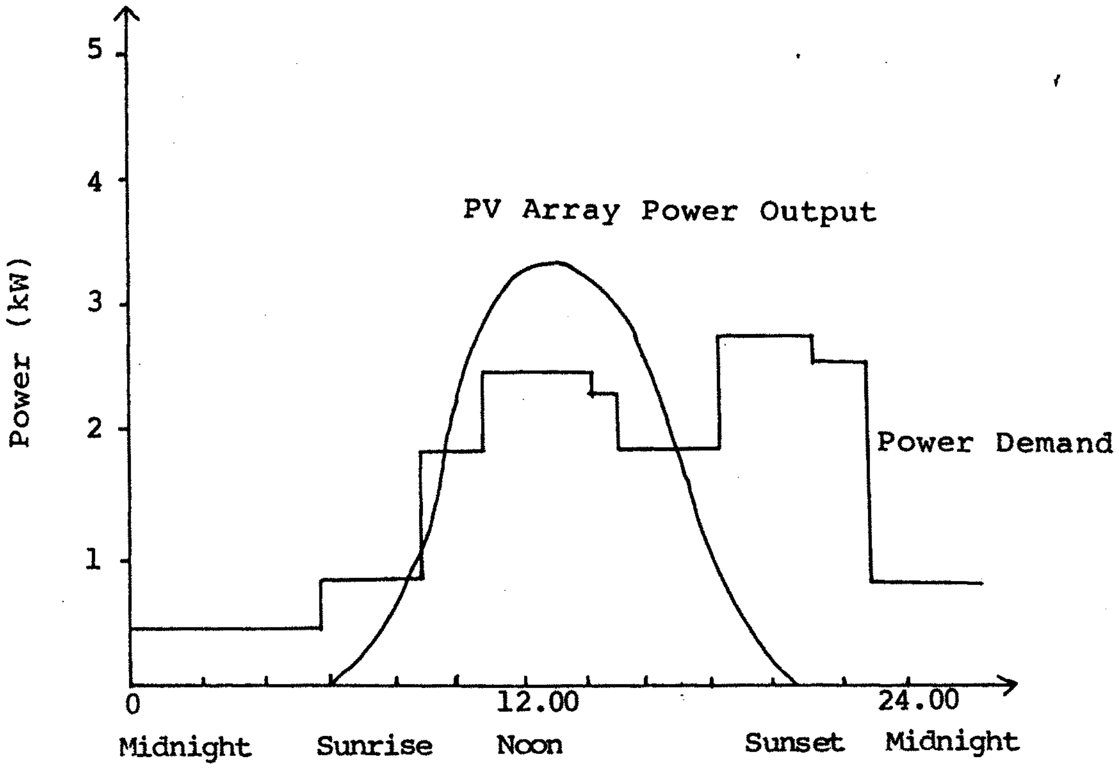

Fig.2.11. Example of power demand and PV array power output vs time.

array output. $Q_2$ is actually the difference between the area under the load curve and the area under the array output curve of Figure 2.11. So,

$$Q = Q_1 + Q_2 \qquad \text{.... (2.7.3)}$$

The nature of SAPV applications forces us to be concerned about energy storage requirements. An example where the total energy demand exceeds the total PV-array output energy is shown in Figure 2.12. The long-term battery capacity, $Q_1$ also takes a similar graphical representation to the nominal battery size Q, as shown in Figure 2.12. This is the case on all SAPV power systems.

In order to determine $Q_1$, first we must find the storage requirement C in days of load. C represents the number of days during which the battery is able to supply the load. C is read from Figure 2.13 for a given M and a ratio R of standard deviation, S, to average insolation, I. The curves in Figure 2.13 give the values of C for 1% LOLP. Once we have found C, $Q_1$ is equal to,

$$Q_1 = (CF)\ C\ (DL) \qquad \text{.... (2.7.4)}$$

$Q_2$ is equal to,

$$Q_2 = (CF)\ (DL)\ (NSR), \qquad \text{.... (2.7.5)}$$

where, no sun ratio (NSR) is the ratio of the night load to the total daily load, or in other words,

NSR = no sun ratio (days)

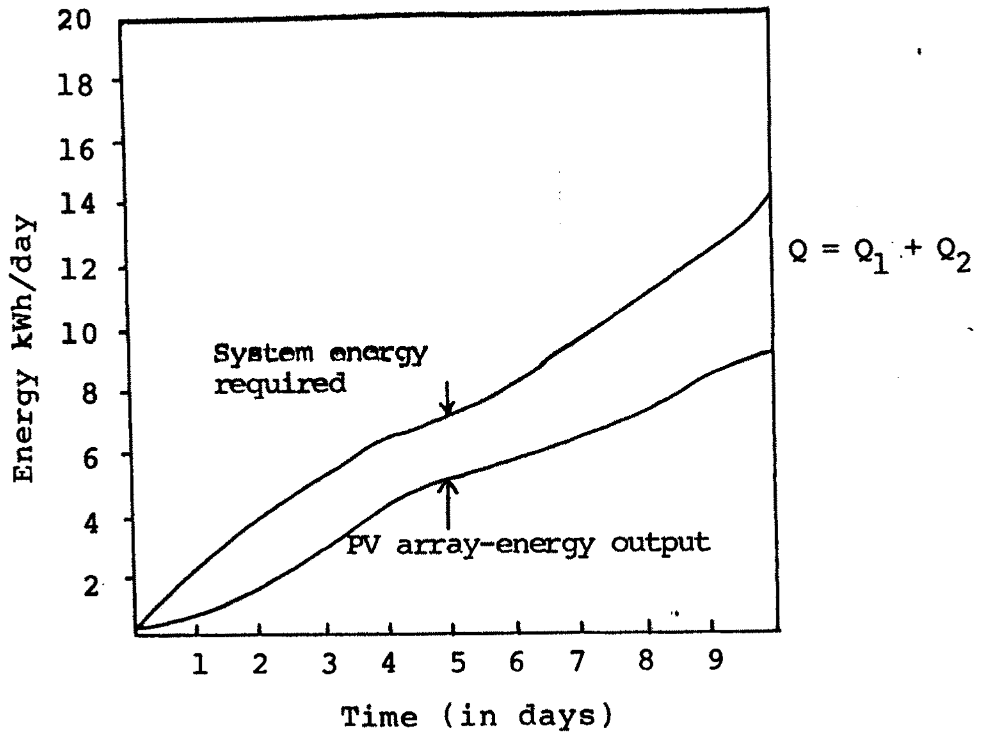

Fig.2.12. Example of energy required and PV array energy output vs time.

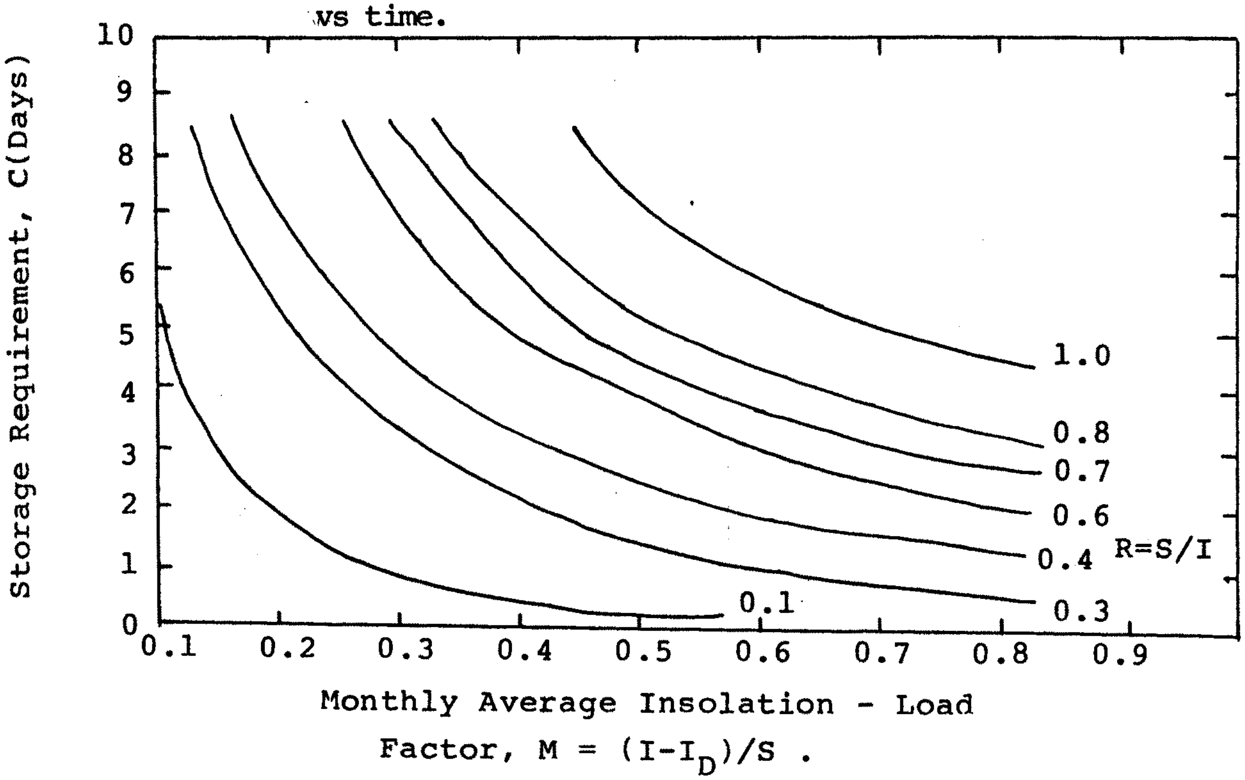

Fig.2.13. Battery storage requirements for 1% LOLP.[31]

$$= \frac{\text{night load (kWh)}}{\text{daily demand (kWh/day)}} \qquad \ldots. (2.7.6)$$

and CF is a factor which depends on the allowable depth of discharge $(DOD)_{max}$ and the battery efficiency of $\eta_B$. Battery depth-of-discharge (DOD) is defined as the percentage of capacity below the manufacturer's rated value or measured total capacity. State-of-charge (SOC) is the ratio of energy presently stored to the maximum rated value (The capacities are normally given in ampere-hours for a specified cutoff voltage and discharge temperature. If the manufacturer's rating is conservative, DOD could be negative and SOC could be greater than 1). CF is equal to,

$$CF = \frac{1}{(DOD)_{max}\ \eta_B} \qquad \ldots. (2.7.7)$$

where $\eta_B$ is the "round-trip" battery efficiency.

Generally, the battery DOD relates to the battery SOC as follows.

$$DOD = 1 - SOC \qquad \ldots. (2.7.8)$$

The rated capacity (RC) in ampere-hours is related to the SOC as follows,

$$RC = Q_p/SOC \qquad \ldots. (2.7.9)$$

where $Q_p$ is the present capacity in ampere-hours.

With these definitions in mind, consider equation, (2.7.1) rewritten to include the expression $S = R \times I$ [31]. From this expression, we see that by increasing M, the array area A is increased.

$$A = \frac{(DL)}{\eta I(1 - M \times R)} \qquad \text{.... (2.7.10)}$$

Also, Figure 2.13 shows that, for any given R, the greater the value of M, the lower the storage requirement C in days of load and thus the smaller the battery size $Q_1$, and therefore Q.

These two observations confirm the balancing effect of M in the determination of the array and battery sizes of a SAPV system. Any choice of M would theoretically be acceptable to obtain A and Q for a specific application, but only one yields the most economical solution.

The process of optimal sizing for a SAPV system was, unitl now, a repetitive one. First, M is chosen arbitrarily; then the array and battery sizes are computed with this chosen value of M, and the life-cycle cost of the system is calculated; next, other values of M are chosen; and the whole process is repeated until it yields the most economical SAPV system.

On December 16, 1978, the world's first village photovoltaic power system began operation [30], providing

Schuchuli with the following services : electric power for water pumping, lighting, family refrigerators and communal wasing machine and sewing machine. The system is all DC to maximize system efficiency. The village of Schuchuli is located on the Papago Indian reservation in Southwestern Arizona. The village's 15 families (95 people) are 17 miles from the nearest electric utility power.

In order to design the residential system one has to work out first the need of the electricity. Consider the typical example of remotely placed village. In the community center of village we need one TV set of 50 watt for 4 hours and 2 lamps of 25 W for five hours. Then total electricity comsumption per day is as follows,

$$\begin{array}{rcl} 1 \times 50 \times 4 & = & 200 \text{ Wh/day} \\ 2 \times 25 \times 5 & = & \underline{250 \text{ Wh/day}} \\ & & 450 \text{ Wh/day} \end{array}$$

This electricity is taken from storage battery. Storage battery has its own conversion efficiency. For best battery it is 80%. Thus the amount of electricity to be produced by PV cell is,

$$80 \text{ Wh} \equiv 100 \text{ Wh}$$

$$450 \text{ Wh} = \frac{450 \text{ X } 100}{80} = 563 \text{ Wh/day}$$

From the standard silicon PV cell of 4 inch diameter, one gets everyday 4.5 Wh. Thus the total number of Si cells required are,

4.5 Wh/day = 1 cell

563 Wh/day = 127 cells

In order to formulate PV panel with 12 volt supply, we will have to make two panels of 17 cells connected in series and 4 series cells in parallel. Thus total cells required will be 136 cells.

The present market price of one such cell is Rs.200. Then total price required is,

136 x 200 = Rs. 27,200=00

In order to store the electricity in storage battery and if we want to store it for a week then total watts to be stored is,

563 X 7 = 3,941 Wh/week

With a standard specification of battery available in market are of 12V, 60 Amp. With this specification, total number of batteries required is 6.

Power = 12 V X 60 A = 720 Watts

Number of batteries = 3941/720 $\cong$ 6

The price of 1 battery = Rs. 2,500=00

For 6 batteries price is Rs. 15,000=00

From above discussion, total cost of power system is 27,200+15,000+3,000 (price of inverter) = Rs.45,200=00. with this investment we will produce electricity of order of 1 unit.

Rajasthan Electronics & Instruments Ltd., (REIL) Manufactured SPV modules having following specifications :

| Modules | I | II | III |
|---|---|---|---|
| Number of cells | 36 | 36 | 36 |
| Open circuit voltage (V) | 21.0 | 21.0 | 21.0 |
| Short circuit current (A) | 2.2 | 2.2 | 2.3 |
| Peak power output ($W_p$) (at 100 mW per $cm^2$ AM 1.5 solar radiation at 25°C operating cell temperature) | 30.0 | 32.0 | 35.0 |
| Current at peak power output (A) | 1.85 | 1.97 | 2.16 |
| Voltage at peak power output (V) | 16.2 | 16.2 | 16.2 |
| Approximate weight (kg) | 5.2 | 5.2 | 5.2 |
| Dimensions (mm) | 1012 X 403 X 41 | | |

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