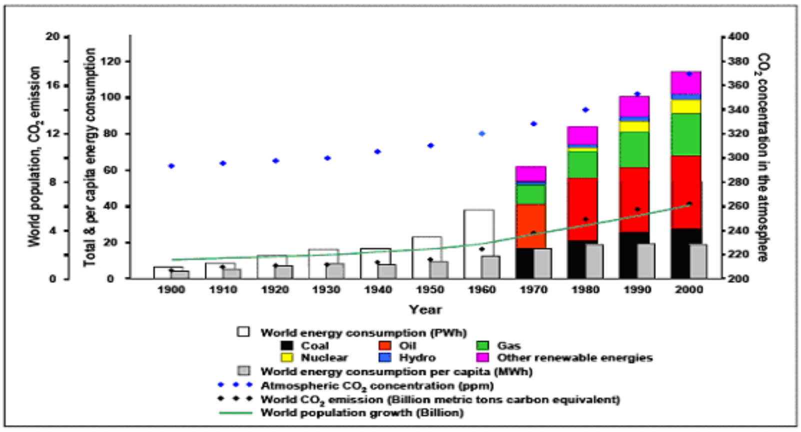
Chapter 1

Background Ideas

1.1 Introduction

Energy resources are limited. But its consumption rate is increasing day by day. The main sources of energy are-coal, oil and gas are once only limited available. So far it has not come to the large scarceness from the reasons mentioned: First of all new fossil energy occurrences are discovered again and again. Secondly there are in the meantime more efficient extraction techniques, so that the exploitation of unprofitable sources is economically worthwhile. And thirdly industry and citizens deal meanwhile substantially more economically with energy. However world energy consumption has still increased due to expected rapid increase of world population (Fig.1.1), especially in the third world and in new industrialized countries (NICs) because ever more humans also need ever more energy. Continually rapid growth is foreseen in the near future, with the world population rising from the present 6 billion to about 8 billion over the next 25 years, and is expected to grow perhaps to 10 billion people by the middle of 21st century. Such a population increase will have a dramatic impact on energy demand, at least doubling it by 2050, even if the developed countries adopt more effective energy conservation policies so that their energy consumption does not increase at all over that period.



World energy situation

Fig 1.1: Bar chart representation of world energy situation.[1]

The annual demand for primary energy would raise to approx. 154 ×1012 kWh in the next 20 years. The World Energy Council expects that demand will raise to 228 × 1012 kWh in 2050. Despite of increase in proportion of renewable energies it is still expected that the role of fossil energy resources will not basically change in the near future.

1.2 Renewable Energy

Renewable energy is energy generated from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). In 2006, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood-burning. Hydroelectricity was

the next largest renewable source, providing 3% of global energy consumption and 15% of global electricity generation.
While most renewable energy projects and production is large-scale, renewable technologies are also suited to small off-grid applications, sometimes in rural and remote areas, where energy is often crucial in human development. Kenya has the world's highest household solar ownership rate with roughly 30,000 small (20–100 watt) solar power systems sold per year.

Some renewable-energy technologies are criticized for being intermittent or unsightly, yet the renewable-energy market continues to grow. Climate-change concerns, coupled with high oil prices, peak oil, and increasing government support, are driving increasing renewable-energy legislation, incentives and commercialization. New government spending, regulation and policies should help the industry weather the 2009 economic crisis better than many other sectors.[8]

1.3 Growth of Renewable Energy

From the end of 2004 to the end of 2008, solar photovoltaic (PV) capacity increased sixfold to more than 16 gigawatts (GW), wind power capacity increased 250 percent to 121 GW, and total power capacity from new renewables increased 75 percent to 280 GW. During the same period, solar heating capacity doubled to 145 gigawatts-thermal (GWth), while biodiesel production increased sixfold to 12 billion liters per year and ethanol production doubled to 67 billion liters per year.[8]

Selected global indicators	**2006**	**2007**	**2008**
Investment in new renewable capacity (annual)	63	104	120 billion USD
Existing renewables power capacity, including large-scale hydro	1,020	1,070	1,140 GWe
Existing renewables power capacity, excluding large hydro	207	240	280 GWe
Wind power capacity (existing)	74	94	121 GWe
Biomass heating			~250 GWth
Solar hot water/ Space heating			145 GWth
Geothermal heating			~50 GWth
Ethanol production (annual)	39	50	67 billion liters
Countries with policy targets for renewable energy use		66	73

Table 1.1: Growth of Renewable Energy[8]

1.4 Main forms/sources of renewable energy

The majority of renewable energy technologies are powered by the sun. The Earth-Atmosphere system is in equilibrium such that heat radiation into space is equal to incoming solar radiation, the resulting level of energy within the Earth-Atmosphere system can roughly be described as the Earth's "climate." The hydrosphere (water) absorbs a major fraction of the incoming radiation. Most radiation is absorbed at low latitudes around the equator, but this energy is dissipated around the globe in the form of winds and ocean currents. Wave motion may play a role in the process of transferring mechanical energy between the atmosphere and the ocean through wind stress.Solar energy is also responsible for the distribution of precipitation which is tapped by hydroelectric projects, and for the growth of plants used to create biofuels.[8]

Renewable energy flows involve natural phenomena such as sunlight, wind, tides and geothermal heat, as the International Energy Agency explains:

Each of these sources has unique characteristics which influence how and where they are used.

- Wind power
- Water power
- Solar energy
- Biofuel
- Liquid biofuel
- Solid biomass
- Biogas
- Geothermal energy

1.5 Solar Energy

The invention of solar cell has some historical background. The theory of photovoltaic effect is invented on 1839 by Edmand Becquerel. In 1883, a few years' later Chalse fritts an American first innovated selenium solar cell. The modern age of solar power technology arrived in 1954 when Bell Laboratories, experimenting with semiconductors, accidentally found that silicon doped with certain impurities was very sensitive to light. In 1956 silicon solar was made whose efficiency was 6%. Since then the production procedure and efficiency has develop day by day. By using the modern technology and reducing the loss which silicon solar cell is being made with efficiency is nearly 25% . GaAs tandem solar cells which has the efficiency of 30%. So far the highest efficient solar cell was achieved by National Renewable Energy Laboratory (NREL) which converts 40.8 percent of the light that hits it into electricity. This is the highest confirmed efficiency of any photovoltaic device to date. [8]

Solar energy, radiant light and heat from the Sun, has been harnessed by humans since ancient times using a range of ever-evolving technologies. Solar radiation, along with secondary solar-powered resources such as wind and wave power, hydroelectricity and biomass, account for most of the available renewable energy on Earth. Only a minuscule fraction of the available solar energy is used.
Solar powered electrical generation relies on heat engines and photovoltaics. Solar energy's uses are limited only by human ingenuity. A partial list of solar applications includes space heating and cooling through solar architecture, potable water via distillation and disinfection, daylighting, solar hot water, solar cooking, and high temperature process heat for industrial purposes.[8]

Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute solar energy. Active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air.[8]

1.6 Energy from the Sun

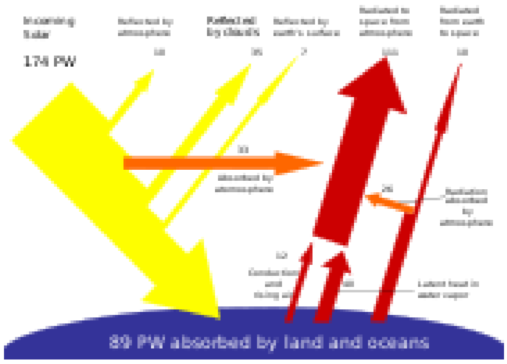


Fig 1.2: Energy from sun

About half the incoming solar energy reaches the Earth's surface.
The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet.
Earth's land surface, oceans and atmosphere absorb solar radiation, and this raises their temperature. Warm air containing evaporated water from the oceans rises, causing atmospheric circulation or convection. When the air reaches a high altitude, where the temperature is low, water vapor condenses into clouds, which rain onto the Earth's surface, completing the water cycle. The latent heat of water condensation amplifies convection, producing atmospheric phenomena such as

wind, cyclones and anti-cyclones. Sunlight absorbed by the oceans and land masses keeps the surface at an average temperature of 14 °C. By photosynthesis green plants convert solar energy into chemical energy, which produces food, wood and the biomass from which fossil fuels are derived. [8]

1.7 Yearly Solar fluxes & Human Energy Consumption

Solar	3,850,000
Wind	2,250 EJ
Biomass	3,000 EJ
Primary energy use (2005)	487 EJ
Electricity (2005)	56.7 EJ

Table1.2: Yearly Solar fluxes & Human Energy Consumption

The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. In 2002, this was more energy in one hour than the world used in one year. Photosynthesis captures approximately 3,000 EJ per year in biomass. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined.

From the table of resources it would appear that solar, wind or biomass would be sufficient to supply all of our energy needs, however, the increased use of biomass has had a negative effect on global warming and dramatically increased food prices by diverting forests and crops into biofuel production. As intermittent resources, solar and wind raise other issues.[8]

1.8 Applications of solar technology

Average insolation showing land area (small black dots) required to replace the world primary energy supply with solar electricity. 18 TW is 568 Exajoule (EJ) per year. Insolation for most people is from 150 to 300 W/m² or 3.5 to 7.0 kWh/m²/day.[8]

Solar technologies are broadly characterized as either passive or active depending on the way they capture, convert and distribute sunlight. Active solar techniques use photovoltaic panels, pumps, and fans to convert sunlight into useful outputs. Passive solar techniques include selecting materials with favorable thermal properties, designing spaces that naturally circulate air, and referencing the position of a building to the Sun. Active solar technologies increase the supply of energy and are considered supply side technologies, while passive solar technologies reduce the need for alternate resources and are generally considered demand side technologies.

- ✓ Architecture and urban planning
- ✓ Agriculture and horticulture
- ✓ Solar lighting
- ✓ Solar thermal
- ✓ Water heating
- ✓ Heating, cooling and ventilation
- ✓ Water treatment
- ✓ Cooking
- ✓ Process heat
- ✓ Electrical generation
- ✓ Solar vehicles

1.9 World's largest photovoltaic power plants

Fig 1.3: Olmedilla Photovoltaic Park[8]

First Solar 40 MW PV Array installed by JUWI Group in Waldpolenz, Germany

As of October 2009, the largest photovoltaic (PV) power plants in the world are the Olmedilla Photovoltaic Park (Spain, 60 MW), the Strasskirchen Solar Park (Germany, 54 MW), the Lieberose Photovoltaic Park (Germany, 53 MW), the Puertollano Photovoltaic Park (Spain, 50 MW), the Moura photovoltaic power station (Portugal, 46 MW), and the Waldpolenz Solar Park (Germany, 40 MW).

Many of these plants are integrated with agriculture and some use innovative tracking systems that follow the sun's daily path across the sky to generate more electricity than conventional fixed-mounted systems. There are no fuel costs or emissions during operation of the power stations.[8]

Topaz Solar Farm is a proposed 550 MW solar photovoltaic power plant which is to be built northwest of California Valley in the USA at a cost of over $1 billion. Built on 9.5 square miles (25 km2) of ranchland,the project would utilize thin-film PV panels designed and manufactured by OptiSolar in Hayward and Sacramento. The project would deliver approximately 1,100 gigawatt-hours (GW·h) annually of renewable energy. The project is expected to begin construction in 2010, begin power delivery in 2011, and be fully operational by 2013.

Name of PV power plant	Country	DC Peak Power (MW)	GW·h /year	Capacity factor
Olmedilla Photovoltaic Park	Spain	60	85	0.16
Puertollano Photovoltaic Park	Spain	50		
Moura photovoltaic power station	Portugal	46	93	0.16
Waldpolenz Solar Park	Germany	40	40	0.11
Arnedo Solar Plant	Spain	34		
Merida/Don Alvaro Solar Park	Spain	30		
Planta Solar La Magascona & La Magasquila	Spain	30		
Planta Solar Ose de la Vega	Spain	30		
Planta Fotovoltaico Casas de Los Pinos	Spain	28		
SinAn power plant	Korea	24	33	

Table 1.3: World's largest photovoltaic power plants[8]

However, when it comes to renewable energy systems and PV, it is not just large systems that matter. Building-integrated photovoltaics or "onsite" PV systems have the advantage of being matched to end use energy needs in terms of scale. So the energy is supplied close to where it is needed.

1.10 World's largest concentrating solar thermal power stations

Capacity (MW)	Technology type	Name	Country	Location
354	parabolic trough	Solar Energy Generating Systems	USA	Mojave desert California
64	parabolic trough	Nevada Solar One	USA	Las Vegas, Nevada
50	parabolic trough	Andasol 1	Spain	Granada
20	solar power tower	PS20 solar power tower	Spain	Seville
11	solar power tower	PS10 solar power tower	Spain	Seville

Table 1.4: World's largest concentrating solar thermal power stations

1.11 Advantages of Solar power

i. The 89 petawatts of sunlight reaching the earth's surface is plentiful - almost 6,000 times more than the 15 terawatts of average power consumed by humans. Additionally, solar electric generation has the highest power density (global mean of 170 W/m²) among renewable energies.
ii. Solar power is pollution free during use. Production end wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under development.
iii. Facilities can operate with little maintenance or intervention after initial setup.
iv. Solar electric generation is economically superior where grid connection or fuel transport is difficult, costly or impossible. Examples include satellites, island communities, remote locations and ocean vessels.
v. When grid-connected, solar electric generation can displace the highest cost electricity during times of peak demand (in most climatic regions), can reduce grid loading, and can eliminate the need for local battery power for use in times of darkness and high local demand; such application is encouraged by net metering. Time-of-use net metering can be highly favorable to small photovoltaic systems.
vi. Grid-connected solar electricity can be used locally thus reducing transmission/distribution losses (transmission losses were approximately 7.2% in 1995).
vii. Once the initial capital cost of building a solar power plant has been spent, operating costs are extremely low compared to existing power technologies.
viii. Compared to fossil and nuclear energy sources, very little research-money has been invested in the development of solar cells, so there is much room for improvement. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% and efficiencies are rapidly rising while mass production costs are rapidly falling.

1.12 Disadvantages of Solar Power

i. Cost may not cover lifespan savings unless a preferential feed-in tariff is offered by the grid network. But this depends on location and energy prices.
ii. Solar electricity is often initially more expensive than electricity generated by other sources.
iii. Solar electricity is not available at night and is less available in cloudy weather conditions from conventional silicon based technologies. Therefore, a storage or complementary power system is required. However, the use of germanium in amorphous silicon-germanium thin film solar cells provides residual power generating capacity at night due to background infrared radiation.
iv. Limited power density: Average daily insolation in the contiguous U.S. is 3-7 kWh/m² [clarification needed] and on average lower in Europe.

v. Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in currently existing distribution grids. This incurs an energy loss of 4-12%.

Chapter 2

Working Principle of Solar Cell

2.1 Working principle

Solar cells (or photovoltaic devices) directly convert light into electricity, and usually use similar physics and technology as that used by the microelectronics industry to make computer chips. The first step in the conversion of sunlight into electricity is that light must be absorbed in the solar cell. The absorbed light causes electrons in the material to increase in energy, at the same time making them free to move around in the material. However, the electrons remain at this higher energy for only a short time before returning to their original lower energy position. To collect the carriers before they lose the energy gained from the light, a *pn* junction is typically used. A pn junction consists of two different regions of a semiconductor material (usually silicon), with one side called the p-type region and the other the n-type region. In p-type material, electrons can grain energy when exposed to light but also readily return to their original low energy position. However, if they move into the n-type region, then they can no longer go back to their original low energy position and remain at a higher energy. The process of moving a light generated carrier from where it was originally generated to the other side of the pn junction where it retains its higher energy is called collection. Once a light generated carrier is collected, it can be either extracted from the device to give a current, or it can remain in the device and gives rise to a voltage. The generation of a voltage due to the light generated carriers is called the photovoltaic effect. Typically, some of the light generated carries are used to give a current, while others are used to create a voltage. The combination of a current and voltage give rise to a power output from the solar cell. The electrons that leave the solar cell as current give up their energy to whatever is connected to the solar cell, and then re-enter the solar (in the n-type region) at their original low energy level. Once back in the solar cell, the process begins again: an electron absorbs light and gains energy, the electron is collected by the pn junction, it leaves the device to dissipate its energy in a load, and then re-enters the solar cell.

Solar cells under incident light elaborate the above statement as Fig 2.1 shows the three main parts of a solar cell schematically: the diffused strong n doped emitter, the space-charge zone and the p-doped base.

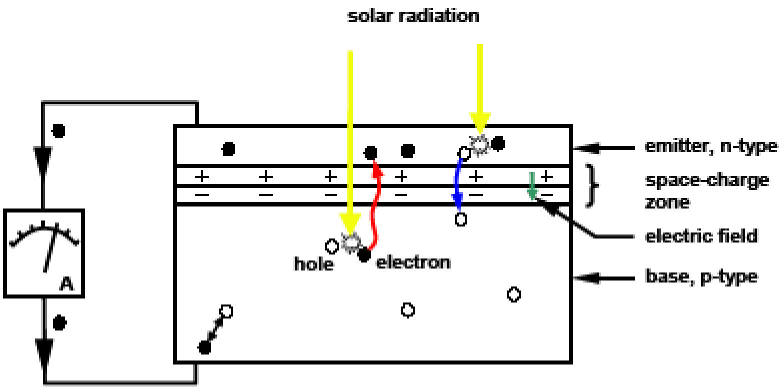


Fig2.1: Operating principle of a solar cell (schematic). [1]

A photon with sufficient large energy falls on the surface of the solar cell, penetrates emitters and space-charge zone and is absorbed in the p-base. An electron-hole pair is developed due to the absorption. Since electrons are in the minority in the p-base, one calls them minority charge carrier contrary to the holes, which are majority charge carrier here. This electron diffuses in the p base until it arrives at the boundary of the space-charge zone. The existing strong electrical field in the space-charge zone accelerates the electron and brings it to the emitter side. Thus a separation of the charge carriers took place. Thereby the electrical field works as separation medium. A prerequisite is that the diffusion length of the electron has to be large enough so that the electron can arrive up to the space-charge zone. In case of too small diffusion length a recombination would occur before reaching the space-charge zone, the energy would be lost.

Absorption of a light quantum in the emitter leads again to the formation of an electron-hole pair. According to the strongly doped n-emitter the holes are here the minority charge carrier. With sufficient large diffusion length the hole reaches the edge of the space-charge zone, is accelerated by the electric field and is brought to the p-base side. If the absorption occurs in the space-charge zone, electrons and holes are immediately separated according to the existing electrical field there.

In consequence of the incident light it yields: If concentration of electrons at the n-emitter side is increased, concentration of holes at the p-base side increases. An electrical voltage is built up. If n-emitter and p-base are galvanic ally connected, e.g. by an ohmic resistor, electrons from the emitter flows through the galvanic connection to the base and recombines with the holes there. Current flow means however power output. This current flow continues so long as the incident light radiation is available. As a result, light radiation is immediately converted into electricity. [1]

2.2 Theoretical Description of the Solar Cell

As already mentioned, illuminated solar cell creates free charge carriers, which allow current to flow through a connected load. The number of free charge carriers is proportional to the incident radiation intensity. So does also the photocurrent (I_{ph}), which is internally generated in the solar cell. Therefore an ideal solar cell can be represented by the following simplified equivalent circuit . It consists of the diode created by the p-n junction and a photocurrent source with the magnitude of the current depending on the radiation intensity. An adjustable resistor is connected to the solar cell as a load. The mathematical process of an ideal exposed solar cell leads to the following equation:

$$I_{cell} = I_{ph} - I_D = I_{ph} - I_0 \cdot \left(e^{\frac{qV}{kT}} - 1 \right)$$

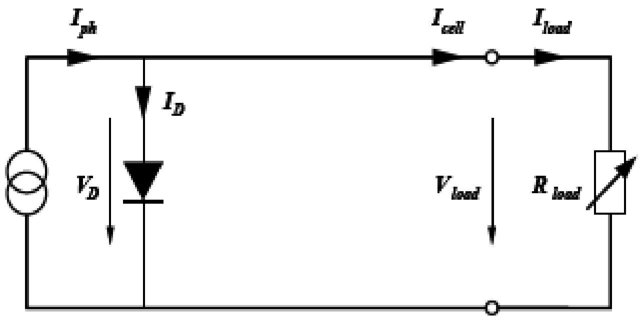


Fig2.2: Equivalent circuit diagram of an ideal solar cell connected to load.[1]

In an imaginary experiment, the I-V characteristic curve for a certain incident radiation will now be constructed, point for point (Fig 2.3):

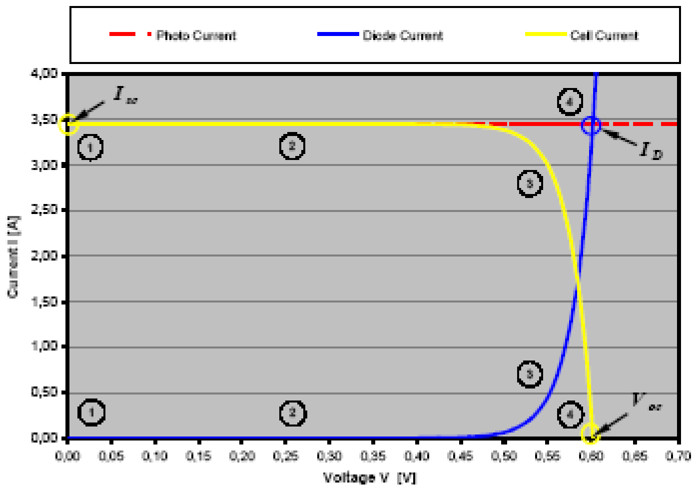


Fig 2.3: Construction of the solar cell curve from the diode curve.[1]

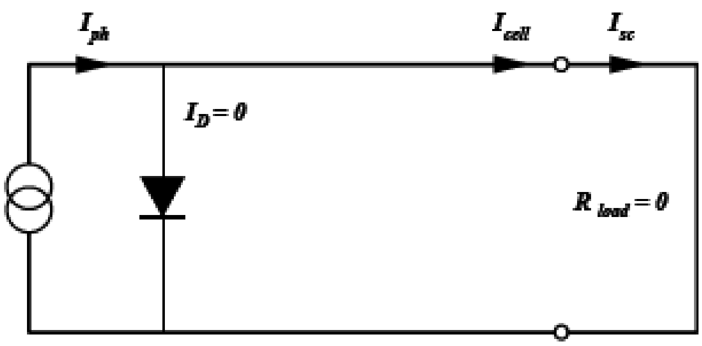


Fig2.4: Equivalent circuit diagram of the solar cell – short-circuit current. [1]

When the terminals are short-circuited (R load = 0) (Fig. 2.5), the output voltage and thus also the voltage across the diode is zero. Since V = 0, no current ID flows (point 1 in Fig 2.3) therefore the entire photocurrent I ph generated from the radiation flows to the output. Thus the cell current has its maximum at this point with the value I cell and refers to the so-called short-circuit current I_{sc}.

$I_{sc} = I_{cell} = I_{ph}$

The current remains constant. Up to a certain voltage value the current flowing through the internal diode remains negligible, thus the output current continues corresponding to the photocurrent (point 2 in Fig 2.4).Until the diode voltage threshold is exceeded after the load resistance is further increased a rapidly increasing proportion of the photocurrent flows through the diode. This current leads to power loss in the internal diode corresponding to an area between the photocurrent curve and the cell current curve. Since the sum of the load current and the diode current must be equal to the constant photocurrent, the output current decreases by exactly this amount (point 3 in Fig 2.4).

The output current is then zero ($I_{cell} = 0$) and thus the entire photocurrent flows through the internal diode (point 4in Fig 2.4). The open-circuit voltage V_{oc} can be therefore derived again –

$$V_{oc} = \frac{kT}{q} \cdot ln\left(\frac{I_{ph}}{I_o} + 1\right)$$

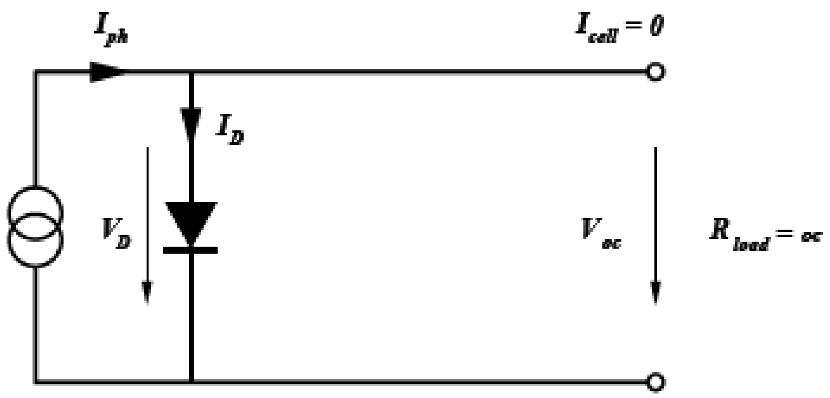


Fig2.5: Equivalent circuit diagram of the solar cell – open-circuit voltage.[1]

In addition, typical value of the open-circuit voltage is located ca. 0.5 – 0.6 V for crystalline cells and 0.6 – 0.9 V for amorphous cells. From this experiment it becomes obvious that the characteristic curve for a solar generator is equivalent to an "inverted" diode characteristic curve, which is shifted upward by an offset equal to the photocurrent (= short-circuit current). Since electric power is the product of current and voltage, therefore a curve of the power delivered by a solar cell can be obtained for a given radiation level (Fig. 2.6).

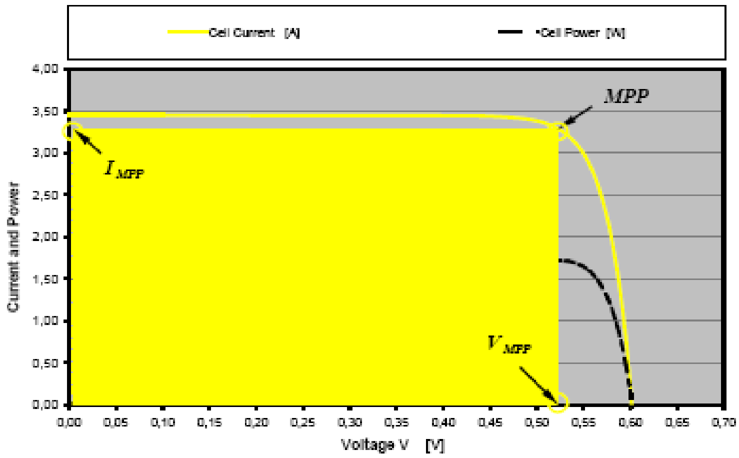


Fig2.6: Power curve and maximum power point (MPP).[1]

Although the current has its maximum at the short-circuit point, the voltage is zero and thus the power is also zero. The situation for current and voltage is reversed at the open-circuit point, so again the power here is zero. In between, there is one particular combination of current and voltage, for which the power reaches a maximum (graphically indicated with a rectangle area in Fig2.6). The so-called maximum power point (MPP) represent the working point, at which the solar cell can deliver maximum power for a given radiation intensity. It is situated near the bend of the I-V characteristic curve. The corresponding values of VMMP and IMMP can be estimated from Voc and I sc as follows-

$V_{MMP} \approx (0.75 – 0.9)\ V_{oc}$

$I_{MMP} \approx (0.85 – 0.95)\ I_{sc}$

In addition, the quantity

$$FF = \frac{(V_{MPP} \cdot I_{MPP})}{(V_{oc} \cdot I_{sc})}$$

FF is called Fill Factor represents the measure for the quality of the solar cell. It indicates how far the I-V characteristic curve approximates to a rectangle. Normally the value for crystalline solar cells is about 0.7-0.8.The maximum output power of the cell is then

$P_{MPP} = V_{MPP} * I_{MPP} = Voc * I\ sc * FF$

Thus the efficiency of the solar cell, which refers to the ratio of the output electrical energy to the input solar radiation (Pin), is defined by the following relation.

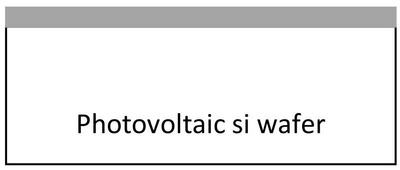
$$\eta = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_{in}}$$

Until now the highest obtained efficiencies of the silicon solar cells with irradiation of a solar spectrum AM 1.5 are approx. 24 %. The efficiencies of the silicon solar cells from the line production for terrestrial applications are situated between 10 and 14 %. The theoretical efficiencies of the silicon solar cell is however ca. 26-27 %.

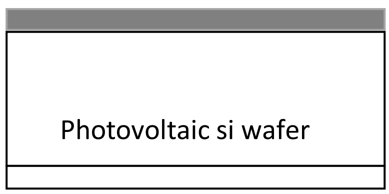
2.3 Ten- step process of photovoltaic device:

The ten step patterning process of photovoltaic device -surface preparation to exposure is given below-

Process step	Purpose	Photovoltaic Si device
1. Surface preparation	Clean and dry wafer surface	

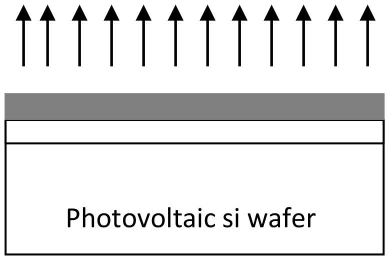


Process step	Purpose	Photovoltaic Si device
2. Photoresist apply	Spin coat a thin layer Of photoresist on surface	



3. Softbake partial evaporation of photoresist

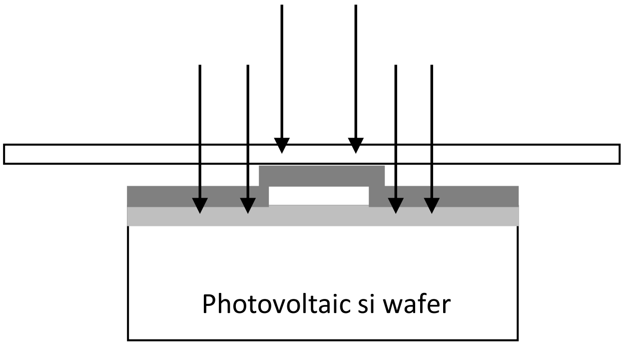
Solvents by heating



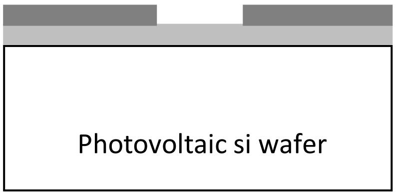
4. Alignment and exposure precise alignment of mask to wafer and

exposure of photoresist.

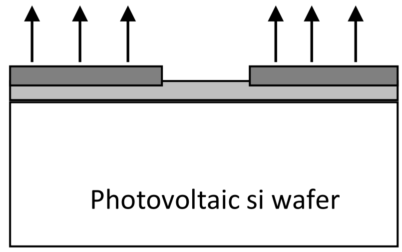
Negative resist is polymerized.



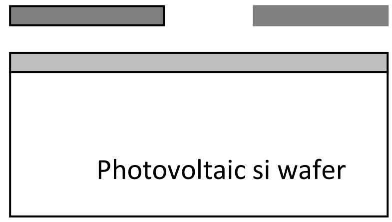
5. Development removal of unpolymerized resist



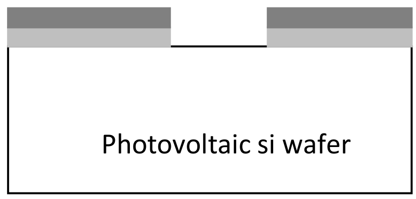
6. Hard bake Additional evaporation of solvents



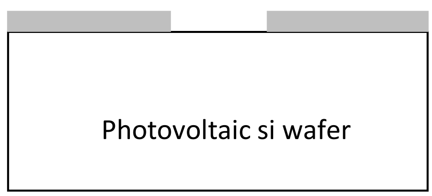
7. Develop inspect inspect surface for alignment and defects



8. Etch top layer of wafer is removed through openingin resist layer



9. Photoresist removal Remove photoresist layer from the wafer



10. Final inspection surface inspection for etch irregularities and other problem

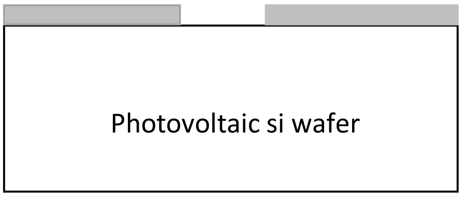


Fig2.7: Ten step photo masking process

2.4 Photoresist Composition

Photoresists are manufactured for both general and specific applications. They are tuned to respond to specific wavelengths of light and different exposing sources. They are given thermal flow characteristics and formulated to adhere to specific surface. There are four basic ingredients in photoresists:

I. Polymers
II. Solvents
III. Sensitizes
IV. Additives

Components	Functions
Polymer	Polymer structure changes from soluble to polymerized or vice versa when exposed by the exposure source in an aligner.
Solvent	Thin resist allowing application of thin layer Spinning.
Sensitizers	control and modify chemical reaction of resist during exposure.
Additives	Various added chemical to achieve process results,

Table 2.1: Photoresist Components & Functions

2.5 Types of Photoresist:

There are two types of photoresist such that-----

- Negative photoresist
- Positive photoresists

2.5.1 Negative photoresist:

Up to the mid – 1970s negative photoresist was dominant in the masking process. The advent of VLSI circuits and image sizes in the 2 to 5 μm range strained the resolution capability of negative resists. With negative resist and a light field masks, the dimension in the resist is smaller than the mask dimension as a result of light wrapping around the image.

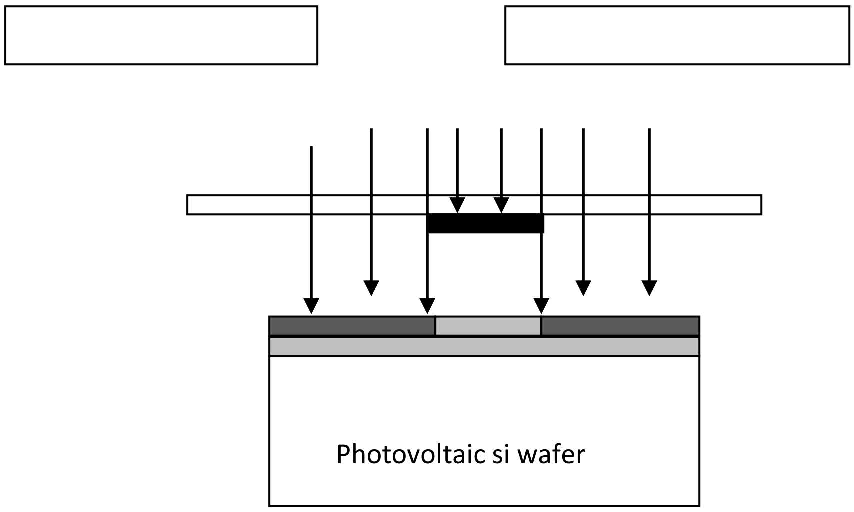


Fig2.8: Change image size reduction with light field mask and negative resist

2.5.2 Positive photoresist:

In the 1980s, positive resist became the resist of choice. The transition was not easy, switching to a positive resist requires changing the polarity of the mask. With a positive resist and dark field mask, the diffraction tends to widen the image.

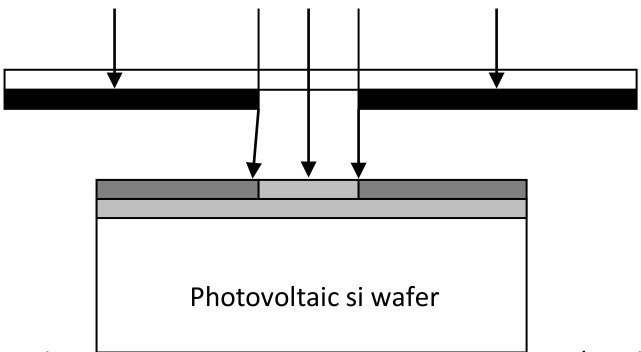


Fig2.9: Change image size reduction with light field mask and positive resist

Most of the images on most of the mask layers are holes. With positive resist, the mask polarity is dark field,which results in additional pinhole protection for the wafer in the Fig.

Chapter 3

Solar Cell Technologies

3.1 Solar cell technologies

A solar cell is a device that converts the energy of sunlight directly into electricity by the photovoltaic effect. Sometimes the term solar cell is reserved for devices intended specifically to capture energy from sunlight, while the term photovoltaic cell is used when the light source is unspecified. Assemblies of cells are used to make solar panels, solar modules and photovoltaic arrays. Solar cell technologies differ from one another based firstly on the material used to make the solar cell and secondly based on the processing technology used to fabricate the solar cells. The material used to make the solar cell determines the basic properties of the solar cell, including the typical range of efficiencies. Most commercial solar cells for use in terrestrial applications (i.e., for use on earth) are made from wafers of silicon. Silicon wafer solar cells account for about 85% of the photovoltaic market. Silicon is a semiconductor used extensively to make computer chips. The silicon Wafers can either consist of one large singe crystal, in which case they called single crystalline wafers, or can consist of multiple crystals in a singe wafer, in which case they are called multi crystalline silicon wafers. Single crystalline wafers will in general have a higher efficiency than multi crystalline wafers. Silicon wafers used in commercial production allow power conversion efficiencies of close to 20%, although the fabrication technologies at present limit them to about 17 to 18%. Multi crystalline silicon wafers allow power conversion efficiencies of up to 17%, with present fabrication achieving between 13 to 15%.The efficiency achieved by a solar cell depends on the processing technology used to make the solar cell. The most commonly used technology to make wafer-based silicon solar cells is screen-printed technology, which achieves efficiencies of 11-15%. Higher efficiency technologies are the buried contact or buried grid technology, which achieves efficiencies op up to 18% and has been in production for about a decade.

Although silicon solar cells are the dominant material, some applications– particularly space applications – require higher efficiency than is possible from silicon or other solar cell technologies. Solar cells made from GaAs or related materials (called III-V materials since they are in general made from groups III and V of the periodic table) have a higher efficiency than silicon solar cells, particularly for the spectrum of light that exists in space. GaAs solar cells have Efficiencies of up to 25% measured under terrestrial conditions. To further increase these efficiencies, solar cells made from different kinds of materials are stacked on top of one another. Such devices are called tandem or multi junction solar cells (the term multi junction applies to other types of Structures as well). Such solar cells have efficiencies of up to 33%.

A final class of solar cell materials is called thin film solar cells. These solar cells can be made from a variety of materials, with the key characteristic being that the thickness of the devices is a fraction of other types of solar cells. Thin film solar cells may be made either from amorphous silicon, cadmium telluride, copper indium dieseline or thin layers of silicon. The efficiencies of thin film solar cells tend to be lower than those of other devices, but to compensate for this the production cost can also be significantly lower. Of these technologies, amorphous silicon is the best developed, and laboratory efficiencies are between 10 to 12%, with commercial efficiencies just over half these efficiencies. The other thin film technologies are still the subject of development, although commercial products exist. The efficiency of these devices is about 6% to 10% efficient.

Most solar cells will theoretically operate with a higher efficiency under intense sunlight than under the conditions encountered on earth. Concentrator solar systems exploit this effect, by focusing sunlight into a concentrated spot or line. Concentrator systems exist for both silicon and III-V solar cells. Silicon concentrator systems have reached efficiencies of 28% while III-V based systems have reached about 33%. Crystalline silicon (c-Si) has been used as the light-absorbing semiconductor in most solar cells, even though it is a relatively poor absorber of light and requires a considerable thickness (several hundred microns) of material. Nevertheless, it has proved convenient because it yields stable solar cells with good efficiencies (11-16%, half to two-thirds of the theoretical maximum) and uses process technology developed.

3.2 Generations of solar cells

Solar Cells are classified into three generations which indicates the order of which each became important. At present there is concurrent research into all three generations while the first generation technologies are most highly represented in commercial production, accounting for 89.6% of 2007 production.

3.2.1 First generation

First generation cells consist of large-area, high quality and single junction devices. First generation technologies involve high energy and labor inputs which prevent any significant progress in reducing production costs. Single junction silicon devices are approaching the theoretical limiting efficiency of 31% and achieve an energy payback period of 5–7 years. [8]

3.2.3 Second generation

Second generation materials have been developed to address energy requirements and production costs of solar cells. Alternative manufacturing techniques such as solution deposition vapour deposition, electroplating, and use of Ultrasonic Nozzles are advantageous as they reduce high temperature processing significantly. It is commonly accepted that as manufacturing techniques evolve production costs will be dominated by constituent material requirements, whether this be a silicon substrate, or glass cover.

The most successful second generation materials have been cadmium telluride (CdTe), copper indium gallium selenide, amorphous silicon and micromorphous silicon. These materials are applied in a thin film to a supporting substrate such as glass or ceramics, reducing material mass and therefore costs. These technologies do

hold promise of higher conversion efficiencies, particularly CIGS-CIS, DSC and CdTe offers significantly cheaper production costs.
Among major manufacturers there is certainly a trend toward second generation technologies; however commercialisation of these technologies has proven difficult. In 2007 First Solar produced 200 MW of CdTe solar cells making it the fifth largest producer of solar cells in 2007 and the first ever to reach the top 10 from production of second generation technologies alone. Wurth Solar commercialised its CIGS technology in 2007 producing 15 MW. Nanosolar commercialised its CIGS technology in 2007 with a production capacity of 430 MW for 2008 in the USA and Germany. In 2007, CdTe production represented 8.9% of total market share, thin-film silicon 5.2% and CIGS 0.5%.

3.2.3 Third generation

Third generation technologies aim to enhance poor electrical performance of second generation (thin-film technologies) while maintaining very low production costs. Current research is targeting conversion efficiencies of 30-60% while retaining low cost materials and manufacturing techniques. They can exceed the theoretical solar conversion efficiency limit for a single energy threshold material, that was calculated in 1961 by Shockley and Queisser as 31% under 1 sun illumination and 40.8% under the maximal artificial concentration of sunlight (46,200 suns, which makes the latter limit more difficult to approach than the former).
There are a few approaches to achieving these high efficiencies including the use of multijunction photovoltaic cells, concentration of the incident spectrum, the use of thermal generation by UV light to enhance voltage or carrier collection, or the use of the infrared spectrum for night-time operation. [8]

3.3 From Single Cells to PV Arrays

Solar cells are rarely used individually. Rather, cells with similar characteristics are connected and encapsulated to form modules in order to obtain higher power values. These modules are then in turn combined to construct arrays. PV arrays for a diversity of applications can be constructed according to this principle in the power range from µW to MW.

3.3.1 Parallel connection

If higher current is required in a system, solar cells are connected in parallel as illustrated in Fig 3.1

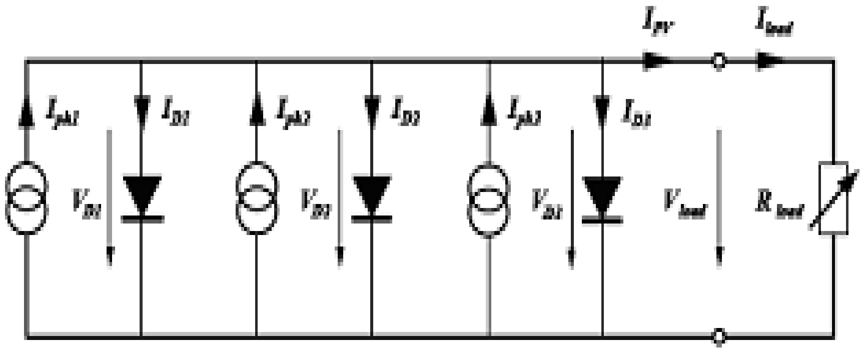


Fig3.1: Parallel connection of solar cells. [1]

Regarding a parallel-connected configuration the voltage across each cell is equal whereas the total current is the sum of all the individual cell currents. Accordingly, the current-voltage characteristic curve of the complete configuration is obtained, as shown in Fig 3.2, by adding the single cell current values corresponding to each voltage value point for point.

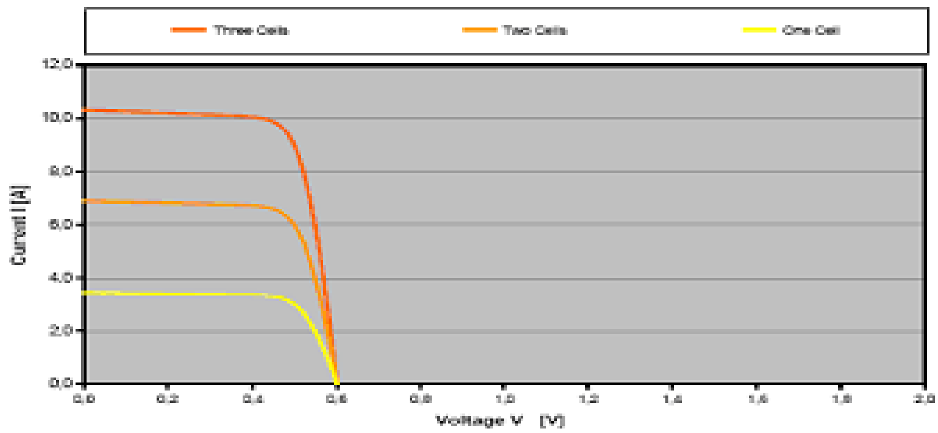


Fig3.2: I-V characteristic curve for parallel connection. [1]

The question of the system performance arises when part of a module is shaded. As indicated in Fig 3.5 three identical cells are connected in parallel and one cell is completely shaded, which then stops generating its photocurrent. The worst case takes place with open-circuit condition, i.e. if there is no external load. Since the shaded cell is cooler than the other two cells, the breakdown voltage of its diode is higher according to their I-V characteristic curves. Whereas the voltage across all three cells is identical, the diode current of the shaded cell is therefore extremely small.

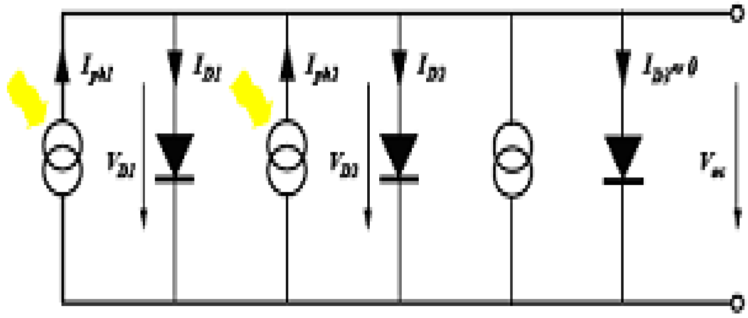


Fig3.3: Partial shading in case of parallel connection. [1]

Pure parallel connection in order to construct a module is usually not suitable for common application because high current requires big cross section of conductor. Besides, low voltage causes high relative losses. For these reasons a series connection is more attractive.

3.3.2 Series connection

In a series connection, as illustrated in Fig 3.4, the same current flows through each cell whereas the total voltage is the sum of the voltage across each cell. The I-V characteristic curve of the complete configuration, as shown in Fig 3.5, is obtained by adding the single cell voltage value corresponding to each current value point for point.

The following characteristic curves result for a given radiation intensity, which is equal for three of solar cells. Series connection of the solar cells causes an undesired effect when a PV module is partly shaded. In contrast with parallel connection, the worst case occurs in case of short-circuit connection.

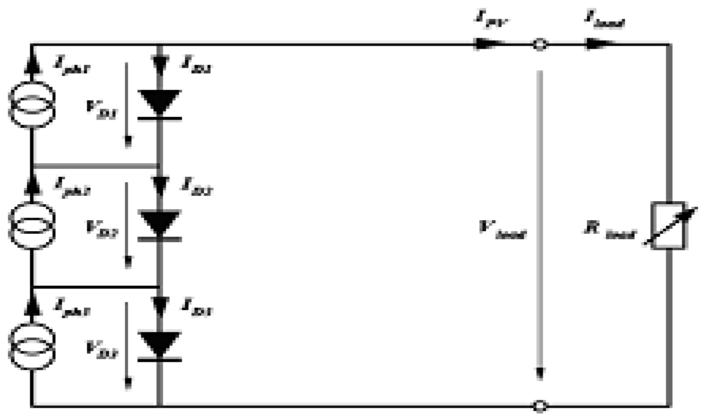


Fig3.4: Series connection of solar cells. [1]

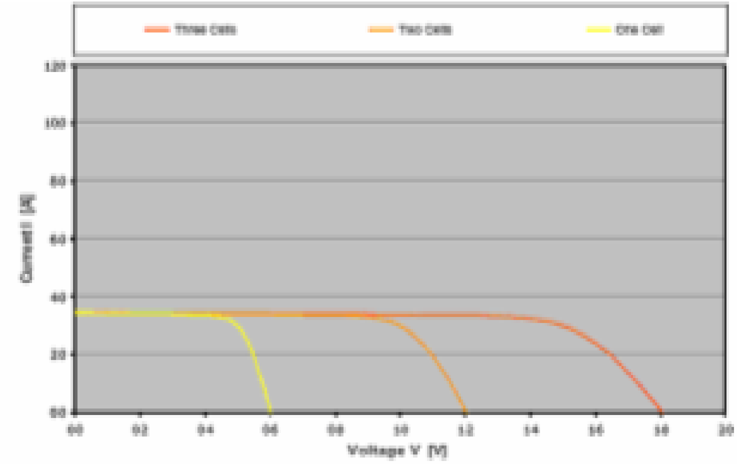


Fig3.5: I-V characteristic curve for series connection. [1]

In case of complete shading as shown in Fig 3.6 the shaded cell generates no current and acts as an open-circuit and therefore no current flows in the circuit. Its diode tends to be reverse biased by the voltage generated from other two cells. However, there is no power dissipation to the shaded cell unless the breakdown voltage of its diode is exceeded. Due to the fact that there is no current flowing in the circuit, the output power in this case is also zero. One solution to this problem is to connect bypass diode anti-parallel to the cells (Fig 3.7) so that larger voltage differences cannot arise in the reverse-current direction of the solar cells. Under normal conditions such as with no shading each bypass diode is reverse biased and each cell generates power.

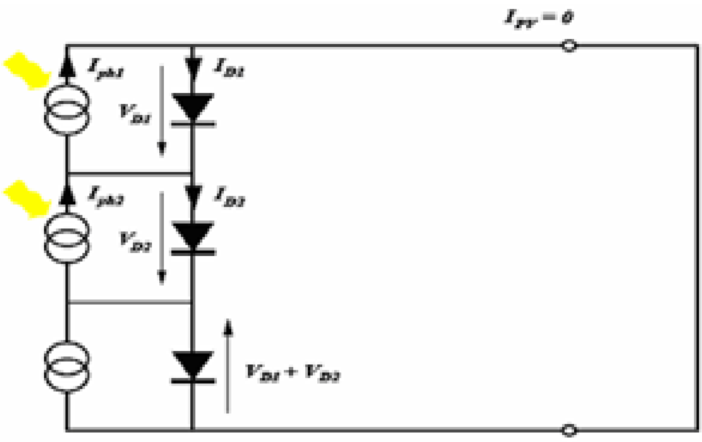


Fig3.6: Series connection – one cell is completely shaded. [1]

As shown in Fig 3.9, when the third cell is shaded, its bypass diode is forward biased and conducts the circuit current. Regarding the I-V characteristic curve of the PV array in case of shading by assuming that the load is adjusted from infinity (open-circuit) to zero (short-circuit), the result is shown in Fig 3.8. Under open-circuit condition no current flows through the circuit and there is no voltage across the third cell. When the load is smaller than infinity, the load voltage is smaller than open-circuit voltage and the voltage across the third cell increases from zero, its bypass diode is therefore forwards based and will conduct the circuit current as soon as its threshold voltage is reached. Afterwards, the characteristic corresponds to the curve of two cells connected in series.

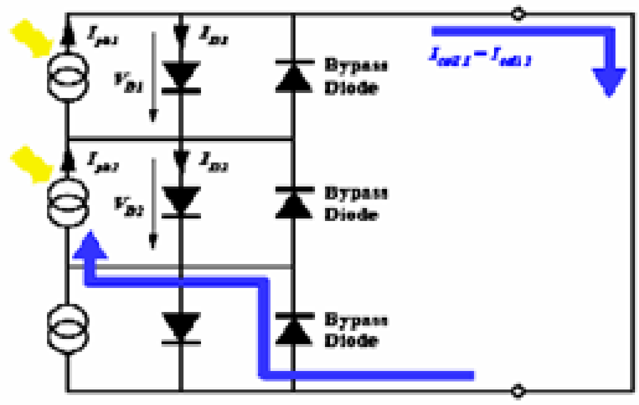


Fig3.7: Series connection with bypass diodes – one cell is completely shaded. [1]

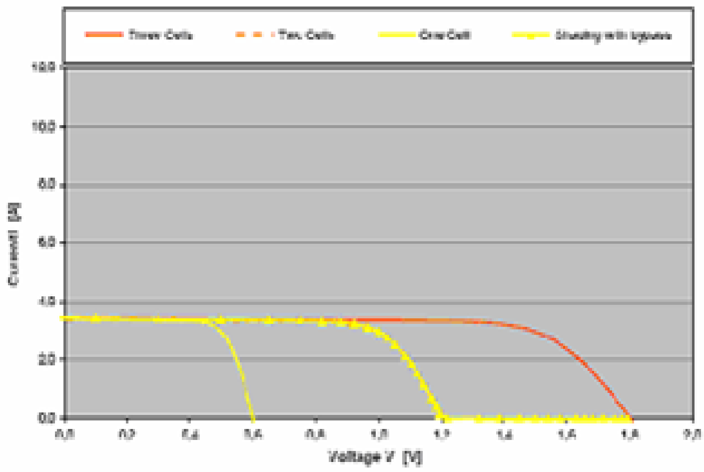


Fig3.8: I-V characteristic curve for series connection – one cell is completely shaded. [1]

In case that the third cell is partly shaded (Fig 3.9), e.g. 20 % irradiation incident on the cell (Fig.3.9), it can produce approx. 20 % of the photocurrent produced by the other two cells. Regarding series connection, although the other two cells can produce their 100 % photocurrents, the amount of current flowing in the circuit can only equal the amount of the current produced by the third cell.
The rest of the current produced by the first cell will flow into its own diode (this is also applied to the second cell). In addition, the diode of the third cell is reverse biased by the voltage generated by the other two cells. Therefore, power dissipation to the third cell arises

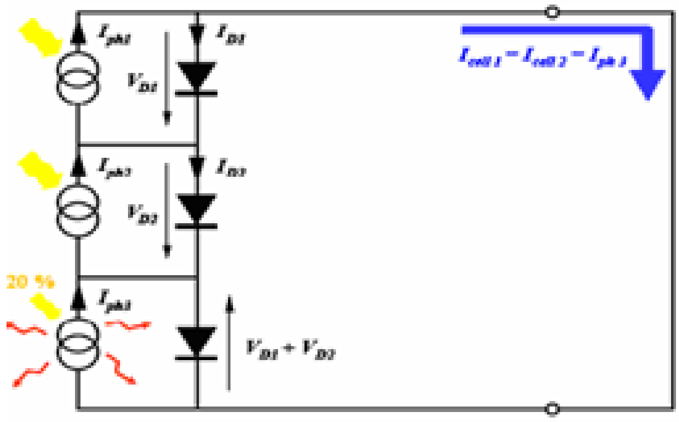


Fig3.9: Series connection – one cell is partly shaded. [1]

Such power dissipation refers to the so-called hot spot: an intolerable effect, which leads to breakdown in the cell p-n junction and in turn to destructions, i.e. cell or glass cracking or melting of solder. However, this can also happen in case of mismatched cells within the module due to manufacturing differences, degradation (cracked) or even unequal illuminated cells, which then result in different outputs. By means of the bypass diodes the problems of mismatched cells and hot spots can be avoided. After the bypass of the third cell conducts, the current flowing through it is equal to the different amount between the circuit current and the current produced by the third cell. The I-V characteristic curve of this case is indicated in Fig 3.11.

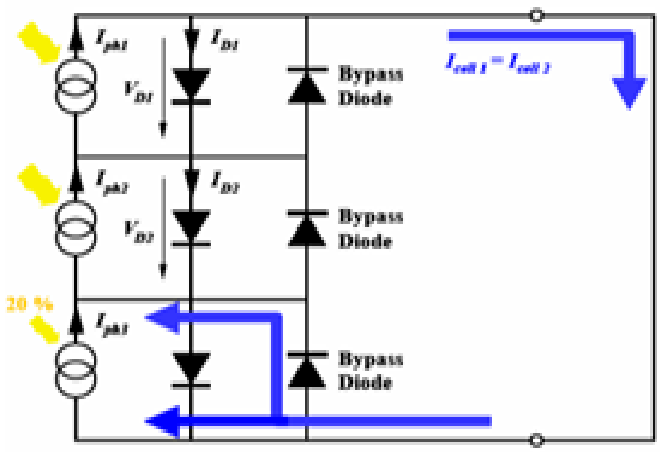


Fig3.10: Series connection with bypass diodes – one cell is partly shaded. [1]

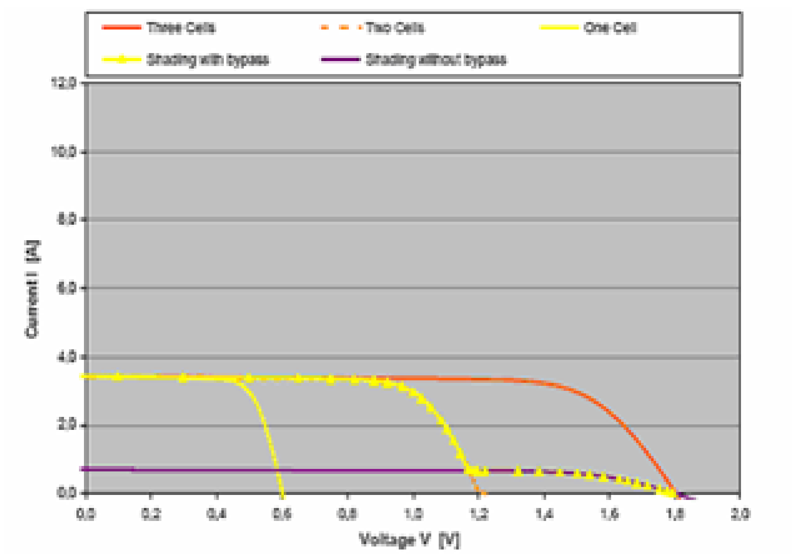


Fig3.11: I-V characteristic curve for series connection – one cell is partly shaded. [1]

However one bypass diode per cell is generally too expensive. In practice, according to reasons of permissible power loss, it is sufficient to provide one diode for every 10 to 15 cells, i.e. for a normal 36-cell module three diodes are needed. In addition, these connections are included in the connection box by the manufacturer. It should be noted that the bypass diodes do not cause any losses while current does not flow through them in normal operation. In addition to protecting the shaded module, the bypass diode also allows current to flow through the PV array when it is partly shaded even if at a reduced voltage and power.

3.4 Cell Temperature

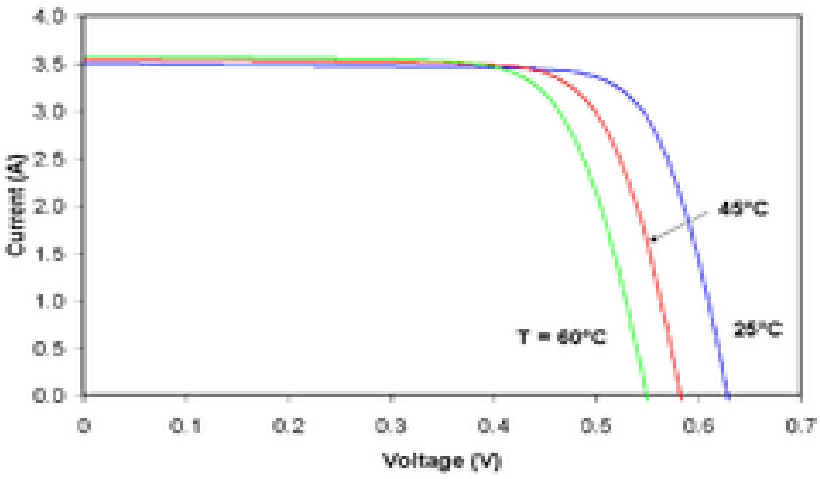


Fig 3.12: Effect of temperature on the current-voltage characteristics of a solar cell

Temperature affects the characteristic equation in two ways: directly, via *T* in the exponential term, and indirectly via its effect on I_0 (strictly speaking, temperature affects all of the terms, but these two far more significantly than the others). While

increasing *T* reduces the magnitude of the exponent in the characteristic equation, the value of I_0 increases exponentially with *T*. The net effect is to reduce V_{OC} (the open-circuit voltage) linearly with increasing temperature. The magnitude of this reduction is inversely proportional to V_{OC}; that is, cells with higher values of V_{OC} suffer smaller reductions in voltage with increasing temperature. For most crystalline silicon solar cells the reduction is about 0.50%/°C, though the rate for the highest-efficiency crystalline silicon cells is around 0.35%/°C. By way of comparison, the rate for amorphous silicon solar cells is 0.20-0.30%/°C, depending on how the cell is made.
The amount of photogenerated current I_L increases slightly with increasing temperature because of an increase in the number of thermally generated carriers in the cell. This effect is slight, however: about 0.065%/°C for crystalline silicon cells and 0.09% for amorphous silicon cells.
The overall effect of temperature on cell efficiency can be computed using these factors in combination with the characteristic equation. However, since the change in voltage is much stronger than the change in current, the overall effect on efficiency tends to be similar to that on voltage. Most crystalline silicon solar cells decline in efficiency by 0.50%/°C and most amorphous cells decline by 0.15-0.25%/°C. The Fig above shows I-V curves that might typically be seen for a crystalline silicon solar cell at various temperatures.

3.5 Effect of resistance on solar cell

3.5.1 Series resistance

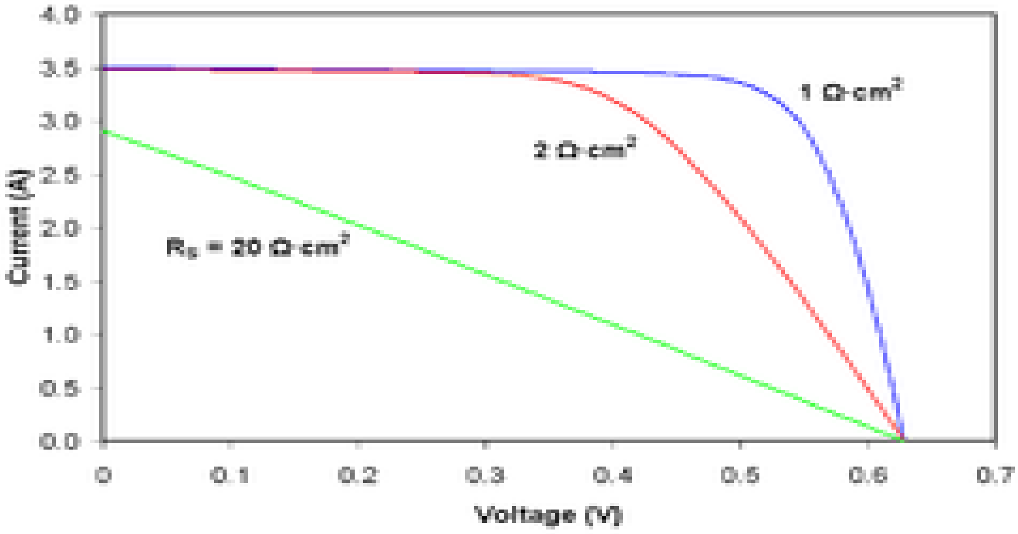


Fig 3.13: Effect of series resistance on the current-voltage characteristics of a solar cell

As series resistance increases, the voltage drop between the junction voltage and the terminal voltage becomes greater for the same flow of current. The result is that the current-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage *V* and a slight reduction in I_{SC}, the short-circuit current. Very high values of R_S will also produce a significant reduction in I_{SC}; in these regimes, series resistance dominates and the behavior of the solar cell resembles that of a resistor. These effects are shown for crystalline silicon solar cells in the I-V curves displayed in the Fig to the right.

3.5.2 Shunt resistance

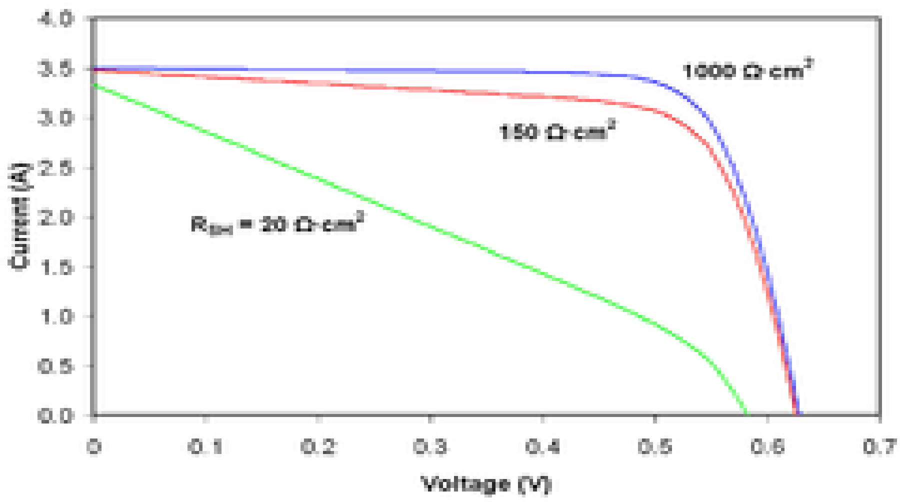


Fig 3.14: Effect of shunt resistance on the current–voltage characteristics of a solar cell

As shunt resistance decreases, the current diverted through the shunt resistor increases for a given level of junction voltage. The result is that the voltage-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal current *I* and a slight reduction in V_{OC}. Very low values of R_{SH} will produce a significant reduction in V_{OC}. Much as in the case of a high series resistance, a badly shunted solar cell will take on operating characteristics similar to those of a resistor. These effects are shown for crystalline silicon solar cells in the I-V curves displayed in the Fig to the right.

3.6 Reverse saturation current

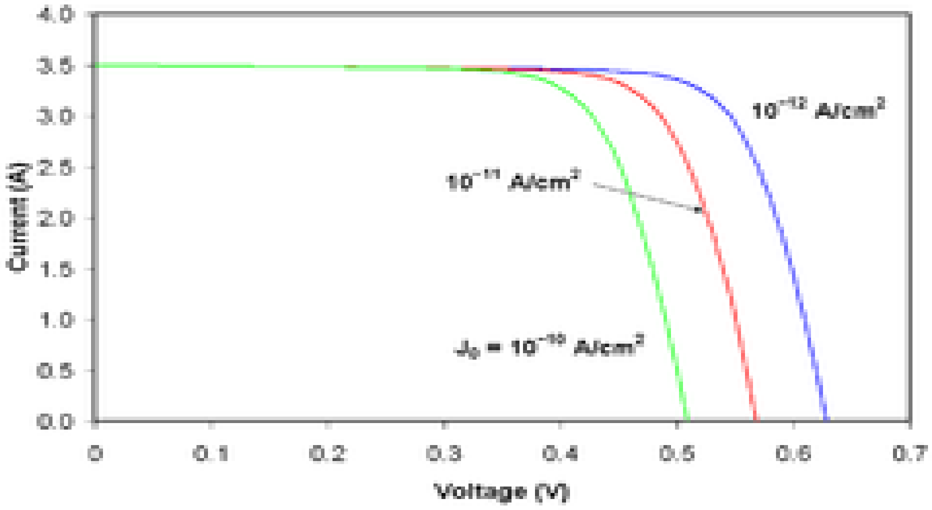


Fig 3.15: Effect of reverse saturation current on the current-voltage characteristics of a solar cell

If one assumes infinite shunt resistance, the characteristic equation can be solved for V_{OC}:

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right).$$

Thus, an increase in I_0 produces a reduction in V_{OC} proportional to the inverse of the logarithm of the increase. This explains mathematically the reason for the reduction in V_{OC} that accompanies increases in temperature described above. The effect of reverse saturation current on the I-V curve of a crystalline silicon solar cell are shown in the Fig to the right. Physically, reverse saturation current is a measure of the "leakage" of carriers across the p-n junction in reverse bias. This leakage is a result of carrier recombination in the neutral regions on either side of the junction.

3.7 Ideality factor

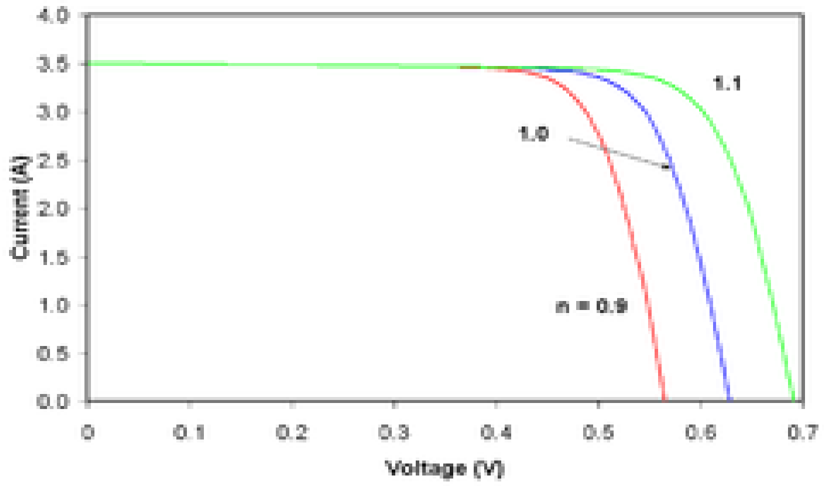


Fig 3.16: Effect of ideality factor on the current-voltage characteristics of a solar cell

The ideality factor (also called the emissivity factor) is a fitting parameter that describes how closely the diode's behavior matches that predicted by theory, which assumes the p-n junction of the diode is an infinite plane and no recombination occurs within the space-charge region. A perfect match to theory is indicated when $n = 1$. When recombination in the space-charge region dominate other recombination, however, $n = 2$. The effect of changing ideality factor independently of all other parameters is shown for a crystalline silicon solar cell in the I-V curves displayed in the Fig to the right.

Most solar cells, which are quite large compared to conventional diodes, well approximate an infinite plane and will usually exhibit near-ideal behavior under Standard Test Condition ($n \approx 1$). Under certain operating conditions, however, device operation may be dominated by recombination in the space-charge region. This is characterized by a significant increase in I_0 as well as an increase in ideality factor to $n \approx 2$. The latter tends to increase solar cell output voltage while the former acts to erode it. The net effect, therefore, is a combination of the increase in voltage shown for increasing n in the Fig to the right and the decrease in voltage shown for increasing I_0 in the Fig above. Typically, I_0 is the more significant factor and the result is a reduction in voltage.

3.8 Sources of losses in solar cells

a) A part of the incident light is reflected by metal grid at the front. Additional reflection losses arise during radiation transition from the air into the semiconductor material due to different indexes of refraction. These losses are reduced by coating the surface with antireflection layer. Another possibility is a structuring the cell surface.

b) The solar radiation is characterized by a wide spectral distribution, i.e. it contains photons with extreme different energies. Photons with small energy than the band gap are not absorbed and thus are unused. Since the energies are not sufficient to ionize electrons, electron-hole pairs will not be produced. In case of photons with larger energy than the band gap, only amount of energy equal to the band gap is useful, regardless of how large the photon energy is. The excess energy is simply dissipated as heat into the crystal lattice.

c) Since the photocurrent is directly proportional to the number of photons absorbed per unit of time, the photocurrent increases with decreasing band gap. However, the band gap determines also the upper limit of the diffusion voltage in the p-n junction. A small band gap leads therefore to a small open-circuit voltage. Since the electrical power is defined by the product of current and voltage, a very small band gaps result in small output power and thus low efficiencies. In case of large band gaps, the open-circuit voltage will be high. However, only small part of the solar spectrum will be absorbed. As a result, the photocurrent achieves here only small values. Again, the product of current and voltage stays small.

d) The dark current is larger than the theoretical value. This reduces the open-circuit voltage.

e) Not all charge carriers produced are collected, some recombine. Charge carriers recombine preferably at imperfections, i.e. lattice defects of crystal or impurities. Therefore, source material must have a high crystallographic quality and provide most purity. Likewise, the surface of the semiconductor material is a place, in which the crystal structure is very strongly disturbed, and forms a zone of increasing recombination.

f) The Fill factor is always smaller than one (theoretical max. value ca. 0.85).

g) Series- and parallel resistance result in reduction of the Fill factor.

Chapter 4

Solar Home System (SHS)

4.1 Solar Home System

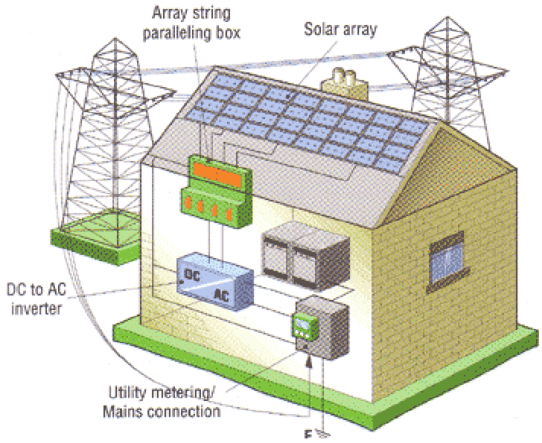


Fig 4.1: Solar Home System and its different connection.

The Solar Panels collect energy from the sun and turn it into electricity. The Inverter converts DC electricity from the Solar Panels and turns it into AC electricity that we use in our homes. Solar power system with Battery backup stores some of the electricity harnessed by the PV solar panels in a battery or batteries. The battery is connected to defined circuits in the house and supply electric

Power to these critical circuits when event of utility outage occurs. The beauty of solar power is it is a free source of energy. Historically, the cost of capturing and maintaining solar power wasn't cheap, but this has changed dramatically in the last ten years. Systems are now much more efficient, with the total cost usually involved in the purchase and installation. Depending on the system, there is almost no maintenance cost and most systems have a 40 or 50 year life span.

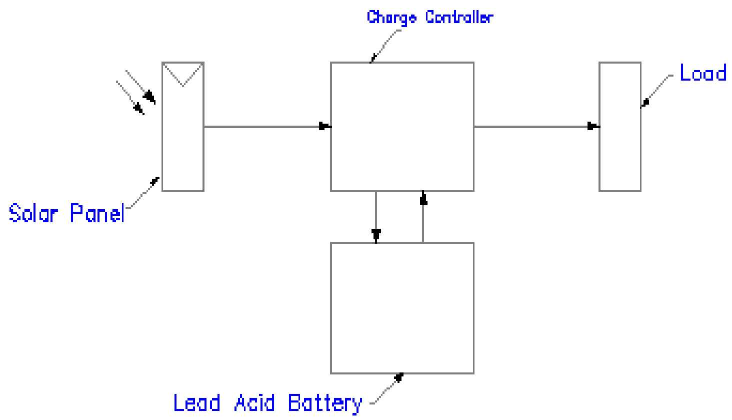


Fig 4.2: solar home system components.

4.2 Components of SHS -

a. Solar Panel
b. Mounting System
c. Charger Controller
d. Battery
e. Inverter
f. Load
g. Misselinous

4.3 Solar panel

4.3.1 General Information

A photovoltaic module or photovoltaic panel is a packaged interconnected assembly of photovoltaic cells, also known as solar cells. The photovoltaic module, known more commonly as the solar panel, is then used as a component in a larger photovoltaic system to offer electricity for commercial and residential applications.

Fig 4.3: Solar panel

Because a single photovoltaic module can only produce a certain amount of wattage, installations intended to produce larger electrical power capacity require an installation of several modules or panels and this is known as a photovoltaic array. A photovoltaic installation typically includes an array of photovoltaic modules or panels, an inverter, batteries and interconnection wiring.

Photovoltaic systems are used for either on- or off-grid applications, and for solar panels on spacecraft. [8]

4.3.2 Theory and construction

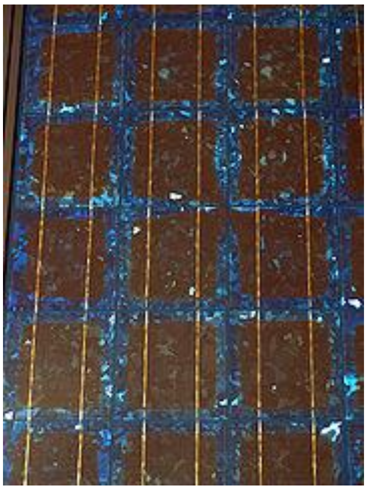


Fig 4.4: PV cells in a panel.

Solar Panels use light energy (photons) from the sun to generate electricity through photovoltaic effect (this is the photo-electric effect). The majority of modules use wafer-based crystalline silicon cells or a thin-film cell based on cadmium telluride or silicon. Crystalline silicon, which is commonly used in the wafer form in photovoltaic (PV) modules, is derived from silicon, a commonly used semi-conductor.
In order to use the cells in practical applications, they must be:

Connected electrically to one another and to the rest of the system

Protected from mechanical damage during manufacture, transport, installation and use (in particular against hail impact, wind and snow loads). This is especially important for wafer-based silicon cells which are brittle.

Protected from moisture, which corrodes metal contacts and interconnects, (and for thin-film cells the transparent conductive oxide layer) thus decreasing performance and lifetime.

Most modules are usually rigid, but there are some flexible modules available, based on thin-film cells.

Electrical connections are made in series to achieve a desired output voltage and/or in parallel to provide a desired amount of current source capability.

Diodes are included to avoid overheating of cells in case of partial shading. Since cell heating reduces the operating efficiency it is desirable to minimize the heating. Very few modules incorporate any design features to decrease temperature; however installers try to provide good ventilation behind the module.

New designs of module include concentrator modules in which the light is concentrated by an array of lenses or mirrors onto an array of small cells. This allows the use of cells with a very high-cost per unit area (such as gallium arsenide) in a cost-competitive way.

Depending on construction the photovoltaic can cover a range of frequencies of light and can produce electricity from them, but sometimes cannot cover the entire solar spectrum (specifically, ultraviolet, infrared and low or diffused light). Hence much of incident sunlight energy is wasted when used for solar panels, although they can give far higher efficiencies if illuminated with monochromatic light. Another design concept is to split the light into different wavelength ranges and direct the beams onto different cells tuned to the appropriate wavelength ranges. This is projected to raise efficiency by 50%. Also, the use of infrared photovoltaic cells can increase the efficiencies, producing power at night.

Sunlight conversion rates (module efficiencies) can vary from 5-18% in commercial production (solar panels), that can be lower than cell conversion.

A group of researchers at MIT has recently developed a process to improve the efficiency of luminescent solar concentrator (LSC) technology, which redirects light along a translucent material to PV-modules located along its edge. The researchers have suggested that efficiency may be improved by a factor of 10 over the old design in as little as three years (it has been estimated that this will provide a conversion rate of 30%). Three of the researchers involved have now started their own company, called Covalent Solar, to manufacture and sell their innovation in PV-modules.

The current market leader in efficient solar energy modules is SunPower, whose solar panels have a conversion ratio of 19.3%. However, a whole range of other companies (HoloSun, Gamma Solar, NanoHorizons) are emerging which are also offering new innovations in photovoltaic modules, with a conversion ratio of around 18%. These new innovations include power generation on the front and back sides and increased outputs; however, most of these companies have not yet produced working systems from their design plans, and are mostly still actively improving the technology. As of August 26, 2009 a world record efficiency level of 41.6% has been reached. [8]

4.3.3 Thin-film modules

Main articles: Thin film, Third generation solar cell, and Low-cost photovoltaic cell

Third generation solar cells are advanced thin-film cells. They produce high-efficiency conversion at low cost.

Rigid thin-film modules

In rigid thin film modules, the cell and the module are manufactured in the same production line.

The cell is created directly on a glass substrate or superstrate, and the electrical connections are created in situ, a so called "monolithic integration". The substrate or

superstrate is laminated with an encapsulant to a front or back sheet, usually another sheet of glass.
The main cell technologies in this category are CdTe, or a-Si, or a-Si+uc-Si tandem, or CIGS (or variant). Amorphous silicon has a sunlight conversion rate of 6-12%.

Flexible thin-film modules

Flexible thin film cells and modules are created on the same production line by depositing the photoactive layer and other necessary layers on a flexible substrate.
If the substrate is an insulator (e.g. polyester or polyimide film) then monolithic integration can be used.
If it is a conductor then another technique for electrical connection must be used.
The cells are assembled into modules by laminating them to a transparent colourless fluoropolymer on the front side (typically ETFE or FEP) and a polymer suitable for bonding to the final substrate on the other side. The only commercially available (in MW quantities) flexible module uses amorphous silicon triple junction (from Unisolar).
So-called inverted metamorphic (IMM) multijunction solar cells made on compound-semiconductor technology are just becoming commercialized in July 2008. The University of Michigan's solar car that won the North American Solar challenge in July 2008 used IMM thin-film flexible solar cells.
The requirements for residental and commercial are different in that the residental needs are simple and can be packaged so that as technology at the solar cell progress, the other base line equipment such as the battery, inverter and voltage sensing transfer switch still need to be compacted and unitized for residental use. Commercial use, depending on the size of the service will be limited in the photovoltaic cell arena, and more complex parabolic reflectors and solar concentrators are becoming the dominant technology.
The global flexible and thin-film photovoltaic (PV) market, despite caution in the overall PV industry, is expected to experience a CAGR of over 35% to 2019, surpassing 32GW according to a major new study by IntertechPira. [8]

4.3.4 Module embedded electronics

Several companies have begun embedding electronics into PV modules. This enables performing Maximum Power Point Tracking (MPPT) for each module individually, and the measurement of performance data for monitoring and fault detection at module level. Some of these solutions make use of Power Optimizers, a DC to DC converter technology developed to maximize the power harvest from solar photovoltaic systems.

4.3.5 Module performance and lifetime

Module performance is generally rated under Standard Test Conditions (STC) : irradiance of 1,000 W/m², solar spectrum of AM 1.5 and module temperature at 25°C.

Electrical characteristics include nominal power (P_{MAX}, measured in W), open circuit voltage (V_{OC}), short circuit current (I_{SC}, measured in Amperes), maximum power voltage (V_{MPP}), maximum power current (I_{MPP}) and module efficiency (%).
In kWp, kW is kilowatt and the p means “peak” as peak performance. The “p” however does not show the peak performance, but rather the maximum output according to STC.
Solar panels must withstand heat, cold, rain and hail for many years. Many Crystalline silicon module manufacturers offer warranties that guarantee electrical production for 10 years at 90% of rated power output and 25 years at 80%

4.4 Mounting System

The mounting system securely attaches PV panels to the roof or, in some cases, on the ground. It is designed to provide support and balance.

4.4.1 Roof Mount

This is the most cost effective and common type of installation for residential, commercial and industrial application. An array of solar panels will be located on the roof of the property. In most cases this array will be attached directly to the structural members of the building. These attachments must be sufficiently robust to withstand sufficient wind loading. Solar panels are typically mounted to aluminum or galvanized steel support structure. For some commercial, flat-roof applications there are the ability to install the solar modules without making any penetrations in the roof. Solar roof installations are typically light weight and usually add less than 4lb/ft2 to the roof load. Virtually all residential and commercial roofs are able to accept this additional load without the need for structural modification. [8]

Fig 4.5: Roof Mount system. [8]

4.4.2 Ground Mount

In cases where there is not sufficient roof space, solar modules can also be mounted on the grounds of your property. The most common type of ground mount is a wedge structure constructed from steel supports anchored in concrete footings. The remainder of the structure is built from aluminum or galvanized steel.

Fig 4.6: Ground Mount system.

4.4.3 Pole Mount

A second type of ground mounted array is a pole mount. In this type of installation an array is mounted on top of a single steel pole. This type of installation has the advantage of being manually adjustable, so that the system owner can change the pitch of the array at different times of the year.

Fig 4.7: pole Mount system with tracker.

4.4.4 Building Integrated Photovoltaic (BIPV)

These installations are integrated into the structure of a building. Common BIPV applications include car ports, awnings, and curtain walls. BIPV installations have the advantage of providing function in addition to power production. For example, in the case of a car port, the solar modules simultaneously produce power and provide shaded parking.

Fig 4.8: Building Integrated Photovoltaic (BIPV).

4.5 Charge Controller

A charge controller, charge regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may prevent against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. It may also prevent completely draining ("deep discharging") a battery, or perform controlled discharges, depending on the battery technology, to protect battery life. The terms "charge controller" or "charge regulator" may refer to either a stand-alone device, or to control circuitry integrated within a battery pack, battery-powered device, or battery recharger.

The solar charge regulator main task is to charge the battery and to protect it from deep discharging. Due to overcharging electrolyte boiling could occur causing damage to the battery or even its destruction. Deep discharging could also damage the battery. Charge regulator electronics is most sensitive and crucial to assuring stable photovoltaic system operation. Charge regulator malfunctioning result in high maintenance cost including battery replacement. An important parameter to consider is charge regulator efficiency percentage. For small photovoltaic systems charge regulators from 5 A to 30 A are available. Some of them could be used in both 12 V and 24 V DC systems.

There are many different types of charge regulators available on the market, the simplest switch on/off regulators, PWM charge regulators which charge the battery with constant voltage or constant current (they are the most often used regulators in PV systems) to the most complex MPPT (Maximum Power Point Tracking) charge regulators. MPPT charge regulators are more expensive and suit large systems better, where the investment in an expensive MPPT regulator returns quickly. In most cases, including inexpensive charge regulators for small systems, regulator set includes all necessary electronics for battery protection, such as protection against deep discharging and against overcharging. Charge regulator functioning is characterised by two different voltage thresholds, battery and module voltage, upon which the battery is charged. At higher voltage, usually 12.4 V for 12 V batteries, charge regulator switches the load to the battery, at lower voltage, typically 11.5 V, regulator switches the load off. On the market you can find charge regulators which allow manual settings of these thresholds, or you could merely adjust the battery type to Pb acid or Gel type, and the regulator will adjust the two voltage thresholds automatically according to the battery type without losing the performance. If excessive ambient temperature swings of more than 5°C are expected, temperature compensated charge regulator electronics should be used.

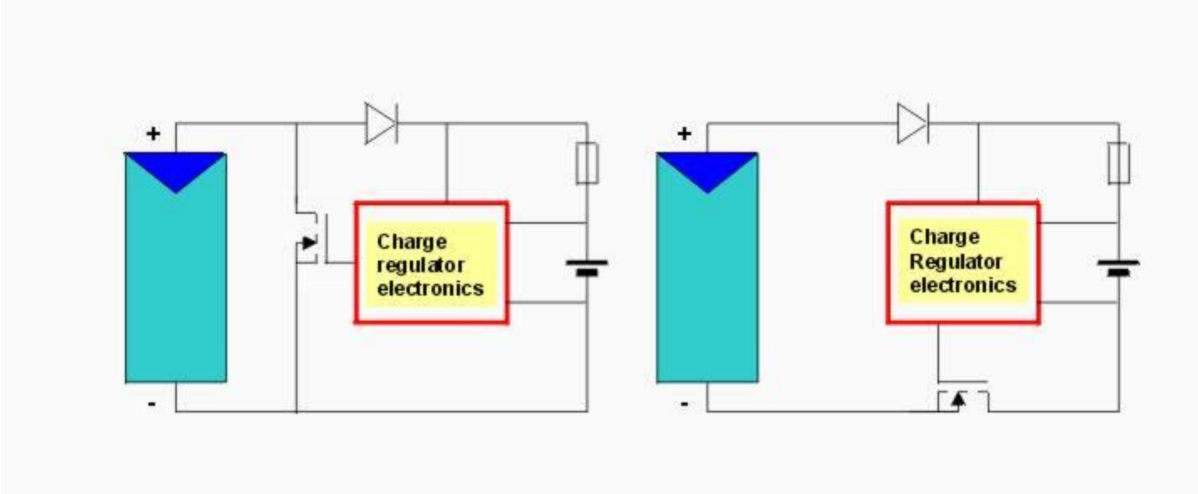


Fig 4.9: Shunt and serial regulator

The energy produced during the day, which wasn't consumed by loads, is saved in batteries. Saved energy can be used at night or during the days with bad weather conditions. Batteries in photovoltaic systems are often charged/discharged; therefore, they must meet stronger requirements than car batteries. Due to the fact car batteries are not suitable for PV systems use! There are many solar battery types available in the market. Most often used classic Pb acid batteries are produced especially for PV systems, where deep discharge is required. Other battery types, such as NiCd or NiMH are rarely used, unless in portable devices. Hermetical batteries often consist of electrolyte in gel form. Such batteries do not require maintenance. Typical solar system batteries lifetime spans from 3 to 5 years, depending heavily on charging/discharging cycles, temperature and other parameters. The more often the battery is charged/discharged the shorter the lifetime.

Lifetime depends on charge/discharge cycle rates numbers. The deeper the battery is discharged the shorter the lifetime. The most important battery parameter is battery capacity, which is measured in Ah. Battery capacity depends on discharging current; the higher the discharging current the lower the capacity, and vice versa. Batteries can be charged in many different ways, for example with constant current, with constant voltage etc., which depends on the battery type used. The charging characteristics are recommended and prescribed by different standards. The solar batteries prices are higher than the prices of classic car batteries, yet their advantages are longer lifetime and lower discharging rates. Consequently, the maintenance costs of the photovoltaic system are lower. [8]

4.6 Battery

4.6.1 General information

The battery stores electricity generated by the PV system. The battery is the most common of the dc sources. A battery consist of a combination of two or more similar cells, a cell is being fundamental sources of electrical energy developed through the convention of chemical. All cells can be divided into the primary or secondary types the secondary is rechargeable, whereas the primary is not. That is the chemical reaction of the secondary cell can be reserve to restore its capacity. The common rechargeable battery is the lead-acid battery. In addition, each has a positive and a negative electrode and an electrolyte to complete the circuit between electrodes within the battery. The electrolyte is the contact element and the sources of ions for conduction between the terminals.

For the secondary lead-acid, the electrolyte is sulfuric lead, and the electrodes are spongy lead (Pd) and lead peroxide (PbO_2). When a load is applied to the battery terminals, there is a transfer of electrons from the spongy lead electrode to the lead electrode to the lead peroxide electrode through the load. This transfer of electrons will continue unit the battery is completely discharged. The discharge time is determined by how diluted the acid has become and how heavy the coating of lead sulfate is on each plate. The state of discharge of a lead storage cell can be determined by measuring the specific gravity of the electrolyte with a hydrometer. The specific gravity of a substance is defined to be the ratio of an equal volume of water at 4°C.For fully charged batteries, the specific gravity should be somewhere between 1.28-1.30. When the specific gravity drops to about 1.1, the battery should be recharged.

Since the lead storage cell is a secondary cell, it can be recharge at any point during the discharge phase simply by applying an external dc current source across the cell that will pass current through the cell in a direction opposite to that in which the cell supplied current to the load. This will remove the lead sulfate and restore the concentration of sulfuric acid. The output of a lead storage cell over most of the discharge phase is about 2.1V. 12.6V can be produced six cells in series. In general, lead-acid storage batteries are used in situation where a high current is required for relatively short period of time. [8]

4.6.2 Chemical reaction of lead-acid battery

At the positive plate

$$PbO_2 + 3H^+ + HSO_4^- + 2e^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} PbSO_4 + 2H_2O$$

At the negative plate

$$Pb + HSO_4^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} PbSO4 + H^+ + 2e^-$$

Resultant

$$PbO2 + Pb + 2H2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2PbSO4 + 2H2O$$

4.6.3 State of charge (SOC)

The State of charge of a battery is its available capacity expressed as a percentage of its rated capacity. Knowing the amount of energy left in a battery compared with the energy it had when it was new. It gives the user an indication of how much longer a battery will continue to perform before it needs recharging.

4.6.4 Methods of Determining the State of charge

A. Direct Measurement

This would be easy if the battery could be discharged at a constant rate. The charge in a battery is equal to the current multiplied by the time for which it flowed. Unfortunately there are two problems with this. In all practical batteries, the discharge current is not constant but diminishes as the battery becomes discharged, usually in a non-linear way. Any measurement device must therefore be able to integrate current over time. Secondly, this method depends on discharging the battery to know how much charge it contained. In most applications except perhaps in qualification testing, the user (or the system) needs to know how much charge is in the cell without discharging it.

It is not possible either to measure directly the effective charge in a battery by monitoring the actual charge put into it during charging. This is because of the coulombic efficiency of the battery. Losses in the battery during the charge - discharge cycle mean that the battery will deliver less charge during discharge than was put into it during charging. The coulombic efficiency or charge acceptance is a measure of how much usable energy is available during discharging compared with the energy used to charge the cell. Charge efficiency is also affected by temperature and SOC.

B. SOC from Specific Gravity (SG) Measurements

This is the customary way of determining the charge condition of lead acid batteries. It depends on measuring changes in the weight of the active chemicals. As the battery discharges the active electrolyte, sulphuric acid, is consumed and the concentration of the sulphuric acid in water is reduced. This in turn reduces the specific gravity of the solution in direct proportion to the state of charge. The actual SG of the electrolyte can therefore be used as an indication of the state of charge of

the battery. SG measurements have traditionally been made using a suction type hydrometer which is slow and inconvenient.
Nowadays electronic sensors which provide a digital measurement of the SG of the electrolyte can be incorporated directly into the cells to give a continuous reading of the battery condition. This technique of determining the SOC is not normally suitable for other cell chemistries.

C. SOC from voltage Measurements

This uses the voltage of the battery cell as the basis for calculating SOC or the remaining capacity. Results can vary widely depending on actual voltage level, temperature, discharge rate and the age of the cell and compensation for these factors must be provided to achieve a reasonable accuracy.

D. SOC from current Measurements

This measures the current entering and leaving the cells as a basis for remaining capacity calculation. The charge transferred in or out of the cell is obtained by accumulating the current drain over time. This method, known as Coulomb counting, provides higher accuracy but it still needs compensation for the operating conditions as with the voltage based method. The simplest method of determining the current is by measuring the voltage drop across a low ohmic value, high precision, series, and sense resistor. This method of measuring current causes a slight power loss in the current path and also heats up the battery. Hall Effect and magneto-resistive transducers avoid this problem but they are more expensive. The former is inaccurate for low currents and the latter can not tolerate high currents and is susceptible to noise. Coulomb counting depends on the current flowing in external circuits and does not take account of self discharge currents. This can be the source of accumulating errors unless the monitoring circuit is regularly reset or calibrated.

The basic law to determine the SOC

SOC= {1-(acid density in fully charged condition-measure acid density)*7.1}*100%

4.6.5 Relation between SOC, Specific Gravity, and battery voltage

The specific gravity (SG) of the battery acid or electrolyte is the truest and most absolute measure of a battery's state of charge. The SG reading is NOT greatly or adversely affected by the load on the battery. Basically if a battery is 50% charged, it will read a specific gravity of 1.200, regardless of whether the battery is on charge, being discharge or being stored. This is not the case for voltage readings.

State of Charge	100%	75%	50%	25%	0%

(%)					
Specific Gravity	1.255-1.275	1.215-1.235	1.180-1.200	1.155-1.165	1.110-1.130

Table 4.1:.Realation between Specific Gravity and terminal Voltage of an industrial Lead Acid Battery

Voltage readings will vary and are greatly affected and dependent on whether the battery is being charged, discharged or in storage (rest or "open cell" voltage). There are two terms for voltage readings:-

1. Load voltage (voltage under load or on charge)
2. Open cell voltage.

Load voltage: When a battery is charged the plates will polarize and develop a resistance to the charge (surface charge). This resistance will add to the battery voltage and therefore using this voltage reading will not reflect the true state of charge. All the so-called "surface charge" will be removed when the battery is being discharged.

Open cell voltage: Open Cell Voltage is determined by taking all the loads off of the battery and letting the battery stand for at least 4 hours before taking a reading. This allows the surface charge to dissipate. To get around this problem determine the 50% state of charge as described.

Determining the 50% state of charge Voltage Reading:- Most three steps chargers or inverters monitor the voltage and have an adjustable set point that determines when the batteries are low (50% discharged) and should be charged. Once this set-point is reached the inverter will either sound an alarm or start a generator or tie the battery bank back into to grid power. Since the voltage will change depending on whether or not the bank is on load the set point can be determined by a specific gravity reading. A gravity reading of 1.200 is equal to 50% discharged.

Battery cable lengths, system set-up and other variables can affect the voltage readings as well. Specific gravity of one cell in the bank Compare this to the table 1, Specific gravity versus state of charge. If the measured specific gravity indicates the state of charge is more than 50%, decrease the low voltage cut-off setting. Similarly if the specific gravity indicates the state of charge is lower than 50%, increase the low voltage cut-off setting. Note: 50% is the desired depth of discharge but it does not have to be exactly 50%. For practical purposes a range of 45-55% is acceptable. The actual battery voltage corresponding to 50% will change with a change in load. In general, the higher the discharge amperage the lower the corresponding voltage.

State of charge (SOC)	12 volt battery (voltage)	Volts per cell (voltage)
100%	12.70	2.12
90%	12.50	2.08
80%	12.42	2.07

70%	12.32	2.05
60%	12.20	2.03
50%	12.06	2.01
40%	11.90	1.98
30%	11.75	1.96
20%	11.58	1.93
10%	11.31	1.89
0%	10.50	1.75

Table 4.2:Relation between SOC & battery voltage

4.6.6 Cycle efficiency

Temperature, charge/discharge rates and the Depth of Discharge each have a major influence on the cycle life of the cells Depending on the purpose of the tests, the temperature and the DOD should be controlled at an agreed reference level in order to have repeatable results which can be compared with a standard. Alternatively the tests can be used to simulate operating conditions in which the temperature is allowed to rise, or the DOD restricted, to determine how the cycle life will be affected.

Similarly cycle life is affected by over charging and over discharging and it is vital to set the correct voltage and current limits if the manufacturer's specification is to be verified. Cycle testing is usually carried out banks of cells using multi channel testers which can create different charge and discharge profiles including pulsed inputs and loads. At the same time various cell performance parameters such as temperature, capacity, impedance and power output and discharge time can be monitored and recorded. Typically it takes about 5 hours for a controlled full charge discharge cycle. This means testing to 1000 cycles will take 208 days assuming working 7 days per week 24 hours per day. Thus it takes a long time to verify the effect of any ongoing improvements made to the cells.

Because the ageing process is continuous and fairly linear, it is possible to predict the lifetime of a cell from a smaller number of cycles. However to prove it conclusively in order to guarantee a product lifetime would require a large number of cells and a long time. For high power batteries this could be very expensive. [8]

4.7 Inverter

4.7.1 Inverter Basic

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the resulting AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

Static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.

The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converters were made to work in reverse, and thus were "inverted", to convert DC to AC.

The inverter performs the opposite function of a rectifier.

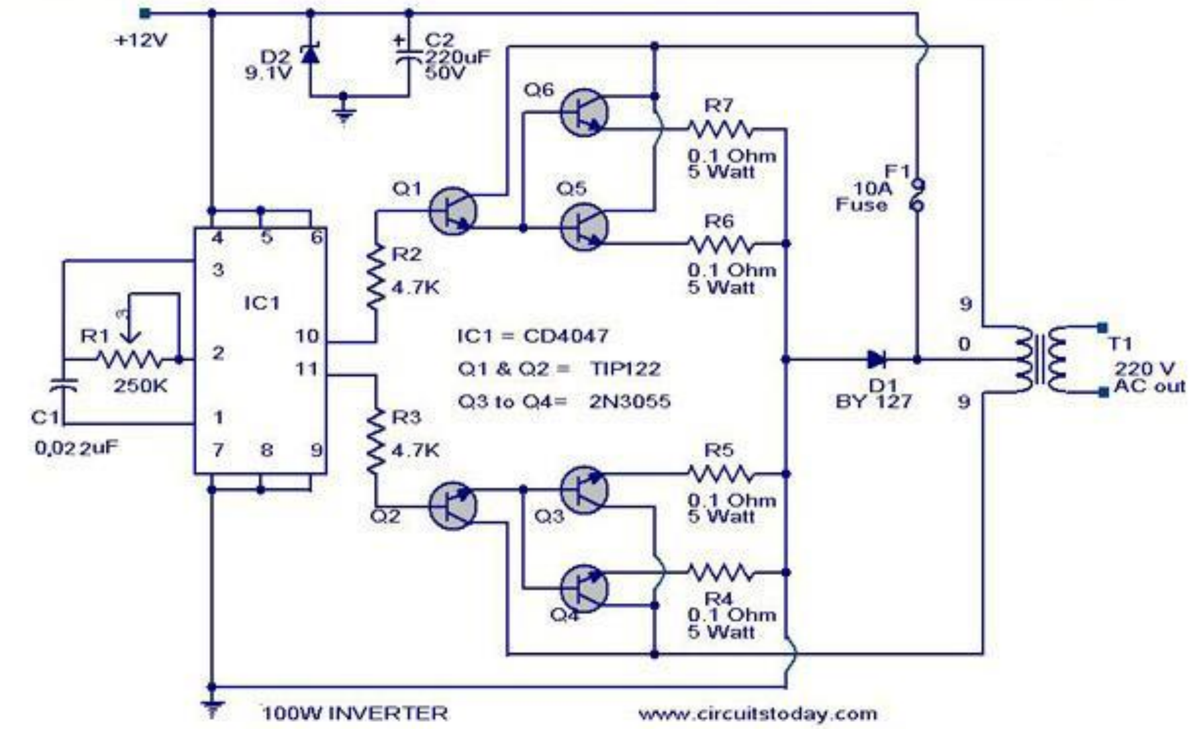


Fig 4.10: 12v DC to 220V AC inverter circuit diagram

An inverter is a device that changes a 12 v dc battery into 120 volts ac useable household electricity. We can run our Lights, TV set, mobile charger, computers, power tools etc. The 12 volts is stepped up to 120 to 125 volts dc, and then the dc is converted into 120 volts ac by a very special design of ours. We can run light bulbs with 120 v dc but to run our TV, VCR etc.. The 120 v dc needs to be converted to AC. Which is no problem, we can do it by electronic switching or use our new mechanical can oil filled canister type commutator design. All we need is to use is a high efficient electric motor that runs in the milliamps to turn the commutator switching shaft, the oil in the can will keep the commutator from sparking! We can even convert an old DC motor from an auto junk yard, rewire it and fill it with oil just as well. we can adjust the speed to get the desired 60 Hz. These plans are not as step by step as many of our other plans but they are well worth the money and loaded with information for anyone wanting to build an inverter. Very easy to build! Can be used as a modified sign wave or pure sine wave if we allow the DC to be pulsed into a large transformer and choke. By doing it this way we should not need an oil switching commutator canister to turn the DC to AC, the transformer will do that for us. 240v could be made by using 2- 12 v dc batteries in series / inputting 24 v dc.

4.7.2. Circuit description

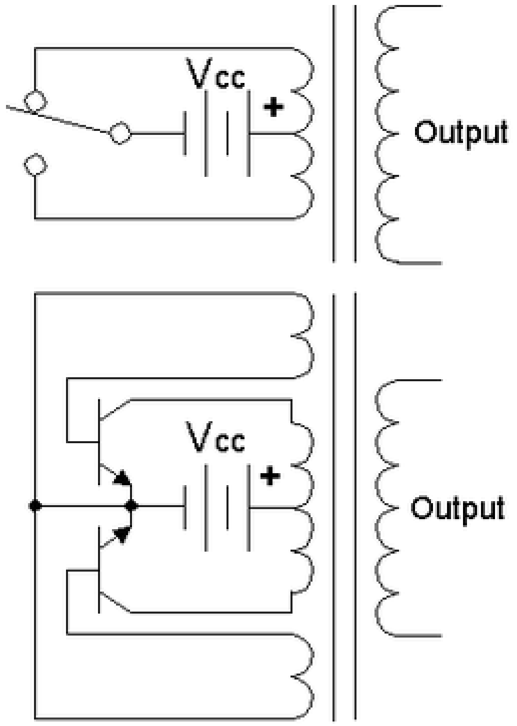


Fig 4.11: Inverter Circuit

Top: Simple inverter circuit shown with an electromechanical switch and automatic equivalent auto-switching device implemented with two transistors and split winding auto-transformer in place of the mechanical switch.

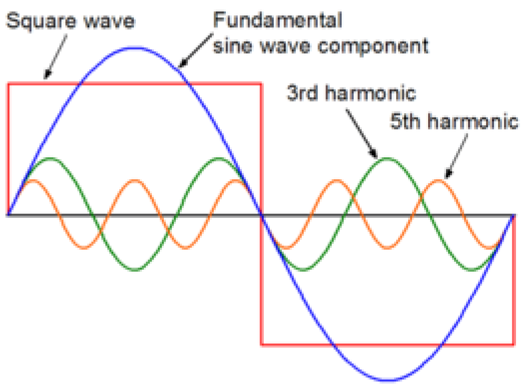


Fig 4.12: Square waveform with fundamental sine wave component, 3rd harmonic and 5th harmonic

Basic designs

In one simple inverter circuit, DC power is connected to a transformer through the centre tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a vibrator or buzzer, was once used in vacuum tube automobile radios. A similar mechanism has been used in door bells, buzzers and tattoo guns.

As they became available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.

Output waveforms

The switch in the simple inverter described above produces a square voltage waveform as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called harmonics, that are included in the series have frequencies that are integral multiples of the fundamental frequency.

The quality of the inverter output waveform can be expressed by using the Fourier analysis data to calculate the total harmonic distortion (THD). The total harmonic distortion is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage:

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

The quality of output waveform that is needed from an inverter depends on the characteristics of the connected load. Some loads need a nearly perfect sine wave voltage supply in order to work properly. Other loads may work quite well with a square wave voltage.

4.7.3 Applications

- DC power source utilization
- Uninterruptible power supplies
- Induction heating
- HVDC power transmission
- Variable-frequency drives
- Electric vehicle drives
- Air Conditioning

Chapter 5

Methods of Testing

5.1 Test result related to the solar panel

Generally the panels are tested in the STC (Standard Testing Condition). But due to the lack of testing facilities we could not perform the proper test for panels. Rather we observe the panels and measure the open circuit voltage and short circuit current in normal operating condition.

5.1.1 Open circuit voltage test

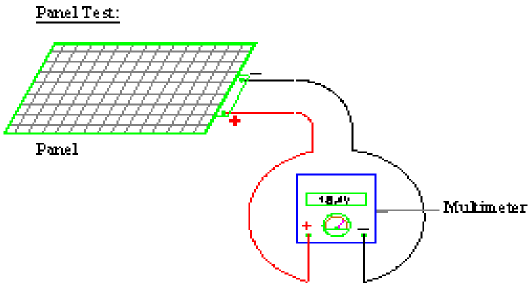


Fig 5.1: Open circuit voltage test of a solar panel

To find out the open circuit voltage, the multi meter was set with the panel's terminal. The positive probe of multi-meter was connected with the positive terminal of the panel and the negative probe of the multi meter was with the panel's negative terminal. The reading of voltage was in between 15V to 20V.

5.1.2 Short circuit current test

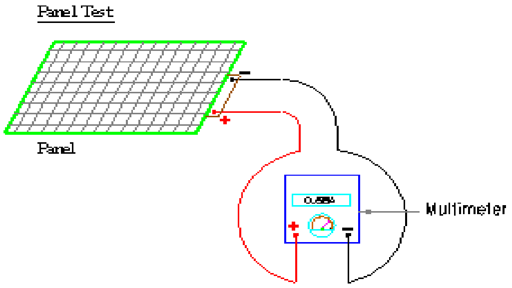


Fig 5.2: Short circuit current test of solar panel

To find out the short circuit current the multi meter was set in series with the panel. The positive probe of multi-meter was connected with the positive terminal of the panel and the negative probe of the multi meter was with the panel's negative terminal. The panel's short circuit current is directly proportional to the radiation incident on it. Due to rainy condition on the test day, the current achieved was below 1A.

5.2 Tests related to the charge controller

5.2.1 Low voltage cut-off test

The battery of the solar home system charges during day and when equipments are in use, it starts discharging. At the same time, it is important for the battery to stop at a minimum voltage for being protected from damage. So charge controller should operate at the specific minimum voltage to disconnect the loads from battery.

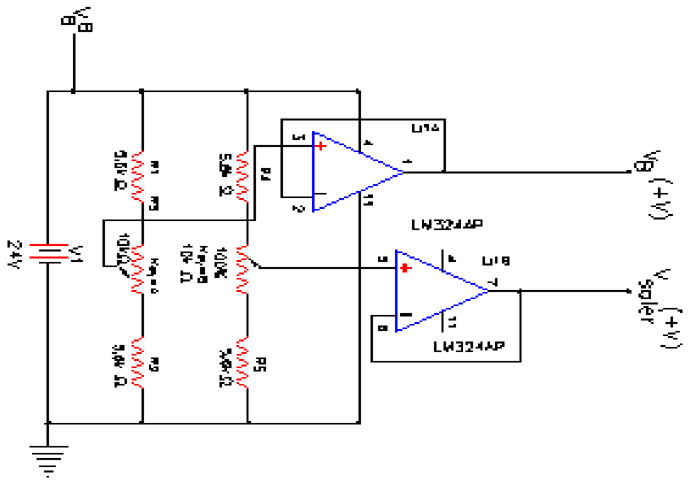


Fig 5.3: Low voltage cut-off test

The lower and higher cut off voltage of a charge controller was measured by a voltage controller circuit shown in the Fig- 34. Connections of wire from the positive end of the battery via voltage controller to the positive terminal of charge controller's battery option and from the negative end of the battery via voltage controller to the negative terminal of charge controller's battery option have been made. Now varying the voltage, it has been observed that the charge controller carries out the cut-off operation in the voltage range of 11.4V to 11.8V. Ideally it is supposed to operate at 11.6 V and disconnect the load from the supply.

5.2.2 High voltage cut-off test

The battery starts charging when the PV modules generate electricity during day time and when the sun is shining. Like the low voltage cut off, high voltage cut off is also necessary as higher than rated voltage is harmful for the battery .So charge controller monitors the battery during charging and discharging. IT bypasses the battery from the panel as the battery is fully charged. As a result, battery remains safe from over- charging.

With the aid of the voltage controller, the same circuit that has been described above is used to carry out the higher voltage cut-off test. Ideally it is supposed to disconnect the battery at 14.4 V but the test results reveal that the charge controller operates within the range of 14.3V to 14.7 and as it causes the panel to be shorted, the battery is stopped from charging.

5.2.3 Short circuit protection test

There is a chance of both the panel and load side being short-circuited. As a result, damage can occur and the charge controller takes precautionary measure to protect the system.

The load is shorted for the purpose of carrying out the short circuit protection test. The input terminal (panel) was protected by a reverse diode and the output was protected by a fuse.

5.2.4 Reverse current leakage protection test

During a gloomy day or when the sky is overcast or at night battery can discharge through the panel if there is no protection. To protect discharging through panel a blocking diode is used inside the controller and its proper operation is necessary. Some panel manufacturers incorporate the blocking diode in the panels.

This test was done to observe whether the charge controller is protected against the reverse current flow when the panel is not generating electricity (ie at night or in rainy days). If this protection is not provided then the battery is discharged through the panel. This protection is done normally by inserting a reverse blocking diode in the panel. If it is not provided in the panel the charge controller will provide itself.

5.2.5 Maximum current handling test

The charge controller is tested for handling 120% over current for one hour duration.

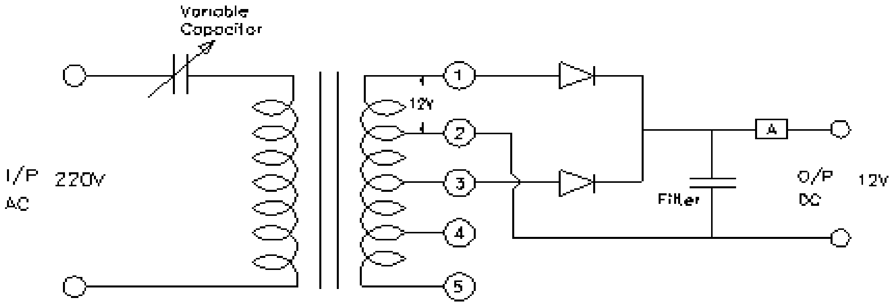
5.2.6 Charge controller self power consumption test

The components inside the charge controller also consume power. The consumption should be very low. In other word, the efficiency of the charge controller should be as high as possible.

At no load condition, the controller is supplied with a constant battery voltage of 12.7V. Although the charge controller is in no load condition, the test reveals the fact that a current of 10 mA in magnitude appears in the ammeter which accounts for the controller's internal power consumption. Consumed power =12.7*10–3= 0.127 watt

5.3 Tests related to the battery performance

5.3.1 Battery charging system



Battery charging Circuit Diagram

Fig 5.4: Battery charging circuit diagram of a lead acid battery.

For this charging system a transformar must be included to cut the ac voltage to a level appropriate for the dc level to be established. In primary side a variable capactor is used to control the current of the secondary side. Battery is normally charged in C/10 charging/ discharging current. The capacity of the battery was 100Ah. So the 10A charging current was provided in the circuit.

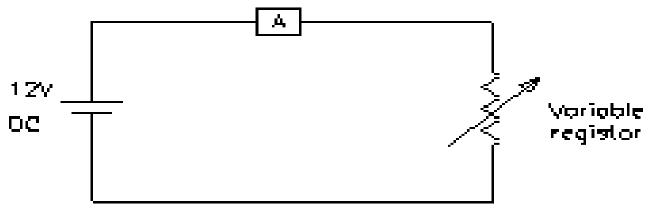
Charging terminal voltage=>$V_T= V_b + I_{charge} * R$

The open circuit voltage and specific gravity of the electrolyte of the fully discharged battery was 12.11 V and 1160 respectively. After charging the final specific gravity of the electrolyte becomes 1220. The temperature rise during charging the battery was from 30°C to 38°C. The charging profile of the battery is given in the following table:

time	0	1	2	3	4	5	6	7	8	9	10	11	11:30
voltage	12.78	12.84	12.94	13.02	13.13	13.2	13.3	13.42	13.56	13.69	13.92	14.3	14.58

Table 5.1: Charging profile of lead acid battery

5.3.2 Battery discharging system



Battery Discharging Circuit Diagram

Fig 5.5: Battery discharging circuit diagram of a lead acid battery.

For discharging the 12-v battery ,had to connect a variable resistance in series with the battery.A variable resistance was chosen to keep the current constant at 10A as discharging should be done in constant current.

Dischageing terminal voltage=>VT=Vb-Idischarge*R

The open circuit voltage and specific gravity of the electrolyte of the fully charged battery was 12.94 V and 1250 respectively. After charging the final specific gravity of the electrolyte becomes 1100. The temperature rise during discharging the battery was from 30°C to 31°C. The discharging profile of the battery is given in the following table:

Time in Hour	0	1	2	3	4	5	6	7	8	9	10	11	11:30
voltage	12.43	12.32	12.23	12.16	12.05	12.02	11.96	11.88	11.77	11.63	11.43	11.08	10.74

Table 5.2: Discharging profile of lead acid battery

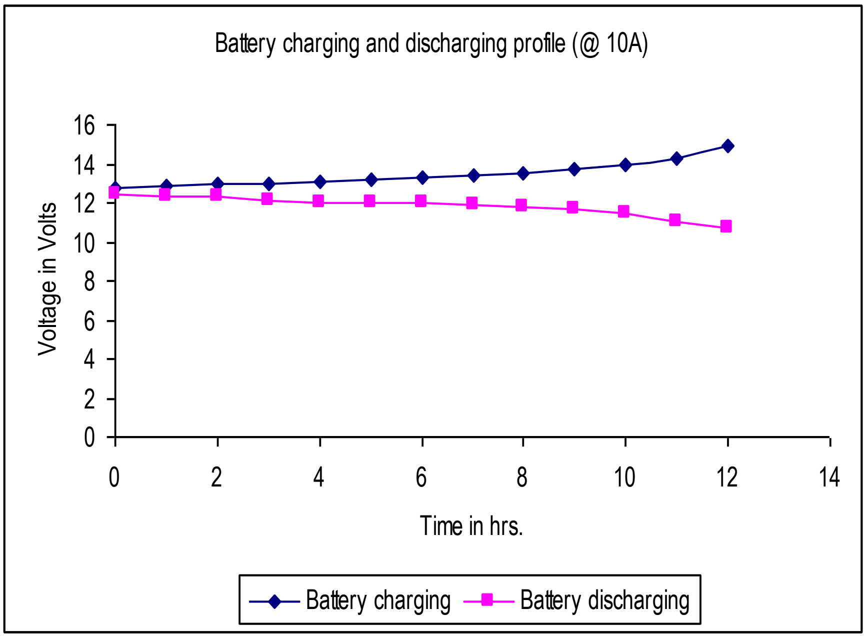


Fig5.6: Battery charging and discharging profile of a lead acid battery.

5.3.4 Cycle efficiency test

The cycle efficiency was calculated from the charging and discharging data. The voltage during charging was increasing and during discharging was decreasing. We took the average voltages of the charging and discharging intervals. The summation of voltage times current multiplied by the charging / discharging duration was calculated. The ration of this discharging summation over charging summation is taken for cycle efficiency calculation.

Hour	0	1	2	3	4	5	6	7
Voltage	12.81	12.98	13.16	13.36	13.53	13.65	13.85	14.19

Table 5.3: charging rate of a lead acid battery

Hour	0	1	2	3	4	5	6	7
Voltage	12.37	12.19	12.05	11.92	11.73	11.57	11.36	10.91

Table 5.4: Discharging rate of lead acid battery

Cycle efficiency = $\frac{\int V \cdot I(disch\arg ing)dt}{\int V \cdot I(ch\arg ing)dt}$

= $\frac{Disch\arg ingAmpereHour}{Ch\arg ingAmperHour}$

From the experimental data (table 5 &6)

The discharging Ampere hour: 941Ah

The charging Ampere Hour: 1075.3Ah

So, the cycle efficiency: = $\frac{941.0}{1075.3}$

= 0.87

=87.5%

5.3.4 Specific gravity of the cells

Fig 5.7: Testing of specific gravity of electrolyte of the battery cells

A hydrometer was taken for the test. Liquid from the battery cell was collected with the help of hydrometer and got an average specific gravity of the cells of 1200 to 1250 kg/m^2.

Specific gravity is the ratio of the weight of a given volume of a substance to the weight of an equal volume of water at 4°C. Specific gravity of the electrolyte is measured with a hydrometer to determine the state of charge of a lead storage cell.

5.3.5 Nominal voltage test

Nominal voltage is the normal open circuit voltage in normal condition. Nominal voltage can be produced by all cells in series.

5.3.6 Capacity test

The industrial batteries are normally rated in ampere-hours (Ah). A battery with an ampere-hour rating of 100 will theoretically provide a steady current of 1A for 100hours, 2A for 50 hours and so on, as determined by the following equation:
Life (hours) = ampere-hour rating (Ah)/ ampere drawn (A)

The capacity of DC battery decreases with an increase the current demand and the capacity of DC battery decreases relatively low and high temperatures. Usually batteries are tested in C/10 discharge rate. That is if a battery has a capacity of 100 Ah, then the capacity in C/10 discharge is tested in a current of 10 amperes.

C/10 discharge (Ampere)= battery capacity in Ah/10 Hrs=100Ah/10 Hrs= 10 Amperes.

5.3.7 Life cycle test

This is perhaps the most important of the qualification tests. Cells are subjected to repeated charge - discharge cycles to verify that the cells meet or exceed the manufacturer's claimed cycle life. Cycle life is usually defined as the number of charge - discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. These tests are needed to verify that the battery performance is in line with the end product reliability and lifetime expectations and will not result in excessive guarantee or warranty claim.

5.3.8 Cycle efficiency test

Cycle efficiency is defined as the ratio of discharging to charging capacity of a battery. To determine the cycle efficiency a fully discharged battery is charged with a C/10 charging current, the time is measured until the battery is fully charged. Then the fully charged battery is discharged with a C/10 discharging current, the time required to discharge the battery is measured. The ratio of discharging current multiplied by the discharging time to the charging current multiplied by the charging time is the cycle efficiency. For a industrial Lead acid battery the typical cycle efficiency is 85 to 95%.

5.4 Tests related to the Lamp Circuit

5.4.1 Inverter electrical efficiency test within the specified voltage range

The power supply was fixed at 12.7 V. connecting the multi-meter probes with inverter's input terminals, the voltage of 12.7V and current of 0.6A were measured.

Input Power, P= (12.7*0.6) W
=7.62 W

The current and voltage of the output of the lamp circuit could not be measured directly by the multi meter, as the output frequency was very high ($\approx 60\, kHz$). To find the output power, a resistance was connected in series with inverter's output terminal. Voltage across resistance was observed in the oscilloscope. The current was then determined by dividing the voltage by the series connected resistance. A PC based digital storage oscilloscope was used to determine the voltage and current .The wave shapes produced by the digital storage oscilloscope display are shown below-

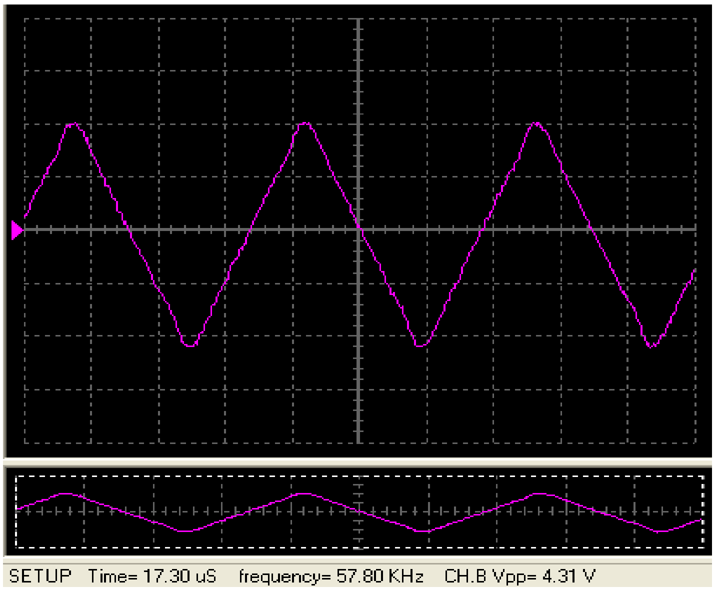


Fig 5.8: Wave shape of inverter's output voltage.

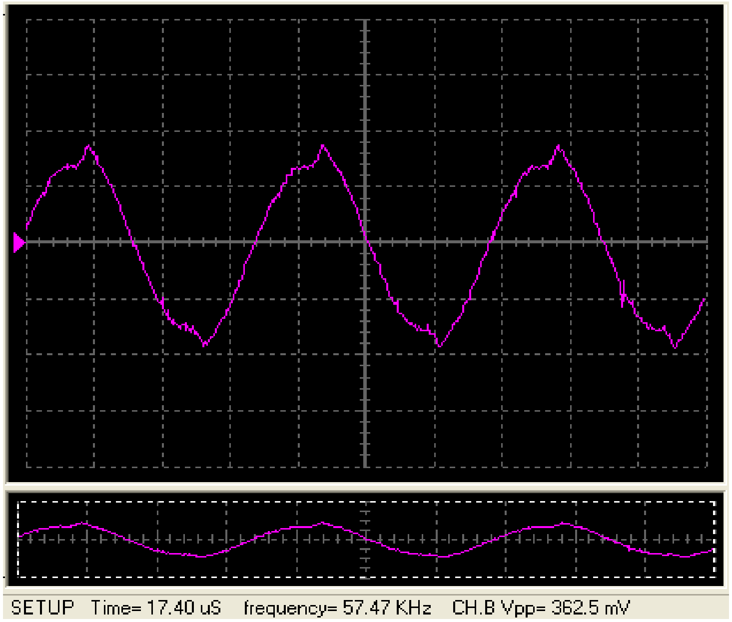


Fig 5.9: Wave shape of inverter's output current.

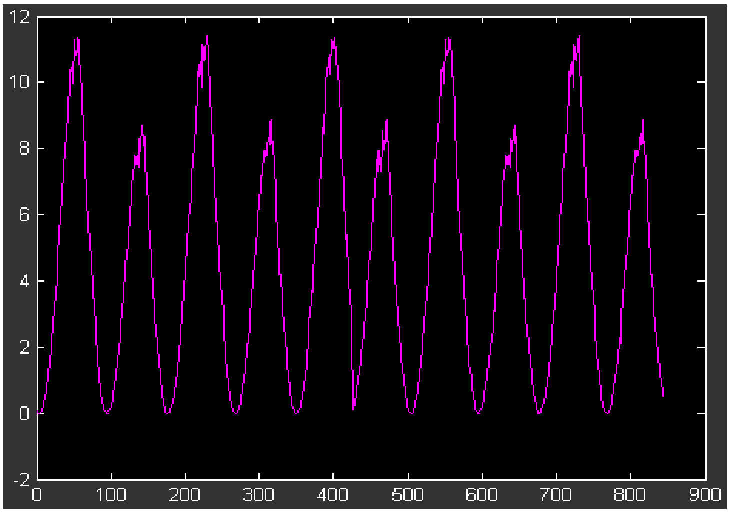


Fig 5.10: Wave shape of inverter's output power.

The values of the output voltage and current were calculated from the oscilloscope display. Then the average power is calculated by using Matlab programming .The efficiency is calculated and found to be 59.31%. Calculation is shown below.

Efficiency of the lamp circuit = (o/p power/i/p power)*100%

= (4.52/7.62)*100%

= 59.31%

The battery supplies D.C current and it needs to be converted to alternating current for the Fluorescent lamp to be operated. The lamp circuit or the inverter does this conversion. The efficiency of the lamp circuit in the solar home system is important. The efficiency of inverter circuit is determined by measuring the input DC power and the delivered AC power to the loads.

5.4.2 Minimum and maximum operating voltage test

The inverter should operate properly at lower cutoff and higher cutoff voltages of the battery.

The lamp circuit was supplied with voltages of lower cutoff and higher cutoff voltage. The lamp was found operating within this voltage range.

5.4.3 Operating frequency test

The lamp circuit requires a frequency greater than 20 kHz for proper operation. The bulb lights up when the voltage is fixed at 12.7V .The Oscilloscope's probe in series with the output terminal of the inverter produces a distorted sine wave shape at the display with a frequency of 64.52 KHz. The display shows a wave shape which is not a pure sine wave

5.4.4 Electrical waveform test

A smooth sine wave makes the Fluorescent lamp light for more years than a distorted wave. But practice shows that slightly distorted wave-form with a little bit of spikes lights the lamp brighter. A distorted wave also causes 'black spot' which produces shades in both ends of the lamp. So the electrical waveform plays a vital role.

5.4.5 Reverse polarity test

The DC power supply is required to be set at 12.7V. In case of reverse polarity at the terminals of the inverter, a current of large magnitude can flow through the inverter circuit and damages it. To protect the device from the reverse current, a protecting system should be provided.

Usually a diode is connected in series with supply to protect the reverse current. But it causes forward voltage drop corresponding 12V supply voltage. That's why a fuse is used in series with supply voltage in the inverter circuit and a reverse diode is connected parallel. If polarity is reversed the fuse inside the inverter circuit blows and the protection of the inverter sustains.

5.4.6 No load protection test

It is important for the circuit to remain ok if a sudden no load condition occurs because even in case of no load there is a flow of power which may damage the lamp circuit . So protection for sudden no load condition is necessary.

The DC power supply at 12.7V is converted to alternating mode by the inverter inside the lamp circuit. For the purpose of no Load protection test the circuit is switched on with no load in the lamp circuit. Now keeping the connection intact, duration of two minutes is allowed to be elapsed. After the interval the lamp is put into the lamp circuit. The fluorescent bulb is found to be operating properly. This confirms the soundness of the circuit even after it undergoes no load.

Chapter 6

User Guidelines for SHS

(According to Grameen Shakti SHS)

9.1 Solar Electricity:

Electricity generated form sunlight is called solar electricity.

9.2 Different parts of solar home system:

1. **Solar panel** : generates electricity from sunlight
2. **Battery** : stores the electric energy produced from sunlight
3. **Charge controller** : regulates the charging and discharging of battery
4. **Load** : special type of DC lamp, radio, TV, cassette, cellular phone etc.

9.3 Use of Solar Electricity:

1. Lightening houses, offices, schools, colleges, clinics, houses of worship, fisheries, poultry farms etc
2. Operating television, radios and cassettes
3. Charging batteries of mobile phones

9.4 User Guidelines

1. Should not be used for other appliances than designated lamp, television, radio or cassette.
2. No load can be used for more than four hours in a day
3. If the battery is not fully charged because of cloudy or misty weather, than the battery should be allowed to be recharged properly by lessening load, other wise battery will not be able to hold the charged and gradually will loss its efficacy
4. Panel, battery and charge controller have to be taken care of properly
5. It is not right to turn switches ON and OFF recurrently. This will blacken tube ends.
6. Bed switch should not be used in a solar system as this will quickly blacken tube ends. [9]

9.5 Special precautions for system warrantee:

1. Preferred distance between panel battery should be within 20 to 25 feet
2. Solar panel should be installed facing southwards on an angle of 23 degree with the ground.
3. The top of solar panel should be cleaned with a soft cloth after every 10/15 days, to get voltage from the solar panel.
4. If there is a forecast of cyclone, tornado, hurricane or any other huge natural disaster, then the solar panel should be bought down.

5. It must be ensured that, shadows of trees or other elements do not fall on the solar panel
6. Solar panel should be installed in a place where there is sunlight for most of the time
7. It must be ensured that air can pass under the panel, when it is attached to tin roof.

9.6 Safety measures for the battery:

1. Space for the battery should be4 kept dry and clean. There should not be any metal objects near the battery.
2. Top of the battery should be cleaned regularly
3. Plastic covering of the battery should be cleaned with a cloth soaked in clean water. If positive/negative terminal are covered with grease, there is no need to clean the terminals. However, one must ensure that the junctions of the terminals are tightly fixed. if they are found loose, user should contact GS office.
4. No fire or explosive products should be taken near the battery or kept near it.
5. Battery should not be covered with polythene or any other material
6. Loads such as special type of DC lamp, radio, TV, cassette, cellular phone etc should not be connected directly with the battery terminal. This will reduce the life of the battery and no guarantee will be considered under this circumstances.
7. Some times, a hydrometer must be used to test the specific gravity of acid water of each cell of the battery to ensure that acid water is up to standard level. If it is not and specific gravity becomes less, then the battery should only be used after charging it for a long time by placing de-mineralized water separately in each cell up to thee standard level
8. If specific gravity becomes less then 1170, then the system should be in rest for minimum 3(three) days and charged without using any load. [9]

9.7 Safety measures for charge controller:

1. No wire should be connected or disconnected from the charge controller
2. Cover of the charge controller should not be removed and water should not be allowed to enter it.

9.8 Safety measures for lamp and other equipment:

1. One can get bright light from the lamp by cleaning dusts from the shade and the glass with a dry cloth from time to time.

2. Grameen shakti uses two types of lamps. One can fix a fuse in a lamp set given earlier with metal shade from outside without opening the cover. The fuse should not be more than 1.5 amp. In case of the lamp with plastic shade, one has to open the black cover of the shade to across the fuse. After that, a new fuse should be placed in place of the old one. If one feels during removing the fuse, that connection is not strong enough, then put a little pressure on the fuse clip to make it thinner before installing the new fuse.
3. In case of DC-DC converters, one cannot play radios/cassettes of more than 6 watts from 6 volts or 9 watts from a 9 volts converter. Keep it in mind that, high volume of sound needs more power. If radio and cassette of more than 6 or 9 watts is used on a DC converter, then it will be damaged soon. Beside this a mobile set may be damaged if it is connected to a mobile charger, which is of a different model from the set selected to be charged.

9.9 Precautions:

1. Please ensure that acid mixed battery water(electrolyte) remains within standard limit
2. Please ensure that battery terminals are covered with grease, this stop rust from forming due to water vapor or acid mixed water
3. If battery charge is low, assuage the load to increase the battery charge
4. Battery should be kept on a dry wooden stool
5. Under no condition, one should replace fese from the lamp to the charge controller or vice versa
6. Neither tube lights or fuses should be changed when they are switched on
7. Place the battery on high ground, if there is a possibility of flood during the rainy season. otherwise, battery may become damaged if water enters it.
8. If any thing is burning due to short circuit, please disconnect any terminal connection from the battery.
9. If your body comes in contact with acid mixed battery water, please wash it with plenty of water and take advice from a doctor (especially in the case of eyes)
10. If you want to change lamp of the plastic shade, pull two sides of the lamp towards outside to bring the tube out of the shade (under no circumstances tube should be rotated) and if the lamp is used with a metal shade, then first rotate the tube and then pull it out of the shade.
11. One must be careful that no accident occurs due to battery acid, when opening battery valve (cork) [9]

Chapter 7

SHS in Bangladesh

7.1 SHS in Bangladesh

Fig 7.1: Connecting a Solar Panel considering the appropriate angle.

The Government of Bangladesh has established goal of providing electrical power to all its citizens. Renewable energy is a key component of the initiative, and Bangladesh has already made impressive gains in reaching the 85 percent of the country's population that lives in rural areas. However, in many rural areas, people live too far from the main electrical grids to make connections reliable or affordable. Without access, these families are forced to rely on more expensive—and nonrenewable energy options such as kerosene or batteries. Even with 400,000 new households gaining access to electricity every year, it could take another 40 years for all the people of Bangladesh to have power.

Bangladesh is situated in the northern hemisphere between 20° 34′ and 26° 38′ north latitude and 88° 01′ and 92° 41′ east longitude . The country is conveniently located in a high solar insulations prone area with average daily solar insulations of 4 - 6.5 kW/m2 . There is a huge potential for harnessing solar energy by using solar photovoltaic (PV) and solar thermal technologies. According to a World Bank report in 1998 , 5.3 million Bangladeshi households could afford solar home systems (SHS). To help speed that process, The government of Bangladesh provides subsidies in the form of financial contribution to NGOs through its subsidiary, Infrastructure Development Company Limited (IDCOL). In 2002, an IDCOL project titled Rural Electrification and Renewable Energy Development Project (REREDP) installed about 200,000 SHS ranging from 40-70 Wp through its 15 partner organizations with a total capacity of 7.4 MWp .Partner organizations(Pos) namely Grameen Shakti, BRAC Foundation, Srizony Bangladesh, COAST Trust, Thengamara Mahila Sabuj Shangha, Integrated Development Foundation, Centre For Mass Education in Science, Upokulio Bidyuatayon O Mohila Shamity,Shubashati, Bangladesh Rural Integrated Development For Grub-Street Economy, Padakhep Manbik Unnayan Kendra, Palli Daridra Bimochan Foundation, HilfulFuzul Samaj Kalyan Sangstha, Mukti Cox's Bazar and Rural Services Foundation. SHSs are sold mostly through micro-credit by POs to the thousands and business entities in the remote and rural areas of Bangladesh. IDCOL provides refinancing, channel grants to the POs. In addition, IDCOL also provides technical, logistic, promotional and training assistance to the POs.

Fig 7.2: Installation, maintenance and use in various places of SHS.

The solar electrification programmed is already yielding a positive impact on the rural economy. SHSs can be used to light up homes, shops, fishing boats etc. It can also be used charge cellular phone, run television, radio and cassette players. SHSs have become increasingly popular among users because they present an attractive alternative to conventional electricity such as no monthly bills, no fuel cost, very little repair, easy to install any where etc.

Fig 7.3: The effective use of SHS.

In November 2007, when cyclone Sidr struck Bangladesh solar was a lifeline: solar mobile phones warned people of the cyclone’s approach, and the majority of solar installations survived its impact.

7.2 IDCOL

Infrastructure Development Company Limited (IDCOL) was established on 14 May 1997 by the Government of Bangladesh (GOB). The Company was licensed by Bangladesh Bank as a non-bank financial institution (NBFI) on 5 January 1998. Since its inception, IDCOL is playing a major role in bridging the financing gap for developing medium and large-scale infrastructure and renewable energy projects in

Bangladesh. In less than a decade, the company now stands as the market leader in private sector energy and infrastructure financing in Bangladesh.
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,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. Now IDCOL has a revised target of financing 200,000 SHSs by year 2009 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. [16]

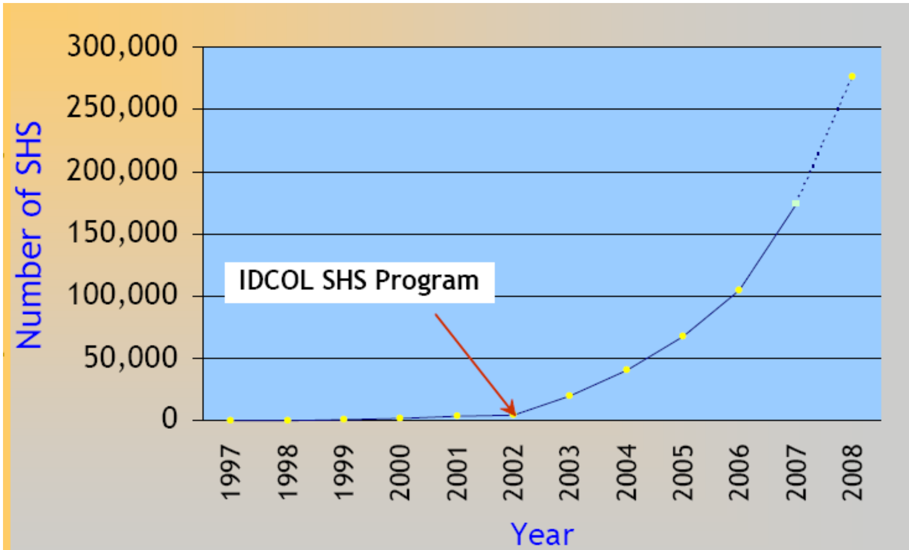


Fig7.4: Year wise SHS installed.

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.

- ✓ IDCOL started its solar energy program in January 2003 with the support from IDA and GEF.
- ✓ Initial installation target was 50,000solar home systems (SHS) in off-grid areas within five and half years.
- ✓ Target was achieved in August 2005, 3 years ahead of completion date and US$ 2 m below estimated cost.
- ✓ Following this success, World Bank, GTZ and KfW have extended support.
- ✓ Asian Development Bank is expected to support the program.
- ✓ IDCOL has revised its target to 1 millionSHSby 2012.
- ✓ Installation of SHS up to May 2008 is 211,000 (11+ MW)i.e. more than 1 million users are getting electricity. [16]

7.3 Battery Recycling

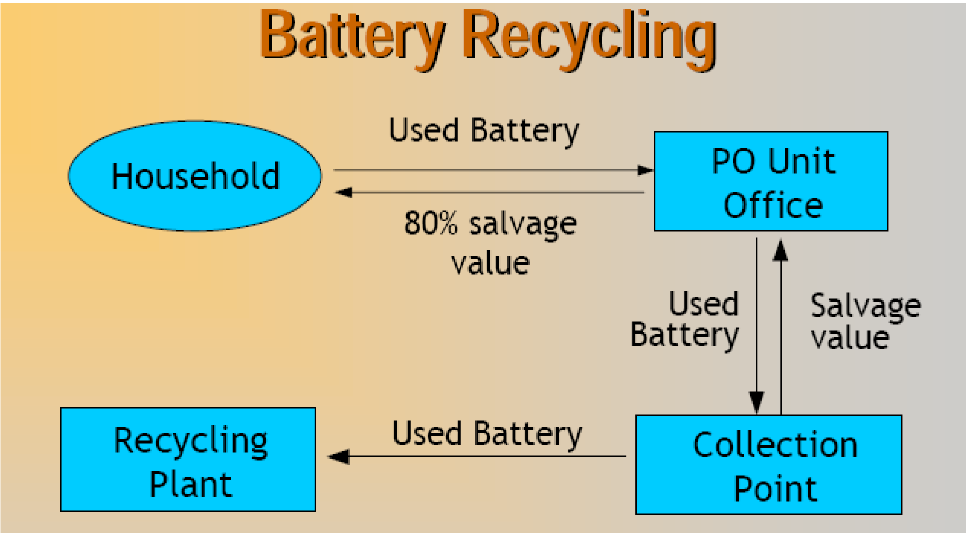


Fig7.5: Battery recycling procedure of IDCOL

•Battery recycling under IDCOL'sSHS program has been made compulsory
•Salvage value will be paid as per the contract signed between PO and battery manufacturer within 45 days of battery collection in the collection point.
•POs will not sell any new battery to the POs without collecting the old one.

7.4 List of Partner Organizations(PO) of IDCOL

SL	Name	Address
1.	Grameen Shakti	Grameen Bank Bhaban, Mirpur-2, Dhaka 1216, Bangladesh. Tel: 9004314, 9004081, 9005257-69 Fax: 8013559 e-mail:g_shakti@grameen.net
2	BRAC Foundation	BRAC Centre

		75 Mohakhali C/A Dhaka 1212, Bangladesh. Tel: 8824180, 9881205 Ext. 2337 Fax: 8826448 Mob: 0171-876092 email:development@brac.net
3	Srizony Bangladesh	2/7, Block-F, Lalmatia, Dhaka-1207 Bangladesh. Tel: 9128581, Fax: 0451-3346 e-mail: srizony@accesstel.net
4	Thengamara Mahila Shabuj Shangha (TMSS)	631/5, West Kazipara, Mirpur-10 Dhaka-1216, Bangladesh. Tel and Fax : 9009089, 9348644 e-mail: tmss@bttb.net.bd
5	COAST Trust	House# 9/2, Road # 2 , Shamoli Dhaka-1207, Bangladesh. Tel : 8125181, 8154673 Fax: 9129395 e-mail: coasttrust@citechco.net
6	Center for Mass Education in Science (CMES)	House # 828, Road # 19 (old), Dhanmondi, Dhaka-1209, Bangladesh. Tel: 8111898, Fax: 8013559 e-mail: cmesbd@yahoo.com
7	Integrated Development Fund (IDF)	House # 2, Road # 2, Block-C, Mirpur-2, Dhaka-1216, Bangladesh. Tel: 9005452, 9014933 Fax: 8016319 e-mail: zamalidf@citechco.net
8	Shubashati	House# 7, Main Road # 3, Section -11, Mirpur, Dhaka-1221, Bangladesh. Tel: 8116688, Fax: 9124027 e-mail: sbashati@bolonline.com
9	Upakulio Biddutayan O Mohila Unnayan Samity (UBOMUS)	Chor Mantaj, Golachipa, Potuakhali Tel: (Dhaka) 9894023, 9887356 Fax: 9880501 e-mail: psl@bd.drik.org
10	Padakhep Manabik Unnayan Kendra (PMUK)	House # 548, Road # 10, Baitul Aman, Housing Society, Adabar,

		Mohammadpur, Dhaka-1207, Bangladesh. Tel: 8151124-6, 9128824 Fax: 9137361 e-mail: padakhep@banglacafe.com
11	Bangladesh Rural Integrated Development For Grub-Street Economy(BRIDGE)	House# 7, Road # 113 Khalishpur Housing Estate, Khulna. Tel: 041-760038, Fax: 041-860825 e-mail: hbali59@yahoo.com
12	MUKTI Cox's Bazar	Sarada Bahaban, Goldighir Par, Cox's Bazar
13	Rural Services Foundation (RSF)	74/D, Arjatpara, Mohakhali, Dhaka-1206. Tel:8143615
14	Hilful Fuzul Samaj Kalyan Sangstha (HFSKS)	21/18, Babar Road (1st Floor) Block# B, Mohammadpur Dhaka-1207, Bangladesh. Tel & Fax: 9146206 e-mail: hfsks@bdonline.com
15	Palli Daridra Bimochan Foundation (PDBF)	House# 51, Road # 10/A, Dhanmondi R/A, Dhaka-1209, Bangladesh. Tel: 9111700

Table 7.1: List of PO

7.5 Progress with SHS's installation up to 26 July 2009

Participating Organization	**Number of SHSs Installed**
Grameen Shakti	209,928
BRAC Foundation	48,974
RSF	32,138
Srizony Bangladesh	9,194
UBOMUS	6,956
BRIDGE	5,183
COAST Trust	3,076
Integrated Development Foundaton	3,405
Centre for Mass Education and Science	2,762
Shubashati	2,471
Hilful Fuzul Samaj Kallyan Sangstha	5,441

TMSS	1,724
PDBF	1,873
PMUK	578
Other	388
Total	**334,091**

Table 7.2: Progress with SHS's installation up to 26 July 2009

7.6 Division wise installation of SHSs

Division	**Number of SHSs Installed**
Barisal	47,333
Chittagong	69,965
Dhaka	73,798
Khulna	54,875
Rajshahi	48,123
Sylhet	39,997
Total	**334,091**

Table 7.3: Division wise installation of SHSs

7.7 Grameen Shakti

7.7.1 Company Details

Grameen Shakti (GS) was initiated in 1996 by the co-builders of Grameen bank in orders to rescue the rural people from energy poverty which hampers their social and economical development. Inspired by the vision of Professor Muhammad Yunus who has great faith in modern technology and inherent creativity and capacity of the rural people, GS strives to create a synergy between renewable energy technology and micro credit in order to give the rural people a chance to improve their quality of life and also take part in income generating activities.

GS provide renewable energy services such as Solar, Biogas, improved cook stove and wind energy in rural remote areas in Bangladesh. GS has designed the most successful market based model for rural electrification through solar PV technology. It has achieved international renown for being the first company in the world to promote solar technology successfully to rural communities and develop a sustainable and cost effective renewable energy program, targeting rural people. For this reason it has won many national and international awards. Currently GS is serving more then one million beneficiaries through its 600 unit offices spread over all districts out of total 64 districts in Bangladesh. It has installed more then 205,000 Solar Home Systems (SHS) as of October 2008 with the capacity of 10MW; more then 8000 SHSs are installed each month, making GS one of the fastest growing companies in the renewable energy sector.

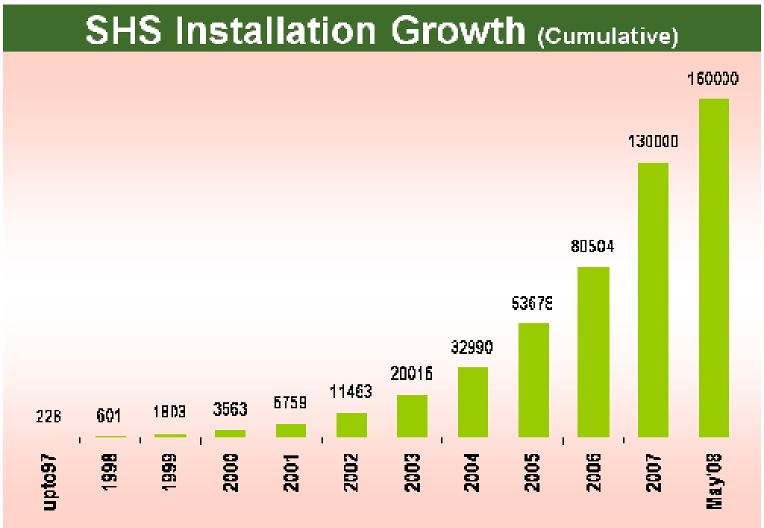


Fig 7.6: SHS installation growth (cumulative)

It has shown that solar energy application can be scaled up massively and rapidly to provide an affordable and climate friendly energy option for the rural people. GS has played a successful pioneer role in promoting renewable energy technologies in Bangladesh, especially its Solar Photovoltaic (PV) Program is internationally renowned. GS is one of the fastest growing rural based renewable energy companies in the world and Bangladesh a country with the fastest growing Solar PV Program in the world.

7.7.2 Activities of GS

1. Solar energy program
2. Biogas program
3. Improved cook stoves

7.7.3 Solar energy program

1. Marketing
2. Set up
3. Servicing
4. Installment collection
5. Customer training

1. Marketing

For selling the solar home system first should marketing. Sometimes some employee goes the villagers to talk with them about the importance & price installment of SHS. Then if any of them are interested to take SHS they will contact with the unit office.

2. Set up

When the customer ensure to the office that he/she wants to buy a SHS, office prepare a date to set up the solar.

3. Servicing

When customer faces some difficulties with the Solar Home System they called the field assistants or Technicians. They try the best of their to solve the problems.

4. Installment collection

In a fixed date of each month field assistants are going to the customers home to collect the monthly installment.

5. Customer training

In each month Shingair unit office arrange a customer training where customers able to know the basis working principals of SHS, advantages, maintenance, basic servicing etc.

7.7.4 Price list of SHS – Grameen Shakti

SL. No.	System in Watt	Load	Package Included	Package Price (Out of Grid Electricity)
1	130Wp	11 Nos. 6 Watt Lamp & 17"-20" B/W TV point	1 No. 130 Wp Solar Module, 2 No. 100 Ah Industrial Battery (Tabular Plate), 1No. 15Amps Charge Controller, 1 No. Structure, 11No.s 6 Watt Lamp, Switch, Switch Board, Installation & Other Accessories	68,000
2	120 Wp	10 Nos. 6 Watt Lamp & 17"-20" B/W TV point	1 No. 120 Wp Solar Module, 2 No. 100 Ah Industrial Battery(Tabular Plate), 1No. 15Amps Charge Controller, 1 No. Structure, 10No.s 6 Watt Lamp, Switch, Switch Board, Installation &Other Accessories	65,000
3	85 Wp	8 Nos. 6 Watt Lamp & 17" B/W TV point	1 No. 85 Wp Solar Module, 1 No. 130 Ah Industrial Battery (Tabular Plate), 1No. 10 Amps Charge Controller, 1 No. Structure, 8 Nos 6 Watt Lamp, Switch, Switch Board, Installation &Other Accessories	42,500
4	75Wp	7 Nos. 6 Watt Lamp & 17" B/W TV point	1 No. 75 Wp Solar Module, 1 No. 100 Ah Industrial Battery (Tabular Plate), 1No. 10 Amps Charge Controller, 1 No. Structure, 7 Nos 6 Watt Lamp, Switch, Switch Board, Installation &Other Accessories	38,000
4	65 Wp	7 Nos. 5 Watt Lamp & 1 No. B/W TV point	1 No. 65 Wp Solar Module, 1 No. 100 Ah Industrial Battery (Tabular Plate), 1No. 5 or 10 Amps Charge Controller, 1 No. Structure, 6 Nos 6 Watt Lamp, Switch, Switch Board, Installation & Other Accessories	34,000
5	50 Wp	4 Nos. 6 Watt Lamp & 1 No. B/W TV point	1 No. 50 Wp Solar Module, 1 No. 80 Ah Industrial Battery (Tabular Plate), 1No. 5 or 10 Amps Charge Controller, 1 No. Structure, 4 Nos 6 Watt Lamp, Switch, Switch Board, Installation & Other Accessories	28,000
6	40 Wp	3 Nos. 6 Watt Lamp & 1 No. B/W TV point	1 No. 40 Wp Solar Module, 1 No. 55 Ah Industrial Battery (Tabular Plate), 1No. 5 or 10 Amps Charge Controller, 1 No. Structure, 3 Nos 6 Watt Lamp, Switch, Switch Board, Installation & Other Accessories	22,500
7	20Wp	1 no. 7 Watt CFL Lamp & 3 Nos LED Lamp (18,36)	1 No. 20 Wp Solar Module, 1 No. 23 Ah Industrial Battery (Tabular Plate), 1No. 1 Charge Controller, 1 No. Structure, 1 Nos 7 Watt CFL & 3 LED Lamp, Switch, Switch Board, Installation & Other Accessories	13,500
8	10Wp	1 no. 5 Watt CFL Lamp & 2 Nos LED Lamp (18,24,36)	1 No. 10 Wp Solar Module, 1 No. 18 Ah Industrial Battery (Tabular Plate), 1No. 1 Charge Controller, 1 No. Structure, 1 Nos 5 Watt CFL & 2 no LED Lamp, Switch, Switch Board, Installation & Other Accessories	9,500

Table7.4: Price list of SHS by Grameen Shakti.

7.7.5 Payment schemes

Mode of payment	Down Payment	Instalment	Servics Charhe (Flat Rate)
Option 1	25%	24 months	4%
Option 2	15%	36 months	6%
Option 3	100% cash payment with 4% discount.		

Table 7.5: Payment schemes of Grameen Shakti

7.7.6 Warranty of Components

Components	Warranty (Years)
Solar Panel	20
Charge Controller	3
Battery	5
Mobile Charger	3
Inverter	3
Light	N/A

Table 7.6: Warranty of components

Wire provided Solar Panel to Charge Controller 15meter & per light 10m.

7.7.8 Solar set up May 2009 (Shingair Unit)

Watt	No. of panels
40	2
50	6
65	3
75	1
85	2
total	14

Table 7.7 Solar set up May 2009 (Shingair Unit)

7.7.9 Problemed faced by customers

1. Light doesn't work.
2. Back up time low.
3. LEDs of charge controller doesn't blink. Etc

If problemed customers informed to office. Them the technician are come to the customers boundary and try their best to solve the problems.

6.2 Activities of GTC (Grameen Technical Center)

1. **Assembling** circuit components of Mobile Charger, Inverters, Light shades.
2. **Repairing** the problemed circuits.
3. **School training** – the School Training has operated by the economical help of USAID. It's taken by the students of class 8, 9 & 10. It's mainly held for

marketing. It's a 1 day program. After this program the students are influenced to their parents to pick a solar in their home to better study.

4. **User training** – its arranged for only the female members whose are buy Solar Home System (SHS). Because of that if minor fault occurs in SHS they can solve their problem. This program held's monthly. About 15 female users attend on this program in 1 day. Its about 322 female percipients join on this training still now on GTC, Shingair branch.
5. **Technician training** – Technician training is scheduled by head office, its 10days training. GTC collected some poor, divorcees by the informed by unit office. Then GTC arranged this program to improve their economical balance. After this training GTC collect 2 women to a partial hand of technical work. It's a fully technical training. About 10 women participate in one session. Everyday every participators get 100tk. After selection GTC set up the whole equipments in their home. They found a SHS freely. Also they get 7tk. per lamp shade & 10tk. per converter set up. It's a big opportunity to improve their economical situation.

6.3 IDCOL newsletters

6.3.1 IDCOL signs USD 100 million Agreement with the World Bank for promotion of renewable energy

Government of Bangladesh, represented by the Economic Relations Division (ERD) has signed a Financing Agreement with the World Bank followed by a Project Agreement between IDCOL and the World Bank. Under these Agreements, IDCOL will receive US$100 million from the World Bank to promote installation of Solar Home Systems (SHS) and other renewable energy projects.

This US$100 million fund is in addition to US$64 million already received by IDCOL from the World Bank. IDCOL, along with its 15 Partner Organisations, is implementing various renewable energy programmes. Installation of SHS in the un-electrified areas is the largest among all of them. So far, under IDCOL's renewable energy programme, a total of about 350,000 SHS have been installed. With the additional funding, IDCOL will be able to finance about 300,000 new SHS and several other renewable energy projects such as solar irrigation pumps, solar mini-grid, biomass gasification based power plants and biogas based power plants etc. IDCOL has a target of financing 1 million SHS by 2012. In addition to the World Bank, ADB, KfW, GTZ and Islamic Development Bank are funding IDCOL's renewable energy programmes.

Ms. Tahseen Sayed, Acting Country Director, World Bank, Dhaka Office and Mr. Islam Sharif, Executive Director and CEO, IDCOL signed the Project Agreement between IDCOL and the World Bank on behalf of their respective organisation.

Over 350,000 households brought under IDCOL's Solar Programme

Beginning from January 2003, Infrastructure Development Company Ltd. (IDCOL) has brought more than 350,000 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. [16]

6.3.2 IDCOL signs agreement with GTZ to promote installation of Solar Home Systems (SHS)

A Financing Agreement has been signed recently between Infrastructure Development Company Limited (IDCOL) and GTZ of Germany to promote installation of Solar Home Systems (SHS). Under these Agreements, IDCOL will receive EURO 2.2 million as grant from GTZ which is in addition to EURO 3.44 million grant already received by IDCOL from GTZ.
With the additional funding, IDCOL will be able to grant finance about 50,000 new SHS. Notably, IDCOL has a target of financing 1 million SHS by 2012. The World Bank, ADB, KfW and Islamic Development Bank also are funding IDCOL's renewable energy programmes. [16]

6.4 Visio of IDCOL:

Set up One million SHS by 2012.

Chapter 8

Discussion & Conclusion

8.1 Improve to Performance of Solar Home System

8.1.1 Solar Tracker

A solar tracker is a device for orienting a daylighting reflector, solar photovoltaic panel or concentrating solar reflector or lens toward the sun. The sun's position in the sky varies both with the seasons and time of day as the sun moves across the sky. Solar powered equipment works best when pointed at or near the sun, so a solar tracker can increase the effectiveness of such equipment over any fixed position, at the cost of additional system complexity. There are many types of solar trackers, of varying costs, sophistication, and performance. One well-known type of solar tracker is the heliostat, a movable mirror that reflects the moving sun to a fixed location, but many other approaches are used as well.

Fig 8.1: Solar Tracker

The required accuracy of the solar tracker depends on the application. Concentrators, especially in solar cell applications, require a high degree of accuracy to ensure that the concentrated sunlight is directed precisely to the powered device, which is at (or near) the focal point of the reflector or lens. Typically concentrator systems will not work at all without tracking, so at least single-axis tracking is mandatory. Very large power plants or high temperature materials research facilities using multiple ground-mounted mirrors and an absorber target require very high precision similar to that used for solar telescopes.

Non-concentrating applications require less accuracy, and many work without any tracking at all. However, tracking can substantially improve both the amount of total power produced by a system and that produced during critical system demand periods (typically late afternoon in hot climates) The use of trackers in non-concentrating applications is usually an engineering decision based on economics. Compared to photovoltaics, trackers can be inexpensive. This makes them especially effective for photovoltaic systems using high-efficiency (and thus expensive) panels.

For low-temperature solar thermal applications, trackers are not usually used, owing to the high expense of trackers compared to adding more collector area and the more restricted solar angles required for Winter performance, which influence the average year-round system capacity. [8]

8.1.2 Solar thermal collector

A solar thermal collector is a solar collector specifically intended to collect heat: that is, to absorb sunlight to provide heat. Although the term may be applied to simple solar hot water panels, it is usually used to denote more complex installations. There are various types of thermal collectors, such as solar parabolic, solar trough and solar towers. These type of collectors are generally used in solar power plants where solar heat is used to generate electricity by heating water to produce steam which drives a turbine connected to an electrical generator.

Types of solar collectors for electric generation

Parabolic troughs, dishes and towers described in this section are used almost exclusively in solar power generating stations or for research purposes. The conversion efficiency of a solar collector is expressed as eta0 or $\eta 0$.

A. **Parabolic trough**

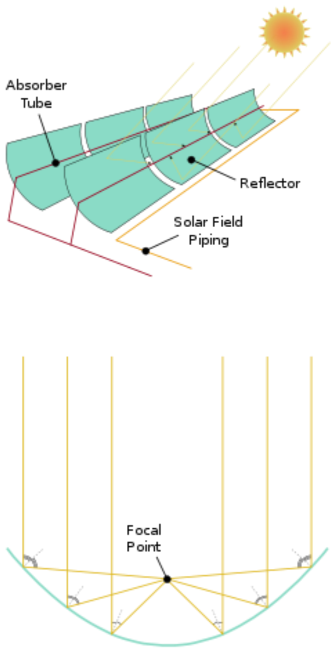


Fig 8.2: Parabolic trough

This type of collector is generally used in solar power plants. A trough-shaped parabolic reflector is used to concentrate sunlight on an insulated tube (Dewar tube) or heat pipe, placed at the focal point, containing coolant which transfers heat from the collectors to the boilers in the power station.

B. **Parabolic dish**

Fig 8.3: Solar Parabolic dish

It is the most powerful type of collector which concentrates sunlight at a single, focal point, via one or more parabolic dishes -- arranged in a similar fashion to a reflecting telescope focuses starlight, or a dish antenna focuses radio waves. This geometry may be used in solar furnaces and solar power plants.

There are two key phenomena to understand in order to comprehend the design of a parabolic dish. One is that the shape of a parabola is defined such that incoming rays which are parallel to the dish's axis will be reflected toward the focus, no matter where on the dish they arrive. The second key is that the light rays from the sun arriving at the earth's surface are almost completely parallel. So if dish can be aligned with its axis pointing at the sun, almost all of the incoming radiation will be reflected towards the focal point of the dish -- most losses are due to imperfections in the parabolic shape and imperfect reflection.

Losses due to atmosphere between the dish and its focal point are minimal, as the dish is generally designed specifically to be small enough that this factor is insignificant on a clear, sunny day. Compare this though with some other designs, and you will see that this could be an important factor, and if the local weather is hazy, or foggy, it may reduce the efficiency of a parabolic dish significantly.

In some power plant designs, a stirling engine coupled to a dynamo, is placed at the focus of the dish, which absorbs the heat of the incident solar radiation, and converts it into electricity. See Knowing Parabolic Concentrators and Concentrating Solar power overview. [8]

C. **Power tower**

Fig 8.4: Power Tower

A power tower is a large tower surrounded by small rotating (tracking) mirrors called heliostats. These mirrors align themselves and focus sunlight on the receiver at the top of tower, collected heat is transferred to a power station below.

D. **Solar pyramids**

Another design is a pyramid shaped structure, which works by drawing in air, heating it with solar energy and moving it through turbines to generate electricity. Solar pyramids have been built in places like Australia. Currently India is building such pyramids.

8.2 Competition with nuclear power

Nuclear power continues to be considered as an alternative to fossil-fuel power sources (see Low carbon power generation), and in 1956, when the first peak oil paper was presented, nuclear energy was presented as the replacement for fossil fuels. However, the prospect of increased nuclear power deployment was seriously undermined in the United States as a result of the Three Mile Island, and in the rest of the world after the Chernobyl disaster. This trend is slowly reversing, and several new nuclear reactors are scheduled for construction.

Physicist Bernard Cohen proposed in 1983 that uranium dissolved in seawater is effectively inexhaustible, and could therefore be considered a renewable source of energy. However, this idea is not universally accepted, and issues such as peak uranium and uranium depletion are ongoing debates.

No legislative body has yet included nuclear energy under any legal definition of "renewable energy sources" for provision of development support, and statutory and scientific definitions of renewable energies normally exclude nuclear energy.

8.3 Conclusion

The thesis team got the task of performance analysis of commonly used solar home system components and was working on relevant fields for last few months. Under the supervision of Gazi Habibul Hyder, the team visited different relevant websites, consulted several books, conducted group studies and laboratory works. For the authenticity of different information that has been used in this thesis, the team has included the data collected for IDCOL project which they have collected by visiting remote areas of the country. 0ne team worked for one month in “Grameen Shakti”, a reputed company in solar energy sector both in home and abroad. During the working sessions in Grameen Shakti the thesis team has acquired some hands-on experience about the entire solar home system including the installation procedure of SHS. The team got the opportunity to analyze the performances of various components of solar home system. During the analysis, the team completed all the tests regarding the components performance. A special test has been carried out on the charge controller and lamp circuit, manufactured by Grameen Shakti. As a part of the thesis work, the entire test has been done in the university laboratory for some more specific analyses. During the work, the team has been ably supported by the

supervisor in the lab. The team has also acquired the knowledge of possible problems that may occur in a solar home system component.
Improved lighting through solar energy has led to enhancement in children's education, household member's recreation and other income generating activities.

Solar lighting has extended working hours in rural market and business centers after dusk that in tern has led to opportunities for extra income. The use of solar powered contributed to further developing the technical skill base.

Access to solar home systems protects rural women from the health hazards of using and maintaining traditional kupi or hurricane lamps, concurrently reducing the amount spend of kerosene.

Rural communities now have the opportunities to become owners of solar home systems for almost the same price as kerosene.

The use of solar home system has created direct and indirect scope for new income generating and employment opportunities.

Solar home system entirely depends on the load. PV module, battery, charge controller, unit size and type of connection cable are selected depending on the load.

Photovoltaic systems are very robust and reliable since there are no moving parts. A photovoltaic system would be expected to last in excess of 20 years. Many manufacturers have 20-year warranties on the photovoltaic modules. The electronic components can also be made reliable, since there are no moving parts involved. But the warranties on these systems tend to be lower and are about 5 years. If the photovoltaic system contains batteries (most stand-alone systems do and residential grid-connected do not), then the batteries need to be replaced every 5 to 10 years.

The main advantage of solar cell is that it does not pollute the environment and it is safer than anyother electrical generation technologies. So as a source of energy, it is more useful than other fossil fuels. The production cost of energy needs to be reduced to popularize the solar energy which is still costlier in comparison with energy produced from oil, gas or coal. Solar cell is already popular in many parts of the world as a source of alternate energy.

Appendix

Appendix A: Characteristic Equation of Solar Cell

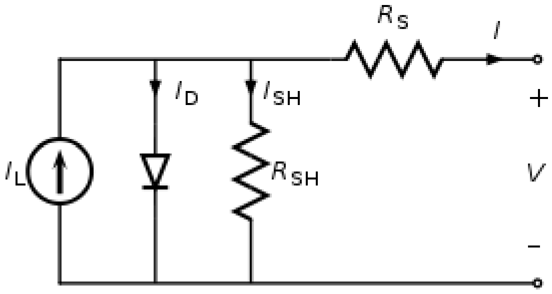


Fig: The equivalent circuit of a solar cell

From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor:

$$I = I_L - I_D - I_{SH}$$

where

- I = output current (amperes)
- I_L = photogenerated current (amperes)
- I_D = diode current (amperes)
- I_{SH} = shunt current (amperes)

The current through these elements is governed by the voltage across them:

$V_j = V + IR_S$

where

- V_j = voltage across both diode and resistor R_{SH} (volts)
- V = voltage across the output terminals (volts)
- I = output current (amperes)
- R_S = series resistance (Ω)

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ \exp\left[\frac{qV_j}{nkT}\right] - 1 \right\}$$

where

- I_0 = reverse saturation current (amperes)
- n = diode ideality factor (1 for an ideal diode)
- q = elementary charge
- k = Boltzmann's constant
- T = absolute temperature
- At 25°C, $kT/q \approx 0.0259$ volts.

By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}}$$

where

- R_{SH} = shunt resistance (Ω)

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$I = I_L - I_0 \left\{ \exp\left[\frac{q(V + IR_S)}{nkT}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}$$

An alternative derivation produces an equation similar in appearance, but with *V* on the left-hand side. The two alternatives are identities; that is, they yield precisely the same results.

In principle, given a particular operating voltage *V* the equation may be solved to determine the operating current *I* at that voltage. However, because the equation involves *I* on both sides in a transcendental function the equation has no general analytical solution. However, even without a solution it is physically instructive. Furthermore, it is easily solved using numerical methods. (A general analytical solution to the equation is possible using Lambert's W function, but since Lambert's W generally itself must be solved numerically this is a technicality.)

Since the parameters I_0, n, R_S, and R_{SH} cannot be measured directly, the most common application of the characteristic equation is nonlinear regression to extract the values of these parameters on the basis of their combined effect on solar cell behavior.

Open-circuit voltage and short-circuit current

When the cell is operated at open circuit, $I = 0$ and the voltage across the output terminals is defined as the *open-circuit voltage*. Assuming the shunt resistance is high enough to neglect the final term of the characteristic equation, the open-circuit voltage V_{OC} is:

$$V_{OC} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

Similarly, when the cell is operated at short circuit, $V = 0$ and the current *I* through the terminals is defined as the *short-circuit current*. It can be shown that for a high-quality solar cell (low R_S and I_0, and high R_{SH}) the short-circuit current I_{SC} is:

$$I_{SC} \approx I_L$$

Effect of physical size

The values of I_0, R_S, and R_{SH} are dependent upon the physical size of the solar cell. In comparing otherwise identical cells, a cell with twice the surface area of another will, in principle, have double the I_0 because it has twice the junction area across which current can leak. It will also have half the R_S and R_{SH} because it has twice the cross-sectional area through which current can flow. For this reason, the characteristic equation is frequently written in terms of current density, or current produced per unit cell area:

$$J = J_L - J_0 \left\{ \exp\left[\frac{q(V + Jr_S)}{nkT}\right] - 1 \right\} - \frac{V + Jr_S}{r_{SH}}$$

where

- J = current density (amperes/cm^2)
- J_L = photogenerated current density (amperes/cm^2)
- J_0= reverse saturation current density (amperes/cm^2)
- R_S = specific series resistance (Ω-cm^2)
- R_{SH} = specific shunt resistance (Ω-cm^2)

This formulation has several advantages. One is that since cell characteristics are referenced to a common cross-sectional area they may be compared for cells of different physical dimensions. While this is of limited benefit in a manufacturing setting, where all cells tend to be the same size, it is useful in research and in comparing cells between manufacturers. Another advantage is that the density equation naturally scales the parameter values to similar orders of magnitude, which can make numerical extraction of them simpler and more accurate even with naive solution methods.

A practical limitation of this formulation is that as cell sizes shrink, certain parasitic effects grow in importance and can affect the extracted parameter values. For example, recombination and contamination of the junction tend to be greatest at the perimeter of the cell, so very small cells may exhibit higher values of J_0 or lower values of R_{SH} than larger cells that are otherwise identical. In such cases, comparisons between cells must be made cautiously and with these effects in mind.

Appendix B: Current–voltage characteristic of Diode

A semiconductor diode's behavior in a circuit is given by its current–voltage characteristic, or I–V curve (see graph at right). The shape of the curve is determined by the transport of charge carriers through the so-called *depletion layer* or *depletion region* that exists at the p-n junction between differing semiconductors. When a p-n junction is first created, conduction band (mobile) electrons from the N-doped region diffuse into the P-doped region where there is a large population of holes (places for electrons in which no electron is present) with which the electrons "recombine". When a mobile electron recombines with a hole, both hole and electron vanish, leaving behind an immobile positively charged donor (the dopant) on the N-side and negatively charged acceptor (the dopant) on the P-side. The region around the p-n junction becomes depleted of charge carriers and thus behaves as an insulator.

However, the width of the depletion region (called the depletion width) cannot grow without limit. For each electron-hole pair that recombines, a positively-charged dopant ion is left behind in the N-doped region, and a negatively charged dopant ion is left behind in the P-doped region. As recombination proceeds and more ions are created, an increasing electric field develops through the depletion zone which acts to slow and then finally stop recombination. At this point, there is a "built-in" potential across the depletion zone.

If an external voltage is placed across the diode with the same polarity as the built-in potential, the depletion zone continues to act as an insulator, preventing any significant electric current flow (unless electron/hole pairs are actively being created in the junction by, for instance, light. see photodiode). This is the *reverse bias* phenomenon. However, if the polarity of the external voltage opposes the built-in potential, recombination can once again proceed, resulting in substantial electric current through the p-n junction (i.e. substantial numbers of electrons and holes recombine at the junction).. For silicon diodes, the built-in potential is approximately 0.6 V. Thus, if an external current is passed through the diode, about 0.6 V will be developed across the diode such that the P-doped region is positive with respect to the N-doped region and the diode is said to be "turned on" as it has a *forward bias*.

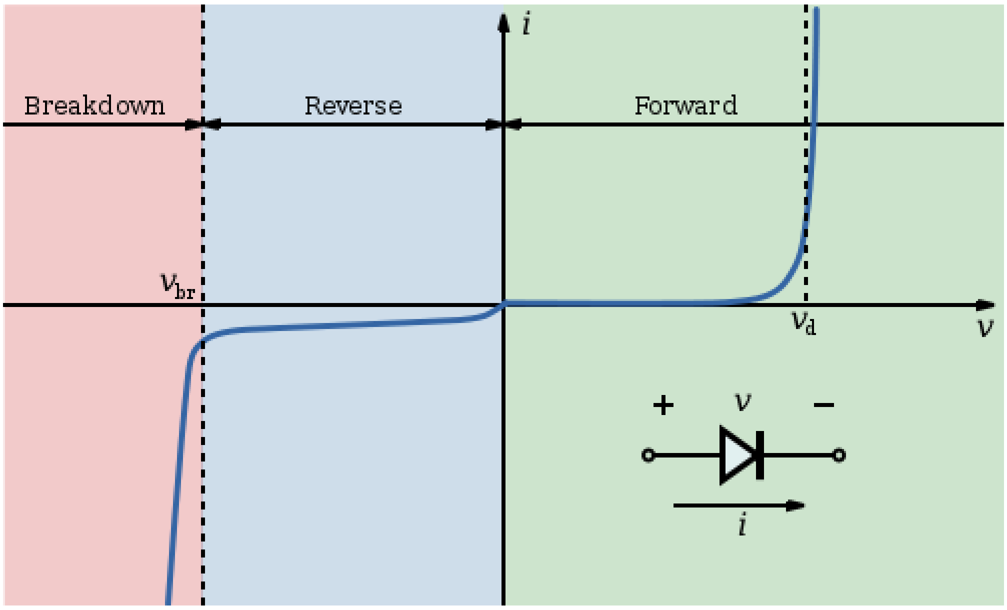


Figure : I–V characteristics of a P-N junction diode.

A diode's I–V characteristic can be approximated by four regions of operation.

At very large reverse bias, beyond the peak inverse voltage or PIV, a process called reverse breakdown occurs which causes a large increase in current (i.e. a large number of electrons and holes are created at, and move away from the pn junction) that usually damages the device permanently. The avalanche diode is deliberately designed for use in the avalanche region. In the zener diode, the concept of PIV is not applicable. A zener diode contains a heavily doped p-n junction allowing electrons to tunnel from the valence band of the p-type material to the conduction band of the n-type material, such that the reverse voltage is "clamped" to a known value (called the *zener voltage*), and avalanche does not occur. Both devices, however, do have a limit to the maximum current and power in the clamped reverse voltage region. Also, following the end of forward conduction in any diode, there is reverse current for a

short time. The device does not attain its full blocking capability until the reverse current ceases.
The second region, at reverse biases more positive than the PIV, has only a very small reverse saturation current. In the reverse bias region for a normal P-N rectifier diode, the current through the device is very low (in the µA range). However, this is temperature dependent, and at suffiently high temperatures, a substantial amount of reverse current can be observed (mA or more).
The third region is forward but small bias, where only a small forward current is conducted.
As the potential difference is increased above an arbitrarily defined “cut-in voltage” or “on-voltage” or “diode forward voltage drop (V_d)”, the diode current becomes appreciable (the level of current considered “appreciable” and the value of cut-in voltage depends on the application), and the diode presents a very low resistance.
The current–voltage curve is exponential. In a normal silicon diode at rated currents, the arbitrary “cut-in” voltage is defined as 0.6 to 0.7 volts. The value is different for other diode types — Schottky diodes can be rated as low as 0.2 V and red or blue light-emitting diodes (LEDs) can have values of 1.4 V and 4.0 V respectively.
At higher currents the forward voltage drop of the diode increases. A drop of 1 V to 1.5 V is typical at full rated current for power diodes.

Appendix C: Fill Factor

in the overall behavior of a solar cell is the fill factor (FF). This is the ratio of the maximum power point divided by the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}):

$$FF = \frac{P_m}{V_{oc} \times I_{sc}} = \frac{\eta \times A_c \times E}{V_{oc} \times I_{sc}}.$$

The fill factor is directly affected by the values of the cells series and shunt resistance. Increasing the shunt resistance (Rsh) and decreasing the series resistance (Rs) will lead to higher fill factor, thus resulting in greater efficiency, and pushing the cells output power closer towards its theoretical maximum

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