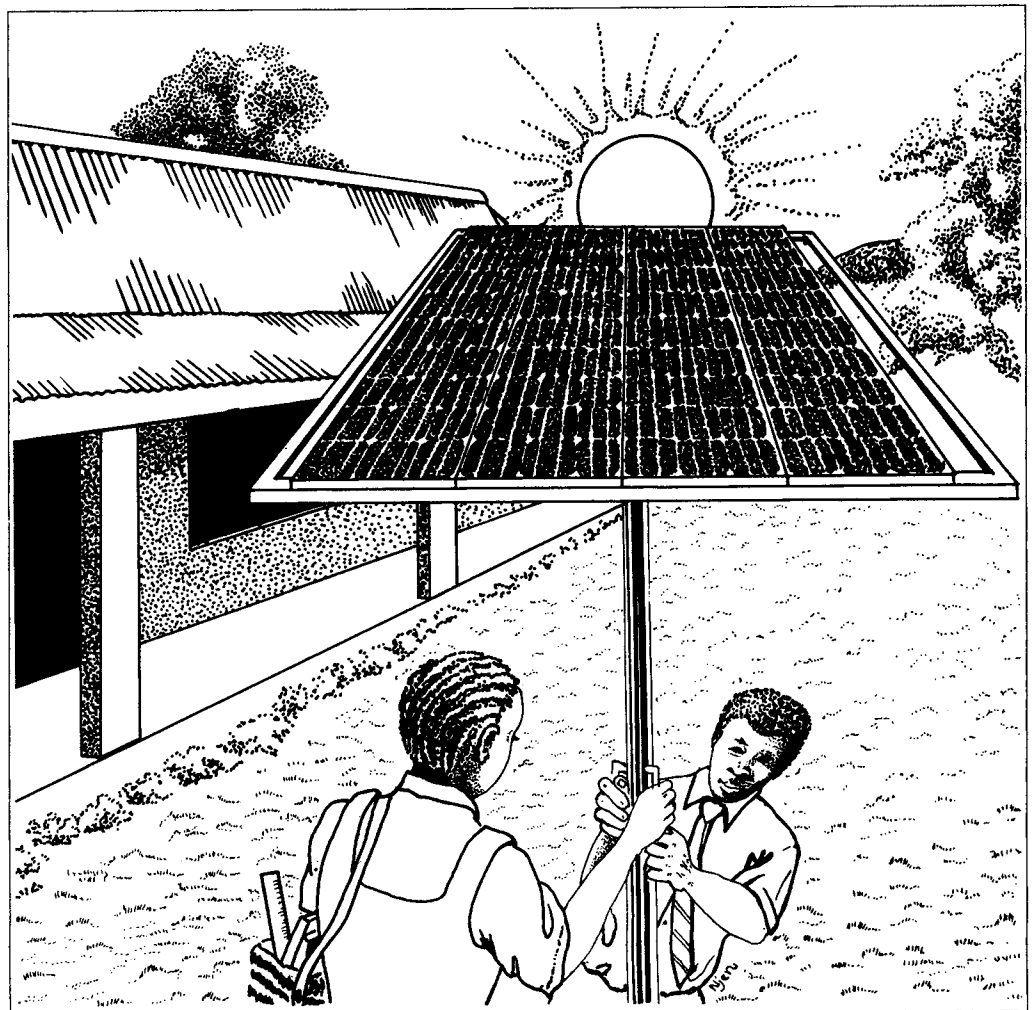
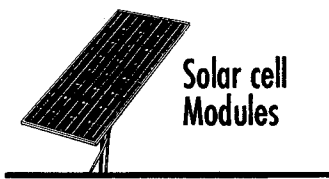


# Chapter 3

## Solar Cell Modules

*This chapter gives general details about solar cell modules. It describes basic principles by which solar cells operate, the types of solar cells and modules available (including monocrystalline, polycrystalline and amorphous), and the methods by which they are manufactured. Module parts are identified, and the system by which they are rated is introduced. The energy output and characteristics of modules under various temperature and weather conditions are explained. This information will help system designers to choose, install and estimate module energy output under nominal conditions.*





Solar cell Modules

The basic unit of solar electric production is the solar cell.

## Solar Cells and the Photo-electric Effect

### The Photo-electric Effect

Solar electricity is the direct conversion of sunlight to useful electricity. Whenever light strikes solar cells they convert *light energy into electric energy*. They do this according to a principle of physics called the *photo-electric effect*. Solar electric devices are also called *photovoltaic* or *PV* devices.

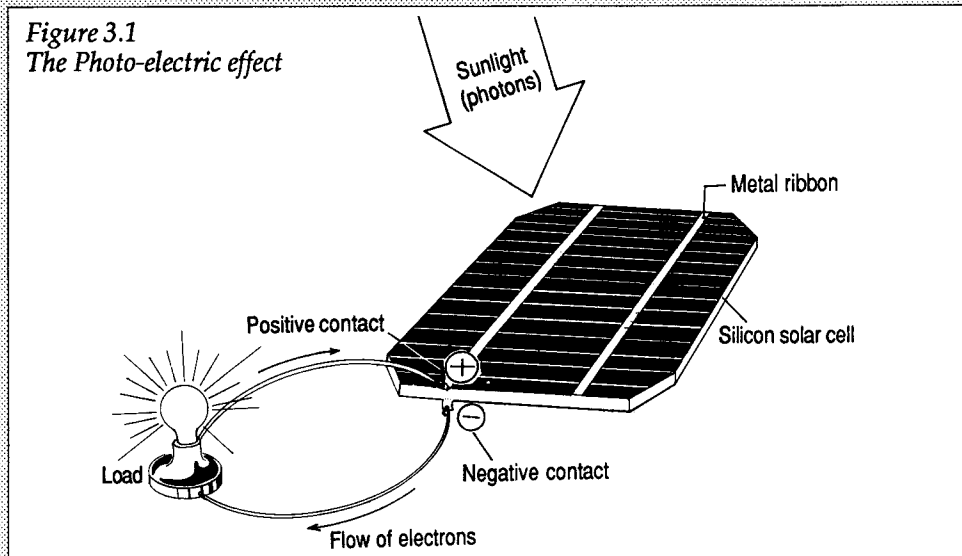
The photo-electric effect was first discovered about 100 years ago by a French physicist, Jacques Becquerel, but did not find a useful power-generating application until the 1950's, when the US space programme started using solar cells to provide electrical power for space ships.

Following the oil crisis in 1973, much research was put into improving the technology for applications on Earth. The first automated production of solar cells began in the USA in 1983. By 1991, the industry was well established and growing. Today solar cells are manufactured in many countries, including the USA, Germany, Spain, Italy, Japan, Brazil, China and India. The price of solar cells fell from about US\$ 100 per peak watt in 1974 to about US\$ 4 per peak watt by 1986. It is expected to fall even further in future.

### Solar Cells

The basic unit of solar electric production is the *solar cell*. Light striking solar cells creates a current powered by incoming light energy.

Figure 3.1  
The Photo-electric effect



### How solar cells work

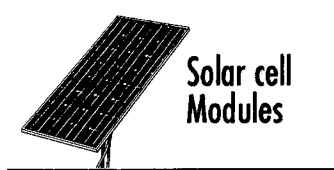
Whole books have been written about solar electricity and the *photoelectric effect*, and it is not the purpose of this book to go deeply into solar electric theory. The following is an extremely rough explanation of the operation of a solar cell; those interested in finding out more should consult the books listed in the reference section.

Solar radiation is composed of millions of tiny high-energy particles called *photons*. Each photon carries a quantity of energy; some have more than others. When a photon of sufficient energy strikes a silicon atom in a solar cell, it pushes the outermost silicon electron out of its orbit around the nucleus, freeing it to move across the cell's electric field.

Solar cells rely on the special electric properties of the element *silicon* (or other *semiconductor* materials) which enable it to act as both an insulator and a conductor. Specially-treated pieces of silicon "sort" electrons dislodged by solar energy in one direction to produce an electric current.

If a load is connected between the negative and positive side of the cell, the electrons flow as a current. Thus, solar energy (in the form of photons) continuously dislodges silicon electrons from their orbitals and "pushes" the electrons through the wires. More intense sunlight gives a stronger current. If the light stops striking the cell, the current stops flowing immediately.

Today solar cells are manufactured in many countries, including the USA, Germany, Spain, Italy, Japan, Brazil, China and India.



Solar cells produce electricity when placed in sunlight. They do not get used up or damaged while generating electric power. Their life is shortened only by breakage or exposure to the elements. If a cell is properly protected behind glass, it should last for more than 20 years.

### Solar Cell Technology

Several varieties of silicon-type solar cells and solar cell modules are available. These include modules with cells made from monocrystalline, polycrystalline and amorphous silicon. Monocrystalline refers to cells cut from a single *crystal* of silicon (a crystal is the regular geometric state taken up by elements in certain conditions; silicon crystals are specially grown through expensive processes). Polycrystalline refers to cells made from *many* crystals. Amorphous refers to silicon that is not in crystalline form and is therefore cheaper. When shopping for modules, it is important to consider the advantages and disadvantages of various types.

Several varieties of silicon-type solar cells are available, including ones made from monocrystalline, polycrystalline and amorphous silicon.

The most common type of solar cells are specially-treated silicon *wafers* (i.e. pieces of very thinly-sliced silicon). These cells are cut out of mono- or polycrystalline silicon crystals which are grown from very pure molten silicon (with trace amounts of boron). The wafers are chemically treated with phosphorus in furnaces, and then anti-reflective coating is applied to the cell surface to help it absorb radiation more effectively. After this, thin metal wires are applied to the front of the cell. These 'ribbons' of metal on the cell act as the positive contact, whereas a solid layer of metal on the back side of the cell acts as a negative contact (see Figure 3.1).

**Monocrystalline** cells have an efficiency of 12-15 %. This means that if solar radiation is striking the cells at a perpendicular angle with an intensity of 1000 W/m<sup>2</sup>, 120 to 150 Watts per m<sup>2</sup> of solar cell is produced as electricity. Monocrystalline cells are chemically stable, so they last for a very long time if properly protected.

Monocrystalline cells were the first to be developed for commercial purposes. They are made by using a special saw to slice thin pieces from a cylindrically-shaped crystal of pure silicon. In the process of slicing, almost as much of the expensive crystal is lost as dust as is cut into cells.

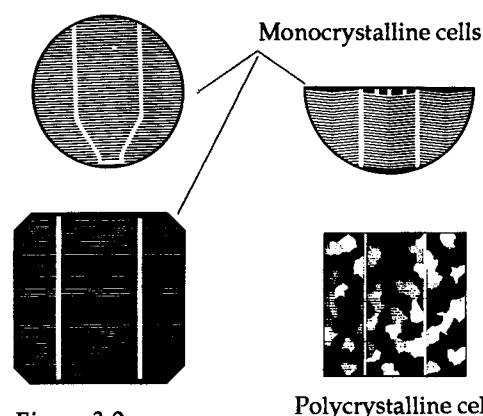


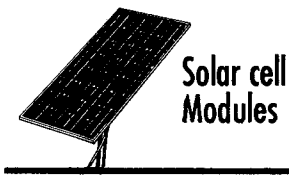
Figure 3.2  
Various types of crystalline solar cells

**Polycrystalline** (or multicrystalline) cells have a slightly lower efficiency than monocrystalline cells (i.e. 10-12 %). Like monocrystalline cells, they have a very long lifetime, and do not degrade over time.

Like monocrystalline cells, polycrystalline cells are sliced from crystals of silicon. However, they are made from cast ingots of polycrystalline silicon which is made by a different process than monocrystalline silicon. The cells have a different appearance than monocrystalline cells (see Figure 3,2). As of 1991, the price per watt of both types of crystalline cells was about the same.

**Amorphous** (or thin film) cells are the most recently developed solar electric technology. Amorphous-type cells do not use silicon in crystalline form, and hence cells can be manufactured much more cheaply than with poly- and monocrystalline cells. With amorphous modules, silicon material is deposited on the back of a glass or plastic surface in very thin layers. The surface is then scored to divide it into a number of cells, and electrical connections are added (see drawing page 23). In this process, very little silicon material is required. This enables mass production of modules at a low cost. The solar cells used in toys, calculators and watches are usually made from amorphous silicon.

Amorphous cells operate according to the same principles as crystalline modules, but have much lower efficiencies (between 4 and 6%). Because they operate at low efficiencies, amorphous modules must be three to four times the size of mono- or poly-crystalline modules to generate the same power.



Amorphous silicon *degrades* over time, meaning that as they get older amorphous cells produce less power. When first installed, new modules produce about 25% more power than their rating; after several months they degrade down to their rated power output and no longer degrade appreciably.

Because of their low cost, amorphous modules are often the most suitable modules for applications of 20 watts and under.

*Other types of cells:* More research is being conducted into the development of cheaper and more efficient solar cells, and these technologies are expected to become important in future. *Tandem* cells utilise two or more types of amorphous films to collect a higher portion of the solar radiation than a single thin film. *Gallium arsenide* cells, which capture a wider portion of the solar spectrum and which operate more efficiently at high temperatures than silicon cells, may become important if more cheaply manufactured.

### Solar Cell Modules and Arrays

Solar cells vary in size and can be used according to the task at hand. No matter the task, though, all silicon-type solar cells generate a potential difference of about 0.4 volts in normal operation. For this reason, solar cells are connected in series to bring the voltage up to a useful level. Five cells in series are enough to power a calculator

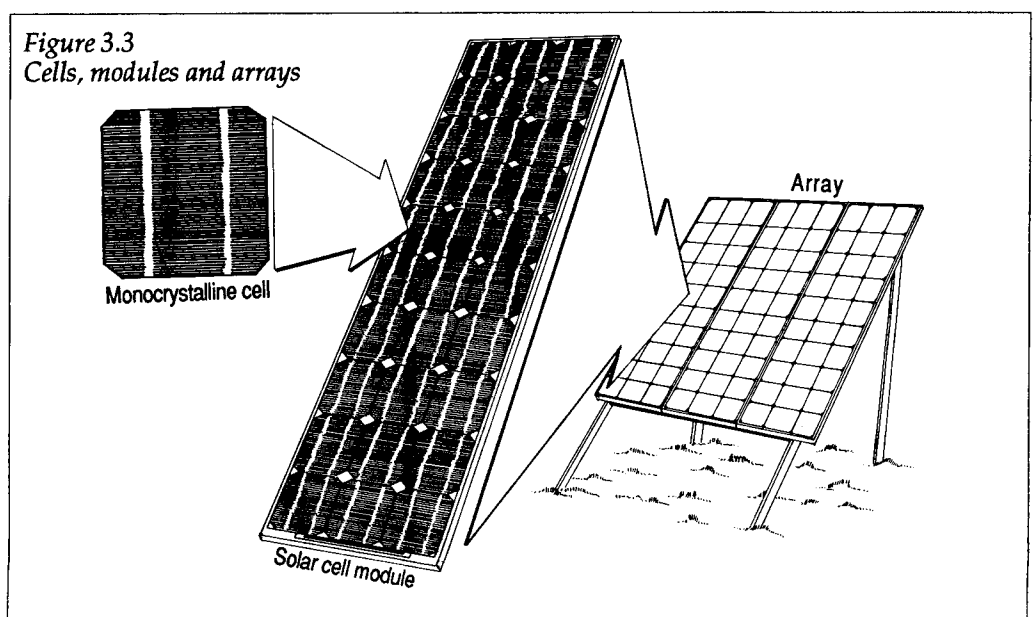
of two volts, and 30-36 cells are enough to charge a 12 volt battery.

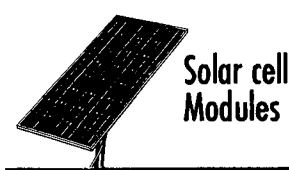
The current produced by a solar cell depends on its size and type. A 10 cm square monocrystalline cell produces a current of about 3.5 amps under *Standard Test Conditions (STC)* of 1000 W/m<sup>2</sup> solar irradiance at 25°C and an air mass of 1.5 (air mass tells how much radiation is absorbed by the atmosphere). Standard test conditions are a set of guidelines commonly used by manufacturers to compare solar cell modules of different types, but modules usually produce *less* power under actual working conditions.

As mentioned before, it is usually not convenient to use single solar cells because their output does not match the load demand. For example, one cell cannot power a radio if the radio requires current at three volts and the cell produces a voltage of only 0.4 V. Thus solar cells are arranged in series to increase voltage. Furthermore, solar cells are fragile, so they must be protected from breakage and corrosion. For these reasons, groups of solar cells are usually sold to consumers in framed glass and plastic units called *solar cell modules*.

**From Solar Cells to Solar Cell Modules**  
Arrangements of many solar cells wired in series, sealed between glass and plastic, and supported inside a metal frame are called *solar cell modules*.

Solar cells are connected in series to increase the voltage. Arrangements of many solar cells wired in series, sealed between glass and plastic, and supported inside a metal frame are called solar cell modules. Groups of modules mounted together are called arrays.





The process of making solar cell modules from mono and polycrystalline silicon cells involves several steps. Once properly prepared and treated with anti-reflection coatings, solar cells are soldered together in series (i.e. the front of one cell is connected to the back of the next) and then mounted between glass and plastic. The process by which mono- or polycrystalline solar cells are sealed between glass and plastic is called *encapsulation*.

During encapsulation, the cells are sealed at high temperature between layers of plastic (a special type called *EVA plastic*) and glass in such a manner that air or water cannot enter and corrode the cells. Modules are then cased in metal or plastic frames to protect their edges and to protect them from twisting. The frame may have holes drilled in it for easy mounting, and a connection point for earthing cables.

Electric contacts are fixed onto the back of the module. These will either be two terminal screws or two wires. With some modules, the terminals are enclosed in a junction box. The negative terminal, usually black in colour, is connected to the negative terminal on the charge controller or battery. Likewise, the positive terminal, usually red in colour, is fixed by a length of wire to the positive terminal on the control or battery. Some modules are wired so that their voltage can be adjusted to either 6 or 12 volts.

#### Module Ratings

All solar cell modules are rated according to their maximum output, or *peak power*. The *peak power*, abbreviated *Wp*, is defined as the amount of power a solar cell module can be expected to deliver at noon on a sunny day when it is facing directly towards the sun at STC (i.e. Standard Test Conditions, which are 1000 W/m<sup>2</sup> of solar irradiance, a temperature of 25°C, and an air mass of 1.5). The module's power rating in peak watts should be specified on the module by the manufacturer or dealer.

By counting the number of cells in a module, it is possible to estimate its voltage. Solar cell modules are available in several voltages and power ratings. For charging 12 volt car batteries, modules usually have between 30 and 36 solar cells wired in series. With good solar insolation, a 40 Wp module with between 33 and 36 cells can harvest enough electricity to power the

lights and small appliances (*but not cookers!*) in a typical East African rural household.

#### Arrays

Often, a number of modules are required to meet the power requirements at a site. When mounted together, groups of modules are referred to as *arrays* (see Figure 3.3). Solar water pumps and solar refrigerators typically require large arrays of modules for their operation.

#### Output of Solar Cell Modules

The power output of a module depends on the number of cells in the module, the type of cells, and the total surface area of the cells.

The output of a module changes depending on:

- the amount of solar radiation,
- the angle of the module with respect to the sun,
- the temperature of the module, and
- the voltage at which the load (or battery) is drawing power from the module.

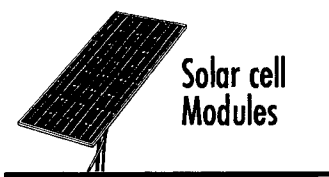
#### The I-V Curve

Each solar cell and module has its own particular set of operating characteristics. These properties can be described by the current - voltage curve, which is better known as the *I-V curve*. I-V curves are used to compare various solar cell modules, and to determine their performance at various levels of insolation and temperatures.

Figure 3.4 shows an I-V curve for a 42 Wp module. The left-hand side (I) gives the current of the module produced depending on voltage. The bottom side gives the voltage produced by the module at various currents. At each point along the line, it is possible to determine the power of the module for particular conditions. For example, imagine that a battery is being charged by a module, and that it has reached 12.0 volts (Point A). The current from the module is 3.2 amps at Point A and the power output is 38.4 watts (amps x volts = power, so 12.0 V x 3.2 A = 38.4 watts).

The shaded portion of Figure 3.4 shows the

The peak power rating of a module (*Wp*) is the amount of electric power it will produce at noon on a sunny day when it is facing directly towards the sun, under standard test conditions.



Solar cell Modules

It is advisable to operate a module as near to the maximum power point as possible.

voltage boundaries within which a lead-acid battery is charged. Note that as the battery gets fully charged, the charging current begins to decrease.

There are several points of interest about the I-V curve in Figure 3.4:

- $I_{sc}$ , the short circuit current, is the point where the curve crosses 0 volts (Point B). This is the maximum current that the module is capable of producing.
- $V_{oc}$ , the open circuit voltage, is the point where the curve crosses 0 amps (Point C). This is the maximum voltage that the module can produce on a sunny day.
- $P_m$ , the maximum power point, is the point on the I-V curve where the module produces the greatest power (its

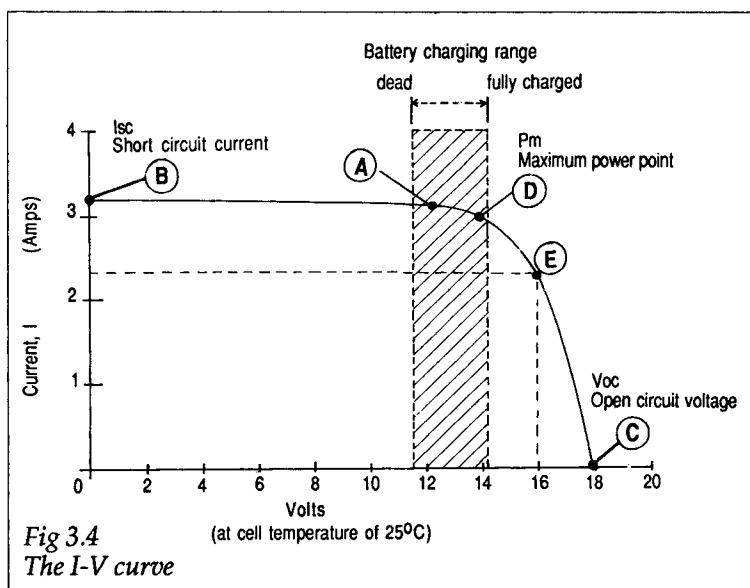
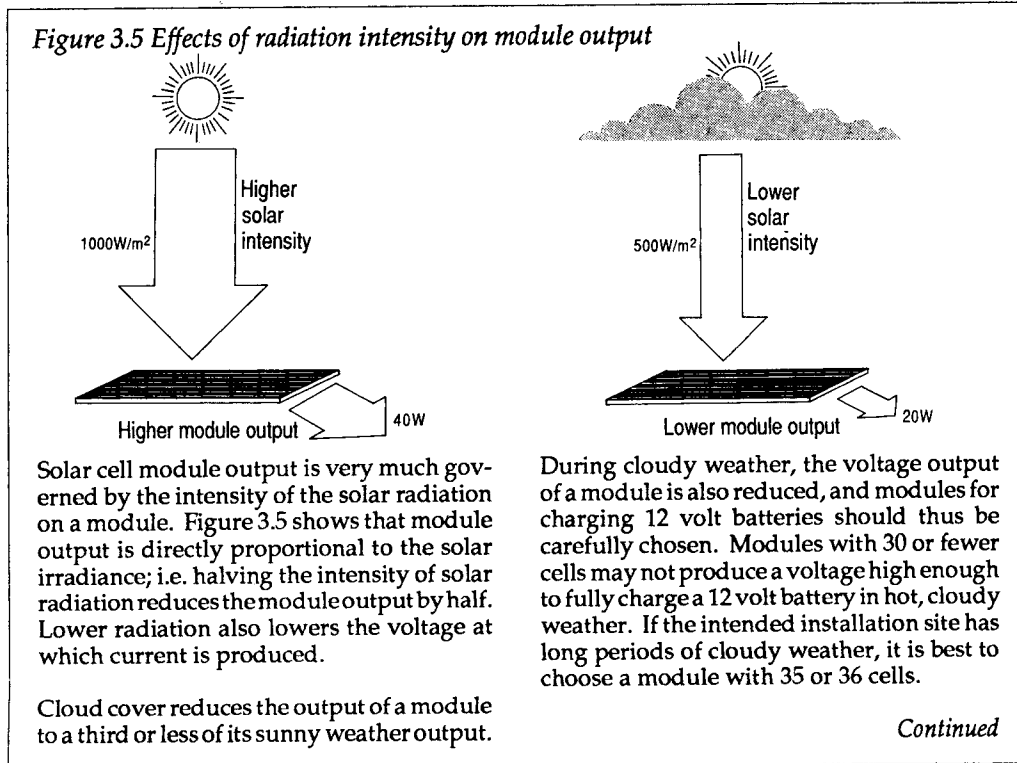
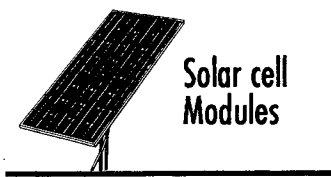


Fig 3.4  
The I-V curve

rated maximum, in this case 42W). The maximum power point is always found at the place where the curve begins to bend steeply downward (i.e. at the knee, Point D). It is advisable to operate a module as near to the maximum power point as possible. If, for example, the module in Figure 3.4 is operating a load that demands 16 volts (Point E), power output (at 36 watts) is much less than that at the maximum power at Point D.



While operating, modules are typically 20°C warmer than the peak ambient temperature.



Solar cell Modules

Halving the intensity of the solar radiation reduces module power output by half.

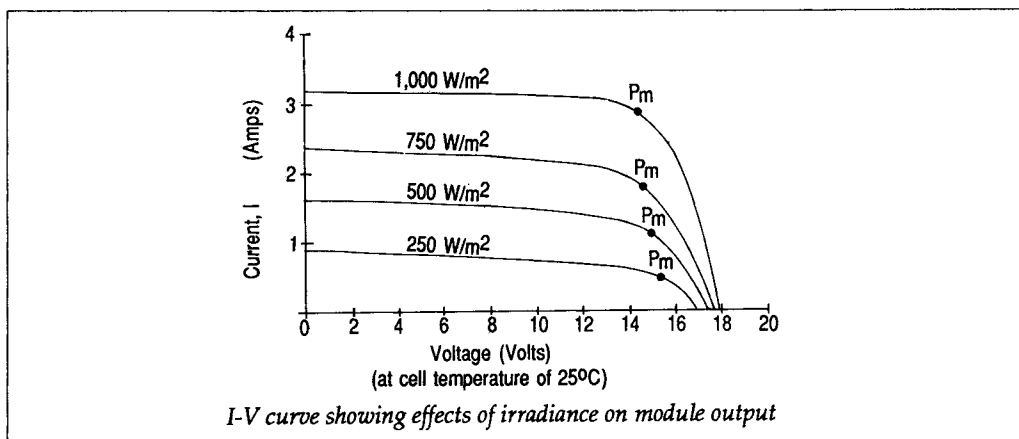
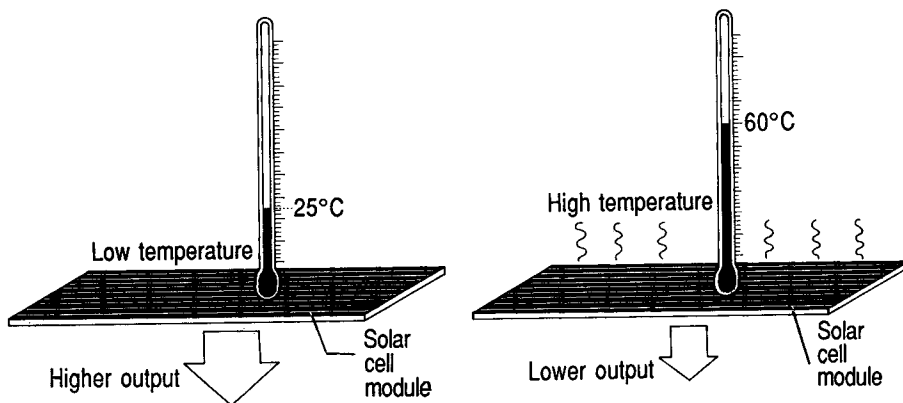


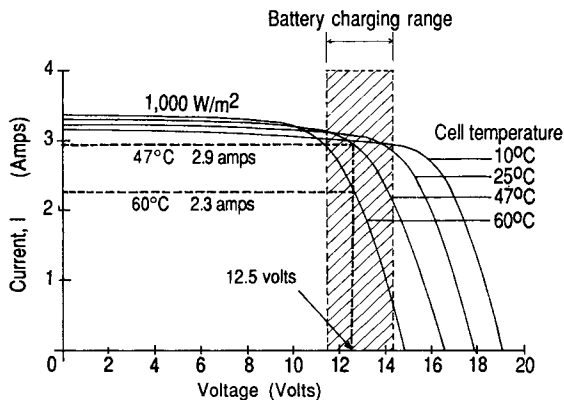
Figure 3.6 Effects of temperature on module output

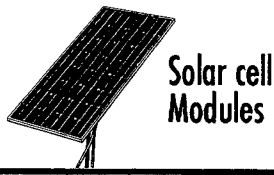


As mentioned previously, solar electric devices are quite different from solar heating devices. Whereas solar water heaters function well when hot, the output of solar cells decreases as they get hotter.

As the temperature increases, power output of monocrystalline solar cells falls by 0.5 % per degree centigrade (this is shown by the I-V curve in Figure 3.6). Thus, a 5 degree rise in temperature will cause a 2.5% drop in power output. In strong sunlight, solar cell

modules may be 20°C warmer than the thermometer temperature. Furthermore, the temperature on *mabati* roof tops may reach as high as 60°C, meaning that the output of the module placed directly on *mabati* may be 15% or more below its rated output. For this reason, installers are encouraged to mount modules on poles, on structures above the roof, or in places where they are cooled by wind so that their output remains as high as possible.





Shading a single cell of a module will considerably lower its output.

### Effects of Shading on Module Output

Obviously, if a shadow falls across all or part of a module, its electric output will be reduced. In fact, even shading a *single cell* will considerably lower a module's output and possibly damage it. Damage occurs because the cells in a module are connected in series, and they each must

carry the same current. When one cell (or more) is shaded, it stops producing current and instead *consumes current*, converting it to heat. If a single cell is shaded for a long time, it may cause the entire module to fail. Even a single tree branch, a weed or a bird's nest could shade one cell and cause electrical production to fall dramatically.

### How Much Energy Does a Solar Module Produce?

The maximum amount of energy that a solar module produces per day in equatorial locations can be roughly estimated by multiplying the *peak power rating* of the module (in Wp, see page 20) by the number of peak sun hours received by the module over the course of the day (for details on peak sun hours see page 12). The actual energy output will be less, depending on how near to the peak power point the module is operated.

Maximum energy produced by a module (in watt hours per day)	≈	Peak power rating of module x peak sun hours at site (in Wp)
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*Example: Solar module output:  
Kisumu in January*

A Siemens M-55 module has a rated power of 53 Wp. Using meteorological records, the maximum daily energy output of such a module mounted flat in Kisumu can be

predicted. Figure 2.6 on page 12 shows that, in January, the expected daily insolation is about 6.5 kWh/m<sup>2</sup>. Following the above equation, the energy produced by the module can be calculated:

Maximum energy produced by module (in watt hours per day)	=	53 Wp x 6.5 peak sun hours
	=	345 watt hours

**Note:** A more accurate method of estimating power output is described on page 61.

This is enough energy to run a 15 watt television for 23 hours, or to run two 8 watt fluorescent tube lamps for about the same amount of time. However, this is not enough energy to run a 1500 watt cooker for more than a few minutes.

### Choosing Solar Cell Modules

Modules should be chosen according to the energy requirements of the system load. Information on calculating the system load and planning systems is given in Chapters 7 and 9. Table 3.1 gives details on three types of modules available in East Africa.

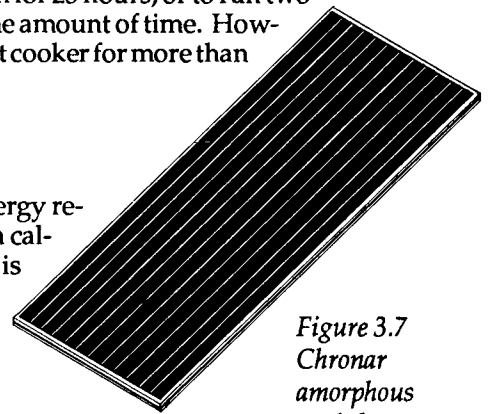


Figure 3.7  
Chronar  
amorphous  
module

Modules should be chosen according to the energy requirements of the system load.

Table 3.1: Features of Three Modules Available in East Africa

MODULE	CHRONAR CSA 13 E	SOLAREX MSX - 30	SIEMENS (ARCO) M-65
Peak Power (Wp)	12 Wp	30 Wp	42 Wp
Type of cells	Amorphous	Polycrystalline	Monocrystalline
Current at Peak Power (I <sub>p</sub> )	0.72 amps	1.75 amps	2.90 amps
Short Circuit Current (I <sub>sc</sub> )	1.08	n/a	3.3 amps
Open Circuit Voltage (V <sub>oc</sub> )	24.0	n/a	18.0 volts
Overall Module Efficiency	4%	10%	12%
Number of Cells	30	36	30