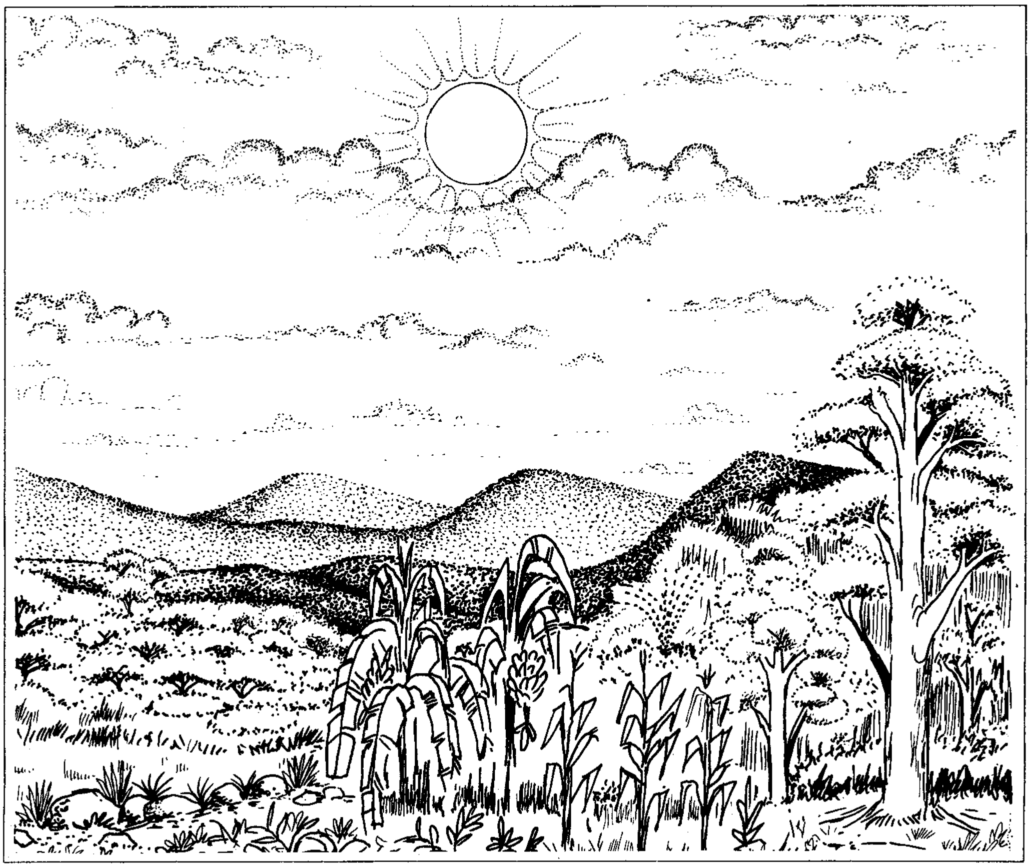
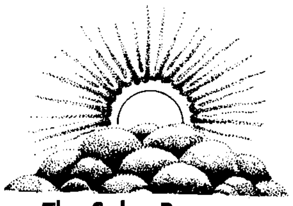
Chapter 2
The Solar Resource

This chapter explains applications and basic principles of solar energy. The theory of diffuse and direct solar radiation, irradiance, and insolation are discussed (as well as the terms kilowatt hours, peak sun hours and langleys). Estimation of energy available at a given site using meteorological records and local knowledge is outlined. Tracking the sun to increase energy output is examined.

Solar cell modules harvest energy from the sun. Their output depends on the amount of sunlight (or *solar radiation*) falling on them. When planning or using a system, you should consider seasonal and daily solar radiation changes. The output of a solar module changes as the sun moves across the sky during the day, and as the angle of the sun changes with seasons. The output also changes depending on how cloudy and how dusty the site is.





Tapping Solar Energy

Solar energy is plentiful in Africa. Sunshine is useful for drying a variety of products including clothes, agricultural produce, cash crops, and bricks. Factories along the Indian Ocean coast have long made industrial use of energy from the sun in the production of salt.

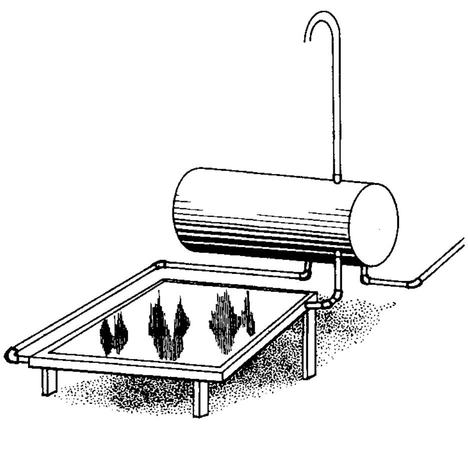
However, solar energy's potential in Africa has not been fully tapped. This is because, unlike energy sources such as petrol or charcoal, solar energy arrives in a spread-out manner that is difficult to trap, convert and store for useful purposes. In order to collect it, solar energy-harnessing equipment must be utilised. Through the use of such equipment, solar energy can generate electricity, provide industrial process heat, cook food or heat water.

As the prices of fuelwood, petroleum, electricity and dry cell batteries rise, solar energy harvesting devices are becoming more economically attractive

Solar energy has, until recently, been overlooked because of the high price of the equipment used to harvest it (in relation to the low cost of other sources of energy). However, as the prices of fuel, wood, grid electricity and dry cells rise, solar energy equipment is fast becoming more economically attractive. In East Africa today, solar water heaters and solar electric systems are increasingly popular because they are powered by freely-available sunshine.

Figure 2.1
Solar water heaters

Solar water heaters, which should not be confused with solar electric devices, consist of glass-covered panels with dark-coloured pipes inside. Water flows through the pipes, is warmed by the sun, and then stored in insulated tanks for use in washing and bathing. Solar water heaters are used in hospitals, schools, hotels and homes throughout East Africa, saving considerable amounts of money that would otherwise have been spent on wood, oil, or electricity.



Solar Radiation Principles

Solar Spectrum and Solar Constant

Sunshine arrives on the earth as a type of energy called *radiation*. Radiation is composed of millions of high energy particles called *photons*. This energy is easily converted into heat energy (objects placed in direct sunshine gain energy and become hot). It can also be converted into stored chemical energy (as plants do through photosynthesis) or it can be converted into electricity using solar cells.

Each unit of solar radiation, or *photon*, carries a certain amount of energy. Depending on the amount of energy that it carries, solar radiation falls into different categories including infrared (i.e. heat), visible (radiation that we can see) and ultraviolet radiation (very high-energy radiation). The *solar spectrum* describes all of these groups of radiation energy which are

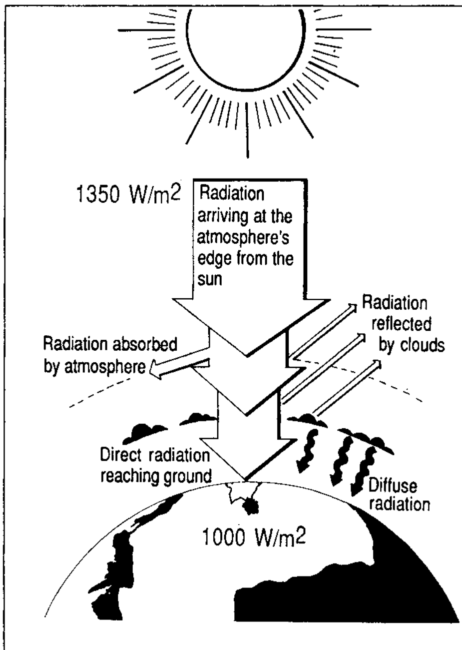


Figure 2.2
Absorption and reflection of solar radiation by the atmosphere

constantly arriving from the sun, and categorises them according to their wavelength. However, solar cells can only convert part of the solar spectrum to electricity and if, for example, a photon from the infrared category strikes a solar cell, its energy will be converted as heat and not electricity.

Solar energy arrives at the edge of the earth's atmosphere at the rate of about 1350 watts per square meter. This does not change throughout the year and is referred to as the *solar constant*. However, not all this energy reaches the earth's surface. The atmosphere absorbs and reflects much of it, and by the time it reaches the earth's surface, it is reduced to a maximum of about 1000 W/m^2 in tropical countries (see Figure 2.2). This means that when the sun is directly overhead on a sunny East African day, solar radiation is arriving at the rate of about 1000 W/m^2. Countries in high northern and southern latitudes receive much less radiation than countries located near the equator.

When the sun is directly overhead on a clear day in East Africa, solar radiation is arriving at the rate of about 1000 watts per square meter.

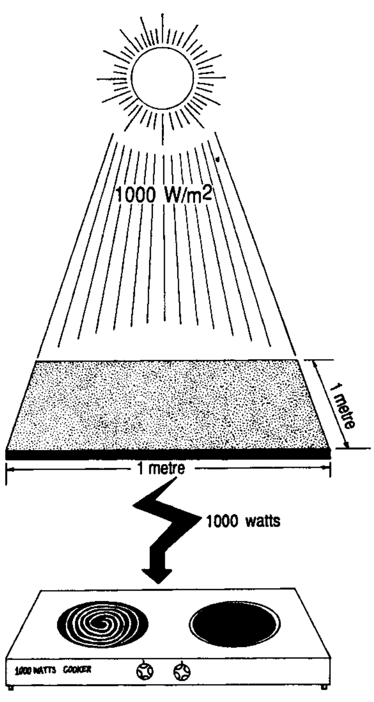


Figure 2.3
How much power is 1000 W/m^2 ?
If all the energy falling on one square metre at noon on a sunny day could be converted to electricity without losses, it would be enough to power a small electric cooker.

Direct and Diffuse Radiation

Solar radiation can be divided into two types: *direct* and *diffuse*. *Direct radiation* comes in a straight beam and can be focused with a lens or mirrors. *Diffuse radiation* has been scattered by clouds or dust. Clouds and dust absorb and scatter radiation, reducing the amount that reaches the ground. On a sunny day, most of the radiation is direct, but on a cloudy day, up to 100% of the radiation is diffuse. Together, direct and diffuse radiation are known as *global radiation*.

Radiation received on a surface in cloudy weather is reduced to one third or less compared to the amount received on a sunny day. It is therefore necessary to design systems that guarantee enough power in cloudy months, or to economise use of energy when it is cloudy.

Solar Irradiance

Solar irradiance refers to the solar radiation actually striking a surface, or the *power received per unit area* from the sun. This is

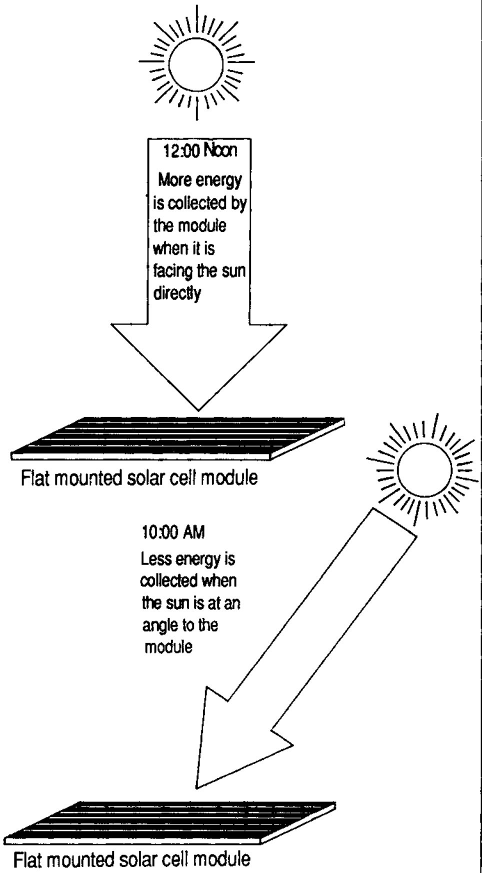
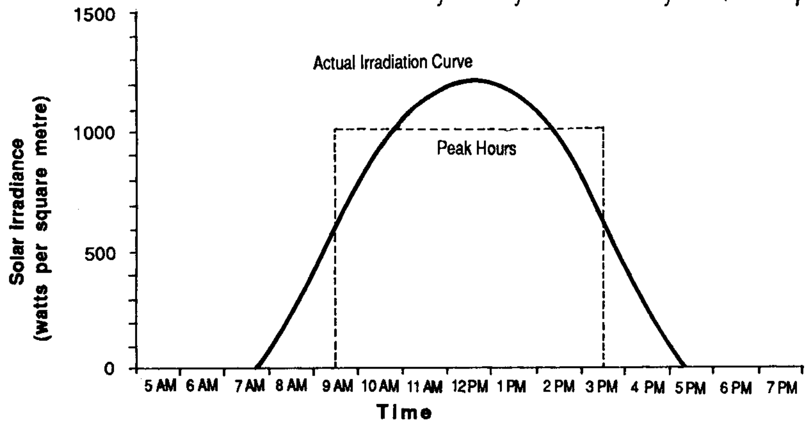


Figure 2.4
The angle between the module and the sun.

Figure 2.5
Solar irradiance received over time on a flat surface in East Africa (watts per square meter)



measured in *watts* or *kilowatts per square metre.* If a solar module is facing the sun directly (i.e. if the module is perpendicular to the sun's rays), *irradiance* will be much higher than if the module is at a large angle to the sun (see Figure 2.4).

Figure 2.5 shows the changes in the amount of power received on a flat surface during a clear day. In the morning and late afternoon, less power is received because the flat surface is not at an optimum angle to the sun and because there is less energy in the solar beam. At noon, the amount of power received is highest. The actual amount of power received at a given time varies with passing clouds and the amount of dust in the atmosphere.

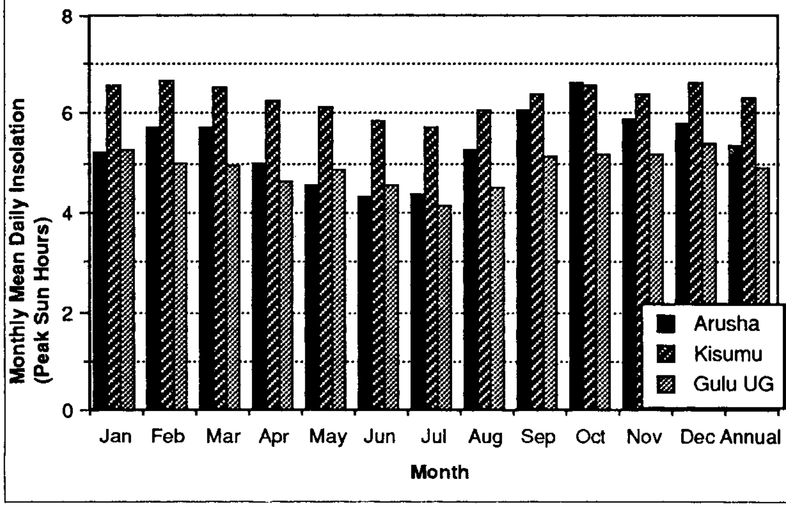
A site which receives six peak sun hours per day receives the same amount of energy that would have been received if the sun had shone for six hours with an intensity of 1000 watts per square metre.

The angle at which the solar beam strikes the surface is called the *solar incident angle.* The closer the solar incident angle is to 90 degrees, the more energy is received on the surface. If a solar module is turned to face the sun throughout the day, its energy output increases. This practice is called *tracking* (see page 15).

Insolation
Insolation (incident solar radiation) is a measure of the solar energy received on a specified area over a specified period of time. It is normally measured in *kilowatt hours per square metre per day (kWh/m² per day), peak sun hours per day* or *langleys per day.* Meteorological stations throughout East Africa keep records of monthly solar insolation which are useful in planning systems.

Kilowatt hours per square metre per day measures the amount of radiant energy collected at a site. It corresponds closely to *peak sun hours,* or the number of hours per day during which solar irradiance averages 1000 W/m² at the site. A site that receives six peak sun hours a day receives the same amount of energy that would have been received if the sun had shone for six hours at 1000 W/m². Actually, the

Figure 2.6 Mean daily insolation by month in three East African towns. The bar graph below compares solar energy availability by month in Arusha, Kisumu, and Gulu.



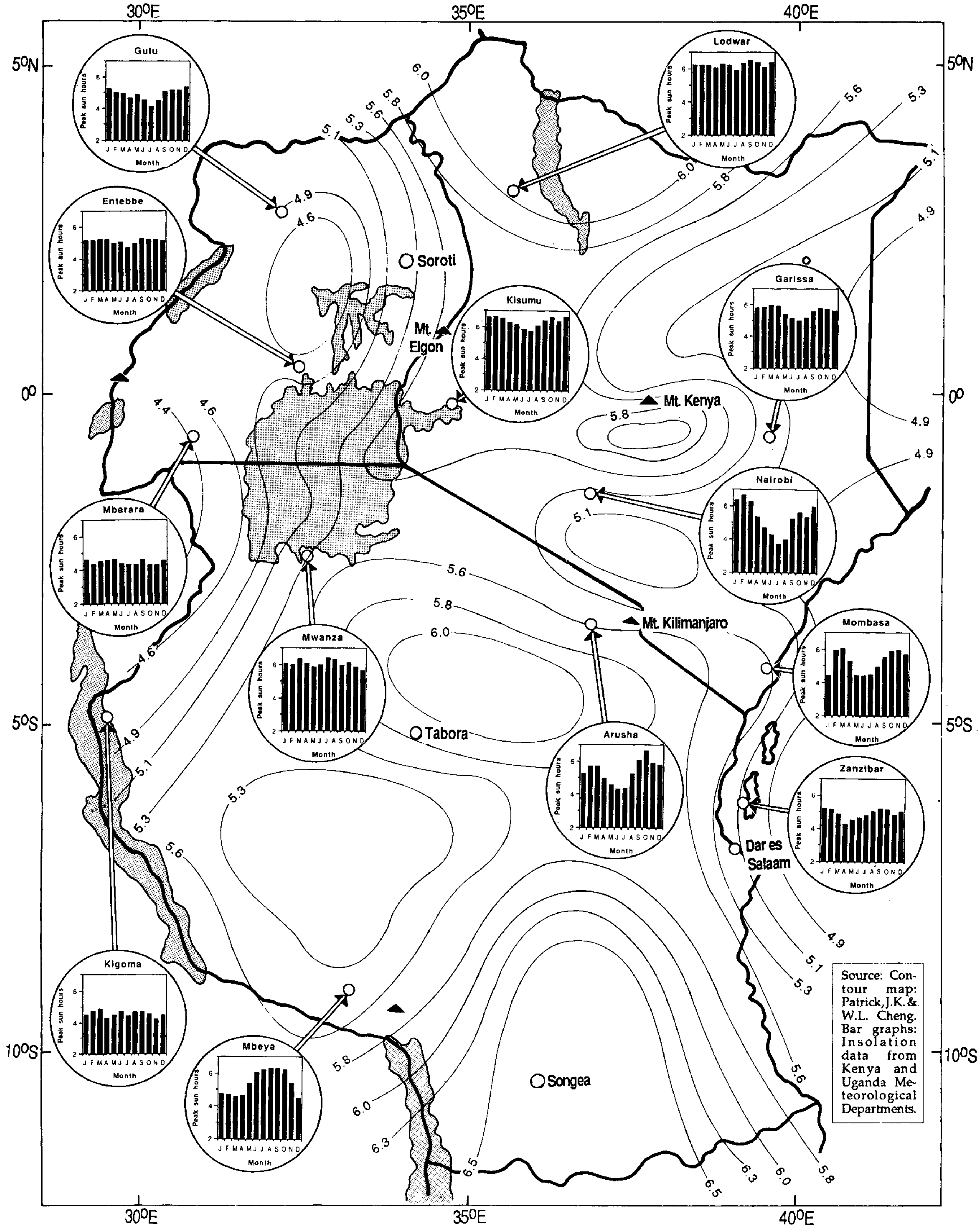


Figure 2.7
Insolation Contour Map of East Africa

This map is an overall depiction of the solar energy availability in East Africa. The contour lines give general indications of the annual mean daily insolation (in peak sun hours or kWh-m^{-2}) in various areas. To use the map, locate the place for which you need information and read the insolation value from the lines on either side. For example, the contours show that the southern areas of Tanzania have a very high annual mean daily insolation (above 6.5 peak sun hours), and that the south-western parts of Uganda have comparatively low levels (below 4.4). Note that the map gives a rough indication of insolation, and that local geographical factors may change actual insolation considerably. The bar graphs inside the circles show monthly mean daily insolation values for selected sites in the region. These graphs are useful for determining seasonal insolation values, and for determining the design month (see page 59). Note, for example, that Lodwar has a constant high level of radiation throughout the year, but that insolation levels change considerably in Nairobi and Arusha.

Peak sun hours

= the equivalent number of hours each day when solar irradiance averages 1000 watts per square metre.

= kilowatt hours per square metre per day of solar insolation

irradiance at such a site changes throughout the day. It is above 1000 W/m² for about three hours, above 800 W/m² (but below 1000 W/m²) for two hours, above 600 W/m² for two hours, above 400 W/m² for two hours and above 200 W/m² for two hours. Still, the energy is equivalent to six hours of irradiance at 1000 W/m² (see Figure 2.5). Peak sun hours are useful because they simplify calculations. They are commonly used when planning systems, and are used throughout this book as a measure of solar energy.

Figure 2.6 shows the mean daily insolation in peak sun hours for each month at three sites in East Africa. Note that the total amount of energy available per day changes considerably from month to month. On a sunny January day, Kisumu receives more than six peak sun hours of insolation. On a cloudy day in July, Arusha receives only 4 peak sun hours.

In East African meteorological stations, insolation is measured in *langleys per day* (calories per square centimetre per day). To convert *langleys* into *peak sun hours,* multiply langleys by 0.0116. For example, 430 langleys is about equal to 5 peak sun hours.

To convert langleys into peak sun hours (or kilowatt hours), multiply by 0.0116.

Using Meteorological Records

Using records kept at meteorological stations, you can estimate the amount of solar energy available in a given location. This information may be kept at the station itself, or at a government meteorological agency in the capital. The most useful information is the monthly mean daily insolation, but the monthly mean daily sunshine hours will be useful if the former is not available (see Table 2.1). Many meteorological stations keep records of monthly average daily insolation and daily sunshine hours.

Locations in East Africa receive between three and seven peak sun hours per day. The exact amount of insolation depends on the location and time of year. Figure 2.6 shows how insolation changes each month in three East African locations. It is difficult to accurately estimate the number of peak sun hours a site will receive on any given day. However, on a monthly basis, it is possible to predict insolation. If it was sunny last December and the December before that, it will probably be sunny this December as well.

Figure 2.7 shows a contour map of East African annual mean daily insolation (in peak hours) prepared by meteorologists. It gives an overall indication of solar energy distribution per year in the region. The circles show mean daily insolation per month in regional cities. However, different seasons and altitudes cause large local variations. For example, insolation is actually much less than shown on the map in the high altitude towns of Arusha, Tanzania and Meru, Kenya because of cloud caused by nearby mountains. If possible, the nearest meteorological station should be consulted when planning a system.

Monthly mean daily hours of sunshine. If records on solar insolation are not kept at a meteorological station, then check for the *monthly mean daily sunshine hours* (which is not the same as peak sun hours). This measures the number of hours each day when the sun is not blocked by clouds. Sunshine hours can be roughly converted into kilowatt hours per square metre (or peak sun hours)(see Table 2.1).

If there are no insolation records at all, then insolation can be very roughly estimated for a day or month using Table 2.1. During a very sunny month near the equator, for example, there would be between six and seven peak sun hours of insolation per day.

Use Table 2.1 to estimate peak sun hour values from mean daily sunshine hours.

Table 2.1: Approximate Peak Sun Hour Values

Site Weather Conditions	Mean Daily Sunshine Hours	Approximate Peak Sun Hours
Cloudy all day	4 or less hours of sunshine	4.5 or less peak sun hours
3-5 hours of cloud cover	4 - 6 hours	4.5 - 5.5 peak sun hours
1-3 hours of cloud cover	6 - 8 hours	5.5 - 6.5 peak sun hours
Completely clear all day	8 hours or more	6.0 or more peak sun hours

Tracking the Sun

Although a module will collect the most energy when facing the sun directly, the sun is not always overhead. As Figure 2.8 shows, between morning and afternoon the sun's position relative to a fixed solar module changes from 90° on one side to 90° on the other side. During the year, the sun changes its angle with respect to a fixed solar module at the equator as well. In December the sun's path is 23.5° to the south, in March and September its path is directly overhead, and in June its path is 23.5° to the north.

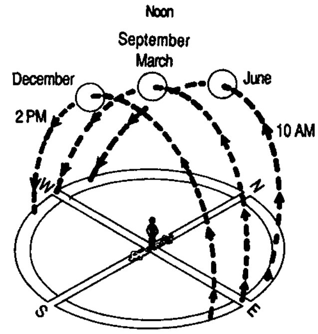


Figure 2.8
Daily and seasonal path of the sun relative to fixed position on the ground. The sun is shown at its noon position.

More solar power can be tapped if solar modules are turned to face the sun directly throughout the day. Turning the modules to follow the sun's movements is called *tracking*.

Manually-operated tracking mounts are used in Kenya to gain an additional 20-30% more power over fixed mounts. The two designs shown in Figures 2.9 and 2.10 are locally-made tracking mounts for one-module home systems and multiple module systems. Both operate on the principle that a rotatable module tilted at 30° will optimally harvest sunshine at 10 AM and at 2 PM. They also effectively harvest sunshine during December and June. During cloudy weather, the module can be turned to face the sun when it appears from behind the clouds. Note that modules on tracking mounts will produce *less* energy than flat-mounted modules if the tracking mount is not properly operated.

A metal frame supported by a pipe holds solar cell modules at an angle of 30° from horizontal. The pipe is slipped inside a larger one which is cemented into a foundation. The frame holding the solar cell modules is free to rotate almost one full turn. With the cells at 30°, the frame can be rotated to make good use of the solar radiation any time of the day or any time of the year.

In practice, both mounts are rotated to face the 10 AM sun in the morning and again at noon to face the 2 PM sun in the afternoon. This simple operation increases the available energy in the system by more than 25% on a clear day. In addition, the rotatable mount can be used to harvest high value sunlight when the sun appears from behind the clouds on sunny days. This type of mount can significantly increase the amount of power available from a group of solar cell modules in locations within 15° to either side of the Equator.

Figure 2.9: Manually-operated solar cell module mount for arrays of 2-6 modules (designed by Harold Burris).

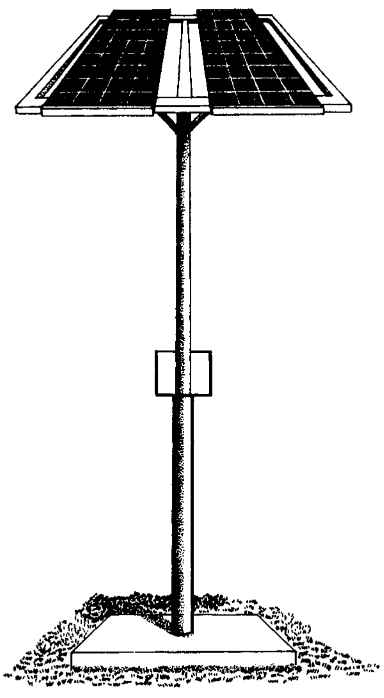


Fig 2.10 Rotatable pole mount for single modules