CHAPTER ONE
CHAPTER 1
INTRODUCTION

1.1 RENEWABLE ENERGY

Energy sources that derive our world could be broadly categorized as a Non Renewable and Renewable energy sources. Non Renewable energy sources include fossil fuels like coal, oil and natural gas. However there is a continuous process of generation of fossil fuels but rate of consumption is much higher than the rate of creation and therefore these fossil fuels are considered as a nonrenewable. Among the fossil fuels radioactive substances have some special character. It is estimated that Uranium will lost in next hundred years but because of breeder reactor it may go much more. Nuclear wastes present major threat to environment.

Renewable energy sources are those sources which lost forever and also environment friendly. Renewable energy sources includes solar, water, wind and tidal energies.

1.2 NEED FOR RENEWABLE ENERGY

Increasing rate of energy consumption is essential for progress of our civilization and therefore main problem is how we produce energy. Extensive use of fossil fuels and nuclear energy has created bad impact on environment, social and sustainability problem. So we need such energy sources that will forever and can be used with out pollution.

To day fossil fuels such as coal, oil and natural gas account for 90percent of total energy supply. The following table presents annual world primary energy consumption in 1992 [1]
Fuel Source Consumption in $10^{18}$J Consumption in mtoe
---
Oil 131 3128
Coal 91 2164
Natural Gas 75 1781
Biomass 55 1310
Hydro 24 561
Nuclear 22 532
TOTAL 398 9478

Energy consumption in developed and developing countries

<table>
<thead>
<tr>
<th>Year</th>
<th>Population (billion)</th>
<th>Total energy use (EJ/Year)</th>
<th>Per capita energy use (GJ/Year)</th>
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</thead>
<tbody>
<tr>
<td>1990 developed countries</td>
<td>1.2</td>
<td>284</td>
<td>237</td>
</tr>
<tr>
<td>1990 developing countries</td>
<td>4.1</td>
<td>142</td>
<td>35</td>
</tr>
<tr>
<td>1990 World</td>
<td>5.3</td>
<td>426</td>
<td>80</td>
</tr>
</tbody>
</table>

According to the United States Department of Energy (US DOE) [2] outlook of energy use throughout the world continues to show strong prospects for rising levels of consumption over the next two decades, led by growing demand for end use energy in Asia. World Energy demands in 2015 is projected to reach by 562 quadrillion British thermal units (Btu). The expected increment in total energy
demand between 1995 and 2015—almost 200 quadrillion Btu—would match total world energy consumption recorded in 1970, just before the energy crisis of 1973. Two-thirds of all energy growth will occur in developing economies and economies in transition with much of that growth concentrated in Asia. Per capita energy use in the world’s industrialized economies, which far exceeds the levels in newly emerging economies is expected to change only moderately in the next two decades. In some emerging economies (India and China) per capita energy use may double. Even with such growth, however, average per capita energy use in developing countries will still be less than one fifth of average of the industrialized countries in 2015. In the longer term consumption of oil as a principal source of commercial energy today, will start to decline after transitional phase (between 2020 and 2060). It is expected that natural gas will continue to be used as long as price and availability are satisfactory but as reserve reduces or price rises coal (which is usually less expensive than natural gas and its international prices are unlikely to rise) will command a greater portion of market. To maintain energy levels and because of world-wide environmental concerns some experts predicts that coal will have to be utilized cleanly, where gasification process will be most environmentally friendly way of its future utilization.

Most important environmental impacts by energy sources are global climate change and acid rain—both of which have the origin in the combustion of fossil fuels and leads to global or transboundary effects. During the last few decades, concerns has been growing internationally that increasing concentrations of greenhouse gases in the atmosphere will change our climate in ways detrimental to our social and economic well-being. Abundant data demonstrate [3-4]that global climate has warmed during the past 150 years. The majority of scientists now believe that global
warming is taking place at a rate of around 0.3 °C per decade and that is caused by increasing concentration of so-called greenhouse gases (CO₂ and CH₄ as a major component) in the atmosphere. Another source of global climate change is global deforestation because of biomass burning to meet energy requirements. Official confirmation of global climate change came in 1995, when the UN Intergovernmental Panel on Climate Change (IPCC) an officially appointed international panel of over 2500 of the world's leading scientific expert found that “... the balance of the evidences suggests a human influence on the global climate change.” IPCC estimates that air temperature will increase by another 1-3.5 °C, and sea levels may rise by to 1.0 meter over the next 100 years. This change will affect many aspects of our lives.

Here are some of them:

- More people will die from heat stress
- Tropical diseases will spread
- Rising sea level will destroy essential habitats and leaving coastal areas more prone to flooding.
- The water cycle will disrupt
- Food crops yield will disrupted
- Endangered species will suffer
- Coral reefs will be harmed
- Acid rain will be a common phenomenon across the entire world leaving damage to soil and trees, destruction of buildings, destroying sweet water of lakes.
- Bad air quality
- Sea pollution caused by transport of oils
- Non Renewable energy have some political and economical problems that some times resulted in war like Gulf war. Non renewable sources are centralized and
therefore easy targets for terrorist. There are security threat if nuclear proliferation could not be stopped. Job opportunities are limited in nonrenewable source.

Fortunately the solution exist. The transition to sustainable energy system requires that share of renewable energy sources will continually grow. Renewable combined with a system of new technologies, can contribute to a considerable extent to energy requirements in the time horizon beyond 2020. Reports for the UN Solar Energy Group for Environment and Development suggest that using technology already on the market or at the advanced engineering testing stage, by the middle of the next century, renewable energy sources could account for 60 percent of the world’s electricity market and 40 percent of the market for fuels used directly.

Renewable energy systems use resources that are constantly replaced and are usually less polluting [5]. All renewable energy sources – solar energy, hydro power, biomass and wind energy have their origin in activity of the sun. Geothermal energy which, because of its inexhaustible potential, is sometimes considered as renewable source is getting energy from the heat of the earth. Renewable energy is a domestic resource which has the potential to contribute to or provide complete security of energy supply. Countries that depend on imports of fossil fuel resources are in danger due to the risk of sharp rise of the cost of imported energy (mainly oil). This is particularly so for in developing countries, where the oil import bill adds every year to the problem of financing an already large external deficit.

Renewables are virtually uninterruptible and is of infinite availability because of its wide spread of complementary technologies - thus fitting well into a policy of diversification of energy supplies. Renewable resources are well-recognized as a good
way to protect the economy against price fluctuations and against future environmental costs. Technologies based on renewables are largely pollution-free and makes zero or little contribution to the greenhouse effect with its predicted drastic climatic changes. In addition, they produce no nuclear waste and are thus consistent with environmental protection policies, building towards a better environment and sustainable development.

The shape of our future will be largely determined by how we generate and apply technological innovation the most powerful force for progress in the modern world. The renewable energy sources are able to have a strong transformative effect on the whole of society in the coming decades [6]. By virtually all accounts, renewable energy resources will be an increasingly important part of the power generation mix over the next several decades. Not only do these technologies help reduce global carbon emissions, but they also add some much-needed flexibility to the energy resource mix by decreasing our dependence on limited reserves of fossil fuels. Experts agree that hydropower and biomass will continue to dominate the renewables arena for some time.

However, the rising stars of the renewable world - wind power and photovoltaics [7] are on track to become strong players in the energy market of the next century. Wind power [8] is the fastest-growing electricity technology currently available. Wind-generated electricity is already competitive with fossil-fuel based electricity in some locations, and installed wind power capacity now exceeds 10,000 MW world-wide. Meanwhile, photovoltaics electricity - although currently three to four times the cost of conventional, delivered electricity - is seeing impressive growth world-wide. Photovoltaics is particularly attractive for applications not served by the
power grid. Advanced thin-film technology (a much less expensive option than crystalline silicon technology) is rapidly entering commercial-scale production. Perhaps even more promising than the technical developments in renewables are the resounding endorsements from major energy companies like Enron, Shell, and British Petroleum, which have invested heavily in photovoltaics and wind energy in recent years and are planning significant increases in these and other renewable efforts [9-10].

The energy-starved developing world, which accounts for a large portion of the projected new electricity demand over the next 20 years, is considered one of the biggest markets for renewables [11]. Many of these countries are attracted to the modular nature of renewable energy technologies, which can be located close to the users. The renewable technologies are far cheaper and quicker to install than central-station power plants and their extensive lengths of transmission line. Renewables are also gaining favour in industrialized countries. In the USA, national surveys show that well over half of consumers are willing to pay more for green power, and a number of power companies are now offering this option. In Europe, strong public support for clean energy is causing the renewable’s market to expand rapidly. In 1997, the European Commission released a white paper on renewable sources of energy, in which it noted that renewables are unevenly and insufficiently exploited in the European Union. Contributing less than 6 percent to the European Union’s energy consumption, it called for a joint effort to increase this level for export potential and to address climate change. More than half of Europe’s energy is imported, and will rise to 70 percent by 2020 without action. Different scenarios [12] show the contribution of renewables by 2010 to a range from 9.9 percent to 12.5 percent, but a goal of 12 percent renewables share (“an ambitious but realistic
objective") was set, to be achieved through the installation of one million PV roofs, 15,000 MW of wind and 1,000 MW of biomass energy. The current 6 percent share includes large-scale hydro, which will not expand for environmental reasons. Growth is expected [13] from biomass, followed by 40 GW of wind and 100 million square meters of solar thermal collectors. Photovoltaics will grow up 3 GWp, geothermal by 1 GWe and heat pumps by 2.5 GWth. Total capital investment to achieve the 12 percent target will be 165 billion ECU (1997-2010), but it would create up to 900,000 new jobs and drop CO2 emissions by 402 million tonnes/a. The European Wind Energy Association estimates up to 320,000 jobs would be created if 40 GW of wind power is installed, the PV Industry Association says it would create 100,000 jobs if 3 GWp is met, the Solar Industry Federation estimates 250,000 jobs under its market objective, and another 350,000 jobs could be created to meet the export market. The white paper proposes a number of tax incentives and other fiscal measures to encourage investments in renewable energies, and measures to encourage passive solar. “The overall objective of doubling the current share of renewables to 12 percent by 2010 can be realistically achieved,” it concludes, and the contribution of renewables to electricity generation could grow from 14 percent to more than 23 percent by 2010 if appropriate measures are instituted. Job creation is one of the most important features related to the development of renewable energy sources.

1.3 SOLAR ENERGY AND RADIATION

Solar energy runs the engines of the earth. It heats its atmosphere and its lands, generates its winds, drives the water cycle, warms its oceans, grows its plants, feeds
its animals, and even (over the long haul) produces its fossil fuels. This energy can be converted into heat and cold, driving force and electricity.

Solar radiation is electromagnetic radiation in the 0.28...3.0 µm wavelength range. The solar spectrum includes a small share of ultraviolet radiation (0.28...0.38 µm) which is invisible to our eyes and comprises about 2 percent of the solar spectrum, the visible light which range from 0.38 to 0.78 µm and accounts for around 49 percent of the spectrum and finally of infrared radiation with long wavelength (0.78...3.0 µm), which makes up most of the remaining 49 percent of the solar spectrum [14].

The sun generates an enormous amount of energy - approximately $1.1 \times 10^{20}$ kilowatt-hours every second. (A kilowatt-hour is the amount of energy needed to power a 100 watt light bulb for ten hours.) The earth's outer atmosphere intercepts about one two-billionth of the energy generated by the sun, or about 1500 quadrillion ($1.5 \times 10^{18}$ ) kilowatt-hours per year. Because of reflection, scattering, and absorption by gases and aerosols in the atmosphere, however, only 47 percent of this, or approximately 700 quadrillion ($7 \times 10^{17}$ ) kilowatt-hours, reaches the surface of the earth.

In the earth's atmosphere, solar radiation is received directly (direct radiation) and by diffusion in air, dust, water, etc., contained in the atmosphere (diffuse radiation). The sum of the two is referred to as global radiation. The amount of incident energy per unit area and day depends on a number of factors, latitude, local climate, season of the year, inclination of the collecting surface in the direction of the sun.
The solar energy varies because of the relative motion of the sun. These variation depend on the time of day and the season. In general, more solar radiation is present during midday than during either the early morning or late afternoon. At midday, the sun is positioned high in the sky and the path of the sun’s rays through the earth’s atmosphere is shortened. Consequently, less solar radiation is scattered or absorbed, and more solar radiation reaches the earth’s surface.

The amounts of solar energy arriving at the earth’s surface vary over the year, from an average of less than 0.8 kWh/m² per day during winter in the North of Europe to more than 4 kWh/m² per day during summer in this region. The difference is decreasing for the regions closer to the equator. The availability of solar energy varies with geographical location of site and is the highest in regions closest to the equator. Thus the average annual global radiation impinging on a horizontal surface which amounts to approx. 1000 kWh/m² in Central Europe, Central Asia, and Canada reach approx. 1700 kWh/m² in the Mediterranean and to approx. 2200 kWh/m² in most equatorial regions in African, Oriental, and Australian desert areas. In general, seasonal and geographical differences in irradiation are considerable and must be taken into account for all solar energy applications.

The amount of solar radiation reaching the earth’s surface varies greatly because of changing atmospheric conditions and the changing position of the sun, both during the day and throughout the year [15]. Clouds are the predominant atmospheric condition that determines the amount of solar radiation that reaches the earth. Consequently, regions of the nation with cloudy climates receive less solar radiation than the cloud-free desert climates. For any given location, the solar radiation reaching the earth’s surface decreases with increasing cloud covers. Local
geographical features, such as mountains, oceans, and large lakes, influence the formation of clouds; therefore, the amount of solar radiation received for these areas may be different from that received by adjacent land areas. For example, mountains may receive less solar radiation than adjacent foothills and plains located a short distance away. Winds blowing against mountains force some of the air to rise, and clouds formed from the moisture in the air as it cools. Coastlines may also receive a different amount of solar radiation than areas further inland.

The solar energy which is available during the day varies and depends strongly on the local sky conditions. At noon in clear sky conditions, the global solar irradiation can in be for e.g. in Central Europe it reaches 1000 W/m² on a horizontal surface (under very favourable conditions, even higher levels can occur) whilst in very cloudy weather, it may fall to less than 100 W/m² even at midday.

Both man-made and naturally occurring events can limit the amount of solar radiation at the earth’s surface. Urban air pollution, smoke from forest fires, and airborne ash resulting from volcanic activity reduce the solar resource by increasing the scattering and absorption of solar radiation. This has a larger impact on radiation coming in a direct line from the sun (direct radiation) than on the total (global) solar radiation. On a day with severely polluted air (smog alert), the direct solar radiation can be reduced by 40 percent, whereas the global solar radiation is reduced by 15 percent to 25 percent. A large volcanic eruption may decrease, over a large portion of the earth, the direct solar radiation by 20 percent and the global solar radiation by nearly 10 percent for 6 months to 2 years. As the volcanic ash falls out of the atmosphere, the effect is diminished, but complete removal of the ash may take several years.
Solar radiation provides us at zero cost with 10,000 times more energy than is actually used worldwide. All people of the world buy, trade, and sell a little less than 85 trillion \(8.5 \times 10^{13}\) kilowatt-hours of energy per year. But that's just the commercial market. Because we have no way to keep track of it, we are not sure how much non-commercial energy people consume: how much wood and manure people may gather and burn, for example; how much water individuals, small groups, or businesses may use to provide mechanical or electrical energy. Some think that such non-commercial energy may constitute as much as a fifth of all energy consumed. But even if this were the case, the total energy consumed by the people of the world would still be only about one seven-thousandth of the solar energy striking the earth’s surface per year [17].

In some developed countries like in the United States people consume roughly 25 trillion \(2.5 \times 10^{13}\) kilowatt-hours per year. This translates to more than 260 kilowatt-hours per person per day - this is the equivalent of running more than one hundred 100 watt bulbs all day, every day. U.S. citizen consumes 33 times as much energy as the average person from India, 13 times as much as the average Chinese, two and a half times as much as the average Japanese, and twice as much as the average Swede.

Even in such heavy energy consuming countries like USA solar energy falling on the land mass can many times surplus the energy consumed there. If only 1 percent of land would be set aside and covered by solar systems (such as solar cells or solar thermal troughs) that were only 10 percent efficient, the sunshine falling on these systems could supply this nation with all the energy it needed. The same is true for all other developed countries. In a certain sense, it is impractical - besides being extremely expensive, it is not possible to cover such large areas with solar systems.
The damage to ecosystems might be dramatic. But the principle remains. It is possible to cover the same total area in a dispersed manner - on buildings, on houses, along roadsides, on dedicated plots of land, etc. In another sense, it is practical. In many countries already more than 1 percent of land is dedicated to the mining, drilling, converting, generating, and transporting of energy. And the great majority of this energy is not renewable on a human scale and is far more harmful to the environment than solar systems would prove to be.

1.4 TERMS IN SOLAR ENERGY

The following terms are more frequently used in solar energy

1.41 Global, beam and diffuse radiations, irradiance and irradiation

**Beam radiation**

Solar radiation intercepted by a surface with negligible direction change and scattering in the atmosphere. It is also known as direct radiation.

**Diffuse radiation**

The solar radiation scattered by aerosols, dust and by Rayleigh mechanism. It does not have a unique direction.

**Global radiation**

The total of diffuse and beam radiation is also called as global radiation.

**Irradiance**

The rate at which the radiant energy is incident on a surface of unit area (W/m²).

**Irradiation**

The incident energy per unit area on a surface, found by integration of irradiance over a specified time (hour or day). It is also called as insolation (J/m²).
Generally, H denotes daily radiation values, while I refers to instantaneous or hourly radiation values. Subscripts are commonly used to distinguish different radiation terms like, b-beam, d-diffuse, t or g-total and o-extraterrestrial etc.

In solar energy studies, it is often convenient to use monthly average or monthly mean values of different time scales (hourly or daily). These are denoted by a bar ("-") above the parameter. Thus, $\overline{H}$ denotes the monthly average daily radiation, while $\overline{i}$ denotes the monthly average hourly radiation.

1.42 Mean day of the month

The monthly average values (say, the daily global radiation on the horizontal surface at a particular location) could be calculated as the average of all the days of the month or they could also be calculated using the mean day of the month. The mean day of the month has been recommended by Klein [18] by noting the day (in the month) whose declination is closest to the average declination for the month.

1.43 Cleanness index

This important radiation parameter (written as K or $K_1$) is defined under two time scales - hourly or daily. It is principally a measure of the radiation that is transmitted through the atmosphere and is therefore dependent only on the extraterrestrial radiation and the radiation falling at the earth's surface.

The hourly cleanness index (k) during a particular hour is the ratio of the hourly global radiation on horizontal surface to the hourly extraterrestrial radiation on horizontal surface (during the same time period).

$$k = \frac{I}{I_o} \quad (1.00)$$
and the monthly average hourly clearness index \( \bar{k} \) is given by

\[
\bar{k} = \frac{\overline{I}}{\overline{I}_o}
\]  

(1.01)

The daily clearness index \( K \) gives the ratio of the daily global radiation on a horizontal surface to the daily extraterrestrial radiation on a horizontal surface. Therefore,

\[
K = \frac{H}{\overline{H}_o}
\]  

(1.02)

the monthly average daily clearness index \( \bar{K} \) or \( \bar{K}_r \) is given by

\[
\bar{K} = \frac{\overline{H}}{\overline{H}_o}
\]  

(1.03)

The monthly average clearness index generally varies from about 0.3 to 0.8.

1.44 Solar time

In solar radiation calculation, solar time (local apparent time) is used to express the time of the day. Solar time is based on apparent angular motion of the sun across the sky. The time when the sun crosses the meridian of the observer is the local solar noon. Generally, it not coincides with the clock time of locality. The sun takes 4 minutes to traverse 1° of longitude, a longitude correction term of 4[Long.(standard)-Long.(local)] should be added to the locality. To calculate solar time, an astronomical correction factor has to be applied which is known as the equation of time (EOT). Thus solar time can be calculated from the standard time as follows
Solar time = National Standard Time + EOT ± 4 [Long.(standard)-Long.(local)]

(1.04)

'+' and '-' signs are used according to whether the place is to the east or west of standard meridian. EOT can be calculated by using the following two methods:

Method I

\[
EOT(\text{minutes}) = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B
\]

where

\[
B = \frac{360}{364} (n - 81)
\]

\[n = \text{day of the year} \ (1 \leq n \leq 365)\]

(1.05)

Method II

\[
EOT(\text{Hours}) = \left[ 0.123 \cos (A + 87) - \frac{1}{6} \sin 2(A + 10) \right]
\]

where

\[A = 0.938[n_i + 30.3(m - 1)] \text{ degrees}\]

\[n_i = \text{number of the day in the month} \ (1 \leq n_i \leq 31)\]

\[m = \text{number of the month in the year} \ (1 \leq m \leq 12)\]

(1.06)

1.5 MEASUREMENTS OF SOLAR ENERGY

For complete radiation study we need following parameters.

1. Global radiation
2. Diffuse radiation
3. Beam radiation (Spectral contribution of different wave lengths)
4. Sun shine hours, bright sun shine hours
5. Maximum and minimum temperature
6. Humidity
7. Pressure
8. Visibility
9. Wind speed and direction
10. Gust Speed
11. Water precipitation
12. Air Mass

To measure above mentioned parameters we require a big laboratory and group of skilled fellows. Although it is a difficult task to maintain and run such a laboratory but the quality and reliability of data of the site then can only be ensured. However there is a wide network of Indian meteorological department (Table 1.00) which provides wide variety of data that includes radiation, meteorological and pollution data. But the radiation data are scared. Word Radiation Centre also provides data of global, beam and diffuse radiation of various cities of the world [17].

1.51 Measurements of global, diffuse and beam radiation

Global and diffuse solar radiation can be measured with the help of a thermoelectric pyranometer. The details [19] of pyranometers are shown in Figures 1.01 and 1.02.

Basically pyranometer is consist of a thin blackened surface supported inside a relatively massive well polished case. When solar radiation falls on this surface, the temperature of the surface rises until its rate of loss of the heat by all causes is equal to the rate of gain of heat by radiation. This rise in temperature sets up a thermal e.m.f. which is measured on a recording milivoltmeter or recorder. Each pyranometer is calibrated and a certificate is provided by the manufacturer. The pyranometer which we are using is manufactured by National Instruments Ltd. (Calcutta) have been calibrated with a calibration factor 5.5 mV/Cal/Cm²/min. For
quality data of solar radiation pyranometer have to be calibrated at regular
intervals and maintenance of pyranometer is required.

Instrument used for measuring the intensity of direct solar radiation i.e. beam
radiation are called pyrheliometer. The Angstrom compensation pyrheliometer is a
standard instrument for the measurement of direct solar radiation, in which the
sensor is fixed at the lower end of a tube provided with a diaphragms so that when
the tube is directed towards sun, the sensing surface is normal to the line joining
the sun to the receiver and only radiation from the sun and a narrow annulus of the
sky is received by the sensor. The aligning is done by means of a sighting device
called the diopter.(Figure 1.03).

In pyrheliometer the absorption of the radiant energy by a blackened metal
strip, exposed to the sun’s ray is determined by measuring the electric current
necessary to heat an identical shielded strip to the same temperature. Since both
strips are mounted similarly and are at the same temperature and the heat
exchange of the strips with surroundings is identical, the rate of generation of heat
in shielded strip due to electric current is equal to the rate of absorption of radiant
energy by the exposed strip. The equivalence or otherwise of the temperature of
the two strips is determined by two fine thermocouples attached to the back of the
strips, connected in series with a sensitive galvanometer. The current through the
shielded strip is determined with an accurate digital milliammeter. The advantage of
the instrument is that the equilibrium current through the shielded strip is not
affected by change in the rate of heat loss from the strips, provided the changes
affect both the strips equally.

Such an instrument in theory is an absolute instrument as all the relevant
factors required for the calculation of the radiation intensity can be measured.
Let \( I = \) The intensity of direct solar radiation in Watts/cm²

\[ A = \text{Area of the strip} \]

\[ \alpha = \text{Absorption of the strip} \]

\[ i = \text{Heating current in amperes} \]

Then we have \( I.A.\alpha = R. i^2 \)

\[ I = \frac{R.i^2}{A.\alpha} = K.i^2 \text{watts/cm}^2 \]

Where \( K = \frac{R}{A.\alpha} \) is a constant for the instrument and depends upon resistance, length, breadth and absorptance of the strip. The constant of the instrument is actually determined by comparison with other standard instrument with constants traceable to the group of standards maintained at the world Radiation Centre in Switzerland.

For a study of the intensity of solar radiation in different regions, Scott glass filter OG1, RG2 and RG8 are used. The Transmission of the filters are given below.

OG1 Transmits from 0.525 \( \mu \) to 2.800 \( \mu \)

RG2 Transmits from 0.630 \( \mu \) to 2.800 \( \mu \)

RG8 Transmits from 0.700 \( \mu \) to 2.800 \( \mu \)

1.52 Measurements of solar radiation using sensors

Many investigators [20-22] have explored the possibility of measurement of solar radiation using sensors. Thermo-pile type pyranometers recommended by the WMO regulations, or equipment calibrated against these standards, are usually employed in the measurement of solar radiation [23]. The advantage of such elements are small size, ruggedness, fast-time response, easy handling and low cost. In some applications, what are usually considered the main disadvantages of such sensors,
namely their spectral sensitivity and temperature dependence, may be considered as advantageous.

1.53 Measurements of meteorological parameters

Sunshine duration is numbers of hours for which sun remains in the sky and can be seen. By bright sun shine [19] we mean numbers of hours per day that the sunshine intensity exceeds some predetermined threshold of brightness. The duration of bright sunshine in a day is measured by means of a sunshine recorder [Figure 1.04]. The sun rays are focused by a glass sphere to a point on a card strip held in groove in a spherical bowl mounted concentrically with the sphere. Whenever there is bright sunshine, the image formed is intense enough to burn a spot on the card strip. Throughout the day as the sun moves across the sky the image moves along the strip. Thus a burnt trace whose length is proportional to the duration of sunshine is obtained on the strip.

Precipitation, temperature, humidity, visibility, wind direction and wind speed etc., the meteorological data are almost easily available for all the cities across the India and world. These meteorological parameters do effect radiation data. www.wounderground.com provides meteorological data of all capitals of state of India. Unfortunately meteorological data of Kanpur is missing on this site. But there are three meteorological stations in Kanpur where some meteorological data are being measured. These are Indian Institute of Pulses Research, Chandra Shekhar Azad Agriculture and Technical University and Chakeri Air Force Station. We procured meteorological data from I. I. P.R (Table 1.01).

1.54 Accessing radiation data through INTERNET

Radiation data of different cities across the globe can be accessed through the internet. There are many sites which are providing radiation data free of cost to be
used for scientific and academic research. Out of these two sites are very useful for Indian researchers. [http://www.imd.ernet.in](http://www.imd.ernet.in) (Indian Meteorological Department), on which radiation observatories (Table 1.02) recording data are available. At all these observatories measurement of global solar radiation is being carried out while at a few selected stations in addition to other parameters like diffuse, direct, net, net-terrestrial and reflected radiation net atmospheric turbidity are also measured. Data loggers have been introduced at the four stations viz. New Delhi, Patana, Jaipur and Thiruvananthapuram.

The second website [http://www.wrdc.mgo.nrel.gov](http://www.wrdc.mgo.nrel.gov) (World radiation data centre) provides global, beam and diffuse component of radiation on horizontal surface for following cities of India (Table 1.03).

Ahmadabad, Bhaunagar, Mumbai, Calcutta(Alipur), Calcutta(DamDum), Goa/Panji, Jodhpur, Kodaikanal, Madras(Minambakkum), Nagpur (Sonegaon), New Delhi(Safdarjung), Poona, Shillong, Trivandrum and Vishakhapatnam.

To obtain data from the WORLD RADIATION DATA CENTRE ON LINE ARCHIVE one has to have a conventional e-mail account. The e-mail address for all automatic data transfer is: data@wrdc-mgo.nrel.gov

There is simple process to download data from WRDC Metadata

To Obtain the information file you are now reading, mail the following command to the online archive:

INFO

To obtain a complete list of site names and site codes, mail the following command

STATIONS

To obtain documentation on the data and data formats, mail the following command
FORMATS

Data

To obtain a solar radiation data set, mail a command in the following four line format. This initiates a data request and defines the parameters for each of the three search categories:

DATA
SITE site1 [site2 … siteN]
MEAS measurement1 [measurement2 … measurement N]
YEAR year1 [year2 … yearN]

Where

"DATA" is a mandatory data request initiator
"SITE" is followed by one or more WMO site identification numbers (from the list available from the STATIONS command), or the word "ALL" for all available sites
"MEAS" is followed by one or more of the measurement types listed below (omit the annotation)

GLOBAL
DIFFUSE
DOWNWARD (Downward atmospheric radiation)
SUNSHINE
DIRECT
TOTAL
TERNET (Net terrestrial surface radiation (upward))
TERSURFACE (Terrestrial surface radiation)
REFLECTED (Reflected solar radiation)
SPECTRAL (Spectral radiation components)
ALL (All available measurements)

"YEAR" is followed by one or more four digit year numbers, or word "ALL" to select all available years.

Examples

1. Send global and total data from three sites for 1991 and 1992

DATA
SITE 745456 34224 424334
YEAR 1991 1992
MEAS GLOBAL TOTAL

2. Send format information, and all available measurements for one site for 1991

FORMAT
DATA
SITE 93343
YEAR 1991
MEAS ALL
SIZE 512 (Fixes size of data to half megabyte)
NEWS (Gives news about WRDC)

1.6 NEED FOR THEORETICAL INVESTIGATION

Knowledge about the amount of available solar energy is extremely important to solar engineers, designers and architects [24-25]. Information on global solar radiation is of paramount necessity for efficiently determining irrigation water needs and the potential yield of crops [26]. In spite of the importance of solar energy, measurements of its intensities in many parts of the world either scarce, sparse or poor [28-42]. This is due to expenses [32], the requirements for maintenance [37] and mal
functioning of the solar equipment. In response to the crucial needs for such information techniques have been formed to predict solar radiation in short areas. These techniques are basically empirical correlations derived by regression analysis of measured data. The best database would be the long-term measured data at the site of proposed solar system. However, the limited coverage of radiation measuring network dictates the need for developing solar radiation models[43].

1.7 EMPIRICAL CORRELATIONS

1.71 Estimation of beam and diffuse radiation

Beam or direct radiation is important in designing systems employing solar energy, such as high temperature heat engines and high intensity solar cells. Measurement of beam radiation is rather difficult and measured data is not readily available. There are two categories of empirical models which predict beam radiation.

- Parametric models
- Decomposition models

Parametric models require detailed information of atmospheric conditions. Meteorological parameters frequently used as predictor include the type, amount and distribution of clouds or other observations, such as a fractional sunshine, atmospheric turbidity and precipitable water content [44-51]. A simpler method was adopted by ASHRAE algorithm [43] and very widely used by the engineering and architectural communities. The Iqbal model [45] offers extra – accuracy over more conventional models as reviewed by Gueymard [50].

Development of correlation models that predict the beam or sky radiation using other solar radiation measurements is possible. Decomposition models usually use information only on global radiation to predict beam and sky components. These
relationships are usually expressed in terms of the irradiations which are time integrals (usually over 1 h) of the radiant flux or irradiance. Decomposition models developed to estimate direct and diffuse irradiance from global irradiance data were found in the literature [52-65].

For most solar energy applications, either global – tilt or direct solar radiation resource data are needed. However, the diffuse radiation on a horizontal surface too has many applications, specially in finding global radiation on tilted surface, illumination design inside a building, and so on. Only a few data are available for diffuse radiation [66]. Most existing work [67-68] on diffuse radiation has been based on data from North America, Canada, Australia or North European stations as well as from Liu and Jordan [52]. The decomposition model [42] to predict hourly diffuse radiation are based on the correlation between the clearness index \( k_i \) and diffuse fraction \( k_d \), diffuse coefficient \( k_D \) or direct transmittance \( k_b \) where \( k_i = \frac{I_g}{I_o} \),

\[
k_d = \frac{I_d}{I_i}, \quad k_D = \frac{I_d}{I_o}, \quad k_b = \frac{I_b}{I_o}, \quad I_i, I_b, I_d \text{ and } I_o \text{ being global, direct, diffuse and extraterrestrial irradiances respectively, on a horizontal surface.}
\]

A detailed comparison of parametric and decomposition models could be found in literature [42].

To predict monthly mean hourly values of diffuse radiation there are three types of correlations. First type express monthly mean daily diffuse fraction \( \frac{H_{d}}{H} \) as a function of the monthly mean daily clearness index [52,69-70]. Second type express \([71-72] \quad \frac{H_{d}}{H} \text{ or } \frac{H_{d}}{H_o} \) as function of sunshine fraction \( \frac{S}{S_o} \). The third type express \( \frac{H_{d}}{H} \) as a function of clearness index and \( \frac{S}{S_o} \)[73]. Skartveit et al
[74] showed that the diffuse fraction depends also on other parameters such as solar elevation, temperature and relative humidity. Literature results [75-76] showed that the diffuse fraction depends also on other variables like atmospheric turbidity, surface albedo and atmospheric precipitable water. A quasi-physical model for converting hourly global horizontal to direct normal insolation proposed by Maxwell in 1987, was reviewed by Battles et al [60]. The model combines a clear physical model with experimental fits for other conditions. Bhattacharya et al [61] and Prasad et al [77] have discussed diffuse solar radiation across the India.

### 1.72 Empirical correlation of daily global radiation with hours of sunshine

The monthly mean daily global radiation on a horizontal surface can be estimated through the number of bright sunshine hours. Angstrom [78] developed first model suggesting that the ratio of the average daily global radiation \( \overline{H} \) and cloudless radiation \( \overline{H}_c \) is related to monthly mean daily fraction of possible sunshine fraction \( \overline{S}_f \) by

\[
\frac{\overline{H}}{\overline{H}_c} = a_t + (1-a_t)\overline{S}_f = a_t + b_t \overline{S}_f
\]

(1.01)

with constant ‘a’ being obtained as 0.25 for Stockholm, Sweden.

The sunshine fraction is obtained from

\[
S_f = \frac{\overline{S}}{\overline{S}_o}
\]

where \( \overline{S} \) is the monthly mean bright sunshine hours and \( \overline{S}_o \) is the average day length.
There may be problems in calculating the $H_e$ accurately. Hence Equation (1.01) was modified by Prescott [79] as reviewed by Gueymard et al. [80] to be used on the extraterrestrial irradiation.

$$\frac{H}{H_o} = a_i + b_i \frac{S}{S_o} \tag{1.02}$$

where $H_o$ is the monthly mean daily extraterrestrial radiation on horizontal surface.

Rietveld [81] examined several published values of $a_1$ and $b_1$ and noted that $a_1$ is related linearly and $b_1$ hyperbolically to the appropriate yearly average value of $\bar{S}_i$ denoted as $\frac{\bar{S}}{S_o}$ such that

$$a_i = 0.10 + 0.24 \left( \frac{\bar{S}}{S_o} \right)$$

$$b_i = 0.38 + 0.08 \left( \frac{\bar{S}}{S_o} \right)$$

If $\left( \frac{S}{S_o} \right) = \frac{\bar{S}}{S_o}$, the Rietveld model [81] can be simplified to a constant -coefficient Angstrom-Prescott equation

$$\frac{H}{H_o} = 0.18 + 0.62 \frac{S}{S_o} \tag{1.03}$$

This equation was proposed for all places of the world and yields particularly superior results for cloudy conditions when $\frac{S}{S_o} < 0.4$. 

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Glover and McCulloch included the latitude $\phi$ (degrees) effect and presented the following correlation as reviewed by Iqbal [45]

$$\frac{H}{H_o} = 0.29 \cos \phi + 0.52 \frac{S}{S_o} \quad \text{for} \phi < 60^\circ \quad (1.04)$$

Gopinathan [82] suggested the regression coefficient $a$ and $b$ in terms of the latitude, elevation ($h$ in km) and percentage of possible sunshine for any location around the world. The correlations are:

$$a_1 = -0.309 + 0.539 \cos \phi - 0.0693h + 0.29 \frac{S}{S_o}$$

$$b_1 = 1.527 - 1.027 \cos \phi + 0.0926h - 0.359 \frac{S}{S_o}$$

The coefficients $'a_1'$ and $'b_1'$ are site dependent [57, 83-86]. Some other predicted values of $a$ and $b$ are due to Bahel et al [83], Alnaser [84], and Louche et al [57].

These coefficients would be affected by the optical properties of the cloud cover, ground reflectivity and average air mass. Hay[87] studied these factors with data collected in western Canada and proposed a site independent correlation

$$\frac{H}{H_o} = \frac{0.1572 + 0.556 \frac{S}{S_{om}}}{1 - \rho_g \left[ \rho_a \left( \frac{S}{S_{om}} \right) + \rho_c \left( 1 - \frac{S}{S_{om}} \right) \right]} \quad (1.05)$$

where $\rho_g$ (dimensionless) is the ground albedo, $\rho_a$ is the cloudless-sky albedo taken as 0.25 and $\rho_c$ is the cloud albedo taken as 0.6. $S_{om}$ is the modified day length for a solar zenith angle $\theta_z$ greater than 85° and is given by

$$S_{om} = \frac{1}{7.5 \cos^{-1} \left( \frac{\cos 85^\circ - \sin \phi \sin \delta_z}{\cos \phi \cos \delta_z} \right)}$$

28
where $\delta_c$ is the characteristic declination, i.e. the declination at which the extraterrestrial irradiation is identical to its monthly average value.

The ratio $\frac{H}{H_o}$ is referred as cloudiness index by Liu and Jordan [88] and Iqbal [71], atmospheric transmissivity by Hay [87] and clearness index by Khogali et al [89] and Duffie and Beckman [90]. The simple form of Angstrom type equation received almost a world-wide acceptance for application [91-107]. However Page [69] pointed out that linear type equation based on climatological means cannot necessarily be expected to be applicable extreme values for particular day, as it overestimates the total radiation on cloudless days i.e. when $\frac{S}{S_o} = 1$ and on overcast days i.e. when $\frac{S}{S_o} = 0$. This fact was later confirmed by Benison et al [108] and Michalsky [109] who considered the relationship on the basis of individual daily records. The former study shows a significant downward curvature of the data points with discontinuity of $\frac{H}{H_o}$ at $\frac{S}{S_o} = 0$, hence, a quadratic form for the relationship between daily global/extraterrestrial radiation and actual/maximum possible hours of sunshine greater than zero was employed as

$$\frac{H}{H_o} = a_2 + b_2 \frac{S}{S_o} + c_2 \left(\frac{S}{S_o}\right)^2$$  \hspace{1cm} (1.06)

where $a_2$, $b_2$ and $c_2$ are the regression constants. The latter investigation rendered a fairly linear fit for the regression except near zero sunshine fraction where the data
points appear to cluster. Hinrichsen [110] also reported that the linear fit yields an realistic steep ascent of regression line, consequently overestimating the clear sky condition. The second order polynomial fitting have also adopted as a reasonable functional form by many investigators [111-112]. A third order polynomial have also fitted using global radiation data of 48 locations around the world [113]. In lieu of best equation we tested a sixth order polynomial.

There are some other form of empirical relations which have been tested by Khogali[89], Alvi[114], Alvi and Elagib [115] and Elagib et al [116], Togrul et al[117].

\[
\frac{H}{H_o} = \alpha_i \left( \frac{S}{S_o} \right)^{b_i} \tag{1.07}
\]

\[
\frac{H}{H_o} = \alpha_4 \exp \left( b_4 \frac{S}{S_o} \right) \tag{1.08}
\]

\[
\frac{H}{H_o} = \alpha_5 \log \left( \frac{S}{S_o} \right) + b_5 \tag{1.09}
\]

Where \( \alpha_i \) and \( b_i \) are the constants \((i=3,4,5)\).

The ranking of different empirical equations for a particular location can be found in recent literature[115-117]. There are a few investigators working for various types of empirical correlations for different months and seasons of year[100,117].

Sen [118] employed fuzzy modeling to represent the relations between solar radiation and sunshine duration by a set of fuzzy rules. A fuzzy logic algorithm has been devised for estimating the solar radiation from sunshine duration measurements. The classical Angstrom equation are replaced by a set of fuzzy-rule bases and applied
for three sites with monthly averages of daily irradiances in the western part of
turkey. Sen work is followed by Gautem et al [119].

Mohandes et al [120] studied the monthly mean radial values of solar
radiation falling on the horizontal surface using the radial basis functions technique.

1.73 Empirical correlation of daily global radiation with
hours of sunshine and meteorological parameters

Several investigators found that relatively accurate estimation of global solar
radiation can be obtained from values of several meteorological parameters. Such a
formula is developed by correlating various climatic data which are normally
available in most meteorological stations. The utilization of several meteorological
parameters in solar radiation model was initiated among others by Reddy [121] who
developed first empirical correlation based on meteorological parameters like relative
humidity and maximum temperatures. Further modification of Reddy’s equation were
carried out by Sabbagh et al [122] and Sayigh [123]. Equation developed by Reddy,
Sabbagh and Sayigh is nonlinear in nature and is grouped as Reddy-Sabbagh-Sayigh
type (or abbreviated as RSS type) equation to distinguish with Angstrom type
equation. This work have been extended by several researchers[124-126].

Several investigators [27,84,109,127-129] have introduced climatological
parameters like maximum temperature, water vapour pressure, relative humidity, the
mean sea level pressure (MSL), the ratio of MSL to water vapour pressure in well
known Angstrom type equation.

1.74 Estimation of monthly mean hourly values of global
solar radiation

Sometimes the design of solar energy devices needs accurate estimation of
hourly values of solar radiation. Such studies were made by Whiller [130], Hottel and Whiller [131] and Liu and Jordan[52]. The hours are designated by the time at midpoint of the hours, and days are considered to be symmetrical about the solar noon. According to Whiller, this process can be used for individual clear days. Collares and Rabl [70] verified Liu and Jordan's work. Garg and Garg [132] checked the adequacy of the Liu and Jordan correlation for Indian locations. Estimation of hourly values of global radiation have been obtained by several investigators from daily values [133-137]. Gopinathan [138] calculated hourly values of global radiation from hourly sunshine duration. Some investigators correlated hourly diffuse fraction with daily diffuse fraction[139-140]. Chendo and Maduekwe [141] obtained hourly values of radiation using sunshine and four climatic parameters following the work of Reindell, Beckman and Duiffe[56].

Panek et al[142] proposed a stochastic method for calculating hourly values of global and diffuse radiation on horizontal surface. This model utilizes the maximum value of hourly radiation( amplitude) to predict hourly values. This model has advantages over different empirical correlation discussed so far.

There are two main different approaches to calculate hourly values ; (a) Deterministic approach that include empirical correlation and ASHRAE model[143], (b) Stochastic approach by Panek et al [142], Aguiar et al [144], Grahman et al [145].

1.8 PRESENT TRENDS IN CORRELATION

Angstrom – Prescott correlation has served as a basic approach to estimate global radiation for long time. Simplicity of Angstrom – Prescott equation have dominated over its several demerits. Coefficients in Angstrom – Prescott equation is
site dependent. Yeboah-Amankwah and Agyeman [146] believed that $a_1$ and $b_1$ are
time dependent and so developed a differential Angstrom model with a set of
coefficient which vary with time. Ninomiya[147] considered the effect of snow and
rain fall of rainy days. Sahin and Sen [148] proposed a method to dynamically
estimate the coefficients. These work do not include radiation damping process when
solar rays pass through the atmosphere. Some researchers [149-150] employing a
damping structure to calculate global solar radiation in clear sky. Their model
consider physical process in detail, so the effect of latitude, elevation and other
factors are taken into account automatically. However damping spectrums are very
irregular and hence numerical integration is indispensible. To overcome all these
difficulties Yang et al [151] proposed a 'Hybrid model' which consider the physical
process but still maintain the simplicity of the Angstrom equation. The author tested
their hybrid model with data of Japan and found that it needs greater turbidity when
applied to urban areas due to air pollution, otherwise, global radiation may be
estimated. Also, the estimation under completely cloudy sky is still difficult. Hybrid
model assumed global radiation has linear relationship with effective beam radiation
and diffuse radiation as well as fractional sunshine time. Yang et al [152] also
proposed a model to calculate solar radiation from upper air humidity. This could be
used to predict numerical weather prediction(NWP).

Lingamgunta and Veziroglu [153] proposed a universal relationship for
estimating clear sky insolation. This relation predicts annual mean daily clear sky
insolation and is function of latitude and altitude only. Author claimed that relation
Author called it as Lingamgunta-Veziroglu relation) predicts radiation fairly accurate
over conventional methods.
Suehrcke [154] proposed an entirely new type of relation between relative sunshine duration and global radiation. This relation unlikely Angstrom – Prescott equation, is nonlinear and it does not require any empirical constants. The local atmospheric conditions are considered through the value of the average daily clear index. Further fractional sunshine can be calculated from Suehrcke relation. Suehrcke’s sunshine radiation relationship have been verified by Anton et al [155] using a global data sheet.

Recently there have been emphasis [156-159] on empirical correlation using satellite images. Most estimation of daily global radiation values from satellite images requires the use of models which allow us to calculate these values from a small number of images per day (usually three). Different methodology have been developed.

Atmospheric pollutants and aerosols absorb and scatter shortwave solar radiations. The interactions have resultant impacts on atmospheric radiative energy transfer and balance. If the pollution increases then diffuse component of global solar radiation will also increase. Spectral and diffuse radiation study of global solar radiation has now gained importance as reflected in recent literature [160-164]. There have been another area of modeling which is gaining importance is estimation of solar radiation potential using artificial neural network [165-172].
Table 1.01: Meteorological data (IIIPR-Kanpur) for the month of March 2001

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature °C</th>
<th>Relative humidity (%)</th>
<th>Evaporation rate (mm/h)</th>
<th>Wind speed (Km/h)</th>
<th>Wind direction</th>
<th>Sunshine (hrs)</th>
<th>Rainfall mm</th>
<th>Cumulative Rainfall mm</th>
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35
Table 1.02: Observatories of Indian meteorological Department

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<td>Non-Departmental Raingauge Stations: Reporting</td>
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<tr>
<td>Non-Reporting</td>
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<td>Non-Departmental Glaciological Observations (Non Reporting): Snowgauges</td>
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<td>Ordinary Raingauges</td>
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<tr>
<td>Seasonal Snow Poles</td>
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<td>Agrometeorological Observations</td>
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<tr>
<td>Evaporation Stations</td>
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<tr>
<td>Soil Moisture Recording Stations</td>
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<tr>
<td>Dew Fall Recording stations</td>
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<tr>
<td>Evapotranspiration Stations</td>
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<td>Ozone Stations</td>
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<td>Radiations Stations</td>
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</tr>
<tr>
<td>Air Pollution Observatories: Background Pollution Observatories</td>
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<tr>
<td>Urban Climatological Units</td>
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<tr>
<td>Urban Climatological observatories</td>
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<tr>
<td>Ships of the Indian Voluntary observing fleet</td>
<td>203</td>
</tr>
<tr>
<td>Seismological Observatories</td>
<td>58</td>
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</table>
Table 1.03: Down load of global radiation data from world radiation data centre

India Ahmadabad
Lat 23.07 Lon 72.63
Year: 1991 Month: 05

<table>
<thead>
<tr>
<th>Daily Insolation (kWh/m²/2/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
</tr>
<tr>
<td>Insolation</td>
</tr>
</tbody>
</table>

| Day  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |
| Insolation | 6.86 | 6.39 | 6.61 | 6.82 | 7.10 | 6.89 | 6.66 | 6.00 | 6.71 | 6.3 |

| Day  | 21  | 22  | 23  | 24  | 25  | 26  | 27  | 28  | 29  | 30  | 31  |

India Ahmadabad
Lat 23.07 Lon 72.63
Year: 1991 Month: 06

<table>
<thead>
<tr>
<th>Daily Insolation (kWh/m²/2/day)</th>
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<tbody>
<tr>
<td>Day</td>
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<tr>
<td>Insolation</td>
</tr>
</tbody>
</table>

| Day  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |
| Insolation | 5.09 | 5.18 | 6.06 | 5.55 | 5.60 | 5.57 | 5.06 | 4.74 | 4.91 | 5.2 |

| Day  | 21  | 22  | 23  | 24  | 25  | 26  | 27  | 28  | 29  | 30  | 31  |
| Insolation | n/a | 6.01 | 6.73 | 6.41 | 6.27 | 6.15 | 6.34 | 5.09 | 5.34 | 4.81 |
Figure 1.01: Pyranometer for measuring global radiation (Courtesy National Instruments Ltd., Calcutta)
Figure 1.02 : Details of Pyranometer (Courtesy National Instruments Ltd., Calcutta).
Figure 1.03: Angstrom Pyrheliometer (Courtesy National Instruments Ltd., Calcutta)
Figure 1.04: Sunshine recorder (Courtesy National Instruments Ltd., Calcutta)