February, 2011

# PERFORMANCE OF SOLAR POWER PLANTS
# IN
# INDIA

**Submitted**

**To**

**Central Electricity Regulatory Commission**

**New Delhi**

# Table of Contents

## List of figures

## List of tables

## 1.0 Introduction

There is a pressing need to accelerate the development of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development. Solar Photovoltaic is a key technology option to realize the shift to a decarbonised energy supply and is projected to emerge as an attractive alternate electricity source in the future. Globally, the solar PV grid connected capacity has increased from 7.6 GW in 2007 to 13.5 GW in 2008 and was 21 GW at the end of 2009. Similarly, annual solar PV production also jumped from 3.7 GW in 2007 to 10.7 GW in 2009[1]. The growth trend is continuing and is likely to explode once the grid parity is achieved.

India is located in the equatorial sun belt of the earth, thereby receiving abundant radiant energy from the sun. The India Meteorological Department (IMD) maintains a nationwide network of radiation stations which measure solar radiation and also the daily duration of sunshine. In most parts of India, clear sunny weather is experienced 250 to 300 days a year. The annual global radiation varies from 1600 to 2200 kWh/sq.m. which is comparable with radiation received in the tropical and sub-tropical regions. The equivalent energy potential is about 6,000 million GWh of energy per year. The highest annual global radiation is received in Rajasthan and northern Gujarat. In Rajasthan, large areas of land are barren and sparsely populated, making these areas suitable as locations for large central power stations based on solar energy.

The Indian government has launched Jawaharlal Nehru National Solar Mission (JNNSM) with a target of achieving 20000 MW by 2022. The goal is to make India one of the leaders in solar energy. Although Solar energy is still expensive today, but costs are coming down with technology development, right governmental policies and R and D efforts.

### 1.1 Jawaharlal Nehru National Solar Mission (JNNSM)

The mission will be carried out in three phases and aims to do the following: to create a policy framework for deployment of 20,000 MW by 2022; to add 1,000 MW of grid solar power by 2013, and another 3,000 MW by 2017. The target for 2017 may be higher based on the availability of international finance and technology transfer.

The scheme also aims at strengthening indigenous manufacturing capability, and achieving 15 million sq. meters solar thermal collector area by 2017 and 20 million by 2022. One of the steps to achieve this will be to make solar heaters mandatory by incorporating byelaws in the National Building Code. Deployment of 20 million solar lighting systems for rural areas by 2022 is also part of the scheme.

[1] Renewables 2010, Global Status Report, REN21.

This mission has received widespread support from agencies like the World Bank and the Clinton Initiative. Also, the launch of organisations like the Solar Thermal Federation of India (STFI) indicates that the industry is gearing up for a shift towards solar.

### 1.2 Energy Security

India needs to focus on developing its own sources of energy. Our major energy sources, oil and coal, are imported in large quantities. Even with the development of nuclear energy, India will be dependent on other nations for fuel. To sustain economic growth, to come out of the energy deficit situation and ensure that energy is available in every town and village, India must utilise its immense potential in solar energy.

### 1.3 Role of Central and State Governments

India is the only country with a Ministry dedicated to New and Renewable Energy. There are nodal agencies in each State, which specifically work on enhancing the percentage of renewable energy in the power-mix. States such as Rajasthan, Karnataka, Maharashtra, Gujarat, and West Bengal have already taken initiatives for installation of large solar power plants. The MNRE also announced Generation Based Incentives (GBI) in 2008, to incentivize development of solar power plants.

## 2.0 Objectives of this report

It is clear from the above discussion that solar energy is becoming an important source of energy all over the World and especially in India. Very few solar plants have been installed in India so far, and therefore no historical experience available. It is important to investigate the performance of solar power plants. Knowledge about the performance of solar power plants will result in correct investment decisions, a better regulatory framework and favorable government policies. In this report, we examine the various factors contributing to the performance of solar power plants, such as radiation, temperature and other climatic conditions, design, inverter efficiency and degradation due to aging. The objectives of this study are summarized below:

- To estimate the performance of solar power plants at different locations in the country
- To assess the degradation of module output associated with aging as per current technology trends
- To recommend future work in the field of solar energy
- To review existing radiation data sources and softwares
- To review design criteria for better performance of power plants

## 3.0 Methodology

For this report, information and data from a wide variety of sources has been used, which includes theoretical knowledge of solar energy technology, for both solar PV and solar thermal power plants, available in standard literature. Data for solar radiation has been analysed from sources such as the Handbook of Solar Radiation for India (Anna Mani, Allied Publishers) India Meteorological Department (IMD), National Aeronautics and Space Administration (NASA), National Renewable Energy Laboratory (NREL), Ministry of New and Renewable Energy (MNRE) and Meteonorm.

Software analysis
It has been found that data from the above sources varies over a wide range, depending on whether it is collected from monitoring stations, extrapolated, or derived from satellite information. Data from the above mentioned sources is analysed using software such as PVSyst and RETScreen. This facilitates easy comparison of irradiation levels from different sources, and power output from solar plants, with variation in type and make of panel used, the angle of tilt of the panel, the use of tracking mechanism, local weather conditions such as temperature, and losses such as panel degradation, inverter losses and so on.

### Long term studies

Further, to evaluate the performance of solar power plants over the long term, data has been obtained from tests conducted by research institutes like the Fraunhofer Institute in Germany, NREL USA etc.. It is noted however, that very little information on long term performance and panel degradation after installation is available for India, as most power plants are relatively new. Solar panel manufacturers also provide guarantees on long term performance of their panels, which is used for comparison with installed-plant data.

### Data from existing power plants

To test the validity of various sources of data, we have collected output measurements from power plants in India, which have been in operation for at least a period of 6 months. This output can be used to analyse whether the data inputs are accurate or not. For example, the output power generated, minus the losses can give a good estimate of the accuracy of the input radiation data and the estimated generation. Since several source of irradiation data are available, this will be useful is evaluating which source of data is the most accurate.

### Performance evaluation

For complete performance evaluation, the following data has to been collected and verified to the extent possible:[2]

[2] International Energy Agency, "Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity", IEA PVPS Task 12, Subtask 20, LCA Report IEA-PVPS T12-01:2009 October 2009.

1. Irradiation – as mentioned, data from different sources has been analysed and the source identified based on the accuracy perception for the present study.
2. Performance ratio – it is observed that performance ratio depends on the irradiation, the optimum angle of tilt, air temperature, design parameters, quality of modules, efficiency of inverter etc. The results have been obtained based on the above parameters using RETscreen software. The results have been compared with some data available on the recently installed grid connected power plants in India.
3. Degradation – All manufacturers stand a guarantee of performance over a period of 25 years with 90% output for first 12 years and up to 80% after 25 years of operation. Various studies carried out by global renowned institutions on the extent of degradation of out put of modules after long term operation in field. These results are analysed to arrive at the actual field performance.
4. Life expectancy – Trends in the accelerated tests for modules, inverters, supporting structure and cabling have been studied.

### 4.0 Technology for Solar power plants

Solar power generation technologies can be broadly classified into two broad categories:

- Solar Photovoltaic technologies
- Solar thermal power plants

### 4.1 Solar Photovoltaic (SPV) technologies

Photovoltaic converters are semiconductor devices that convert part of the incident solar radiation directly into electrical energy. The most common PV cells are made from single crystal silicon but there are many variations in cell material, design and methods of manufacture. Solar PV cells are available as crystalline silicon, amorphous silicon cells such as Cadmium Telluride (Cd-Te), Copper Indium diselenide, and copper indium gallium diselenide (CIGS), dye sensitised solar cells DSSC and other newer technologies such as silicon nano particle ink, carbon nanotube CNT and quantum dots.

| **Wafer-based c-Si** | | **Thin Films** | | |
|---|---|---|---|---|
| Mono-Si | Multi-Si | a-Si; a-Si/μc-Si | CdTe | CIS/CIGS |
| 15-20% | 15-17% | 6-9% | 9-11% | 10-12% |

Table 1: Commercial efficiencies of photovoltaic modules

Crystalline silicon (c-Si) modules represent 85-90% of the global annual market today. C-Si modules are subdivided in two main categories: i) single crystalline (sc-Si) and ii) multi-crystalline (mc-Si).

Thin films currently account for 10% to 15% of global PV module sales. They are subdivided into three main families: i) amorphous (a-Si) and micromorph silicon (a-Si/μc-Si), ii) Cadmium-Telluride (CdTe), and iii) Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

Emerging technologies encompass advanced thin films and organic cells. The latter are about to enter the market via niche applications. Concentrator technologies (CPV) use an optical concentrator system which focuses solar radiation onto a small high-efficiency cell. CPV technology is currently being tested in pilot applications.

The above technologies are mainly used on roof tops of commercial and residential buildings, and as large scale grid connected power plants. For optimum output, larger installations use tracking devices which change the orientation of the panels to correspond with the trajectory of the sun to focus sunlight directly onto the panels.

### 4.2 Solar thermal power plants

Solar thermal power plants produce electricity by converting the solar radiation into high temperature heat using mirrors and reflectors. The collectors are referred to as the solar-field. This energy is used to heat a working fluid and produce steam. Steam is then used to rotate a turbine or power an engine to drive a generator and produce electricity

All CSP plants are based on four basic essential systems which are collector, receiver (absorber), transport/storage and power conversion. Parabolic Trough, Solar towers, Parabolic Dishes and Linear Fresnel Reflectors are the four main technologies that are commercially available today. The details are given below:

Fig. 1: Solar Thermal Technologies

### Parabolic trough

Parabolic trough shaped mirrors collect and reflect the solar energy onto receiver tubes positioned along the focal line of parabolic mirrors. The troughs are usually designed to track the Sun along one axis, predominantly north–south. Heat transfer fluids, such as synthetic thermal oil suitable for temperatures up to 400 °C, circulating through the tubes are used to generate steam through heat exchangers and steam generators and drive turbine to generate electricity through a steam cycle. This is a well established and proven CSP technology.

### Solar Towers

A circular array of heliostats concentrates sunlight on to a central receiver mounted at the top of a tower. The heliostats tack the sun on two axes. The central receiver can achieve very high concentrations of solar irradiation thus resulting in extremely high temperature for the operating fluid. A heat-transfer medium in this central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy, which is used to generate superheated steam for the turbine through the Rankine cycle. Brayton cycle systems are also under testing because of the higher efficiencies. Spain has several solar tower systems operating or under construction, up to 20 MW capacity.

### Parabolic Dish

The parabolic shaped dish tracks the sun, through a two axis movement, onto a thermal receiver mounted at the focal point. The concentrated beam radiation is absorbed into a receiver to heat a fluid or gas to approximately 750°C. This fluid or gas is then used to generate electricity in a small piston or Stirling engine or a micro turbine.

Dish technology produces relatively small amount of electricity compared to other CSP technologies – typically in the range of 10 to 25 kW which results in high capital costs.

### Linear Fresnel Reflectors

Use reflectors made of several slices of mirrors with small curvature approximating a parabola. Mirrors are mounted on trackers and configured to reflect sunlight onto elevated linear reflectors. Water flows through the receivers and is converted into steam and the intermediate heat transfer fluid is not required. These systems have lower investment costs and also lower optical performance as compared to parabolic trough collectors. This technology is still in the developmental stage.

## 5.0 Performance of solar power plants

The performance of solar power plants is best defined by the Capacity Utilization Factor (CUF) , which is the ratio of the actual electricity output from the plant, to the maximum possible output during the year. The estimated output from the solar power plant depends on the design parameters and can be calculated , using standard softwares. But since there are several variables which contribute to the final output from a plant, the CUF varies over a wide range. These could be on account of poor selection /quality of panels, derating of modules at higher temperatures, other design parameters like ohmic loss, atmospheric factors such as prolonged cloud cover and mist.

It is essential therefore to list the various factors that contribute to plant output variation. The performance of the power plant however depends on several parameters including the site location, solar insolation levels, climatic conditions specially temperature, technical losses in cabling, module mismatch , soiling losses, MPPT losses, transformer losses and the inverter losses. There could also be losses due to grid unavailability and the module degradation through aging.

Some of these are specified by the manufacturer, such as the dependence of power output on temperature, known as temperature coefficient. The following factors are considered key performance indicators:

1. **Radiation at the site**
2. **Losses in PV systems**
3. **Temperature and climatic conditions**
4. **Design parameters of the plant**
5. **Inverter efficiency**
6. **Module Degradation due to aging**

These are covered in detail in the following sections.

### 5.1 Radiation

#### Solar radiation basics and definition

Solar radiation is a primary driver for many physical, chemical and biological processes on the earth’s surface, and complete and accurate solar radiation data at a specific region are of considerable significance for such research and application fields as architecture, industry, agriculture, environment, hydrology, agrology, meteorology, limnology, oceanography and ecology. Besides, solar radiation data are a fundamental input for solar energy applications such as photovoltaic systems for electricity generation, solar collectors for heating, solar air conditioning climate control in buildings and passive solar devices [3].

Several empirical formulae have been developed to calculate the solar radiation using various parameters. Some works used the sunshine duration others used the sunshine duration, relative humidity and temperature, while others used the number of rainy days, sunshine hours and a factor that depends on latitude and altitude.[3]

The primary requirement for the design of any solar power project is accurate solar radiation data. It is essential to know the method used for measuring data for accurate design. Data may be instantaneously measured (irradiance) or integrated over a period of time (irradiation) usually one hour or day. Data maybe for beam, diffuse or total radiation, and for a horizontal or inclined surface. It is also important to know the types of measuring instruments used for these measurements.[4]

For the purpose of this report, data sources such as NREL, NASA, IMD and so on were compared. All these sources specify global irradiance, measured over one hour periods and averaged over the entire month. The data is available for horizontal surfaces and must be suitably converted for inclined solar collectors. Monthly average daily solar radiation on a horizontal surface is represented as H, and hourly total radiation on a horizontal surface is represented by I. The solar spectrum, or the range of wavelengths received from the Sun are depicted in the figure below. Short wave radiation is received from the Sun, in the range of 0.3 to 3 μm, and long wave radiation (greater than 3 μm) is emitted by the atmosphere, collectors or any other body at ordinary temperatures.[5]

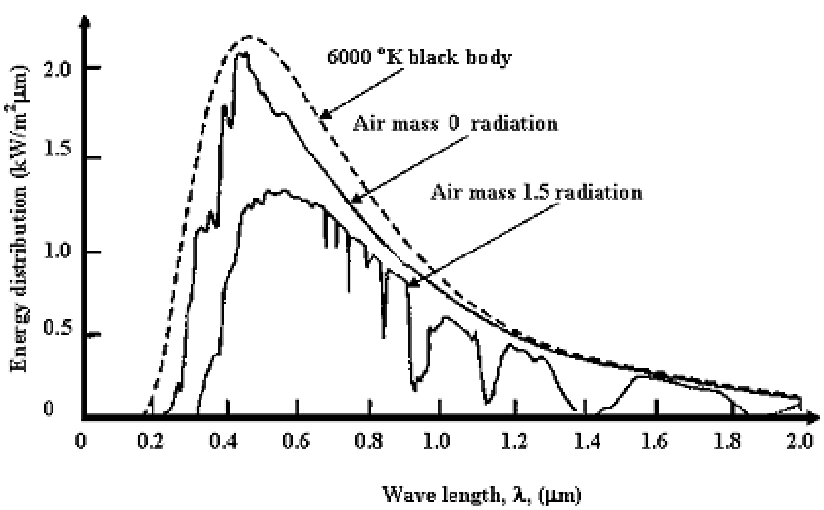


Figure 2: *Source* Sen, Zekai, Solar energy fundamentals and modelling techniques: atmosphere, environment, climate change and renewable energy.[6]

---

[3] M. Chegaar, A. Lamri and A. Chibani, "Estimating Global Solar Radiation Using Sunshine Hours", Physique Energétique (1998) 7 – 11.
[4] Duffie John A, William Beckman A, "Solar Engineering of Thermal Processes, 3rd Edition, 2006, John Wiley and Sons Inc, pages 3 – 138.
[5] Ibid.
[6] Sen, Zekai, Solar energy fundamentals and modeling techniques:atmosphere, environment, climate change and renewable energy, Springer, 2008, pp 44-70.

**Definitions and terminology**

**Beam Radiation** – solar radiation received from the Sun without being scattered by the atmosphere and propagating along the line joining the receiving surface and the sun. It is also referred as direct radiation. It is measured by a pyrehiliometer.

**Diffuse Radiation** – the solar radiation received from the Sun after its direction has been changed due to scattering by the atmosphere. It does not have a unique direction and also does not follow the fundamental principles of optics. It is measured by shading pyrenometer.

**Total Solar Radiation** – the sum of beam and diffused radiation on a surface. The most common measurements of solar radiation is total radiation on a horizontal surface often referred to as 'global radiation' on the surface. It is measured by pyrenometer.

**Irradiance ($W/m^2$)** – the rate at which incident energy is incident on a surface of unit area. The symbol G is used to denote irradiation.

**Irradiation ($J/m^2$)** – the incident energy per unit area on a surface, found by integration of irradiation over a specified time, usually an hour (I) or a day (H).

**Solar Constant -** The solar constant is the amount of incoming solar radiation per unit area, measured at the outer surface of Earth's atmosphere, in a plane perpendicular to the rays

**Direct Normal Insolation (DNI) -** It is the direct component of the solar radiation incident normal to the collector; that is, the angle of incidence of solar radiation with the normal of the collector is zero throughout the day.

### 5.1.2 Measurement of Solar Radiation

Measurements may be direct or indirect. Direct methods are those involving the use of devices such as pyrheliometers and pyranometers at radiation stations. Indirect methods use satellite data, the number of sunshine hours, or extrapolation to arrive at values for radiation at a place. The solar radiation data should be measured continuously and accurately over the long term. Unfortunately, in most areas of the world, solar radiation measurements are not easily available due to financial, technical or institutional limitations

Solar radiation is measured using pyrheliometers and pyranometers. Ångström and Thermoelectric Pyrheliometers are used for measurement for direct solar radiation and global solar radiation is measured using the Thermoelectric Pyranometer. A Thermoelectric Pyranometer with a shading ring is used for measurement of diffuse radiation. Inverted pyranometers and Sunphotometers are used for measuring reflected solar irradiance and solar spectral irradiance and turbidity respectively.[7]

---

[7] Solar Radiation Hand Book, Solar Energy Centre, MNRE and Indian Metrological Department, 2008.

In India, large scale measurements are carried out by the India Meteorological Department at 45 radiation observatories with data loggers at four of these stations.[8] The stations are depicted on the map below (Fig 2), obtained from the IMD Pune website.

Another method of acquiring data is through mathematical modeling and extrapolation of data using variables such as sunshine hours, cloud cover and humidity. This modeled data generally is not very accurate for several reasons. Models require complex calibration procedures, detailed knowledge of atmospheric conditions and adjustments to produce reasonable results. Further inaccuracies arise in micro-climates and areas near mountains, large bodies of water, or snow cover.

The third source of radiation data is satellite measured data such as that provided by NASA. NASA data is available for any location on Earth, and can be obtained by specifying the coordinates of the location. The data is available in near real time for daily averages and for 3 hour intervals. Also, this data can be accessed free of cost online

[8] IMD Pune website, http://www.imdpune.gov.in/, accessed on 20th June 2010

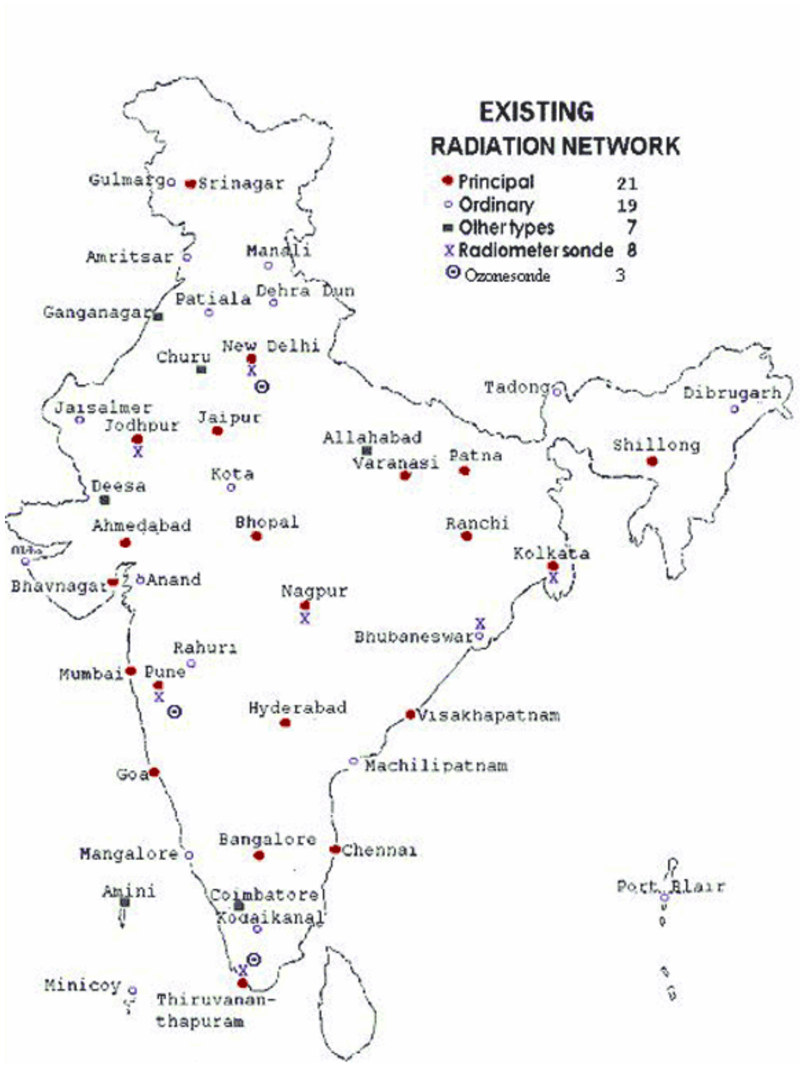


Figure 3: List of radiation stations installed by IMD. Source: IMD website.

### 5.1.3 Sources of radiation data

Radiation data is available from various sources, such as IMD, NREL, Meteonorm, NASA, WRDC (World Radiation Data Centre) and so on. Some of these agencies provide data free of cost and with others, the data needs to be purchased. The following are the key features of the some data sources considered by us:

**Meteonorm**

Provides data of more than 8,055 weather stations. The measured parameters are monthly means of global radiation, temperature, humidity, precipitation, days with precipitation, wind speed and direction, sunshine duration. Time periods 1961-90 and 1996-2005 for temperature, humidity, precipitation and wind speed are available. Satellite data is used for areas with low density of weather stations. Interpolation models are provided in the software to calculate mean values for any site in the world. The user may import data for use in the models. This data is not freely available, and must be purchased along with the Meteonorm software.

**WRDC**

WRDC (World Radiation Data Center) provides monthly irradiance for 1195 sites in the world, averaged during periods between 1964 and 1993. Many of them are only over a few years. These data doesn't include temperatures, which should be obtained from another source. This data is available free of cost.

**RETScreen**

RETScreen is Canadian software which holds a complete database for any location in the world, optimised for using the best available data at each location from about 20 sources, the main ones being the WRDC and the NASA irradiance data. Temperatures and wind velocities are also provided probably with good reliability. NASA and WRDC data are available free of cost, and hence RETScreen data is also free.

**IMD**

IMD has 45 radiation observatories recording various radiation parameters. At all these stations, measurement of global solar radiation is being carried out while at a few selected stations other parameters like diffuse, direct, net, net-terrestrial and reflected radiation and atmospheric turbidity are also measured. Data loggers have been introduced at four stations viz. New Delhi, Patna, Jaipur and Thiruvanathapuram.

Besides the measurements on the surface, fortnightly airborne soundings are made with radio metersondes to measure directly the vertical distribution of the infrared radiation flux and radiation cooling from surface upto a height of 20 Km or more in the free atmosphere, at New Delhi, Srinagar, Thiruvananthapuram, Pune, Nagpur, Jodhpur, Calcutta and Bhubaneshwar. Radiometersonde ascents are being conducted regularly at Maitri, the Indian Antaractic station also.

**NASA**

NASA provides over 200 satellite-derived meteorology and solar energy parameters. These are monthly averages from 22 years of data. Global solar energy data is available for 1195 ground sites. These data are available free of cost.

**3TIER**

3TIER provides custom reports enabling assessment for commercial and utility-scale solar projects. This organization provides FullView Solar Site Climate Variability Analysis (CVA) which describes a complete picture of the solar resources at required site. Based on a satellite derived 11 to 13-year time-series, this product includes the intensity and variability of irradiance values and additional data on wind speed and temperature.

| Database | Region | Values | Source | Period | Availability |
|---|---|---|---|---|---|
| **Meteonorm** | Worldwide | Monthly | 1770 stations and interpolation | 1960-2005 | Software (to be purchased) |
| **NASA** | Worldwide | Monthly | Satellites | 1983-1993 | Free (web) |
| **WRDC** | Worldwide | Hourly, | 1195 | 1964-1993 | Free (web) |

| | | | | | |
|---|---|---|---|---|---|
| | | Daily, Monthly | stations | | |
| **RETScreen** | Worldwide | Monthly | Various sources compiled, including WRDC and NASA | 1961-1990 | Software (free) |
| **IMD** | India | Monthly | Terrestrial | 1957-2008 | To be purchased |
| **3TIER** | Worldwide | Monthly | Satellites | 1991-2008 | To be purchased |

Table 2: Radiation data sources

**Comparison of various sources of data**

The radiation data can be used from all the above mentioned sources. However, each has its own accuracy levels.

The satellite data has the following limitations:[9]

- The sensors generally cannot distinguish between clouds and snow cover.
- The measurements are less accurate near mountains, oceans or other large bodies of water.
- All measurements are essentially made at the top of the atmosphere and require atmospheric models to estimate the solar radiation at the ground.

NASA estimates that their measurements of average daily solar radiation have an RMS error of 35 W/m2 (roughly 20% inaccuracy). The World Climate Research Program estimated that routine-operational ground solar radiation sites had end-to-end inaccuracies of 6-12%, with the highest quality research sites in the range of 3-6% inaccuracy.1 Other researchers comparing NASA solar radiation measurements to ground-based sites have found comparable results (19% average error in the daily data).

Based on the merits and demerits of the different sources of radiation data, it can be concluded that the most reliable data is obtained from ground based weather stations. Therefore it is recommended that the IMD/MNRE Handbook of Solar Radiation at 23 locations based on actual measurements should be used for assessing the performance of solar power plants. In locations where IMD is data is not available, NASA/Meteonorm data may be used.

[9] Hall James and Hall Jeffrey, "Evaluating the Accuracy of Solar Radiation Data Sources", Solar Data Warehouse, February 2010.

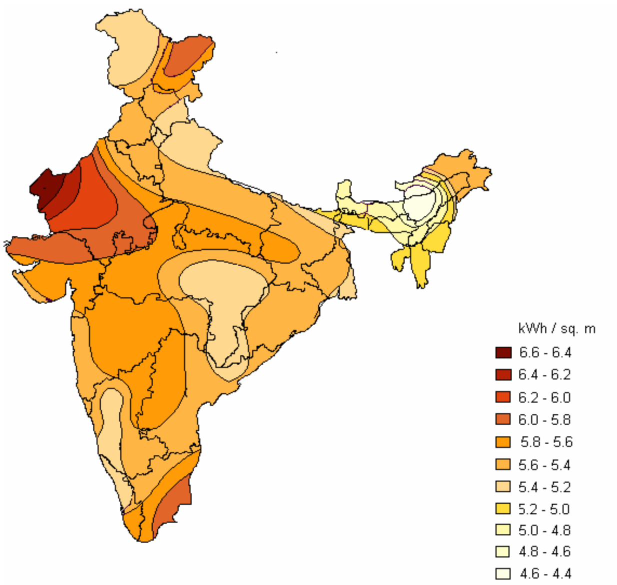


Figure.4 Solar radiation zones as per TERI based on the IMD database.

### 5.2 Losses in PV Solar systems

The estimated system losses are all the losses in the system, which cause the power actually delivered to the electricity grid to be lower than the power produced by the PV modules. There are several causes for this loss, such as losses in cables, power inverters, dirt (sometimes snow) on the modules, ambient temperature, varying insolation levels and so on. While designing a PV system, we have to take into consideration all possible losses.

**Reflection losses**

PV module power ratings are determined at standard test conditions, which require perpendicular incident light. Under field conditions larger incidence angles occur, resulting in higher reflection losses than accounted for in the nominal power rating. Calculations show that for modules faced towards the equator, and with a tilt angle equal to the latitude, yearly reflection losses relative to STC are about 1%.

**Soiling**

Soiling of solar panels can occur as a result of dust and dirt accumulation. In most cases, the material is washed off the panel surface by rainfall; however dirt like bird droppings may stay even after heavy rains. The most critical part of a module is the lower edge. Especially with rather low inclinations, soiling at the edge of the frame occurs. By often repeated water collection in the shallow puddle between frame and glass and consecutive evaporation dirt accumulates. Once it causes shading of the cells, this dirt reduces the available power from a module. The losses are generally 1%, however the power is restored if the modules are cleaned.

**Mismatch effects**
Mismatch losses are caused by the interconnection of solar modules in series and parallel . The modules which do not have identical properties or which experience different conditions from one another. Mismatch losses are a serious problem in PV modules and arrays because the output of the entire PV array under worst case conditions is determined by the solar module with the lowest output. Therefore the selection of modules becomes quite important in overall performance of the plant.

**MPPT Losses**

**Maximum Power Point Tracking (MPPT)**

Power output of a Solar PV module changes with change in direction of sun, changes in
solar insolation level and with varying temperature.

The PV(power vs. voltage) curve of the module there is a single maxima of power. That is there exists a peak power corresponding to a particular voltage and current. Since the module efficiency is low it is desirable to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and insolation conditions. Hence maximization of power improves the utilization of the solar PV module. A maximum power point tracker (MPPT) is used for extracting the maximum power from the solar pv module and transferring that power to the load. A dc/dc converter(step up/step down) serves the purpose of transferring maximum power f rom the solar PV module to the load. Maximum power point tracking is used to ensure that the panel output is always achieved at the maximum power point. Using MPPT significantly increases the output from the solar power plant.
As depicted in the V-I curves for the monocrystalline solar module below, the maximum power point is achieved at the intersection of the current and voltage curves at a particular value of irradiation.

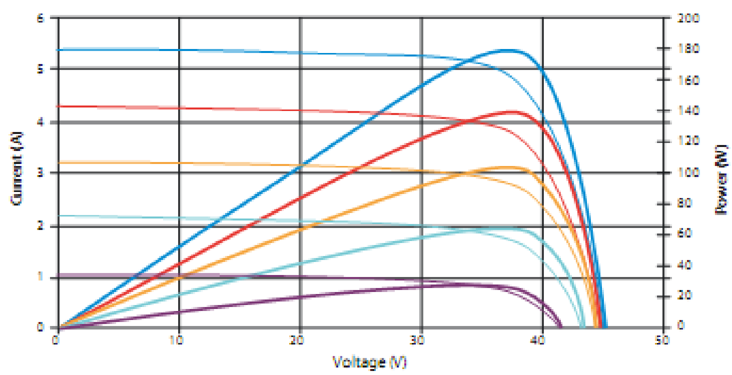


Figure 5: Maximum Power Point Tracking

There are losses in the cabling, transformer, inverter and transmission systems, which are easy to determine in most cases.

**Inverter efficiency**

A solar PV inverter is a type of electrical inverter that is made to change the direct current (DC) electricity from a photovoltaic array into alternating current (AC) for use with home appliances or to be fed into the utility grid. These inverters may be stand alone inverters, which are used in isolated systems, or grid tie inverters which are used to connect the power plant to the grid.

The efficiency of an inverter has to do with how well it converts the DC voltage into AC. The currently available grid connected inverters have efficiencies of 96 to 98.5%, and hence choosing the correct inverter is crucial to the design process. There are less efficient inverters below 95% also available.

Inverters are also much less efficient when used at the low end of their maximum power. Most inverters are most efficient in the 30% to 90% power range.

### 5.3 Solar Plant design

The long term commercialization of utility based solar PV electric generation requires the development of safe, efficient, reliable, affordable components and systems that meet utility expectations of performance and life cycle cost per kWh production goals, while allowing for full integration of time variant intermittent renewable generation resources in the utility generation portfolio.
Cost reductions available through design, material specification and construction techniques developed by the power industry in response to the need for lower cost traditional generating stations can effect significant cost savings when applied to PV generation systems. Higher generation through proper design and use of efficient system components effectively means lower cost of power.

Some critical factors which must be kept in mind during design include proper selection of modules, optimum angle of tilt, minimization of ohmic losses with proper selection of conductors, selection of efficient transformers and inverters etc. Use of reliable and long life components is equally essential for expensive solar power plants.

The actual energy output that one can expect from a given PV system depends on a large number of factors. Some of these are:

- The PV efficiency is affected to a greater or lesser extent by the temperature of the module, usually decreasing with increasing temperature.
- Nearly all module types show decreasing efficiency with low light intensity. The strength of this effect varies between module types.

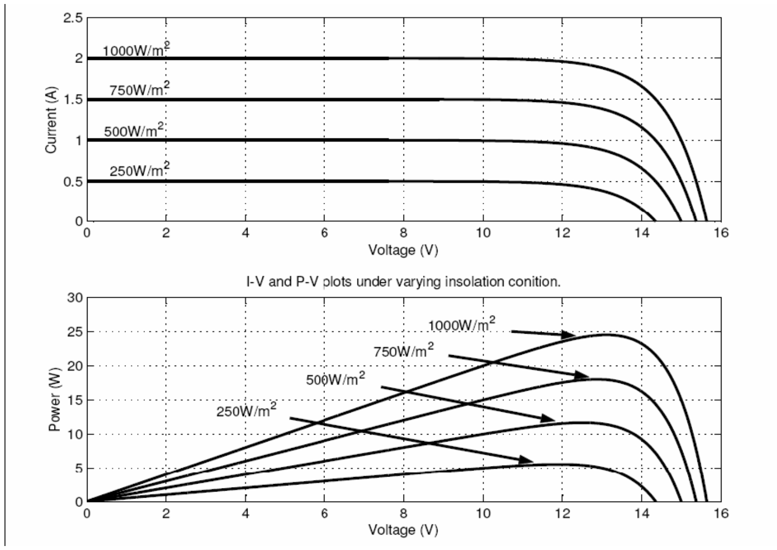


Fig. 6 Changes in the characteristics of the solar pv module due to change in insolation level

- Some of the light is reflected from the surface of the modules and never reaches the actual PV material. How much depends on the angle at which the light strikes the module. The more the light comes from the side (narrow angle with the module plane), the higher the percentage of reflected light. This effect varies (not strongly) between module types.
- The conversion efficiency depends on the spectrum of the solar radiation. Where nearly all PV technologies have good performance for visible light, there are large differences in the efficiency for near-infrared radiation. If the spectrum of the light were always the same this effect would be assumed to be part of the nominal efficiency of the modules. But the spectrum changes with the time of day and year, and with the amount of diffuse light (light not coming directly from the sun but from the sky, clouds etc.).
- Finally, some module types have long-term variations in the performance. Especially modules made from amorphous silicon are subject to seasonal variations in performance, driven by long-term exposure to light and to high temperatures.
- **Mounting position**
  For fixed (non-tracking) systems the way the modules are mounted will have an influence on the temperature of the module, which in turn affects the efficiency (see above). Experiments have shown that if the movement of air behind the modules is restricted, the modules can get considerably hotter (up to 15°C at 1000W/m2 of sunlight).

- **Inclination angle**
  This is the angle of the PV modules from the horizontal plane, for a fixed (non-tracking) mounting .It is also noted that the global radiation measurements are done on horizontal surface. The maximum radiation can be obtained by tilting

the surface at an optimum angle, which is determined by the latitude of the location.   Comparison for Indian metro cities is given below.

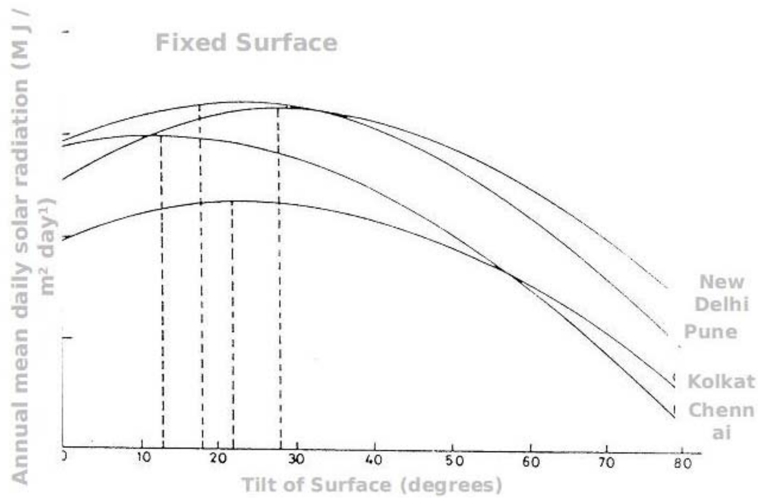


Figure 7: Global radiation at different tilt angle

Table 3  Daily global radiation ( MJ m-2 per day)

| CITY | Horizontal Radiation | Optimum tilt Radiation |
|---|---|---|
| **New Delhi** | **19.67** | **21.54** |
| **Kolkata** | **17.47** | **19.07** |
| **Pune** | **20.4** | **21.94** |
| **Chennai** | **20.12** | **20.99** |

**Temperature**

Module performance is generally rated under Standard Test Conditions (STC): irradiance of 1,000 W/m², solar spectrum of AM 1.5 and module temperature at 25°C. All electrical parameters of solar module depend on temperature. The module output decreases with increase in temperature. The loss of power as defined by **Temperature coefficients.**

This effect can be seen in the sample V-I characteristics, obtained from the specification sheet for commercially available module.

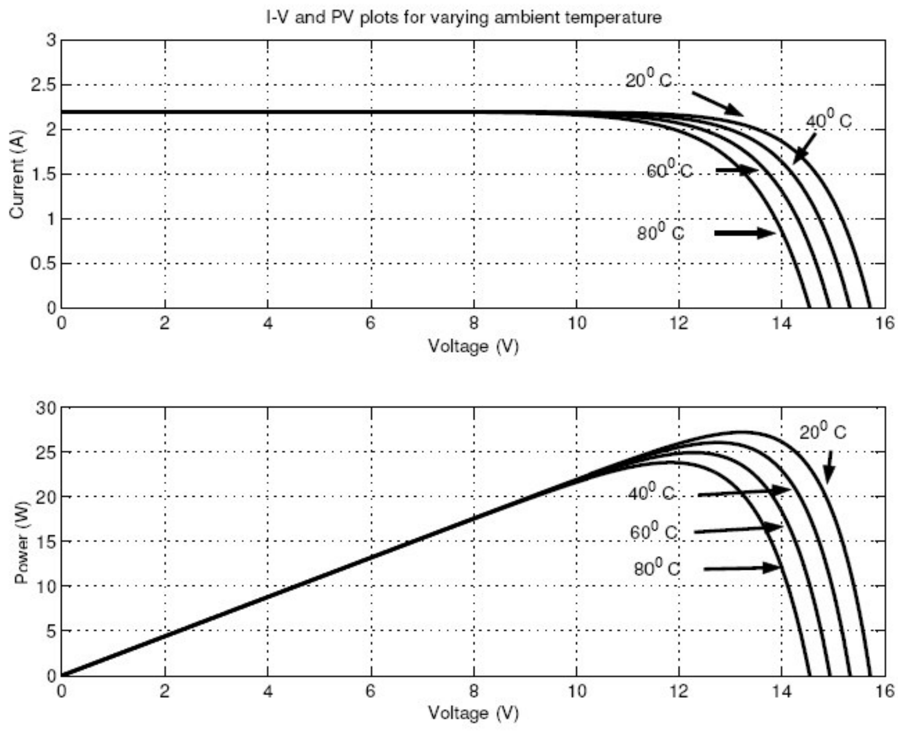


Figure 8: Temperature coefficient for crystalline cells

The temperature coefficient represents the change in power output with different temperatures. Typical values of temperature coefficient for for crystalline silicon are as follows:

$\gamma$ ($P_{mpp}$) typical values for crystalline modules is -0.4 to 0.45%/K
$\gamma$ ($P_{mpp}$) typical values for amorphous modules is -0.2 to 0.23%/K
$\gamma$ ($P_{mpp}$) typical values for CdTe modules is -0.24 to 0.25%/K

Therefore thin film modules will certainly give higher performance at elevated temperature when compared to crystalline silicon.

### 5.4 Long term reliability

The long term reliability of photovoltaic modules has been improving steadily, with manufacturers offering over 25 years guarantee on their panels. However, no power plant has been in existence for such a long period of time, for verification of the guarantee. Some reports have been published on this subject by NREL, Fraunhofer Institute and so on. This report intends to extend the same study for panels in India, by getting data from installed power plants.

It is important for the PV industry to know the long term reliability, since it impacts the life of the PV system, and hence changes the cost considerations. The factors mentioned as other losses in the section above are used for accelerated rate testing since it is not feasible to test for 25 years to get results[10]. However, these accelerated tests still do not completely simulate real conditions and hence field accelerated techniques are used wherein one of the factors is artificially enhanced and tests are done, but on installed plants[11].

NREL tests have concluded that the degradation and the losses in maximum power are almost entirely due to losses in short circuit current, and that these losses are almost identical for single and poly crystalline panels and are highly dependent on the process used in manufacture[12]. The drop in current production by the modules can be attributed in part to the visually observable physical defects including EVA browning, delamination at the Si- cell/EVA interface and the occurrence of localized hot spots.

## 6.0Module Degradation

### 6.1 Background

The degradation of solar modules with temperature and time contributes significantly to the final output from the panel. As the output reduces each year, so does the revenue from sale of power, and therefore accurate data must be available at the outset to ensure that the power plant design is exact and not over or under the required output. Lifetime of the module is one of the four factors besides system price, system yield and capital interest rate which decides the cost of electricity produced from the module, and this lifetime is decided by the degradation rate.

The effect of degradation of photovoltaic solar modules and arrays and their subsequent loss of performance has a serious impact on the total energy generation. And with respect to this maximum power at standard test conditions, (Pmax at STC) is the most critical characteristic of the photovoltaic module or array for all of its operational life. For calculation of the system size to the associated investment costs Pmax is a key working value. The effective cost of power generation Rs./kWh is dependant on the initial investments, expected returns (KWh) and the assumption that the module will operate for a sufficiently long period (lifetime) to guarantee the return of the investment.[13]

Most manufacturers indicate the extent to which the panel will degrade, through the guarantee. This is specified as a ratio of the maximum power available at the time time of installation. Most manufacturers claim their panels will produce 90% of the maximum power after a period of 10 years, and 80% of the maximum power after 25 years. Hence, most power plants are also designed for a life of 25 years.

---

[10] Ibid.

[11] A.M. Reis, N.T. Coleman, M.W. Marshall, P.A. Lehman, and C.E. Chamberlin, “Comparison OF PV Module Performance before and after 11 years of field exposure”, Proceedings of the 29th IEEE Photovoltaics Specialists Conference New Orleans, Louisiana May, 2002

[12] C.R. Osterwald, A. Anderberg, S. Rummel, and L. Ottoson, “Degradation Analysis of Weathered Crystalline-Silicon PV Modules”, 29th IEEE PV Specialists Conference, New Orleans, Louisiana, May 20-24, 2002.

[13] Ewan D. Dunlop, David Halton, “The Performance of Crystalline Silicon Photovoltaic Solar Modules after 22 Years of Continuous Outdoor Exposure”, Prog. Photovolt: Res. Appl. 2006; 14:53–64

However, since most installed solar PV power plants are less than 25 years old, this data is not available readily, and especially in the Indian scenario where solar power plants are relatively new.

### 6.2 Causes of degradation

Tests on module degradation are performed using real-time and accelerated exposures. These tests are conducted by institutions of international repute such as the Fraunhofer Institute, the National Renewable Energy Laboratory, Solar Energy Research Institute of Singapore and so on. These tests have successfully demonstrated that there is module degradation (usually less than 1% per year), and the possible reasons for this are the slow breakdown of a module's encapsulant (usually ethylene vinyl acetate; EVA) and back sheet (polyvinyl fluoride films), the gradual obscuration of the EVA layer between the module's front glass and the cells themselves, and the deterioration of solar cells due to temperature increase. The silicon cells themselves have infinite life, except for the slight degradation due to thermal effects. The degradation of the module itself is due to a collection of factors as mentioned above.

Module encapsulant protects the cells and internal electrical connections against moisture ingress. Some amount of moisture does enter, and is forced back out on a daily basis, as module temperature increases. Sunlight slowly breaks down the encapsulation materials through ultraviolet (UV) degradation, making them less elastic and more plastic. Over time, this limits a module's ability to force out moisture. The trapped moisture eventually leads to corrosion at the cell's electrical connections, resulting in higher resistance at the affected connections and, ultimately, decreased module operating voltage.

The second source for output degradation occurs as UV light breaks down the EVA layer between a module's front glass and the silicon cells. The properties of the encapsulant are critical to the long-term performance of modules. The silicon solar cells are fragile and an encapsulant is needed to protect them against cracking and breaking. This gradual breakdown of the material isn't usually visible to the naked eye, but over time this obscuration limits the amount of sunlight that can hit the cell.[14] A slight but incremental decrease in cell output current is the result. The main cause of reduction in output is the discolouration of the EVA layer due to interactions between cross-linking peroxides and certain stabilizing additives, and also due to oxidation of the EVA layer.

The third cause for degradation is inherent to the silicon cells, resulting from exposure to sunlight, resulting in defects called metastable dangling bonds. These can be removed by heating the cell to a high temperature, something that is not possible in practice. The dangling bonds capture electrons, therefore reducing the electrical output and hence the efficiency. Research has shown that this form of degradation leads to a 15-20% reduction in efficiency.[15]

---

[14] Peter Klemchuk, Myer Ezrin, Gary Lavigne, William Halley, James Susan Agro, "Investigation of the degradation and stabilization of EVA-based encapsulant in field-aged solar energy modules." Polymer Degradation and Stability 55 (1997) pp. 347-365.

[15] Saren Johnston, "Sunproofing Solar Cells Computer simulations help explain why solar cells degrade in sunlight", Insider, April 2003.

To estimate the lifetime from degradation, standard tests called ‘Type Approval Tests’ have been introduced by the International Electrotechnical Commission (IEC). These are essentially accelerated test procedures based on accelerated climatic testing. However, there is still some uncertainty as to whether these accelerated tests can accurately simulate real time long term exposure. The IEA guidelines recommended life expectancy used in life cycle assessment studies of photovoltaic components and systems as follows:

- Modules: 30 years for mature module technologies (e.g. glass-tedlar encapsulation),
life expectancy may be lower for foil-only encapsulation;

- Inverters: 15 years for small size plants (residential PV); 30 years with 10% of part replacement every 10 yrs (parts need to be specified) for large size plants (utility PV, (Mason et al. 2006);

- Structure: 30 years for roof-top and façades and between 30 to 60 years for ground mount installations on metal supports. Sensitivity analyses should be carried out by varying the service life of ground mount supporting structures within the time span indicated.

- Cabling: 30 years

**Guarantees and long term studies**

We listed the guarantees given by panel manufacturers. It was noted that most panels are guaranteed to produce outputs of 90% after 10 years of use and 80% after 20 years of use. This data has been compared with the degradation data obtained from long term tests conducted by various institutes, and it is seen that the modules do not degrade by more than 10% in 10 years and more than 20% in 25 years. Recent trends in the manufacturer’s guarantee indicate that the power Hence, with this data, it is reasonable to assume that the yearly reduction in power output is 0.5%. The table below lists the various solar modules considered and the guarantees provided by the manufacturers.

Table 4: Garantees offered by different suppliers

| Manufacturer | Country | Model Number | Watts (p) | Life in years/ Guarantee given |
|---|---|---|---|---|
| **Bosch** | Germany | M 240 3 BB | 240 | 10 years-90%, 25 years-80% |
| **Canadian solar** | Canada | CS5A-170 | 170 | 25 years |
| **Coenergy** | US | Power Plus 215P | 215 | 12 years-92%, 25years-80% |
| **Del Solar** | Taiwan | D6P_E | 120 | 10 years-90%, 25 years-80% |
| **Evergreen solar** | US | ES-A series | 200 | 25 years |
| **First solar** | US | FS Series | 70 | 10 years-90%, |

| | | | | |
|---|---|---|---|---|
| | | | | 25 years-80% |
| **Isofoton** | Spain | IS series | 160 | 10 years-90%, 20 years-83%, 25 years-80% |
| **JA solar holdings** | China | JAS | 165 | 10 years-90%, 25 years-80% |
| **Kyocera** | US | KD235GX-LPB | 235 | 10 years-90%, 25 years-80% |
| **Mitsubishi** | Japan | TD/TE series | 190 | |
| **Mo-Tech** | US | GEPVp series | 205 | 10 years-90%, 25 years-80% |
| **Photowatt** | France | PW2050 | 210 | 12 years-90%, 25 years-80% |
| **Q cells** | Germany | SL 1 | 70 | 25 years |
| **RE corporation** | Norway | PE series | 215 | 10 years-90%, 25 years-80% |
| **Sanyo** | Asia | HIT series | 210 | 25 years-80% |
| **Schott** | Germany | MONO | 180 | 25 years-90% |
| **Solar fabric** | Germany | Premium S Poly | 125 | 10 years-90%, 25 years-90% |
| **Suntech** | China | STP series | 185 | 12 years-90%, 18 years-85%, 25 years-80% |
| **Solarfun** | China | SF series | 160 | 10 years-90%, 25 years-80% |
| **Sunways** | Germany | SM series | 210 | 12 years-90%, 25 years-80% |
| **Solarworld** | US | SW series | 220 | 25 years-80.2% |
| **United Solar Ovonic** | US | PVL series | 68 | 92% at 10 years, 84% at 20 years, 80% at 25 years |
| **PLG Solar** | India | | | 10 years-90%, 25 years-80% |
| **Moser Baer** | India | | | 10 years-90%, 25 years-80% |
| **Tata BP Solar** | India | | | 10 years-90%, 25 years-80% |
| **BP SOLAR** | US | BP 3230T | 230W | 93% over 12 years 85% power output over 25 years |

### 6.3 Case studies on module degradation

There are few long term studies currently available, and research laboratories use accelerated testing methods to simulate the effect of long term exposure of solar modules. This involves several hours of exposure to conditions such as dry heat (85°C, RH < 20%) or damp heat (85°C, RH>85%) and so on. Some long term studies have also been conducted, the results of which are presented below:

1. **Fraunhofer Institute Long Term Study of Schott solar panels**

Fraunhofer Institute conducted a long term study on Schott solar modules that were delivered in 1984 and tested in 2009 and found that 18 out of the 20 modules tested, showed an average power output of 7% below the nominal output listed by the manufacturer on delivery, even after 25 years of use.[16]

2. **NREL Degradation Analysis**

The NREL degradation study was conducted on 2 different single crystal and 2 different polycrystalline modules. The solar weathering program at NREL found a linear relationship between maximum power degradation and the total UV exposure for four different types of commercial crystalline Si modules. The results obtained from the long term studies are depicted in the table below. It was also concluded that most of the degradation occurred in the 800-1100 nm wavelength region, and not in the shorter wavelengths. The PV modules were subjected to real time and accelerated exposures at fixed tilt. For the four crystalline-Si module types in this study (both single and polycrystalline), a linear correlation between the normalized module maximum output power (Pmax) and the total UV exposure was found, due to the absorption of UV radiation at or near the top surface. On comparing the values of short circuit current loss obtained, it was concluded that the losses are clearly due to UV exposure and not due to browning of the encapsulation.

| Module Type | Power (W) | $P_{max}$ Rate (% / year) | $I_{sc}$ Rate (% / year) | $V_{oc}$ Rate (% / year) |
|---|---|---|---|---|
| Single #1 | 11 | -0.88 | -0.59 | -0.12 |
| Single #2 | 16 | -0.76 | -0.60 | -0.14 |
| Poly #1 | 9 | -0.70 | -0.25 | -0.14 |
| Poly #2 | 18 | -0.53 | -0.24 | -0.08 |

Figure:5 Power degradation, Source: NREL

It was concluded that the average degradation rate for the 4 types of modules was 0.71% per year.[17]

---

16 Fraunhofer Institute: Module Power Evaluation Report, commissioned by Schott Solar AG.

17 C.R. Osterwald, A. Anderberg, S. Rummel, and L. Ottoson, "Degradation Analysis of Weathered Crystalline-Silicon PV Modules", 29th IEEE PV Specialists Conference, New Orleans, Louisiana, May 20-24, 2002.

### 3. Study on comparison of degradation rates by NREL[18]

The study was conducted by NREL in 2006 on all types of modules, includes single and poly crystalline, CIS, CIGS etc. From monthly blocks of output power data, ratings were determined using multiple regressions to Performance Test Conditions (PTC). The results of the study are summarized in the table below.

| Manufacturer | Module Type | Exposure (years) | Degradation Rate (% per year) | Measured at System Level? | Ref. |
|---|---|---|---|---|---|
| ARCO Solar | ASI 16-2300 (x-Si) | 23 | -0.4 | N | 2 |
| ARCO Solar | M-75 (x-Si) | 11 | -0.4 | N | 3 |
| [not given] | [not given] (a-Si) | 4 | -1.5 | Y | 4 |
| Eurosolare | M-SI 36 MS (poly-Si) | 11 | -0.4 | Y | 5 |
| AEG | PQ40 (poly-Si) | 12 | -5.0 | N | 6 |
| BP Solar | BP555 (x-Si) | 1 | +0.2 | N | 7 |
| Siemens Solar | SM50H (x-Si) | 1 | +0.2 | N | 7 |
| Atersa | A60 (x-Si) | 1 | -0.8 | N | 7 |
| Isofoton | I110 (x-Si) | 1 | -0.8 | N | 7 |
| Kyocera | KC70 (poly-Si) | 1 | -0.2 | N | 7 |
| Atersa | APX90 (poly-Si) | 1 | -0.3 | N | 7 |
| Photowatt | PW750 (poly-Si) | 1 | -1.1 | N | 7 |
| BP Solar | MSX64 (poly-Si) | 1 | 0.0 | N | 7 |
| Shell Solar | RSM70 (poly-Si) | 1 | -0.3 | N | 7 |
| Würth Solar | WS11007 (CIS) | 1 | -2.9 | N | 7 |
| USSC | SHR-17 (a-Si) | 6 | -1.0 | Y | 8 |
| Siemens Solar | M55 (x-Si) | 10 | -1.2 | Y | 9 |
| [not given] | [not given] (CdTe) | 8 | -1.3 | Y | 9 |
| Siemens Solar | M10 (x-Si) | 5 | -0.9 | N | 10 |
| Siemens Solar | Pro 1 JF (x-Si) | 5 | -0.8 | N | 10 |
| Solarex | MSX10 (poly-Si) | 5 | -0.7 | N | 10 |
| Solarex | MSX20 (poly-Si) | 5 | -0.5 | N | 10 |

Table: 6 NREL degradation study, Source: C.R. Osterwald, J. Adelstein, J.A. del Cueto, B. Kroposki, D. Trudell, and T. Moriarty, National Renewable Energy Laboratory (NREL), "Comparison of degradation rates of individual modules held at maximum power". 2006.

The study concludes that for crystalline silicon, it will be more reasonable to assume a figure of less than 0.5% for degradation.

### 4. Study on comparison of PV module performance before and after 11 years of field exposure

This study, conducted by Schatz Energy Research Center, Humboldt State University concluded that the average module short circuit current and maximum power production at NOCT have decreased by 6.38% and 4.39%, respectively. These modules were installed in 1990 and tested in 2001. All modules were tested within two hours of solar noon with module temperatures ranging from 26.5°C to 62.5°C. The measurements were conducted under clear sky conditions with irradiance values greater than 800 W/m$^2$. Before testing a subsection of the array, the cover glass of each of the modules in that subsection was cleaned in order to remove any residue after which he module was electrically disconnected from the remainder of the PV array and connected across the capacitive load test circuit in order to generate the I-V curve.  As shown in the table below, the change in power

[18] C.R. Osterwald, J. Adelstein, J.A. del Cueto, B. Kroposki, D. Trudell, and T. Moriarty, National Renewable Energy Laboratory (NREL), "Comparison of degradation rates of individual modules held at maximum power". 2006.

output over a period of 11 years was only 4.39%, which is lower than what is quoted by most manufacturers.[19]

| Parameter | 1990 | | 2001 | | % Change |
|---|---|---|---|---|---|
| | $\bar{x}$ | $s_x$ | $\bar{x}$ | $s_x$ | |
| $P_{max}$ (W) | 39.88 | 0.849 | 38.13 | 1.67 | -4.39 |
| $V_{oc}$ (V) | 18.19 | 0.131 | 18.15 | 0.108 | -0.22 |
| $I_{sc}$ (A) | 3.29 | 0.044 | 3.08 | 0.120 | -6.38 |
| $R_s$ (Ohms) | 0.347 | 0.115 | 0.384 | 0.184 | 10.66 |
| $R_p$ (Ohms) | 171 | 39.2 | 115 | 48.7 | -32.75 |
| $ekt$ ($V^{-1}$) | 0.709 | 0.125 | 0.896 | 0.26 | 26.38 |
| $V_{mp}$ (V) | 13.9 | 0.20 | 14.2 | 0.33 | 2.16 |
| $I_{mp}$ (A) | 2.88 | 0.033 | 2.69 | 0.111 | -6.60 |

Figure: 7 Degradation data, Source: Schatz Energy Research Center

### 5. Module testing at Telstra Research Laboratories

The New Energy and Industrial Technology Development Organization (NEDO) of Japan, together with Telstra Corporation of Australia, conducted a 15 year project studying photovoltaic module degradation under laboratory and outdoor field trial situations. The crystalline silicon panels were installed in 1982 and thin film panels in 1987 and have been studied since then. From their long term study on panels, it was concluded that the degradation is 7% over a period of 10 years.[20]

### 6. Results from NREL PV module reliability workshop – "Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years?"

NREL conducted a study in 2010, on two sets of modules, one installed by the Solar Power Corporation in Beverly, Massachusetts and the other installed by Mobil Solar in Gardner, Massachusetts. The results are presented below:[21]

1. Percentage Power Loss Per Year for Solar Power Corporation G12-361CT Modules (Beverly, Massachusetts)

- Average annual power loss from original NOCT rating for 30.2W for all tested modules: 0.539%
- Median annual power loss from original NOCT rating for 30.2W for all tested modules: 0.546%

---

[19] A.M. Reis, N.T. Coleman, M.W. Marshall, P.A. Lehman, and C.E. Chamberlin, "Comparison OF PV Module Performance before and after 11 years of field exposure", Proceedings of the 29th IEEE Photovoltaics Specialists Conference New Orleans, Louisiana May, 2002

[20] Ian Muirhead and Barry Hawkins, "Research into new technology photovoltaic modules at Telstra Research Laboratories – What we have learnt", 1996.

[21] James M. Bing, "Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years? Preliminary Findings", NREL PV Module Reliability Workshop, 2/19/2010.

2. Percentage Power Loss Per Year for Mobil Solar Ra-30-12H Modules (Gardner, Massachusetts)

- Average annual power loss from original STC rating for 30.0W for all tested modules: 0.180%
- Median annual power loss from original STC rating for 30.0W for all tested modules: 0.082%

**7. "The performance of Crystalline Silicon Photovoltaic Solar modules after 22 Years of continuous outdoor exposure", a study conducted by the European Commission, DG Joint Research Centre, Institute for Environment and Sustainability, Renewable Energies Unit.**

This paper presents the results of 40 silicon based PV modules, originating from 6 different manufacturers, which were tested and characterised originally at the European Solar Test Installation, (ESTI), in 1982–1984. The performance of the same modules has been re-measured in 2004 after 20–22 years of continuous outdoor weathering. The researchers compared the results obtained with the typical guarantees given by module manufacturers and concluded that in general the manufacturers are conservative with their power guarantees. Most modules exceed the minimum power levels given for 10 years exposure, even after 22 years in the field, therefore concluding that the actual lifetime of the modules is significantly more than 20 years.[22] The report concludes that, "At the present time many manufacturers give a double power guarantee for their products, typically 90% of the initial Pmax after 10 years operation and 80% after 25 years. Applying these criteria to the data measured here and including a typical measurement uncertainty of a testing laboratory of ±2.5% on Pmax, we find that for the 90% level at 10 years we have only eight modules which fall outside this condition even after twenty two years of outdoor exposure. Considering the second condition of 80% after 25 years in this study we have only two modules that fall outside this range."

**8. Study of a 20 year old power plant**

A study to estimate the Mean Time Before Failure (MTBF) of the first power plant commissioned in Europe in 1982 investigates the performance of the power plant after 20 years of operation in 2002 and compared those with results from accelerated testing of modules. Results show that, after about twenty years, 59% of the modules exhibited a variation of less than -10% to the stated nominal power, 35% of modules exhibited a variation of between -10% and -20%, and only for the 6% of modules showed a variation loss greater than -20%. For a period of 20 years, manufacturers provide a guarantee much higher than the loss in maximum power as

[22] Ewan D. Dunlop, David Halton, "The Performance of Crystalline Silicon Photovoltaic Solar Modules after 22 Years of Continuous Outdoor Exposure", Prog. Photovolt: Res. Appl. 2006; 14:53–64

observed here(since almost 60% of the modules show a loss of less than 10%). This further strengthens the claim that manufacturer warranties are given with a margin of safety.

**RESULTS SUMMARY**

Analysis of the data from various studies indicates that the actual degradation is much lower than the guarantees given by module manufacturers. Over 12 years and 20% for 25 years.

It has been observed that the confidence among manufacturers has increased over time, with some of them giving a guarantee of only 10% degradation over a period of 12 years and 15% over 25 years. This is evident from the increase in guarantee period being provided by module manufacturers, as shown in the table below.

| Module warranty period | Length of warranty |
|---|---|
| **Before 1987** | 5 years |
| **1987 to 1993** | 10 years |
| **1993 to 1999** | 20 years |
| **Since 1999** | 25 years |
| **Expected by 2013** | 30 years |

*Table 7:Module reliability, Source: Wohlgemuth John H, "Long Term Photovoltaic Module Reliability", NCPV and Solar Program Review Meeting 2003.*

The data from long term tests shows that module degradation for 10 years can be in the range of 4 to 7 percent, lower than the 10% degradation currently guaranteed by most manufacturers. This information is extremely relevant during power plant design for getting an accurate estimate of the amount of power and therefore income expected each year after installation. NREL study suggest that a more reasonable thumb of rule will be degradation less than0.5% per year.

One can conclude from all available data that the manufacturers provide a guarantee with a definite margin of safety and for design purpose a lower degradation percentage can be employed. Further, the length of warranty period is continuously increasing, indicating the increase in confidence among manufacturers, as they realise durable quality of their products, due to technology improvements and quality assurance practices.. And lastly, this has important consequences in calculation of electricity cost from the power plant and with increased lifetimes, one can expect better returns on investment. The quality of module is of immense importance. It is safe to assume no degradation for the first three years and then a maximum of 0.5% per year over the life of modules.

## 7.0 Estimation of CUF of Solar Plant at different locations

***Software available for solar PV power estimation***

For estimation of power generation from PV power plants several softwares are available. Some of these are:

### *RETScreen*

The RETScreen Clean Energy Project Analysis Software is a clean energy decision-making software. It is provided completely free-of-charge by the Government of Canada. RETScreen allows engineers, architects, and financial planners to model and analyze any clean energy project. Decision-makers can conduct a five step standard analysis, including energy analysis, cost analysis, emission analysis, financial analysis, and sensitivity/risk analysis.

*For the purpose of this report, we used RETScreen in order to compare the output from standard 1 MW power plants using IMD data wherever available and RETscreen data in other cases. Certain assumptions about the efficiency and expected losses were included and kept as constants for all simulations.*

### PVSyst[23]

PVSyst is available freely for a 15 day trial period, during which period the full version is accessible. Data is included for certain stations and new data set can be created by importing data. PVSyst has a preliminary and a project design mode, and the preliminary mode can be used to get an approximate value of radiation and power output from the system. The project design mode allows for user defined losses, inverter efficiency, shading analysis and several other variables which provide a more accurate output.

The software has the following three main modules:

Preliminary design

This is a simple tool for grid, stand-alone or pumping system pre-sizing. Upon user's requirements like energy/water needs and "Loss of load" probability, and very few other input parameters, this provides the PV-system component sizes, evaluates the monthly production and performances, and performs a preliminary economic evaluation of the PV system.

Project design

This is used for performing detailed simulation in hourly values, including an easy-to-use expert system, which helps the user to define the PV-field and to choose the right components. This produces a complete printable Report with all parameter and main results.

Tools

This module performs the database meteorological and components management. It provides also a wide choice of general solar tools (solar geometry, meteorological on

[23] http://www.pvsyst.com/5.2/index.php (accessed on 15th July 2010)

tilted planes, etc), as well as a powerful mean of importing real data measured on existing PV systems for close comparisons with simulated values.

**HOMER**[24]

HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation (DG) applications. HOMER's optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options and to account for uncertainty in technology costs, energy resource availability, and other variables. HOMER models both conventional and renewable energy technologies.

In 2009 NREL granted a license to distribute and enhance HOMER to HOMER Energy (another version of the software). HOMER Energy provides a highly visible commercial outlet for NREL's renewable energy simulation tools, with the goal of enhancing the use of HOMER by industry and decision makers. HOMER Energy will distribute HOMER worldwide through its affiliates and will provide customization, training, and technical support for its global user base.

Based on the details discussed above it was decided to use the radiation data for 23 locations as per IMD for the purpose of calculations of CUF. The wellknown RETScreen software was used for these calculations. The assumptions made and the results are described below both for crystalline technology and thin film technology.

The following data for 45 (23 from MNRE booklet +22 others) locations has been prepared using RETScreen software, and radiation data from the MNRE handbook on Solar Radiation. The assumptions made in RETScreen are given below for reference.

**ASSUMPTIONS**

**Table: 8 Crystalline Silicon Modules**

| **Photovoltaic** | | |
|---|---|---|
| Type | | c-Si |
| Power capacity | kW | 1,000.00 |
| Manufacturer | | Moser Baer |
| Model | | MBPV-CAAP |
| Efficiency | % | 13.0% |
| Nominal operating cell temperature | °C | 47 |
| Temperature coefficient | % / °C | 0.43% |
| Solar collector area | m² | 7,692 |
| Control method | | Maximum power point tracker |
| Miscellaneous losses | % | 7.5% |

[24] https://analysis.nrel.gov/homer/ (accessed on 20th July 2010)

**Inverter**

| | | |
|---|---|---|
| Efficiency | % | 96.0% |
| Capacity | kW | 1000.0 |
| Miscellaneous losses | % | 0.0% |

Amorphous modules

**Photovoltaic**

| | | |
|---|---|---|
| Type | | a-Si |
| Power capacity | kW | 1,000.00 |
| Manufacturer | | Moser Baer |
| Model | | MBTF Power series |
| Efficiency | % | 6.0% |
| Nominal operating cell temperature | °C | 47 |
| Temperature coefficient | % / °C | 0.20% |
| Solar collector area | m² | 16,667 |
| Control method | | Maximum power point tracker |
| Miscellaneous losses | % | 7.5% |

**Inverter**

| | | |
|---|---|---|
| Efficiency | % | 96.0% |
| Capacity | kW | 1000.0 |
| Miscellaneous losses | % | 0.0% |

Assumptions used in RETScreen for crystalline and amorphous silicon modules

The average irradiation is in kWh/m$^2$, and the electrical output is in Mega Watt Hour.

Table 9: showing the CUF at various locations.

| Sl. No. | City | Average Radiation | Ambient Temp | Crystalline output | CUF | Thin film output | CUF | Optimum Tilt |
|---|---|---|---|---|---|---|---|---|
| 1 | **Srinagar** | 4.10 | 13.6 | **1,337.97** | **15.27** | **1,373.51** | **15.68** | 34.1 |
| 2 | ***Delhi*** | 5.09 | 25.1 | **1,611.9** | **18.40** | **1,708.4** | **19.50** | 28.6 |
| 3 | ***Jodhpur*** | 5.52 | 26.1 | **1,732.40** | **19.78** | **1,845.10** | **21.06** | 26.3 |
| 4 | **Jaipur** | 5.52 | 26.1 | **1,741.10** | **19.88** | **1,854.40** | **21.17** | 26.8 |
| 5 | **Varanasi** | 4.88 | 25.1 | **1,521.90** | **17.37** | **1,609.20** | **18.37** | 25.3 |
| 6 | **Patna** | 4.83 | 25.3 | **1,509.80** | **17.24** | **1,596.40** | **18.22** | 25.6 |
| 7 | **Shillong** | 4.54 | 16.5 | **1,510.05** | **17.24** | **1,556.50** | **17.77** | 25.6 |
| 8 | **Ahmedanad** | 5.35 | 27.5 | **1,643.20** | **18.76** | **1,753.80** | **20.02** | 23.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 9 | **Bhopal** | 5.23 | 25.3 | **1,635.35** | **18.67** | **1,734.89** | **19.80** | 23.3 |
| 10 | **Ranchi** | 4.70 | 24.3 | **1,484.00** | **16.94** | **1,562.46** | **17.84** | 23.4 |
| 11 | **Kolkata** | 4.50 | 26.9 | **1,378.60** | **15.74** | **1,458.30** | **16.65** | 22.5 |
| 12 | **Bhavnagar** | 5.70 | 27.2 | **1,743.20** | **19.90** | **1,863.80** | **21.28** | 21.8 |
| 13 | **Nagpur** | 5.12 | 27.0 | **1,563.27** | **17.85** | **1,662.80** | **18.98** | 21.1 |
| 14 | **Mumbai** | 5.03 | 27.5 | **1,506.13** | **17.19** | **1,601.85** | **18.29** | 19.1 |
| 15 | **Pune** | 5.41 | 24.7 | **1,648.50** | **18.82** | **1,745.40** | **19.92** | 18.5 |
| 16 | **Hyderabad** | 5.67 | 26.7 | **1,706.00** | **19.47** | **1,818.70** | **20.76** | 17.5 |
| 17 | **Vishakapatnam** | 5.13 | 28.4 | **1,537.20** | **17.55** | **1,638.90** | **18.71** | 17.7 |
| 18 | **Panjim** | 5.50 | 27.4 | **1,645.87** | **18.79** | **1,756.70** | **20.05** | 15.5 |
| 19 | **Chennai** | 5.36 | 28.8 | **1,560.40** | **17.81** | **1,667.60** | **19.04** | 13 |
| 20 | **Bangalore** | 5.47 | 24.1 | **1,642.90** | **18.75** | **1,736.10** | **19.82** | 13 |
| 21 | **Port Blair** | 4.73 | 26.2 | **1,420.00** | **16.21** | **1,500.27** | **17.13** | 11.7 |
| 22 | **Minicoy** | 27.2 | 27.5 | **1,487.30** | **16.98** | **1,577.50** | **18.01** | 8.3 |
| 23 | **Thiruvanan-tapuram** | 5.41 | 27.3 | **1,581.30** | **18.05** | **1,682.50** | **19.21** | 8.5 |
| 24 | **Chandrapur** | 5.12 | 27.5 | **1,562.59** | **17.84** | **1,664.87** | **19.01** | 20 |
| 25 | **Pahalgam** | 4.70 | 0.0 | **1,703.90** | **19.45** | **1,698.50** | **19.39** | 34 |
| 26 | **Gangapur** | 4.97 | 25.0 | **1,569.60** | **17.92** | **1,659.70** | **18.95** | 26.5 |
| 27 | **Ludhiana** | 5.23 | 22.6 | **1,708.10** | **19.50** | **1,801.80** | **20.57** | 30.9 |
| 28 | **Manali** | 4.59 | -1.6 | **1,664.50** | **19.00** | **1,650.20** | **18.84** | 32.3 |
| 29 | **Dehra Dun** | 5.32 | 11.4 | **1,837.40** | **20.97** | **1,884.20** | **21.51** | 30.3 |
| 30 | **Churu** | 4.92 | 24.1 | **1,555.70** | **17.76** | **1,641.50** | **18.74** | 28.3 |
| 31 | **Jaisalmer** | 5.17 | 25.9 | **1,609.10** | **18.37** | **1,708.40** | **19.50** | 26.9 |
| 32 | **Allahbad** | 5.79 | 25.9 | **1,822.50** | **20.80** | **1,943.90** | **22.19** | 25.5 |
| 33 | **Darjeeling** | 4.80 | 9.0 | **1,641.00** | **18.73** | **1,663.60** | **18.99** | 27.1 |
| 34 | **Dibrugarh** | 3.92 | 17.1 | **1,320.58** | **15.08** | **1,357.42** | **15.50** | 27.5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 35 | **Kota** | 5.08 | 25.4 | **1,592.70** | **18.18** | **1,686.70** | **19.25** | 25.2 |
| 36 | **Palanpur** | 5.15 | 26.6 | **1,594.80** | **18.21** | **1,694.90** | **19.35** | 24.2 |
| 37 | **Vadodara** | 5.29 | 27.5 | **1,621.60** | **18.51** | **1,730.20** | **19.75** | 22.3 |
| 38 | **Bhuvaneshwar** | 4.82 | 26.9 | **1,476.63** | **16.86** | **1,566.03** | **17.88** | 20.3 |
| 39 | **Ahmadnahar** | 5.17 | 25.6 | **1,582.70** | **18.07** | **1,678.87** | **19.17** | 19.1 |
| 40 | **Machilipatnam** | 4.95 | 28.0 | **1,479.50** | **16.89** | **1,573.60** | **17.96** | 16.2 |
| 41 | **Mangalore** | 5.08 | 27.3 | **1,513.06** | **17.27** | **1,608.91** | **18.37** | 12.9 |
| 42 | **Coimbatore** | 5.12 | 26.2 | **1,512.30** | **17.26** | **1,601.90** | **18.29** | 11 |
| 43 | **Dindigul** | 5.00 | 24.9 | **1,485.40** | **16.96** | **1,566.20** | **17.88** | 10.4 |
| 44 | **Amini** | 5.76 | 27.4 | **1,690.90** | **19.30** | **1,690.90** | **19.30** | 11.1 |
| 45 | **Jallandhur** | 5.39 | 20.4 | **1,766.80** | **20.17** | **1,856.30** | **21.19** | 31.3 |
| 46 | **Rae Bareli** | 5.05 | 24.9 | **1,594.80** | **18.21** | **1,687.60** | **19.26** | 26.2 |
| 47 | **Nadiad** | 5.60 | 28.16 | **1630.60** | **18.61** | **1,741.80** | **19.88** | 22.7 |
| 48 | **Okha** | 6.11 | 26.1 | **1895.30** | **21.64** | **2025.60** | **23.12** | 22.2 |
| 49 | **Bhatinda** | 5.08 | 23.4 | **1,648.70** | **18.82** | **1740.40** | **19.87** | 30.2 |
| 50 | **Dindigul** | 5.00 | 24.9 | **1501.40** | **17.14** | **1583.10** | **19.87** | 10.4 |
| 51 | **Siliguri** | 4.85 | 19.4 | **1626.00** | **18.56** | **1693.90** | **19.34** | 26.7 |
| 52 | **Ajmer** | 5.14 | 24.7 | **1633.90** | **18.65** | **1728.30** | **19.73** | 26.5 |

It is very clear that the CUF depends not only on solar radiation level but also on air temperature.

## 8.0 Performance of Operating plants

There are a few plants which have been commissioned in India and are working for some time. These are mainly in Chandrapur, Maharashtra, Amritsar (Punjab), Kolar and Belgaum ( Karnataka), West Bengal which are in the MW range. We have tried to get the actual generation data from these plants and compare it with our design. The only one year data is available from Chandrapur and is given below. The design data of the delve eloper agrees very well with our design and the actual performance exceeds the estimated generation. Similarly Azzure power has reported higher performance during the first month of working itself. More data is available but not sufficient to compare. However the data available agrees with our model. The data from Kolar and Belgaum is also available for few months, and their generation is slightly on the lower side. The efficiency of the inverter is clearly reflected in the performance of the plants. Similarly two months data available from 54.4KW grid connected plant at NDPL and the generation agrees with the design.

**Table 10 MEDA (Chandrapur Solar Plant)**

| | Generation in MWhrs | | |
|---|---|---|---|
| Month | Designed | Actual | Our Model |
| January,2009 | 130 | 154 | 151.89 |
| February,2009 | 160 | 154 | 152.41 |
| March,2009 | 170 | 170 | 170.44 |
| April,2009 | 173 | 159 | 162.80 |
| May,2009 | 141 | 151 | 156.36 |
| June,2009 | 90 | 107 | 111.84 |
| July,2009 | 85 | 94 | 97.60 |
| August,2009 | 75 | 93 | 96.70 |
| September,2009 | 123 | 116 | 118.78 |
| October,2009 | 147 | 144 | 144.43 |
| November,2009 | 155 | 152 | 149.20 |
| December,2009 | 144 | 156 | 152.42 |
| **TOTAL** | **1593** | **1650** | 1664.87 |
| **CUF** | **18.18** | **18.84** | **19.01** |

Table: 11

**Monthly Generation Status up to 31.12.2010**

| Sr. No. | Month | Generation (KWH) | PLF % | Reason for less PLF |
|---|---|---|---|---|
| 1 | April 2010 | 32800.00 | 4.55 | Failure of 1250 KVA, 415V/33 KV Oil Filled Transformer |
| 2 | May 2010 | 73620.00 | 9.89 | Plant working with substitute 500 KVA 415V/33 KV Oil filled Transformer |
| 3 | June 2010 | 10860.00 | 14.8 | Rainy Season |
| 4 | July 2010 | 96550.00 | 12.9 | Rainy Season |
| 5 | Aug 2010 | 105890.00 | 14.2 | Rainy Season |
| 6 | Sept 2010 | 100390.00 | 13.9 | Rainy Season |
| 7 | Oct 2010 | 114770.00 | 15.4 | Rainy Season |
| 8 | Nov 2010 | 105660.00 | 14.675 | Less Solar Insolation (Expected: 6.040 Kwh/$m^2$/day* & Actual: 4.462 Kwh/$m^2$/day**)<br><br>& Grid failure: 970.0 minutes |
| 9 | Dec 2010 | 112570.00 | 15.13 | Less Solar Insolation due to Cloudy weather from dt.7.12.10 to 10.12.10, on 29.12.10 & 31.12.10 &Grid failure: 51 minutes |
| Total Generation up to 31.12.2010 | | 84911.00 | | |

- Source: NASA data.
- **: Site Specific Data

Expected Annual Generation: 1.583 MU'S

Table 12

Actual Power generation at Plant commissioned by M/s.Azure Power in Punjab.

| Month, 2010 | Exported Units*(KWh) |
|---|---|
| February | 118,890 |
| March | 152,715 |
| April | 147,785 |
| May | 132,410 |
| June | 144,605 |
| July | 128,600 |
| August | 115,820 |
| September | 141,980 |
| October | 129,320 |
| November | 197,645 |
| December | 195,065 |
| Total Till Dec. 2010 | 1,604,835 |

**Designed CUF is 20.8 Actual is 16.79**

**Table: 13**

**Actual power generation at 3 MW Kolar and Belgaum plants**

| MONTH | GEN KOLAR | GEN BELGAUM |
|---|---|---|
| 10-Jan | 404779.7 | 333639 |
| 10-Feb | 406440.6 | 376002 |
| 10-Mar | 419099 | 392788 |
| 10-Apr | 364077 | 408986 |
| 10-May | 374000 | 363517 |
| 10-Jun | 305650 | 294000 |
| 10-Jul | 239600 | 260562 |
| 10-Aug | 153100 | 240876 |
| 10-Sep | 137700 | 305534 |
| 10-Oct | 149000 | 315976 |
| 10-Nov | 114300 | 268200 |
| 10-Dec | 280700 | 337600 |
| Cumulative | 3348446.3 | 3897680 |

It is to be noted that all the values of radiation etc are average over a period of time and so the actual values may differ from year to year but the average over a period will hold. The performance in 2010 is poor due to more rains and partly due to technical breakdowns.

## 9.0 Conclusions and Recommendations

Solar Photovoltaic and thermal power plants will play an important role in the overall energy supply. The grid parity is likely to be achieved around 2017-2020.

Solar radiation data is available from several sources including satellite simulations. The data collection and simulation is a complex procedure and can have inaccuracies varying from 3 to 20%. The most reliable data is ground measured with accurate instruments.

The performance (Capacity utilization factor ) CUF depends on several factors including the solar radiation, temperature, air velocity apart from the module type and quality, angle of tilt(or tracking), design parameters to avoid cable losses and efficiencies of inverters and transformers. There are some inherent losses which can be reduced through proper designing but not completely avoided.

Thin film modules will perform better than the crystalline modules in high temperature zones. The estimated capacity factor varies from 16 to 20% in various parts of the country. At most locations in Rajasthan and Gujrat it is around 20%. In overall most of the places it is around 19% .In some places where the CUF is around 18%, it is advisable to increase to 19% by adding 50 KWp of modules for every MW of capacity to compensate for the inherent losses in the system. This will require an additional investment of Rs.40 to 45 Lakhs per MW.

The modules show degradation in power output through years of operation. It is observed that quality modules is very important in determining the extent of degradation. The improvements in technology and quality assurance have reduced this degradation considerably. Several manufacturers are proposing extended warranties although with a safety of margins. Based on the results of past studies and trends, one can fairly assume degradation of maximum 0.5% per year from 3$^{rd}$ year of deployment. This can also be compensated by addition of 5 KW of modules per year from 4th year to 24$^{th}$ year of operation requiring an expenditure of Rs.4 to 4.5 lakhs per year at current market rates.

It would be desirable to monitor the solar plant installations and build up database for future work. It is also recommended to carry out a detailed study for several locations with active involvement of IMD database.

## References

[1] International Energy Agency, “Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity”, IEA PVPS Task 12, Subtask 20, LCA Report IEA-PVPS T12-01:2009 October 2009.

[2] M. Chegaar, A. Lamri and A. Chibani, “Estimating Global Solar Radiation Using Sunshine Hours”, Physique Energétique (1998) 7 – 11.

[3] Zaharim Azami, Razali Ahmad Mahir, Gim Tee Pei, Sopian Kamaruzzaman, "Time Series Analysis of Solar Radiation Data in the Tropics", European Journal of Scientific Research, Vol.25 No.4 (2009), pp.672-678.

[4] Duffie John A, William Beckman A, "Solar Engineering of Thermal Processes, 3rd Edition, 2006, John Wiley and Sons Inc, pages 3 – 138.

[5] Sen, Zekai, Solar energy fundamentals and modeling techniques:atmosphere, environment, climate change and renewable energy, Springer, 2008, pp 44-70.

[6] Solar Radiation Hand Book, Solar Energy Centre, MNRE and Indian Metrological Department, 2008.

[7] IMD Pune website, http://www.imdpune.gov.in/, accessed on 20th June 2010

[8] Hall James and Hall Jeffrey, "Evaluating the Accuracy of Solar Radiation Data Sources", Solar Data Warehouse, February 2010.

[9] Saren Johnston, "Sunproofing Solar Cells Computer simulations help explain why solar cells degrade in sunlight", Insider, April 2003.

[10] M. Chegaar, P. Mialhe, "Effect of atmospheric parameters on the silicon solar cells performance", Journal of Electron Devices, Vol. 6, 2008, pp. 173-176

[11] Wohlgemuth John H, "Long Term Photovoltaic Module Reliability", NCPV and Solar Program Review Meeting 2003.

[12] C.R. Osterwald, A. Anderberg, S. Rummel, and L. Ottoson, "Degradation Analysis of Weathered Crystalline-Silicon PV Modules", 29th IEEE PV Specialists Conference, New Orleans, Louisiana, May 20-24, 2002.

[13] A.M. Reis, N.T. Coleman, M.W. Marshall, P.A. Lehman, and C.E. Chamberlin, "Comparison OF PV Module Performance before and after 11 years of field exposure", Proceedings of the 29th IEEE Photovoltaics Specialists Conference New Orleans, Louisiana May, 2002

[14] Fraunhofer Institute: Module Power Evaluation Report, commissioned by Schott Solar AG.

[15] Ewan D. Dunlop, David Halton, "The Performance of Crystalline Silicon Photovoltaic Solar Modules after 22 Years of Continuous Outdoor Exposure", Prog. Photovolt: Res. Appl. 2006; 14:53–64

[16] Peter Klemchuk, Myer Ezrin, Gary Lavigne, William Halley, James Susan Agro, "Investigation of the degradation and stabilization of EVA-based encapsulant in field-aged solar energy modules." Polymer Degradation and Stability 55 (1997) pp. 347-365.

[17] Ian Muirhead and Barry Hawkins, "Research into new technology photovoltaic modules at Telstra Research Laboratories – What we have learnt", 1996.

[18] C.R. Osterwald, J. Adelstein, J.A. del Cueto, B. Kroposki, D. Trudell, and T. Moriarty, National Renewable Energy Laboratory (NREL), "Comparison of degradation rates of individual modules held at maximum power", 2006.

[19] James M. Bing, “Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years? Preliminary Findings”, NREL PV Module Reliability Workshop, 2/19/2010.

Submitted by Dr.B D Sharma

Mob. 9350871056

FEBRUARY 2011