ADVANCES IN SOLAR RADIATION RESOURCE ASSESSMENT IN INDIA

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ABSTRACT: India launched National Solar Mission in 2010, which aims at to set up 20 000 MW of grid connected solar power, besides 2 000 MW equivalent of off-grid applications and cumulative growth of solar thermal collector area to 20 million m^2 by 2022. Availability of reliable and accurate solar radiation data is crucial to achieve the targets. As a result of this initiative, Ministry of New and Renewable Energy (MNRE) of Government of India (GoI) has awarded a project to Centre for Wind Energy Technology, Chennai in the year 2011 to set up 51 Solar Radiation Resource Assessment (SRRA) stations using the state-of-the-art equipment in various parts of the country, especially the sites with high potential for solar power. The GoI project has synergy with SolMap project, which is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in cooperation with the MNRE. SolMap project is contributing to SRRA project in establishing quality checks on the data obtained as per International protocols and helping data processing to generate investment grade data. The paper highlights the details of SRRA stations and an attempt has been made to present some of the important results of quality control and data analysis with respect to DNI and GHI. While our analysis of the data over one year finds that intensity and profile of the insolation are not uniform across the geographic regions, the variability in DNI is particularly high. Strong influence of monsoon is also identified. SRRA infrastructure aims to develop investment grade solar radiation resource information to assist project activities under the National Solar Mission of India.

Keywords: solar radiation, pyranometer, pyrheliometer measurements, solar resource evaluation

1 INTRODUCTION

In 2009, the Indian Ministry for New and Renewable Energy (MNRE) launched its ambitious Jawaharlal Nehru National Solar Mission (JNNSM) under which it has set a target of installing 20 GW of solar power by the year 2022. This 20 GW of solar power will be equally divided into Solar Photovoltaic (PV) and Concentrating Solar Power (CSP) technologies, representing an installation of 10 GW of each technology in approximately 12 years. This has caused a rapid growth and development of PV industry in India. In addition the reverse bidding mechanism has made the market even more competitive, with companies bidding lower prices. A French company Solairedirect SA offered the lowest bid price for PV at 7.49 INR/kWh today approximately 92 EUR/MWh. [1]. All of these have resulted in demand of high quality solar resource data for India.

Until around 2008 availability of solar radiation maps of India was quite limited. Besides worldwide data sets in coarse resolution like NASA-SSE [2] there was the Global Horizontal Irradiance (GHI) map provided by the Indian Meteorological Department (IMD) based on interpolation of ground-based measurements [3]. Additionally time-series and maps based on ground-based measurements and model-derived solar radiation values of DNI and GHI also can be obtained from the Meteonorm software [4]. In 2009 NREL released its first version of a satellite-based solar radiation map providing GHI and DNI covering the North West of the country. In 2010 an updated version was released by NREL, which then covered entire India. Meanwhile several commercial satellite-derived data sets became available like 3TIER (2011), the Solemi data set of DLR (Deutsches Zentrum für Luft- und Raumfahrt – German Aerospace Center), the iMaps data of GeoModel Solar [5], and the data from IrSOLaV [6]. But the uncertainty of solar radiation data in India is still very high [7]. Ground truth of the satellite-derived data sets is still widely missing.

The high uncertainty of solar radiation data is acting as a hurdle to the development of solar power plants in India. As a result, to provide a solid database for solar energy deployment in India MNRE is funding the project Solar Radiation Resource Assessment (SRRA) at Centre for Wind Energy Technology (C-WET). The SRRA-project is mainly covering the set up and operation of a countrywide collection system of solar radiation data. In 2011 a network of 51 solar radiation measurement stations distributed all over most states of India was erected. These stations are measuring direct, diffuse and global irradiance with high quality.

SolMap is a project under the Indo-German Bilateral Cooperation and supported by the German Ministry for Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit - BMU). In SolMap the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) together with its contractors PSE AG and Suntrace GmbH are cooperating with C-WET. The project Solar Mapping and Monitoring (SolMap) has the main goal to accelerate the planning and implementation of solar power plants in India and increase their power output. SolMap shall support a countrywide system for the collection and analysis of solar and other relevant meteorological data. Further, the project shall support establishing a system for performance monitoring (Solar Monitoring) of photovoltaic plants.

One of the main goals of SolMap project is to implement a quality control and data processing system for data being measured by 51 SRRA stations. In this article we describe quality control algorithms implemented by Suntrace GmbH on behalf of GIZ GmbH as part of SolMap/SRRA project. Initial data of a short duration has been analyzed and preliminary results are presented here for various representative sites.

2 SOLAR RADIATION RESOURCE ASSESSMENT

The Solar Radiation Resource Assessment (SRRA) cell of MNRE is located at C-WET, Chennai. The SRRA team was initially responsible for selecting locations where these 51 SRRA stations would be installed. Different regions of the country have been selected so as to gain knowledge of as many regions as possible; especially regions of India with highest potential for development of solar power plants are covered densely with SRRA stations. As can be seen in Figure 2, majority of stations are located in North-West of India, covering the states of Rajasthan and Gujarat.

Figure 1: Map showing the location of 51 SRRA stations in India.

The SRRA team was also responsible for determining the type of instruments required, minimum requirements that should be met by instruments, the design of SRRA station etc. A global tender was floated for supply, installation and maintenance of 51 stations. After reviewing the bids received, the tender was awarded to SGS Weather and Environmental Systems India Pvt. Ltd. The installation of SRRA stations began in end of May 2011 and ended in November 2011.

2.1 Standard SRRA Station Design

All 51 SRRA stations are identical in design and have the same quantity and model of instruments. Table I below gives a list of the instruments that form a complete SRRA station. It should be noted here that only first class pyrheliometers and secondary standard pyranometers as classified by ISO 9060 [8] are used in this network. In addition to this, SRRA has also acquired two absolute cavity radiometers (ACR), which will be required for recalibration of solar radiation sensors.

All other meteorological parameters like ambient temperature, relative humidity, atmospheric pressure, wind speed and direction and precipitation are also measured by SRRA stations, following WMO guidelines [9]. SRRA stations are provided with autonomous power using solar photovoltaic panel and battery storage system in order to provide uninterrupted power supply.

	Instrument used	Parameter measured
solar radiation sensors	Pyranometer 1	GHI
	Pyranometer 2	DHI
	pyrheliometer	DNI
meteorological parameter sensors	air temperature sensor	ambient air temperature
	relative humidity sensor	ambient air relative humidity
	ultrasonic wind sensor	wind speed and wind direction
	barometer	atmospheric pressure
	pluviometer/rain gauge	precipitation (rain rate)

Table I: List of meteorological instruments used in SRRA stations.

Figure 2: Typical SRRA station design (left); solar tracker with pyrheliometer and platform to carry pyranometers and shading assembly (right).

Initially all meteorological parameters were sampled every 10 s and mean of 60 such samples was taken and stored in the datalogger. All SRRA stations are equipped with GPRS based telecommunication system and transmit data stored in data logger to Central Receiving Station (CRS) located at C-WET head office in Chennai every 10 minutes. At present all SRRA stations have been upgraded and all meteorological parameters are sampled every 10 s and mean of 6 such samples is taken and stored in the datalogger.

2.2 System architecture

At present the data measured by the stations is received and stored in a Central Receiving Station (CRS) located at C-WET head office in Chennai. This server system is named as Level 1 (L1) system and stores all data as received from all 51 stations. In the L1 server system only basic quality tests are implemented. In order to protect data from being getting lost and for security reasons, a RAID 5 back-up system with two hot-swappable servers is used.

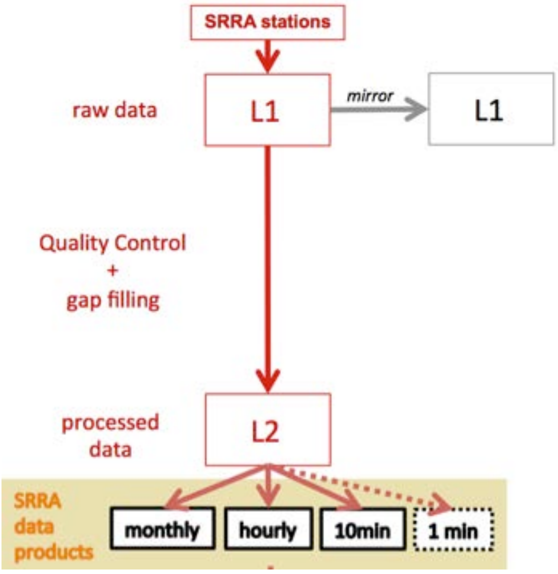

Figure 3: Data flow from SRRA-stations to L2 data products.

Once the data is stored in L1 server, it is checked for its quality i.e. missing data, plausibility of data measured etc. This is done in another server system, which is called Level 2 (L2) system. L2 system consists of data processing and processed-data storage (see Figure 3). Once data are quality controlled, various reports and data products are created in different temporal resolutions like hourly, daily, monthly, yearly reports etc.

3 QUALITY CONTROL OF DATA

Quality control algorithms are directly applied to the raw data. This chapter describes various tests performed on raw measured data as part of the quality control processing implemented in L2 system. The quality control algorithms test solar radiation parameters (DNI, GHI and GHI) and auxiliary meteorological parameters like ambient temperature, relative humidity, wind speed and direction etc. separately. Data is checked for various errors and is flagged accordingly. Figure 4 illustrates the test sequence in a flow chart.

3.1 Irradiance

The tests applied for global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) are based on Baseline Surface Radiation Network (BSRN) rules set by the World Meteorological Organization (WMO). These tests are elaborated by the project Management and Exploitation of Solar Resource Knowledge (MESOR), see [10], and those developed and published by [11] and [12]. These tests are enhanced by further experiences by CIEMAT, DLR, NREL, ENTPE and others in the evaluation of ground-measured solar radiation data with the goal of reaching low false alarm rates and good detection efficiency.

The data is tested on physical limits, if the data are below or above physical possible values. Another test considers a clear sky model. The measured values should be lower than the model output of a clean and dry atmosphere. As the three components of irradiance (global, diffuse and direct) are measured by independent instruments, these measurements can be checked for redundancy and for tracking errors.

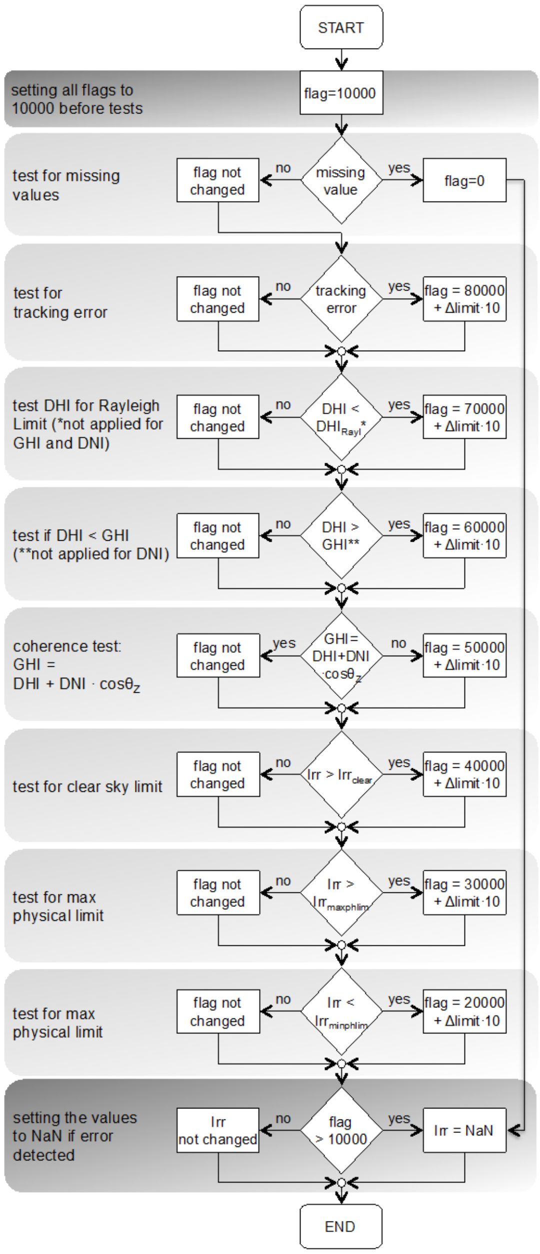

Figure 4: Flow chart showing the various tests performed on three major solar radiation parameters GHI, DNI and DHI.

3.1.1 Physical limits

Following [10] and [11] physical possible maximum, (individual for GHI, DNI and DHI) and minimum limits are applied. According to BSRN the physical minimum for irradiance values is with -4 W/m^2 below zero as negative values can be produced by thermal sensors due to radiative cooling at night and can be used for zero offset calibration. Since the incoming irradiance never can be negative the limit for the L2 post processing of the raw data is set to 0 W/m^2. This is avoiding a slight negative bias by negative nighttime values for daily and monthly averages.

3.1.2 Limits of a clear sky condition

In this test the GHI, DHI and DNI are compared to the values obtained under clear sky conditions. The DHI is tested against the clear sky GHI as a maximum limit since the DHI can be very low under clear sky conditions in a clear and dry atmosphere. In [12] a minimum limit, the Rayleigh Limit as DHI under really clear and dry sky conditions, is given for the DHI. Most of the time, these conditions lead to the maximum values of the GHI and the DNI. However, there are some conditions mainly at broken cloud conditions when scattering on cumulus clouds can lead to situations when GHI is exceeding even the 'solar constant'. This cloud enhancement effect can cause irradiances higher than the clear sky limit, only concerns GHI. GHI data, which exceed the clear-sky limit, thus should be considered only as "potentially" erroneous.

3.1.3 Coherence between measurements

The DHI should not be higher than the GHI within the limits of accuracy of the instruments. In addition, the GHI should be close to the sum of the diffuse and the direct components. The used limits are suggested by [11] and [12]. Caution should be taken when dealing with values averaged over one hour or more. In those cases, the distribution of cloudy and non cloudy conditions within the averaging period has an increasing influence, limits therefore should be higher. Since the quality control is applied on data in 1 minute and 10 minute time resolution these limits are adequate.

3.1.4 Tracking error

Following [12], if measured DHI is greater than 50 W/m^2 and the ratio of measured GHI to clear sky GHI is greater than 0.85 and if the ratio of measured DHI to measured GHI is greater than 0.85, the corresponding DHI values are flagged as tracking error. Additionally, if the measured DNI value is less than 150 W/m^2 and the above-mentioned conditions are fulfilled, the corresponding DNI values are flagged also as tracking error. In addition tracking error is also assigned, when it is identified by visual analysis of the data or reported by the station keeper.

3.1.5 Testing sequence

A logical order of the various tests is applied from simple to more complex tests. Instead of a separate flag for each test a long integer value is used to avoid using too much memory. If the result of one test is identifying an error, the flag of the former test is overwritten.

4 DATA ANALYSIS

Generally solar radiation values should be given for one complete year of measurements, which cover all sun-positions in the sky. Actual installation of 51 SRRA stations started in June 2011, with the first stations being installed and commissioned in Indian states Tamil Nadu and Rajasthan. The installation of other stations was carried out in different phases, with the last station being installed in Andhra Pradesh in November 2011. As a result, at the time of writing this paper not all stations have one complete year of measurements. Due to seasonal variation of solar radiation (both GHI & DNI) giving solar radiation values over a partial year, which does not cover all sun positions in the sky, would be misleading for the user. So, results of data analysis are presented here only for selected stations for which one complete year of measurements is available. For this paper the results of SRRA stations located in Indian states of Rajasthan and Tamil Nadu are presented.

However it should be noted that since values presented here are based on only one year of ground-measurements, they should not be mistaken to represent 'long-term average' value as they don't represent inter-annual variability of solar radiation. As a result these values should not be compared with long-term solar radiation averages derived from satellite data. Moreover, due to spatial variation of solar radiation, values presented here are representative of the single point measurements and should not be considered to represent the solar resources of the entire region or country as a whole. But at the same time these values can be used as a rough estimate of the values that can be expected in similar regions that have similar climatic conditions in the country.

4.1 GHI solar resource

The GHI solar resource in Rajasthan and Tamil Nadu measured by SRRA stations are presented here as monthly averages as can be seen in Figure 5 & Figure 6. At first look it can be seen that there is a small variation in the annual cycle (seasonal variation) of GHI in both these states. During the months from April to June 2012, when N. India (Rajasthan) experiences an increase in GHI, S. India experiences a decrease in GHI.

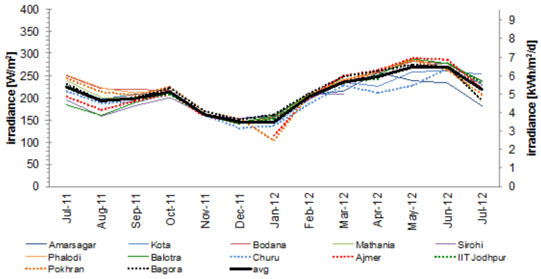

Figure 5: Graph showing monthly average values of GHI from July 2011 to July 2012 at SRRA stations in Rajasthan.

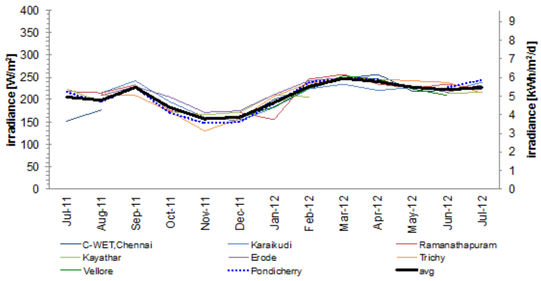

Figure 6: Graph showing monthly average values of GHI from July 2011 to July 2012 at SRRA stations in Tamil Nadu.

From Figure 5 & Figure 6 it can also be noticed that the spatial variability of GHI within the respective states is also quite less. The average standard deviation of GHI monthly average values within Rajasthan for the whole period is 13 W/m^2, whereas the minimum and maximum standard deviation is 5 W/m^2 and 22 W/m^2 respectively. For the same period the average standard deviation of GHI monthly averages for the whole period is 12 W/m^2, whereas the minimum and maximum standard deviation is 6 W/m^2 and 20 W/m^2 respectively.

During one year of ground-based measurements from August 2011 to July 2012, the average GHI values from all stations in Rajasthan is found to be 210 W/m^2 or

1835 kWh/m^2/a or 5.02 kWh/m^2/d. Co-incidentally for the same period, the average values from all stations in Tamil Nadu is also found to be 210 W/m^2 or 1835 kWh/m^2/a or 5.02 kWh/m^2/d. These values are low compared to the values from satellite-derived data for these locations. However, as mentioned before, the values presented here are based on only one year of measured data, without considering the factor of inter-annual variability. It should also be noted that these low values are suspected due to soiling of instruments.

4.2 DNI solar resource

The DNI solar resource in Rajasthan and Tamil Nadu measured by SRRA stations are presented here as monthly averages as can be seen in Figure 7 & Figure 8. At first look it can be seen that there is a variation in the annual cycle (seasonal variation) of DNI in both these states. This is mainly due to the fact there are two monsoon seasons in Southern India (Tamil Nadu) as compared to one monsoon season in Northern India (Rajasthan). During the months of October, November, December when N. India receives good DNI, it is relatively low in S. India due to the second monsoon season. This is called Northeast monsoon or retreating monsoon.

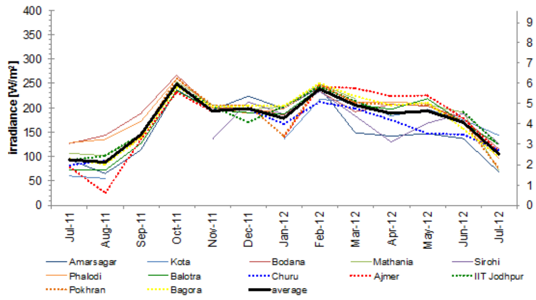

Figure 7: Graph showing monthly average values of DNI from July 2011 to July 2012 at SRRA stations in Rajasthan.

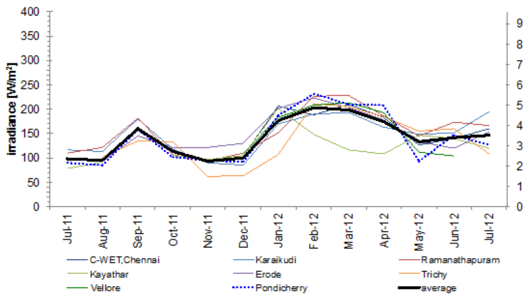

Figure 8: Graph showing monthly average values of DNI from July 2011 to July 2012 at SRRA stations in Tamil Nadu.

From Figure 7 & Figure 8 it can also be noticed that the spatial variability of DNI within the respective states is a more than that for GHI. The average standard deviation of DNI monthly average values within Rajasthan for the whole period is 22 W/m^2, whereas the minimum and maximum standard deviation is 12 W/m^2 and 34 W/m^2 respectively. For the same period the average standard deviation of DNI monthly averages for the whole period is 24 W/m^2, whereas the minimum and maximum standard deviation is 12 W/m^2 and 34 W/m^2 respectively.

During one year of ground-based measurements from August 2011 to July 2012, the average DNI values from all stations in Rajasthan is found to be 182 W/m^2 or 1600 kWh/m^2/a or 4.38 kWh/m^2/d. Similarly, for the same period, the average values from all stations in Tamil Nadu is found to be 149 W/m^2 or 1300 kWh/m^2/a or 3.58 kWh/m^2/d. These values are quite low compared to the values from satellite-derived data for these locations. However, as mentioned before, the values presented here are based on only one year of measured data, without considering the factor of inter-annual variability. It should also be noted that these low values are suspected due to soiling of instruments, pyrheliometers in particular.

4.3 Comparison of solar resources with other countries

Compared to some other sunny countries where a lot of solar power activities are carried out or are currently going on, these values are comparatively low as can be seen in Table II. However, it should be noted that solar resource in India is distributed more uniformly throughout the year, instead of having very high solar radiation in summer and low in winter (see Figure 9 & Figure 10). This is beneficial to PV, CPV & CSP power plants as they can be designed operate over a significantly greater time of the year.

country		India	India	South Africa	Spain
state		Rajasthan	Tamil Nadu	N. Cape	Andalusia
site	quantity	Phalodi*	Ramanathapuram*	De Aar	PSA
kWh/m^2/a	DNI	1702	1397	2770	2130
	GHI	1916	1853	2100	1900
kWh/m^2/d	DNI	4.66	3.83	7.6	5.8
	GHI	5.25	5.08	5.8	5.2
W/m^2	DNI	194	159	317	243
	GHI	219	212	240	217

Table II: Comparison of DNI & GHI annual averages of SRRA stations in Phalodi, Rajasthan and Ramanathapuram, Tamil Nadu with that in De Aar, South Africa and Plataforma Solar de Almería, Spain [14]. * Values based on only one year of measurements.

This leads to higher plant capacity load utilization factor, leading to greater yield. Very high GHI values are not frequently observed in India, with very few occurrences of GHI above 1100 W/m^2. Very high DNI values greater than 1100 W/m^2 are also not observed in India as compared to South Africa and Spain [13].

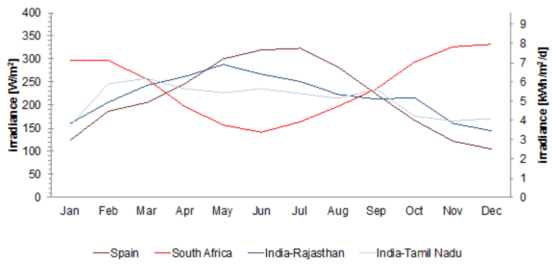

Figure 9: Graph comparing the annual cycle (seasonal variation) of GHI in Phalodi, Rajasthan and Ramanathapuram, Tamil Nadu with that in Plataforma Solar de Almería, Spain and De Aar, South Africa.

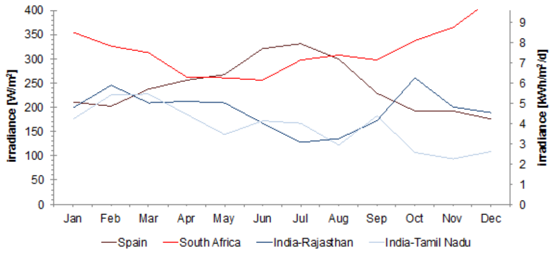

Figure 10: Graph comparing the annual cycle (seasonal variation) of DNI for stations in various countries as in Fig.9.

4.4 Ambient temperatures

Monthly average ambient temperature measured at SRRA stations in Rajasthan and Tamil Nadu are shown in Figure 11 & Figure 12 respectively. The variability of ambient temperatures measured at all stations in Rajasthan & Tamil Nadu is very less, as compared to the variability of GHI & DNI. This is quite common due to the fact that temperature is more uniform over regions with similar topography, microclimate etc.

As seen in Figure 11, average ambient temperatures in Rajasthan during summer can reach as high as 35°C, with maximum temperatures reaching close to 50°C. Whereas in winters the average temperatures can reach up to 10°C, with rare occurrences of subzero temperatures. Such high temperatures may be of disadvantage to polycrystalline PV technology with its efficiency decreasing with increasing ambient and hence module temperatures and vice-versa for thin film PV technology.

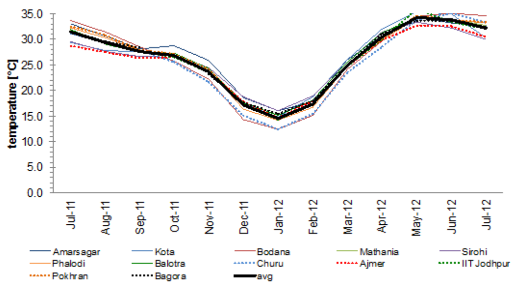

Figure 11: Graph showing monthly average values of ambient temperature from July 2011 to July 2012 at SRRA stations in Rajasthan.

Although average ambient temperatures in Tamil Nadu during summer are not as high as in Rajasthan, average ambient temperatures in winter are not too low. As a result, average annual ambient temperatures in Tamil Nadu are similar or slightly less than those in Rajasthan. Average annual temperatures experienced in Spain and South Africa are shown in Figure 13 for comparison purpose.

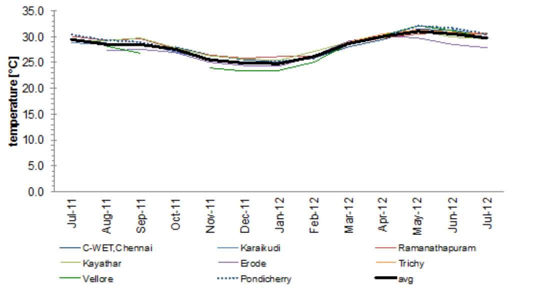

Figure 12: Graph showing monthly average values of ambient temperature from July 2011 to July 2012 at SRRA stations in Tamil Nadu.

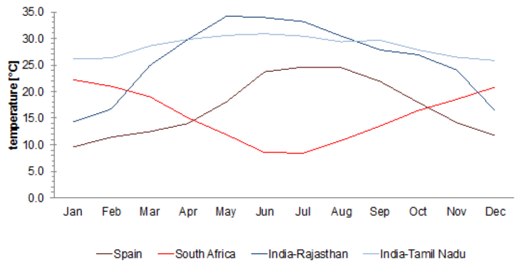

Figure 13: Graph comparing the annual cycle (seasonal variation) of ambient temperature in various countries as in Fig.9.

5 ESTIMATION OF ENERGY YIELD OF PV PLANTS

In order to see the influence of different radiation and temperature regimes over different locations on the energy yield of PV modules, simple PV performance simulation has been done using HOMER software. The question of interest was to roughly estimate what may be the extent of variation on output energy yield of 1 kW_p PV module in different locations in India. Solar radiation (GHI) and ambient temperature values are taken for two representative sites in Rajasthan and Tamil Nadu. The stations selected are Phalodi in Rajasthan and Ramanathapuram, Tamil Nadu. GHI annual average in Phalodi is 1916 $kWh/m^2/a$ or 5.25 $kWh/m^2/d$ or 219 W/m^2. GHI annual average for Ramanathapuram is 1853 $kWh/m^2/a$ or 5.08 $kWh/m^2/d$ or 212 W/m^2. A simplistic simulation was carried out by assuming the tilt angles of PV modules to be fixed in their respective angle of latitude. The polycrystalline Si modules were considered in the exercise. Only DC output energy from the PV modules were of interest to this analysis.

The output of simulation results is that for the site in Phalodi, Rajasthan the output is 1502 kWh/kW_p; while for the site in Ramanathapuram, Tamil Nadu it comes out to be 1346 kWh/kW_p. Thus it can be clearly seen that within India the expected electrical energy from PV plants can have significant difference only because of the difference in climatic conditions, keeping other impacting factors of yield out of discussion.

6 CONCLUSIONS

The SRRA measurement network is running since its commissioning in October 2011. With its 51 stations each equipped with a solar tracker, a pyrheliometer, a shaded and an unshaded thermopile pyranometer today it is the largest known national network of precision radiometers.

Data are continuously checked for their quality. Early data gathered by this network are biased, because regular cleaning of the instruments was not realized. Due to soiling the readings tend to underestimate.

The first stations installed in July 2011 now completed the first year of measurements. Based on preliminary measurements results show that global radiation GHI is relatively uniformly distributed over India and provides good conditions for PV in most regions.

The ratio of DNI to GHI is relatively low at most stations due to high aerosol load. Thus, there are only few regions in India, which are well suited for concentrating PV.

Due to monsoon the irradiation levels in summer are relatively moderate compared to other countries. On the other hand there is relatively high irradiation during winter, because cloud frequency tends to be low then. Together with low temperatures in Northern India this are very favorable conditions for PV yields. Due to the observed low seasonal variation PV output is expected to be relatively high during all seasons in India.

The absolute level of the measured solar radiation has still high uncertainty due to soiling issues and the short observation period. Measurements should be combined with satellite-derived solar radiation time-series to get reliable long-term averages. Continued measurements by SRRA help to achieve better results from year to year.

The 51 stations are distributed mainly in the Southwest and South India where JNNSM was expecting highest number of solar energy projects. Also in other parts of the country good conditions for PV are expected. The MNRE decided to extend SRRA by another 60 stations of similar kind.

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