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Towards building solar in India - A combined mapping and monitoring approach for creating a new solar atlas

Jana Müller [a,*], Indradip Mitra [b], Theresa Mieslinger [a], Richard Meyer [a], Kaushal Chhatbar [a], S. Gomathinayagam [c], G. Giridhar [c]

[a] Suntrace GmbH, Grosse Elbstrasse 145c, 22767 Hamburg, Germany
[b] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 1st Floor, B-5/2, Safdarjung Enclave, New Delhi – 110 029, India
[c] National Institute of Wind Energy, Government of India, Velachery - Tambaram Main Road, Pallikaranai, Chennai - 600 100, India

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ABSTRACT

Against the background of rising energy demand and climate change, solar energy applications are expected to become one of the fastest growing sources in India. To support India's solar policy and to respond to a growing demand for high-accuracy solar resource data a new solar resource atlas was created in the study presented. To derive temporal and spatial consistent datasets measured values from 51 ground measurement stations distributed over the whole country were used to derive site-specific correction factors. Another 61 stations were used to validate the resulting maps of long-term monthly-averaged datasets. Correlation factors were transferred to the needed spatial extent using geospatial interpolation and used to adjust satellite-derived data sets with a resolution of approx. 3 × 3 km. Solar datasets created based on the years 1999 to 2014 provide a comprehensive overview of solar resources in India. Long-term averages, annual averages for each month of the year, as well as standard deviations, are presented for all three components of irradiation. The results show that the adjustment using monthly correlation factors significantly improves the quality of long-term estimations from satellite-derived sources and reduces the associated uncertainty.

Introduction

Global energy demand is expected to rise worldwide over the next three decades. The largest increase in energy demand is projected for non-OECD countries with less mature economies and rapid population growth, particularly India and China (U.S.EIA, 2016). India is also one of the largest emitters of greenhouse gasses. Since 1950 fossil fuel sourced CO_2 emissions have increased in average 5.7% per year making India one of the five largest CO_2-emitting countries (Boden et al., 2011). As by today, the energy sector is responsible for 71% of country's total greenhouse gas emissions (Ministry of Environment, Forest and Climate Change, 2015).

It is expected that fossil fuels will remain the largest source for energy production for many years, however, renewable energy sources are likely to become the world's fastest growing source increasing by an average 2.6%/year between 2012 and 2040 (OECD/IEA, 2015). In 2016, India's installed capacity in solar reached 6.7 GW. Compared to an overall power generation capacity of 306 GW this shows how solar power offers great possibilities for further development replacing fossil sources in power generation (CEA, 2016; MNRE, 2016). India is already considered a pioneer in solar energy production being ranked under the ten leading countries in terms of solar electricity production per Watt installed. This is also due to the JNN Solar Mission launched in 2010 by the Government of India. The mission adopts a 3-phase approach with the target of deploying 100 GW of grid connected solar power by 2022. The objective of the mission is to create a policy and regulatory environment that enables large-scale investment in a timely manner lowering the cost for solar energy applications (Government of India, 2016). India's targets for solar energy deployment are ambitious and to succeed the right issues must be addressed. Therefore, it is important to establish an operating environment for solar energy development that encourages investors and challenges potential barriers such as financial viability, regulatory approval and grid infrastructure.

Any energy policy should aim to develop the right type of resource at the right location at the right time (Chattopadhyay and Chattopadhyay, 2012). A key factor to ensure a proper design and secure bankability of a solar project is to accurately assess solar resources at potential locations (Hoyer-Klick, 2009; Polo et al., 2011; Vignola et al., 2012). It is in no doubt that India, in general, has high potential due to its location in the sunbelt of the Earth. However, solar irradiation over India varies

* Corresponding author.
E-mail addresses: jana.mueller@suntrace.de (J. Müller), indradip.mitra@giz.de (I. Mitra), theresa.mieslinger@suntrace.de (T. Mieslinger), richard.meyer@suntrace.de (R. Meyer), kaushal.chhatbar@suntrace.de (K. Chhatbar), dg.niwe@gov.in (S. Gomathinayagam), giridhar.niwe@gov.in (G. Giridhar).

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significantly and not knowing this variation can seriously harm the return of investment for solar energy projects (Lohmann et al., 2006). Financial stakeholders become progressively aware of risks associated with the accuracy of solar resource data, particularly because they are used to calculate the projects cash flow from early stages of the project development ongoing. The projects capital structure and accordingly the ability to obtain financing for projects are directly affected by the quality of the available solar resource data. Another important effect of the availability of standardized solar data is that the performance of solar projects can be assessed more accurately, resulting in increasing competition among solar companies and thus improvements in cost, performance, and pricing.

Two main sources of solar resource estimates are used in practice: satellite-derived models and measurements. Satellite derived model results are available from numerous public and private sources. They have the advantage to be available for most locations and over long time periods. On the downside, the information is limited to the grids resolution and although satellite data is improved by numerical models to reproduce the effect of the atmosphere and gap-filling techniques, they have a significantly lower accuracy than measurements. A well planned and maintained measurement campaign is best practice to obtain accurate information about solar resource at the selected location. Nonetheless, a measurement campaign commonly covers only one complete year and therefore cannot capture inter-annual variability and how well the period of record represents the long-term historical average.

Maps showing the distribution of solar radiation for India are available for more than 50 years. Few studies originate from the 60s of the last century and intended to better understand the general balance of energy on earth. They were created using ground measurement stations complemented by empirical relationships using the same physical principles as today. For example, Mani et al. (1966) created monthly averaged maps showing the distribution of the solar radiation over the Indian ocean by the adaption of 107 ground stations. Depending on the lack of data, early studies are characterized by low resolution and even lower accuracy due to the high uncertainty of the measurements with up to 15%. It is surprising that it took another 20 years until the next comprehensive study on solar potential for India became available. The Handbook of Solar Radiation Data for India (Mani, 2008) was the first comprehensive document that provided ground measured data and solar radiation maps and was considered a standard for meteorologists in India.

Nevertheless, the availability of spatial comprehensive and high-resolution maps remained rather limited until 10 years ago. Connected to the upcoming use of satellite derived data and their availability to the public, several global datasets became available, e.g. NASA SSE (NASA SSE, 2008). Although global datasets provide respectable information, they suffer from accuracy in spatial and temporal resolution.

In 2010, NREL published new solar resource maps and data for India. The dataset covers global horizontal, direct normal, and diffuse horizontal irradiance, as well as auxiliary meteorological data for the period from 2002 to 2014 on a 10 km × 10 km grid. Later versions of the maps were validated using five ground measurements from pyranometers and pyrheliometers and compared to previous versions of the map. It should be noted that according to Sengupta et al. (2014) the mean bias error of the Direct Normal Irradiance (DNI) predicted by the satellite was found to be approximately 60 W/m^2 for three stations but more than 110 W/m^2 for the other two stations, while results for GHI were much better. Of particular interest is the comparison of the newer map version to the previous version, that shows a relative difference of DNI up to 120%. This study is, as others, subject to the inherent limitations of any satellite data based estimation of DNI, a consequence of high temporal and spatial variability of DNI.

One year later, Polo et al. (2011) published a study to estimate solar radiation over India using satellite images with a significantly higher resolution of 5 km × 5 km. In the study, solar radiation estimations have been performed for six Indian locations using the generating time series of hourly values of two radiation components during the period of 2000–2007. The results were compared to the previously described NREL maps and few available ground measurements. Compared to the NREL maps, slightly lower values of GHI and DNI were retrieved. However, the authors note that to accurately validate the model results the number of ground measurements must be increased, especially for DNI.

Altogether, the quality of previous studies can be considered acceptable having in mind that the satellite data is characterized by higher uncertainties. One shortcoming all studies suffer from is the lack of ground measurements for calibration and validation of satellite-derived data sets. Against this background, 15 years of satellite-derived solar irradiance data was combined with ground-based data from 51 measurement stations distributed over India to construct high quality and spatially consistent solar resource data for India.

Materials and method

The methodology applied in this study aims to create consistent and high-resolution solar resource data spatially covering the whole country of India. Satellite-derived radiation covers large areas but is also associated with a lower accuracy, compared to measurements. Moreover, the most important advantage is the long continuous time series of satellite data reaching back to 1980 for some places on earth. Calculating inter-annual variability and long-term averages of solar radiation data at a specific site requires datasets covering at least 10 years (Lohmann et al., 2006). Data from ground-based measurement stations, on the other hand, is known to be very precise but at the same time limited in its spatial representation.

The applied methodology addresses the described issue by combining high-quality measurements from SRRA stations of one to three years with satellite-derived data covering 16 years. Fig. 1 gives an overview of the applied methodology and the datasets used in this study.

Solar radiation measurements from SRRA network

The measured solar radiation data used for this study was provided by the currently largest network of solar radiation resource assessment stations measuring simultaneously in India - the Solar Radiation Resource Assessment (SRRA) stations. The location of each station wasselected with care to gain the best knowledge of solar radiation distribution over the country. Moreover, regions with high potential for solar power plants were prioritized resulting in the majority of stations to be located in the north-west of India, a region with promising potential for solar resources (Mitra et al., 2014). The distribution of the measurement stations is shown in Fig. 2.

The installation of 117 SRRA stations was implemented in two phases. Under the first phase, finished until October 2011, a total of 51 stations were installed. Another 60 stations were installed in 28 states until June 2014 under phase 2. In addition, stations from a local weather service were taken into account. All stations are identical in design and are equipped with the same number of sensors that comply with the highest international accepted criteria for quality (e.g. ISO 9060 (International Organization for Standardization, 2016) and CIMO Guide(WMO, 2008)) to ensure comparability while reducing the uncertainty of the provided solar data. The solar measurements are made accessible to the public under the data sharing and accessibility policy of the Ministry of New and Renewable Energy, India.

Solar radiation reaching the earth surface can be divided into different components. All of them are important to know to get a comprehensive overview of solar resources at a certain location. Therefore, all SRRA stations are equipped with sensors to cover all three components of solar irradiation. Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI) are measured by two pyranometers, respectively. A first class pyrheliometer was installed to measure Direct Normal Irradiance (DNI). A two-axis solar tracker is used to track