Subject 4: Components for PV systems; Subtopic: 4.3 Standardization as tool for Innovation and Cost Reduction

Performance of 51 high precision solar radiation measurement stations in India

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Summary: A network of automatic solar radiation monitoring stations has been set up in 2011 by the Ministry of New and Renewable Energy, India across 51 locations in India which is one of the largest such networks in the world. This paper reports on the quality control tests that have been applied to determine data correctness and accuracy and data processing methodologies implemented for producing investment grade resource products. Extensive analysis on the performance of the monitoring stations has been done and the results are described here, which can be used as learning lessons and practical experiences for other similar networks. Data errors and gaps in measurement were replaced with "basic gap filling" procedures which are helpful for solar project designers.

Purpose of the work: A network of automatic solar radiation monitoring stations has been set up in 2011 by the Ministry of New and Renewable Energy, India across 51 locations in India. This paper investigates on the errors encountered in measurement and also on overall performance of stations since their inception. Gap filling procedures have also been developed to produce continuous time series. **B) Approach:** Various quality control tests are applied that check the plausibility of data, identify correctly measured data and differentiate them from erroneous data. A data flagging system is implemented to identify, differentiate and quantify different types of errors. This paper also describes an experiment carried out to validate the functionality of quality checks applied. Data errors and gaps in measurement were replaced with "basic gap filling", a set of procedures, which are developed under this project. From the set of global, diffuse and direct normal radiation a single missing parameter can be calculated from the other two. When two or more are missing for short gaps clearness indices are derived to calculate the missing irradiance components. **C) Scientific Innovation and Relevance:** This new network of 51 stations is the largest measurement campaign, which includes pyrheliometers, on a country. Significant amount of applied research and development has been conducted in order to implement this system of quality control, make it functional and operational. The wealth of knowledge created in the course of implementation is very useful to the scientific and commercial solar community. Particularly at present there are no international standard procedures/protocols for gap filling of solar radiation data. Some applied research is being carried out on it as part of the IEA Task 46, IEA SolarPACES and EU research project ENDORSE. However, such quality check and gap filling procedures are not yet applied to data from high research quality networks like BSRN, GAW, etc. Here gap filling procedure is implemented for the data from all 51 stations. **D) Results:** An extensive data analysis has been carried out to determine the performance of the 51 stations. Since the installation around August 2011 until October 2012 it is found that on average over all 51 stations, 92 % of the solar radiation data are classified as correct. On an average over all 51 stations, ca. 3 % of solar radiation data do not pass the coherence test. Tracking errors are observed during 0.7 % on an average over all 51 stations. For one station after applying gap-filling procedure, the values of DNI and GHI increased by 2% over a period of 15 months. **Conclusions:** SRRA infrastructure has developed investment grade solar radiation resource information to assist project activities under the National Solar Mission of India. The data quality check and control system has been implemented successfully and is fully functional and operational now since ca. one year. This system has proven to be very efficient for detecting errors in functionality of the stations, which can be useful for their easy and fast rectifications. From the data analysis, it is observed on an average the network is running well. This analysis shall help in future improvement of the operation of the network.

1. Introduction

The Indian Ministry of New and Renewable Energy (MNRE) of Government of India (GoI) has awarded a project to Centre of Wind Energy technology, Chennai in the year 2011to 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. (Kumar et al. 2012). Each of these 51 SRRA stations is equipped with one secondary standard pyranometer to measure Global Horizontal Irradiance (GHI), one secondary standard pyranometer to measure Diffuse Horizontal Irradiance (DHI) and a first class pyrheliometer to measure DNI. A two-axis solar tracker is used to track the sun, on which the pyrheliometer and shading disc for DHI pyranometer are mounted. Apart from solar radiation parameters, these stations also measure other auxiliary meteorological parameters like ambient temperature, wind speed and direction, humidity, pressure, rain rate etc. All these data were previously measured in 10-minute time resolution and since August 2012; they are measured in 1-minute time resolution.

Gaps may occur due to loss of power, misalignment, failure of instruments, insufficient cleaning etc. Quality check procedures identify such malfunctioning and mark untrustworthy data by flags. Even well maintained stations with good equipment usually show some existence of gaps. However many applications such as solar energy performance simulations need continuous time-series. Therefore it is required to fill the measurement gaps with reasonable data.

One of the main aims of SolMap project is to support SRRA project in providing investment grade bankable solar radiation data to solar policy and decision makers, solar project developers and scientific community. It is envisaged that this data will also be used for improvement and validation of satellite-derived solar radiation data for India. Under such circumstances, quality check and control of data forms the backbone of this data collection and monitoring system, ensuring proper operation and maintenance of the system.

This paper documents the overall performance of the stations for last over a year and documents the specific problems and errors observed in real life. This paper also reports on the basic gap filling procedures which have been developed under this project.

2. Highlights of the performance of the stations

An extensive data analysis has been carried out to determine the performance of such a large network of high precision solar radiation measurement stations. This analysis is done for the data from all 51 stations. The time period of analysis is from the date of installation of each station (ca. August 2011) until October 2012. The results of this data analysis are presented here in brief in terms of the statistical parameters over all 51 stations. The three types of errors observed most frequently are shown in the table below.

Solar Radiation Parameter	**GHI**			**DNI**			**DHI**		
Statistical parameter*	avg	min	max	avg	min	max	avg	min	max
Error Type	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Values do not pass coherence test	3.4	0.1	17.1	3.6	0.1	17.3	3.6	0.1	16.9
Missing values	2.7	0.1	23.7	2.3	0.1	13.4	2.3	0.1	13.4
Tracking error	-	-	-	0.7	0.03	5.6	0.6	0.02	4.9

Table 1: Overview of the statistics of three major types of error observed for GHI, DHI & DNI over all 51 SRRA stations.

It is found that on an average over all 51 stations the most frequently observed error is 'the solar irradiance values do not pass the coherence test'. There are some stations that perform very well, for example it can be seen in Table 1 that the minimum amount of data that was flagged with error 'the solar irradiance values do not pass the coherence test' for a particular station was only 0.1%. At the same time the maximum amount of this error observed at a particular station is 17%. The detailed results of extensive analysis will be presented in the paper.

3. Highlights of Gap filling

The gap filling procedure implemented considers solar radiation and auxiliary meteorological data separately due to the fact that the occurrence and amount of gaps observed in these two types of data are significantly different. For gap filling of solar radiation data, the applied methodology depends on **a.** the availability of three components of solar radiation being measured i.e. Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI) and **b**. the duration (length) of the gap. The methodology differentiates if only one, two or all three solar radiation components are not available (gaps). In terms of the length of gaps, the methodology differentiates between gaps up to 3 hours, greater than 3 hours and gaps greater than 24 hours.

Depending on the availability of the three components of solar radiation and the duration (length) of gaps, gaps are filled either by using equation relating the three components or modeled values or linear interpolation of clearness indices or by replacing data from neighboring days. The methodology of gap filling followed and implemented as part of this project is shown in Figure 1.

Case 1: 1 component of solar radiation is missing (gap)

If only one of the three solar radiation parameters is flagged as incorrect or is missing, then this parameter will be calculated from the remaining two correctly flagged solar radiation parameters based on the physical relationship. For ex: if for a given time stamp DHI is flagged as incorrect or is missing but GHI & DNI are flagged correct, then for that time stamp DHI will be calculated from GHI & DNI following the equation

$$GHI = DHI + DNI * \cos\theta_z \qquad \textit{Equation 1}$$

Case 2: 2 components of solar radiation are missing (gap)

When two of the three solar radiation parameters are flagged as incorrect or are missing and one solar radiation parameter is flagged correct, then a two-step approach will be followed. This case is applicable only when GHI is available and both DNI and DHI are missing.

- Using the correctly flagged solar radiation parameter (GHI) as input to Skartveit Model described in Skartveit et al. 1998. DHI is determined from this model for the missing time stamp.
- In the next step, these two solar radiation parameters (GH) & DHI) are used to calculate the third solar radiation parameter (DNI) just like in Case 1 using equation 1.

Case 3: All 3 solar radiation parameters are flagged as incorrect or are missing (gap)

When all three solar radiation parameters are flagged as incorrect or are missing, statistical techniques are applied to fill the gaps. In this case, the duration (length) of gaps is taken into consideration.

- In the first step, gaps less than 3 hours are taken into consideration. For this case, clearness indices are calculated for GHI & DNI for all the time stamps, when these parameters are available and flagged correctly. Then for the missing time stamps, clearness indices are calculated by applying linear interpolation. The values of GHI and DNI are then calculated for the missing time stamps. From these newly calculated GHI & DNI values, DHI is calculated using equation 1. For this procedure of linear interpolation of clearness indices, the duration (length) of gap is limited to 3 hours following the method proposed in MESOR project. (Hoyer-Klick et al. 2009)
- When gaps in data are more than 3 hours, such gaps are replaced with data from neighboring days (in case they are available). In its current stage, the gap filling procedure can fill gaps up to 10 days if data for days before and after the gaps is available. The first 5 days will be replaced with data from the day before start of the gap, whereas the last 5 days will be replaced with data from the day after end of the gaps.

The outcome of gap filling is a continuous time-series without gaps in hourly time resolution.

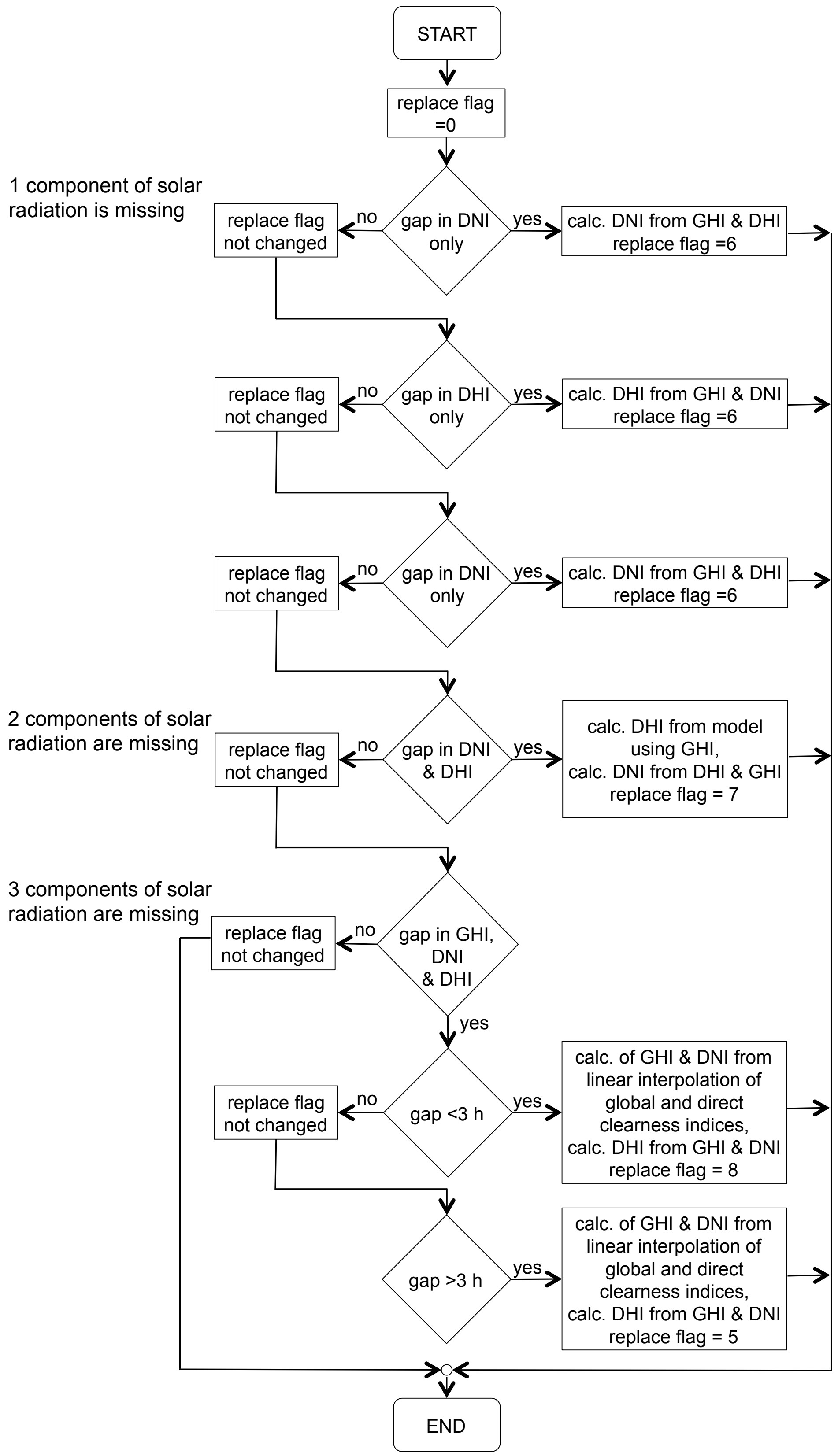

Figure 1: Flow-chart representing the steps followed for gap-filling of solar radiation data