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Development and test of gap filling procedures for solar radiation data of the Indian SRRA measurement network

Marko Schwandt[a]*, Kaushal Chhatbar[a], Richard Meyer[a], Katharina Fross[b] Indradip Mitra[b], Ramadhan Vashistha[b], Godugunur Giridhar[c], S. Gomathinayagam[c], Ashvini Kumar[d]

[a] *Suntrace GmbH, Brandstwiete 46, Hamburg, 20457, Germany*
[b] *GIZ GmbH, Chennai, India*
[c] *Centre for Wind Energy Technology, Chennai, India, Ministry of New and Renewable Energy, Chennai, India*
[d] *Solar Energy Corporation of India, New Delhi, India*

Abstract

Solar radiation measurements as most time-series data suffer from interruptions. Gaps may occur due to loss of power, misalignment, failure of instruments, insufficient cleaning or other reasons. Quality check procedures identify such malfunctioning and mark untrustworthy data by flags. Even well maintained stations with good equipment usually show gaps. In the case of the Indian SRRA network with its 51 stations operating since 2011, typically around 7% of the data are flagged as potentially erroneous or missing. Duration of gaps ranges from few minutes to several days. 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. Depending on duration and type of missing parameters various procedures can be used to fill gaps. This paper describes a set of procedures called 'basic gap filling' for solar irradiance, which can be applied without having available additional data. From the over-determined set of global, diffuse and direct radiation a single missing parameter can be calculated from the other two. When two or more solar irradiance components are missing for short gaps, clearness indices are derived to calculate the missing irradiance components. Basic gap filling procedure is applied as part of the SRRA/SolMap projects. The accuracy of the applied basic gap filling methodology is tested and the results show a mean bias of ca. 3 % over GHI, DNI and DHI over all types of gaps.

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Keywords: *Solar irradiance; gap filling procedure; DNI; GHI; satellite based gap filling; solar radiation; quality control;SRRA*

* Corresponding author. Tel.: +34-622-298-766.
E-mail address: marko.schwandt@suntrace.de.

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1. Introduction

Solar radiation measurements as most time-series data suffer from interruptions. Gaps may occur due to loss of power, misalignment, failure of instruments, insufficient cleaning or other reasons. Quality check procedures identify such malfunctioning and mark untrustworthy data by flags. Even well maintained stations with good equipment usually show gaps. Duration of gaps can range from few minutes to several days. Depending on duration and type of missing parameters various procedures can be used to *fill gaps*. Many applications such as solar energy performance simulations need continuous time-series. Therefore it is required to fill the measurement gaps with reasonably accurate data.

The Indian Ministry of New and Renewable Energy (MNRE) of Government of India (GoI) has awarded a project to Centre for Wind Energy Technology (C-WET), 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 at sites with high potential for solar power [1]. The GoI SRRA project has synergy with SolMap project, which is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in cooperation with MNRE. SolMap project contributes to SRRA project in establishing quality checks on the data obtained as per International protocols and helping data processing to generate investment grade data. SolMap project also aims to develop a solar radiation atlas for the country. Various quality control tests are applied that check the plausibility of data, identify correctly measured data and differentiate them from erroneous data.

Each of the 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 Direct Normal Irradiance (DNI). A two-axis solar tracker is used to track the sun with the pyrheliometer and a shading assembly for the DHI pyranometer. 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 data were previously averaged in 10-minute time resolution. Since August 2012 they are measured in 1 s and integrated to 1 min.

At present there are no standard procedures/protocols for gap filling of solar radiation data. Some applied research is being carried out in this direction 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. This paper describes a set of procedures called ‘basic gap filling’, which can be applied without having available additional data and introduces the concept of satellite-based gap filling, which needs overlapping satellite-derived data.

2. Quality check and quality control of SRRA data

One of the main aims of SRRA is to provide investment grade bankable solar radiation data to the solar industry, project developers, decision makers in the financing institutions and policy and also to the 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. Various quality control tests are applied that check the plausibility of data, identify correctly measured data and differentiate them from erroneous data. The tests applied here follow international best practices like those established by NREL’s SERI-QC [2], WMO’s BSRN [3], [4] and those used in the EU-project MESOR [5].

A data flagging system is implemented to identify, differentiate and quantify different types of errors. Such flags give feedback to users for identification of possible types of errors, which prove useful for rectification. These quality checks leads to identification, flagging and hence differentiation of correctly measured data from erroneous data. Such *erroneous data* along with *missing data* are considered as *gaps*. An extensive analysis of the amount of gaps in GHI, DNI and DHI at all 51 SRRA stations from their respective dates of commissioning up to May 2013 is done. Based on the gap filling methodology developed and applied, the total amount of gaps are divided into three categories: i) when the gap is in only one solar irradiance component: GHI only or DNI only or DHI only ii) when the gap is in two solar irradiance components DNI and DHI iii) when the gap is in all three solar irradiance components.

Figure 1 shows the amount of gaps in GHI, DNI and DHI for all 51 SRRA stations. The most frequently observed type of gap is when all three components of solar irradiance are missing, followed by when only two components of solar irradiance (DHI and DNI) are missing. On an average over all stations, the amount of gaps is 0.1 % of the data when one solar irradiance component (GHI, DNI or DHI) is missing.

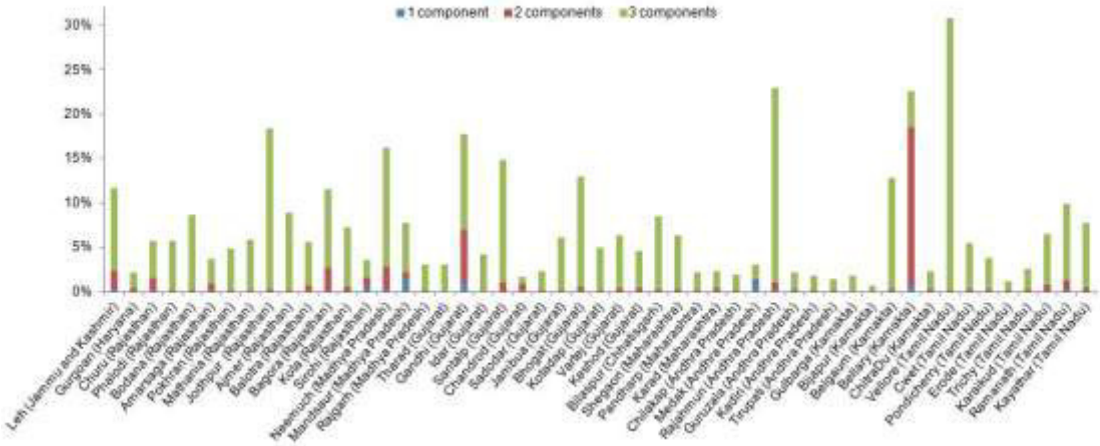

Fig. 1. Analysis of the amount of gaps in GHI, DNI and DHI at all 51 SRRA stations from their respective dates of commissioning up to May 2013. The total amount of gaps is divided into three categories: i) when the gap is in only one solar irradiance component: GHI only or DNI only or DHI only ii) when the gap is in two solar irradiance components DNI and DHI iii) when the gap is in all three solar irradiance components. Data gaps include data flagged as incorrect and missing data.

The minimum amount of gap in only one component is 0.001 % at station Idar (1819), whereas the maximum value of 1.6 % is observed at station Mandsaur (1945). On an average over all stations, 0.9 % of the data have gaps in two solar irradiance components (DNI and DHI), reaching a maximum value of 18 % for Bellary (1936). The average amount of gap over all stations rises to 6 % when the gap is in all three components, reaching a maximum value of 31% for station Vellore (1933) whereas a minimum value of 0.6 % is observed at station Bijapur (1946). The total amount of gaps (sum over all three categories) on an average over all stations is 7.5 % of the data, with a minimum value of 0.6 % at station Bijapur (1946) and a maximum value of 31% for Vellore. Due to such gaps the usage of these data gets limited. These gaps should be filled with valid data. As a result a gap filling procedure is developed and implemented as part of the SolMap project.

3. Gap filling procedure

The gap filling procedures developed as part of SolMap/SRRA projects are divided into basic gap filling and satellite-based gap filling. The main difference between the two procedures is that basic gap filling procedure does not require additional overlapping satellite-derived data, whereas it is a must for satellite-based gap filling procedure. Due to the non-availability of additional satellite-derived data, satellite-based gap filling is not implemented for SolMap/SRRA project. Both these procedures are explained in the following.

3.1. Basic gap filling

The basic gap filling procedure considers solar radiation and auxiliary meteorological data separately. 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 gap filling 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, modeled values, linear interpolation of clearness indices or by replacing data from neighboring days. The methodology of 'basic gap filling' followed and implemented as part of this project is shown in Figure 2.

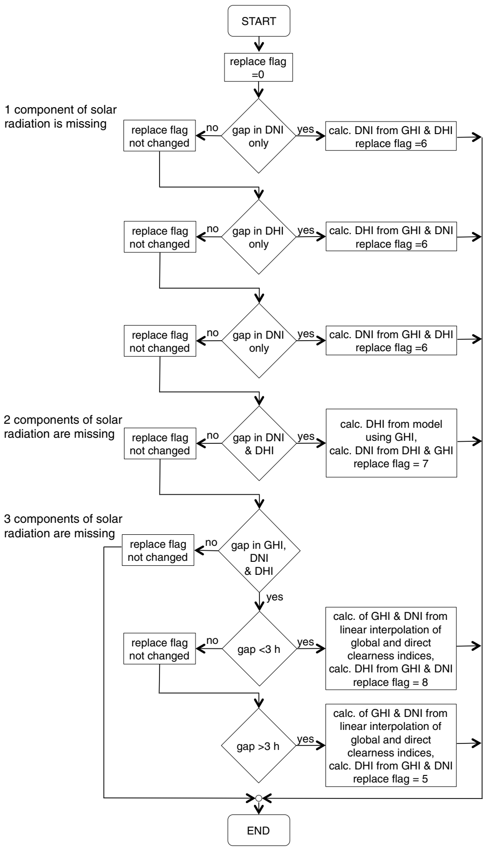

Fig. 2. Flow-chart representing the steps followed for basic gap filling of solar irradiance data

Case 1: One (1) component of solar irradiance is flagged as incorrect or is missing (gap)

If only one of the three solar irradiance components 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.

$$GHI = DHI + DNI * \cos\theta_z \quad (1)$$

Case 2: Two (2) components of solar irradiance are flagged as incorrect or are missing (gap)

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

- Using the correctly flagged solar irradiance component (GHI) as input to Skartveit Model described in [6]. DHI is determined from this model for the missing time stamp.
- In the next step, these two solar irradiance components (GH) & DHI) are used to calculate the third solar irradiance component (DNI) just like in Case 1 using Equation 1.

Case 3: All three (3) solar irradiance components are flagged as incorrect or are missing (gap)

When all three solar irradiance 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 components 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 [5].
- 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. This limit of 10 days is set due to the fact that in atmospheric science it is assumed that weather stays constant for a period of 5 days. Moreover, since the sun position does not deviate significantly for a period of 5 days, this procedure is applied to solar radiation data, so that the data matches with sunrise and sunset times and also with sun elevation and azimuth angles.

For gap filling of auxiliary meteorological data, only Case 3 discussed for solar radiation data is applied and the applied methodology depends only on the duration (length) of the gap. When duration (length) of gaps is less than 3 hours, instead of linear interpolation of clearness indices the values of the parameters are directly linearly interpolated. The outcome of gap filling is a continuous time-series without gaps in hourly time resolution.

Figure 3 shows a graphical representation of the basic gap filling procedure when applied to three types of sky situations i.e. clear-sky day, broken cloud sky day and cloudy-sky day. For each day gap filling procedure is represented for three cases i.e. when the gap is in only one component of solar irradiance (DHI) b) when the gap is in two components of solar irradiance (DNI and DHI) and c) when the gap is in all three components of solar irradiance (GHI, DNI and DHI).

3.2. Satellite-based gap- filling

Satellite-based gap filling uses satellite-derived solar radiation data and hence this gap filling procedure is possible only when additional satellite-derived solar radiation data is available. In this approach, site-specific satellite-derived solar radiation data are required at least in 60 minutes time resolution for overlapping period as that of ground-based measurements. As an example for satellite-based gap filling, the same stations as used for basic gap filling (Figure 3) are used and the results of applying this procedure are shown in Figure 4. As satellite-derived solar radiation series is not available for all 51 SRRA stations, this method is not implemented in SolMap/SRRA project.

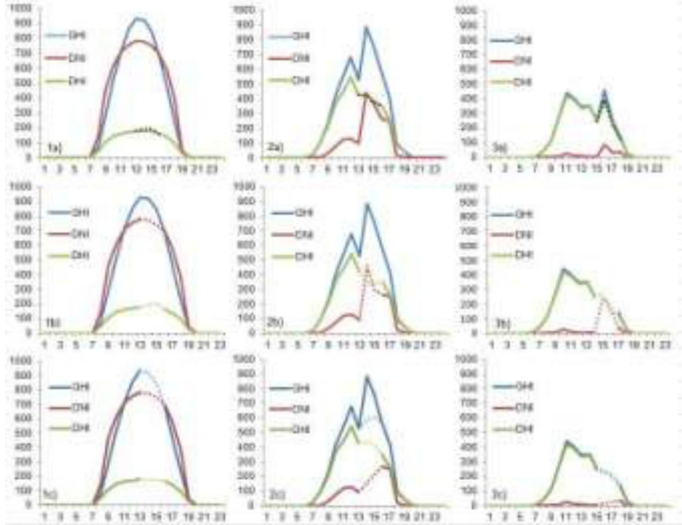

Fig. 3. Figures illustrating the implementation of basic-gap filling procedure. Daily cycle of GHI, DNI and DHI (Station Medak, Andhra Pradesh) are shown in the figures, where Y-axis represents solar irradiance in W/m^2. Solid lines represent originally measured solar irradiance values, while dotted lines represent solar irradiance values after applying basic gap filling procedure. a) when the gap is in only one component of solar irradiance (DHI) b) when the gap is in two components of solar irradiance (DNI and DHI) and c) when the gap is in all three components of solar irradiance (GHI, DNI and DHI). The three types of gaps-filling procedure are shown for 1) clear-sky (20.3.2012), 2) broken cloud (29.5.2012) and 3) cloudy-sky conditions (19.08.2012).

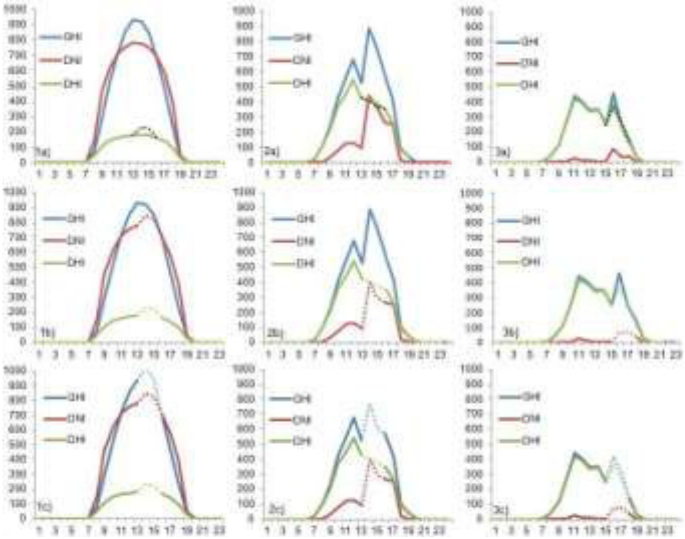

Fig. 4. Figures illustrating the implementation of satellite-based gap filling procedure. Daily cycle of GHI, DNI and DHI (Station Medak, Andhra Pradesh) are shown in the figures, where Y-axis represents solar irradiance in W/m^2. Solid lines represent originally measured solar irradiance values, while dotted lines represent solar irradiance values after satellite-based gap filling procedure. a) when the gap is in only one component of solar irradiance (DNI) b) when the gap is in two components of solar irradiance (DNI and DHI) and c) when the gap is in all three components of solar irradiance (GHI, DNI and DHI). The three types of gaps-filling procedure are shown for 1) clear-sky (20.3.2012), 2) broken cloud (29.5.2012) and 3) cloudy-sky conditions (19.08.2012).

Replacing a single missing solar radiation component by satellite-derived solar radiation data (Figure 4, 1a), 2a) and 3a)) can lead to substantial differences from the real value. In this case it is better to calculate the missing component from the closure equation, as it is done with the basic gap filling procedure (Figure 3, 1a), 2a) and 3a)). If 2 components are missing (Figure 4, 1b), 2b) and 3b)) the satellite-derived values can lead to more realistic values for broken and cloudy skies. In the clear-sky case (Figure 4, 2a)) however the satellite-derived values are substantially higher for DNI as well as for DHI, because on this day the satellite-derived radiation is assuming lower turbidity than actual and thus more radiation in all three components. In such cases the basic gap filling leads to better results. It is often observed that satellite-derived irradiance data tend to systematically over- or underestimate radiation in clear-sky situations. Such could be improved by adapting the satellite-derived solar radiation values to the measurements by methods such as the procedures described in Schumann [7]. Further it is recommended that if 2 components are missing only one of the missing two, DNI should be derived from satellite-data. The second missing component, DHI, better should be calculated from measured GHI and the satellite-derived DNI using Equation 1. Typically the calculated component should be the diffuse irradiance, which in most cases is less important for solar energy applications.

Similarly if 3 components are missing (Figure 4, 1c), 2c) and 3c)) the satellite-derived values can lead to more realistic values for broken and cloudy skies and less realistic values for clear sky days. Here it is also recommended to use site-adapted satellite-derived irradiance data instead of the original to reach a better match with the real data. When using the original satellite-derived data DHI could be taken straight from the satellite-source, as it should be consistent with total and direct irradiance.

4. Results and discussions

Using the basic gap filling procedure explained in this paper, data from all 51 SRRA stations were processed and gaps in solar radiation time series were filled. As a user of SRRA data it becomes important to know the impact of gaps on the averages of solar radiation. Consequently we analyzed the differences in the averages of solar radiation at all 51 SRRA stations before and after applying gap filling. This analysis is done for data from all 51 SRRA stations from their respective date of commissioning (ca. August 2011) until May 2013. The analysis is presented as relative mean bias in values after applying gap filling in Figure 5, which shows the differences in averages of GHI, DNI and DHI between the original data with gaps and the gap-filled data.

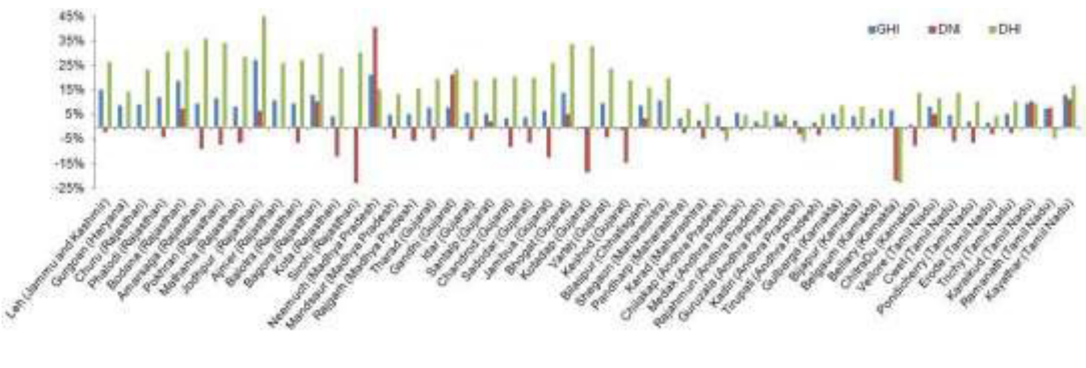

Fig. 5. Analysis of the differences in averages of GHI, DNI and DHI before and after implementation of basic gap filling procedure. The analysis is done for all 51 SRRA stations from their respective dates of commissioning up to May 2013. The values are represented as relative mean bias in % between original (Level 2) and gap-filled values (Level 3). A positive mean bias indicates increase in the solar irradiance average after applying basic gap filling. A negative bias indicates decrease in the solar irradiance average after applying basic gap filling.

For most stations GHI and DHI are increased after performing basic gap filling procedure, whereas DNI is reduced. DHI increases for most stations by around 15 % to 25 %, reaching a maximum of 50 % for Jodhpur (1813) and a minimum of -23 % for Bellary (1936). On an average over all 51 SRRA stations DHI increases by 17 %, with the median over all stations also being 17 %. GHI increases less than DHI, reaching for most stations values between 5 % and 10 %, with a maximum of 27 % for Jodhpur (1813) and a minimum of -1 % for Kotadapitha (1820). On an average over all 51 SRRA stations, the increase in GHI is 7 %, whereas the median of the increase in GHI over all stations is 6 %. A marginal effect of gap filling on DNI is observed, with a reduction of DNI values by 2 % on an average over all stations. For most of the stations change in DNI values is nominal, however significant increase and decrease in DNI values at particular stations affects the overall average. DNI decreases by values up to 22% at Bellary (1963) and Sirohi (1798) and increases up to 41 % for Neemuch (2006).

Discussion of results:

From the results it can be inferred that most of the gaps (error or missing) in GHI and DHI values occur during that time of the day when respective solar radiation values are high i.e. probably during noontime. Since these high radiation periods are not considered in original time series due to gaps, the averages of GHI and DHI are less than actual values. Gap filling helps to fill such gaps of high radiation periods, hence increasing the averages of GHI and DHI. Most of the errors in DNI occur during low DNI periods i.e. either morning or evening time. When a gap is there in two components of solar radiation (DHI and DNI) and GHI is measured correctly, a global to diffuse conversion model is used to calculate DHI from GHI. DNI is then calculated from GHI and DHI using Equation 1. At present this global to diffuse conversion model with same assumptions are used for all SRRA stations. In future this model may be adjusted to varying atmospheric conditions at different places When gaps are present in all three components of solar irradiance, GHI & DNI are calculated based on the linearly interpolated clearness indices for global and beam. The cloud-formation in the sky during these 3 h periods plays an important role in determining the values of clearness indices, which in the present case are linearly interpolated. For gaps greater than 3 hours in all three components (GHI, DNI & DHI) data from neighboring days is used to fill the gaps, therefore changes in cloud cover lead to a strong changes in solar radiation values.

Quantification of the effect of gap filling

In the next step of analysis, the aim was to quantify the effect and determine the accuracy of gap filling by creating artificial gaps in time series with correctly measured data. For this a sample of 9 SRRA stations located in different states of India and hence representing different climatic conditions and also operational condition of the stations was taken. Artificial gaps were created in the time-series of data from all these stations based on four main categories of gaps: when the gap is in only one component of solar irradiance (DHI) b) when the gap is in two components of solar irradiance (DNI and DHI) and when the gap is in all three components of solar irradiance (GHI, DNI and DHI) for c) gaps smaller than 3 hours and d) gaps greater than 3 hours. Gaps were created on a continuous basis for these four types of gaps.

After creating these artificial gaps, basic gap filling procedure was applied to the time series and results obtained are presented. The results are presented in Figure 6 a), Figure 6 b), Figure 7a) & Figure 7b) as relative mean bias between the gap-filled data and original data without gaps. After applying gap filling procedure to data with artificially created gaps, it is found that:

- When gaps are present in one component only (GHI, DNI or DHI), GHI increases by 0.3 %, DNI decreases by 0.8 % and DHI decreases by 0.7 % on an average over all 9 SRRA stations after applying basic gap filling procedure. These values are found to be quite reasonable taking into consideration the inaccuracies involved in the averaging of hourly values of solar radiation and zenith angles.

- When gaps are present in two components of solar radiation (DHI and DNI), DNI increases by 19 % and DHI decreases by 9 % on an average over all 9 SRRA stations after applying basic gap filling procedure. On cloudy days the model used for gap filling underestimates values for DHI, which leads to an overestimation of DNI. For Station Kayathar (Figure 6b)) days used for this analysis were mainly cloudy, resulting in a higher mean bias compared to other stations that included more clear days.
- When gaps smaller than 3 hours are present in all three components of solar radiation (GHI, DNI and DHI), GHI decreases by 2 %, DNI decreases by 2 % and DHI decreases by 1 %.
- Finally, when gaps greater than 3 hours are present in all three components of solar radiation (GHI, DNI and DHI) GHI increases by 4% and DHI decreases by 0.5 %. DNI increases for some stations to a large extent, because here data from the neighboring day is taken to fill the gaps. In some cases the data on a cloudy day is replaced by data from a clear sky day, which increases DNI significantly. Santalpur and Bilaspur stations are examples of such extreme outliers.

a) b)

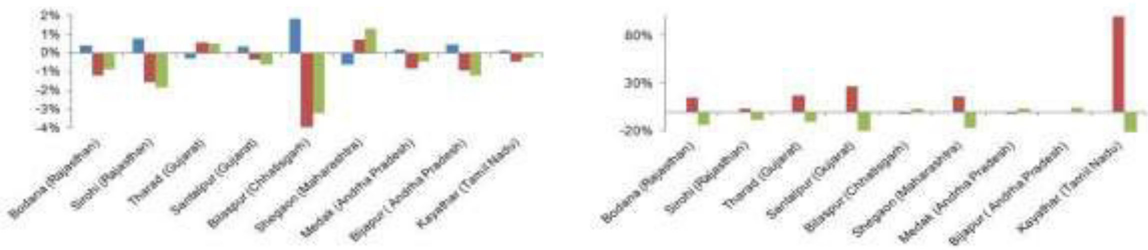

Fig. 6. Artificial gaps for a) one and b) two solar irradiance component are created for all 24 hours in original solar irradiance data (Level 2) from 10 SRRA stations with good data on purpose to quantify the performance of basic gap filling procedure. Results from the tests of basic gap filling procedure are represented as relative mean bias in % between original (Level 2) and gap-filled values (Level 3). A positive mean bias indicates increase in the solar irradiance average after applying basic gap filling. A negative bias indicates decrease in the solar irradiance average after applying basic gap filling.

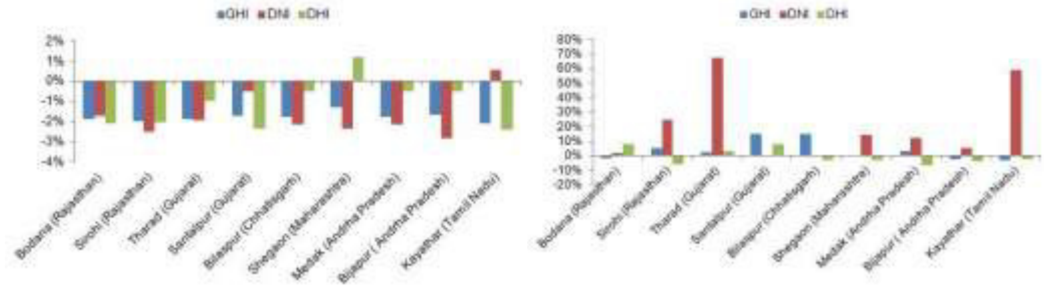

Fig. 7. Artificial gaps for all three solar irradiance components (GHI, DNI and DHI) for a) gaps <3h between 7 & 9, 11 &13, 16 & 18 (UTC+5) and b) gaps >3h gaps between 7 & 18 (UTC+5) are created in original solar irradiance data (Level 2) from 10 SRRA stations with good data. Results from the tests of basic gap filling procedure are represented as relative mean bias in % between original (Level 2) and gap-filled values (Level 3). A positive mean bias indicates increase in the solar irradiance average after applying basic gap filling. A negative bias indicates decrease in the solar irradiance average after applying basic gap filling.

The accuracy of the applied basic gap filling methodology is tested and the results show a mean bias of ca. 3 % over GHI, DNI and DHI over all types of gaps. This accuracy is close to the accuracy of the applied solar irradiance measuring instruments, indicating that the gap filled values stay within the tolerance limits.

5. Conclusions and Outlook

Two new gap filling procedures, *basic gap filling* and *satellite-based gap filling* are presented in this paper. For basic 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 gap filling 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.

As satellite-derived solar radiation series is not available for all 51 SRRA stations, this method is not implemented in SolMap/SRRA project. Basic gap filling procedure presented in this paper is implemented as part of SRRA and SolMap projects. After applying basic gap filling procedure it is observed that with respect to data with gaps, on an average over all 51 SRRA stations the deviation in gap filled GHI values is 7 %, for DHI it is 17 % whereas marginal deviation of 2 % is observed in DNI values. The accuracy of the applied basic gap filling procedure is determined by creating artificial gaps in time-series of correctly measured solar irradiance values. After applying gap filling procedure to data with artificially created gaps, the results show a mean bias of ca. 3 % over GHI, DNI and DHI over all types of gaps, representing the accuracy of the applied basic gap filling procedure. This accuracy is close to the accuracy of the applied solar irradiance measuring instruments, indicating that it stays within the tolerance limits.

Further improvement in the basic gap filling procedure can be achieved for the case when two components of solar irradiance (DHI and DNI) are missing by linear interpolation of beam clearness indices to calculate DNI and later calculating DHI from the equation relating GHI, DNI and DHI. For the case when gaps >3 h are present in all three solar irradiance components, a method to use either historical data, data from neighboring stations or data from statistical methods should be developed so as to have as much as possible representative data.

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