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Impact Assessment of Short-Term Temporal Variability of Solar Power in Rajasthan Using SRRA Data

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Abstract

During the last decade, worldwide deployment of solar photovoltaic power plants has registered an unprecedented growth owing to – initially – politically motivated support programs and – finally – economic competitiveness. India has also witnessed an exponential growth in solar PV installation during the recent years and has set an ambitious target of 100 GW solar PV installed capacity by 2022. In Rajasthan alone, a solar power capacity of around 5.8 GW is aimed to be achieved by that time. However, short-term solar variability can be a hindrance in the process of large scale solar power deployment, as this makes operation of large solar PV plants difficult and management of power grid challenging.

Here, the aim is to study the impact of short-term temporal variability of solar power in Rajasthan. Also, another motive is to observe the effect of spatial smoothing and to quantify the suppression of variability due to the same. The data sets used consist of 1-min solar irradiance data measured at ten time-synchronized solar radiation resource assessment (SRRA) sites dispersed across Rajasthan. The methodology includes calculation of clear sky index (K_t*) using Bird clear sky model, computation of site-pair correlation using the parameter 'Change in clear sky index' (ΔK_t*), evaluation of proposed parameter 'Percentage change in generation' to observe Dispersion-Smoothing effect and sample calculation of parameter 'Diversity Filter' to estimate suppression of variability due to regional smoothing.

Key Words: *Short-term temporal variability, Spatial smoothing, PV power ramps.*

1. Introduction

India, a country of around 1.3 billion population, is power starved. Today still around 22% of the Indian population has no access to electricity (The World Bank, 2015). The Indian government (GOI) has recognized the fact that renewable energy (RE) will play a very important role in reducing the percentage of people, who are deprived of electricity, by providing easier access to clean energy and is working assiduously to create a conducive environment for renewable energy infrastructure growth in the country. Last sexennial, India has witnessed an unprecedented growth in green energy installations. As of June 2015, India's net grid-connected RE capacity stood at 36.47 GW, of which almost 65 % came from wind, while solar PV contributed to nearly 11 % of total RE installed capacity (MNRE, 2015a). Though contribution of solar PV has been meagre compared to the share from wind previously, the scenario is about to change. By the year 2022, the GOI aims to achieve an updated target of 100 GW of solar PV capacity under its Jawaharlal Nehru National Solar Mission (JNNSM) program. In Rajasthan alone, the target is to achieve solar PV power installed capacity of 5.8 GW (MNRE, 2015b).

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However, short-term solar variability may be an impediment to the large scale solar deployment. Solar variability, which – on the very short-term time scale – happens mainly due to the movement of clouds, can drive a PV power plant from generation at rated power to nearly no generation mode or vice versa in matter of seconds. An array of cloud structures passing in front of the sun can cause an abrupt change in power generation, thus making the operation of solar PV power plants difficult and the management of electrical grids challenging.

In addition, a sudden variation in solar generation due to short-term solar resource variability can be a source of unprecedented challenges for power generation companies, transmission companies and distribution system operators (DSOs). Changes in solar irradiance over a short time scale (seconds) can create power quality problems like voltage flicker & harmonic distortion etc., which may be detrimental to critical, sensitive loads at consumer end. Serious grid level problems like issues with power quality and network outages may occur, when, due to sudden variation in solar power generation and unavailability of sufficient ramping capability, the grid fails to cater to system load. In addition to this, variable PV generation can also have a serious impact on local feeders and substations, which are highly specific to local conditions like demand profile, grid distribution and existing system constraints (CAT Projects, 2015). Tab. 1 lists different impacts on power system due to variable solar generation (IEA, 2015). The grid operator may sometimes need to take corrective actions like using voltage limiters, ensuring availability of ample operating reserve and ramping capability and load following etc.

Tab. 1: Potential impact on power system due to short-term solar variability (IEA, 2015)

Time interval of change in solar irradiance	Potential impact on power system
Seconds	Voltage fluctuation
Minutes	Regulation reserves
Minutes to hours	Load following

Hence, short term solar variability is a very important parameter to study, as the outcome of the study may throw light on the extent to which variability can be experienced and the balancing resources needed to lessen its impact. In recent years, this topic has attracted attention of a large number of researchers and there have been numerous publications on this topic, most notably by (Hoff & Perez, 2010, 2012a, 2012b), (Mills & Wiser, 2010) and (Perez et al, 2015). For most of these studies, synthetic data or satellite data has been used to evaluate the impact of short-term variability over a wide area. (Mills & Wiser, 2010) used ground measured irradiance data from 23 time-synchronized stations to study the event of solar variability in the Southern Great Plains area.

Here, a short-term solar variability study for the state of Rajasthan is conducted using 1-min resolution irradiance data, measured at the Solar Radiation Resource Assessment (SRRA) stations. This is the first time, a wide-area study on assessing the impact of solar variability has been conducted for any state in India using high-quality ground measured irradiance data sets. Also, another motive behind this study is to observe the effect of spatial smoothing and to quantify the suppression of variability due to spatial smoothing. The main rationale behind choosing Rajasthan for this study is the proposed development of solar energy infrastructure in the state in the coming years. Recently, the Indian government has proposed setting up of ultra-mega solar power farms at Sambhar, Bhadla and Jaisalmer of Rajasthan. In the years to come, Rajasthan is going to witness a steep increase in solar power generation and in that context, the selection of Rajasthan for a variability study can be justified.

2. Methods

2.1. Quantifying solar variability for a single site, for a fleet of solar generators & suppression of variability

For properly quantifying variability, the parameters needed to be defined are: (a) the physical quantity that varies (b) the time interval over which it varies and (c) the time period of variation.

The most important physical quantity under assessment can be solar PV power generated from a single site or from a fleet of PV plants, as it is of the highest concern for a solar power producer or grid operator. Solar power generated is also a linear function of solar resources available. Hence, researchers study variability of global horizontal irradiance (GHI) or direct normal irradiance (DNI) in case of unavailability of power generation data. Studying variability of DNI is more relevant for concentrating technologies, while the former is more important for non-concentrating flat plate solar systems. Short-term GHI variability considers variation due to both predictable solar geometry and unpredictable cloud motion. The effect of predictable components can be excluded by analysing the clear sky index K_t*, the ratio of GHI to clear sky GHI. This parameter is calculated by applying a clear sky irradiance model with a specific set of atmospheric parameters as input. K_t* as a normalized quantity then clearly shows any deviation from this highly predictable clear sky situation – especially any cloud induced variability. In this work, the clear sky index K_t* is used based on the clear sky irradiance model from (Bird, 1984; Myers, 2013).

Time interval (Δt) is the time over which the selected physical quantity, K_t*, varies. ΔK_t* is defined as the change that the clear sky index undergoes during the time interval Δt. The time interval can vary from few seconds to hours depending on the concern of the user. For large PV generators or regional grid operators, solar variability over few seconds may not be a serious matter to worry about, but it will be troublesome for a small PV generator or for a single site.

Time period is the time span over which variability is studied. Time span is always a multiple of time interval. Here, for this work, the time period of study is one year.

Now, a nominal variability metric for a single site can be defined as the standard deviation of the change in clear sky index ΔK_t* during a time interval Δt over the selected time period (Perez & Hoff, 2013).

$$\sigma\ (\Delta Kt^*_{\Delta t})\ = \sqrt{Var(\Delta Kt^*_{\Delta t}\ )} \qquad \text{(eq.1)}$$

The quantity σ (ΔK_t*) is a normalized dimensionless quantity. This variability is directly proportional to the standard deviation of the change in generated power. Absolute power output variability is expressed by:

$$\sigma(\Delta P_{\Delta t})\ = \sqrt{Var(\Delta P_{\Delta t}\ )} \qquad \text{(eq.2)}$$

Where $\Delta P_{\Delta t}$ = change in power generated during time interval Δt.

Again, normalized power variability is given by:

$$\sigma(\Delta P_{\Delta t})_{Norm} = \sqrt{Var(\Delta P_{\Delta t}\ )}\ /P_{installed} \qquad \text{(eq.3)}$$

Where $P_{installed}$ = net installed capacity at the site under study.

Ideally,

$$\sigma(\Delta Kt^*_{\Delta t}) = \sigma(\Delta P_{\Delta t})_{Norm} \qquad \text{(eq.4)}$$

For a fleet of solar generators, the absolute power variability of N plants is given by (Perez & Hoff, 2013):

$$\sigma^{fleet}_{\Delta t} = \sqrt{Var(\textstyle\sum_{n=1}^{N} \Delta P^n_{\Delta t})} \qquad \text{(eq.5)}$$

Where $\Delta P^n_{\Delta t}$ = change in generation at n^{th} site during time interval Δt.

For a special case, when all the plants in the fleet have the same installed capacity, exhibit the same variability and their power output time series are uncorrelated, the above equation simplifies to:

$$\sigma^{fleet}_{\Delta t} = \sqrt{(N * Var(\Delta P_{\Delta t}))} \qquad \text{(eq.6)}$$

For this special case, the relative normalized power variability for the fleet of generators is given as follows:

$$(\sigma^{fleet}_{\Delta t}\ )_{Norm} = \sqrt{(N * Var(\Delta P_{\Delta t}))}\ /(N * P_{installed}) \qquad \text{(eq.7)}$$

Where $P_{installed}$ is the net installed capacity of an individual power plant.

Hence, the relative variability for a fleet of identical generators with their power output time series uncorrelated, experiencing same variability equals each individual plant's relative variability divided by square root of the number of plants N (Perez et al, 2015).

$$\text{Fleet Relative Variability} = (\text{Single Relative Plant Variability})/\sqrt{\text{N}} \qquad \text{(eq.8)}$$

Hence, the following equation mentioned in terms of clear sky index (K_t*) can be applied to the relative variability for a fleet of identical generators:

$$(\sigma_{\Delta t}^{fleet})_{\text{Norm}} = \sigma_{\Delta t}^{1}/\sqrt{N} \quad \text{(eq.9)}$$

Here, $(\sigma_{\Delta t}^{fleet})_{\text{Norm}}$ is the fleet's normalized variability and $\sigma_{\Delta t}^{1}$ is a single location's nominal variability. This event of suppression of variability is also known as spatial smoothing effect, which signifies suppression of power variability experienced (by a factor of 1/√N) at a single PV generator when integrated to a fleet of similar but uncorrelated PV power plants. The above equations hold good for a fleet of identical uncorrelated generators, but in actual case, there will be a correlation among any two sites under study, which is a function of distance between them, the time interval and the time period of analysis. Therefore, the key parameter to find is the site-pair correlation (ρ).

Now, considering a pair of identical stations with site-pair correlation ρ, (eq. 9) can be re-written as:

$$(\sigma_{\Delta t}^{pair})_{\text{Norm}} = \frac{\sqrt{(\rho+1)}}{\sqrt{2}} * \sigma_{\Delta t}^{1} \quad \text{(eq.10)}$$

This site-pair correlation parameter for a pair of sites can be evaluated by deriving the weighted mean of each individual day's correlation. Again individual day's correlation is found by correlating the change in clear sky index values between a pair of stations for different time intervals. The weighting factor is the day's variability quantified by the daily variance of ΔK_t* (Perez et al, 2012).

$$\rho_{\Delta t}^{L} = \frac{\sum_{j=1}^{n}(\rho_{\Delta t,j}^{L} * Var(\Delta Kt_{\Delta t}^{*}))}{\sum_{j=1}^{n} Var(\Delta Kt_{\Delta t}^{*})} \quad \text{(eq.11)}$$

Where $\rho_{\Delta t}^{L}$ = Site-pair correlation for a pair of sites separated by a distance L for a time interval Δt,
n = total number of station days analyzed.

In this work, the site-pair correlation between any two sites has been evaluated for n = 365 with Δt varying from 1 minute to 60 minutes and L ranging from 47 km to 532 km.

For a fleet of identical PV generators (whether correlated or uncorrelated), absolute power variability is given by the expression:

$$\sigma_{\Delta t}^{fleet} = \sqrt{Var(\textstyle\sum_{n=1}^{N} \Delta P_{\Delta t}^{n})} = \sqrt{(\textstyle\sum_{i=1}^{N}\sum_{j=1}^{N} \text{Cov}(\Delta P_{\Delta t}^{i}, \Delta P_{\Delta t}^{j}))} \quad \text{(eq.12)}$$

Relative Power Variability for a fleet of identical generators can be expressed as:

$$(\sigma_{\Delta t}^{fleet})_{\text{Norm}} = \sigma_{\Delta t}^{fleet}/(N * P_{installed}) \quad \text{(eq.13)}$$

$$(\sigma_{\Delta t}^{fleet})_{\text{Norm}} = \sqrt{(\textstyle\sum_{i=1}^{N}\sum_{j=1}^{N} \sigma_{\Delta t}^{i}\sigma_{\Delta t}^{j}\ \rho_{\Delta t}^{i,j})} \quad \text{(eq.14)}$$

To quantify the suppression of variability, a factor termed as Diversity Filter (Mills & Wiser, 2010) has been introduced. Diversity Filter denotes the factor by which spatial smoothing takes place. It is expressed by the ratio of agglomerated variability of all sites to the sum of variability at individual sites.

$$\text{Diversity Filter} = \text{D} = \frac{\sigma_{\Delta t}^{fleet}}{\sum_{i=1}^{N} \sigma_{\Delta t}^{i}} \quad \text{(eq.15)}$$

So, for a group of N uncorrelated sites with same variability, Diversity Filter (D) is 1/√N, which is the theoretical maximum by which suppression of variability, for a group of PV generators, can take place. But, for a group of correlated sites the diversity factor can be calculated by using (eq. 15). In our study, we have evaluated Diversity Filter values for ten SRRA sites for time intervals, Δt = 1 minute, 5 minute, and 15 minute on a highly variable 165th day of the year 2014. This value signifies the suppression of variability that can be achieved, by combining outputs from PV plants at these ten different sites and feeding them to a common regional grid.

2.2. Experimental data

2.2.1. SRRA Stations

For this work, we have collected ground measured environmental parameter data-sets from ten solar radiation resource assessment (SRRA) stations in Rajasthan. SRRA stations are automatic stand-alone systems consisting of several high quality/high resolution instruments, which measure available solar radiation (global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), and direct normal irradiance (DNI)) along with other weather parameters like ambient temperature, relative humidity, atmospheric pressure, and wind speed etc. at a temporal resolution of 1 minute. In the year 2011, the erection and commissioning of 51 SRRA stations was started by the National Institute of Wind Energy (NIWE) with funding from the Ministry of New & Renewable Energy (MNRE), Government of India and technical assistance from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ GmbH) under the SolMap Project. The SolMap project was initiated under Indo-German Bilateral Cooperation and was supported by the German Ministry for Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, BMUB).

In the second phase, NIWE has established 60 more SRRA stations in 28 states and 3 union territories. As of May 2015, there is a total of 121 SRRA stations operating all over India being maintained by NIWE (Fig 1). The SRRA network with 121stations is one of the world's largest pyrheliometric networks and ensures the availability of a solid database of ground measured solar radiation data essential for the deployment of solar power plants in India.

All station data quantifying global, direct and diffuse irradiance as well as other environmental parameters are acquired at SRRA stations and stored in a server at Central Receiving Station (CRS) established at NIWE. The raw data sets are further processed by applying different quality control algorithms. If any errors or inconsistencies are detected, then corresponding data points are flagged. Quality control algorithms are based on Baseline Surface Radiation Network (BSRN) rules set by the World Meteorological Organization (WMO). The radiation data obtained is also compared to modelled clear sky irradiance and to the physical limits. Once, the data points have cleared all the tests, they are cached in another server at CRS (Kumar et al., 2014). For this work, the archived datasets for the year 2014 measured at some selected SRRA stations in Rajasthan, have been extracted from CRS.

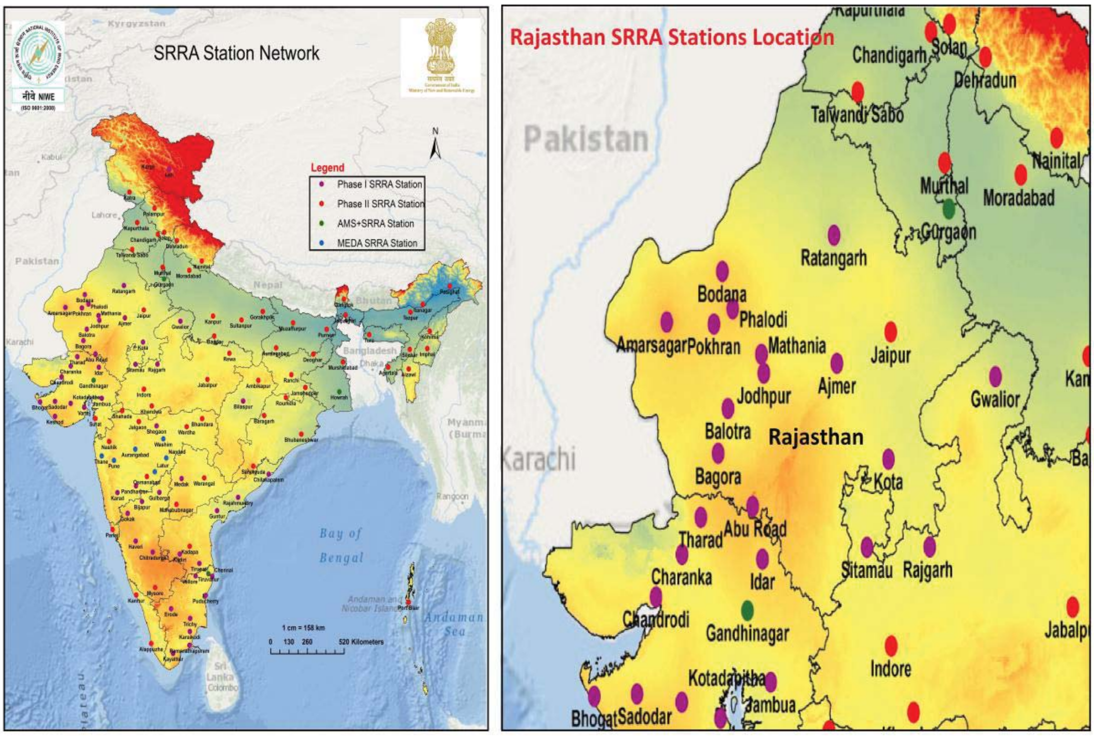

Fig.1: Map of the full SRRA network (left) and the SRRA stations in Rajasthan (right), as of May 2015.

2.2.2. Specification of used data sets

Mentioned below are different environmental parameters studied:

- Temperature (in deg. C), relative humidity (in %) and pressure (in hPa) data sets measured at ten different SRRA stations across Rajasthan for calculating clear sky GHI values.

- Measured GHI (in W/m2) values for calculating the clear sky index (K_t*).

Tab. 2 gives additional details about the quality, temporal resolution and time period of data sets used. As can be seen from the table, the data sets acquired from ten SRRA stations are of high quality as 98.62 % i.e. almost 99% of the meteorological data points pass the quality control tests (Kumar et al., 2014). The use of such high quality radiation data corroborates the authenticity and the validity of the study. Tab. 3 and Fig. 1 (right) provide more detailed information regarding the location of the SRRA stations under observation. Fig. 2 depicts different SRRA stations in Rajasthan. Tabled values of latitude, longitude and elevation at each location have been used to evaluate the Bird model clear sky GHI values, which are subsequently used to calculate the clear sky index (K_t*) at each time step (Bird, 1984; Myers, 2013).

Tab. 2: Detailed Specification of SRRA data sets used.

Details	Specification
Parameters studied	Temperature (in deg. C), relative humidity (in %), pressure (in hPa) and GHI (in W/m2).
Temporal resolution of data sets	1 Minute
Temporal horizon	1 year (analysis done for the year 2014)
Quality control statistics (Percentage of error free values)	98.62 %

Tab. 3: SRRA Stations under study.

SRRA Stations	Latitude (North)	Longitude (East)	Elevation (m amsl)
Aburoad	24º51'57.8" N	72º49'58.0" E	362
Ajmer	26º24'01.6"N	74º39'38.2"E	501
Amarsagar	26º56'30.89"N	70º52'27.28"E	288
Bagora	25º12'50.6"N	72º1'03.3"E	91
Balotra	25º48'19.35" N	72º14'12.95"E	126
Kota	25º08'27.3" N	75º48'35.1" E	304
Mathania	26º16'15.8" N	72º59'7.2' E	271
Phalodi	27º7' 03.6" N	72º20' 43.0" E	242
Pokhran	26º54'58.4" N	71º55'39.5" E	293
Ratangarh	28º4'43.32" N	74º37'18.84" E	312

Fig.2: SRRA stations at Bagora (top left), at Balotra (top right), at Kota (middle left), at Mathania (middle right), at Ajmer (bottom left) & at Phalodi (bottom right).

3. Results

The objective here is to understand site-pair correlation and the factors upon which it depends. Another intention behind the study is to observe the effect of spatial smoothing and to quantify the factor by which suppression of variability takes place due to spatial smoothing.

3.1. Evaluating site-pair correlation

As mentioned before, site-pair correlation value is a very important parameter to evaluate, as it will help in understanding the impact of aggregation of outputs from several PV sites. Here in our study, we have obtained site-pair correlation values among different SRRA sites at Rajasthan for a time interval of 1 minute, 5 minutes, 15 minutes, 30 minutes, and 60 minutes with the time period of the study being one year.

Fig. 3 shows the correlation of change in the clear sky index across the time scales of 1 minute to 60 minutes for pair of sites at different distances from one another. Fit curves, as function of distance between the pair of sites and time interval, can be drawn for all these scattered plots and the equation of the curve can be used to find correlation for intermediate/other distance values.

In Fig. 3, a near-zero correlation for the 1-minute time interval is observed between all ten sites in SRRA network in Rajasthan. Even the closest sites in the network, separated by a distance of 47 km, exhibit zero correlation of change in the clear sky index values (of time interval of 1 minute). Similarly, for the 5-minute time interval, site-pair correlation values are almost zero. Hence, for 1 minute and 5-minute time intervals the ten sites under SRRA networks are almost uncorrelated. Now, if output from PV generators with the same installed capacity at these sites is combined and the power variability at these sites is identical, a smoothing by a factor of $1/\sqrt{N}$ (with N = number of PV generators) will take place. But for the 15-minute time interval, a slight increase in site-pair correlation values is observed with percentage correlation values hovering around 3% - 5% and for 30 and 60-minute time intervals, higher correlation between sites are more evident.

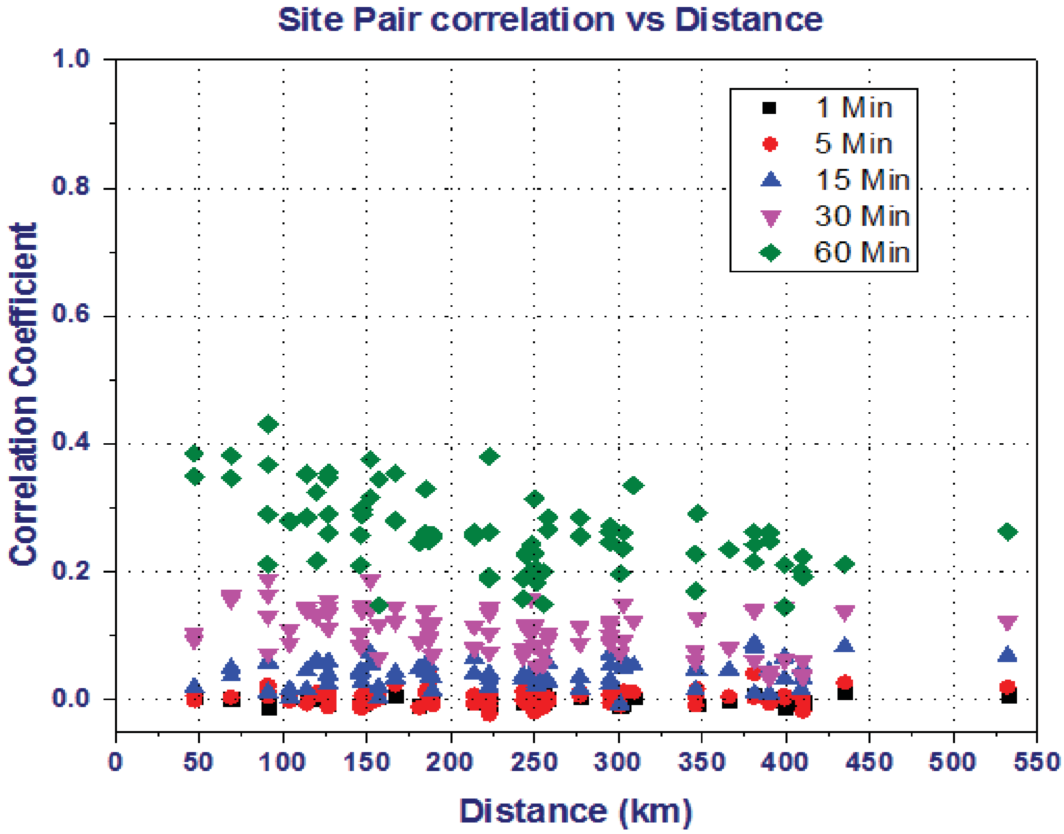

Fig. 3: Site-pair correlation as a function of distance for time intervals Δt = 1min, 5 min, 15 min, 30 min, and 60 min.

3.2. Dispersion-smoothing effect

To observe the pattern of spatial smoothing over a wide area with geographical diversity for a highly variable day, a parameter titled 'Percentage Change in Generation' has been introduced.

The 'Percentage Change in Generation' parameter is defined as:

$$\text{Percentage Change in Generation} = (GHI_2 - GHI_1) / GHI_1 * 100 \qquad \text{(eq. 16)}$$

Where, GHI_1 = GHI measured at time t_1
GHI_2 = GHI measured at time t_2
$t_2 > t_1$, Time Interval, $\Delta t = t_2 - t_1$

The above parameter is analogous to ramp rate (rate of change of power generation in a certain time) as change in solar resources results change in PV power generated and hence, the higher the 'Percentage Change in Generation' value, the higher will be the ramp rate. So, it is an appropriate parameter to demonstrate the effect of smoothing. The above equation has not been used for situations when, $(GHI)_1$ is equal to zero or of extremely small value as the calculation of 'Percentage Change in Generation' parameter would lead to infinity or an unrealistically high value.

We have calculated the 'Percentage Change in Generation' parameter for several days in the year 2014 and here, we have included our observations on a highly variable 165th day of the year i.e. on 14-06-2014. In Fig. 4, the 'Percentage Change in Generation' value for a single site is compared with the same quantity for all 10 sites combined for a certain 'time block' to observe the spatial smoothing effect over a wide area. The term 'time block' has been taken from Central Electricity Regulatory Commission (CERC) documents (CERC, 2011) and describes a time interval of 15 minutes. This value received increasing importance after modification of the bidding time block from one hour to 15 minutes in the day-ahead market. Scheduling is also done on a 15-minute time interval.

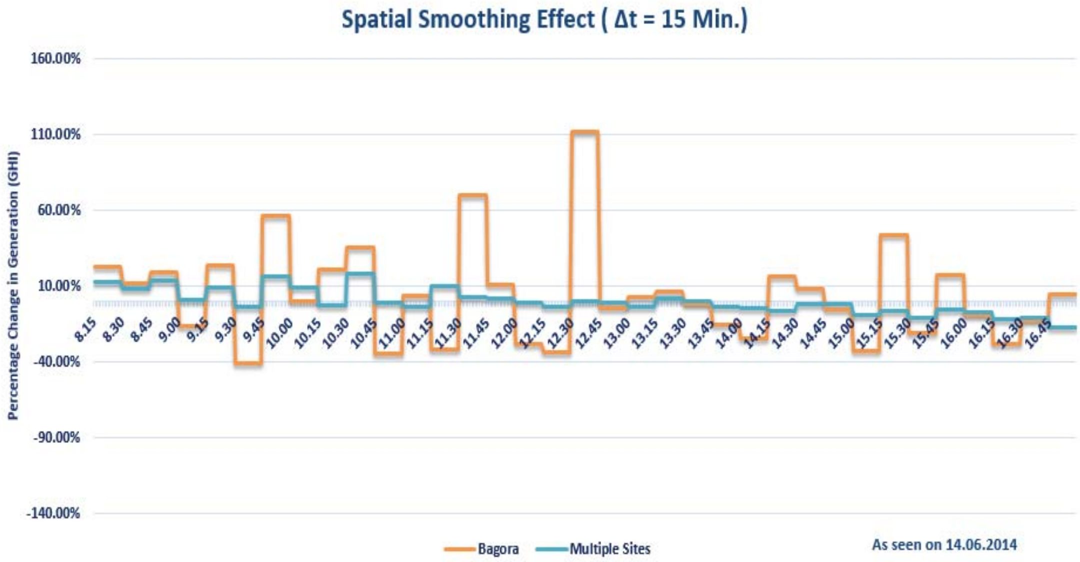

Fig. 4: Spatial smoothing effect observed for multiple sites for the time interval Δt = 15 min.

3.3. Results from sample calculation of diversity filter on a highly variable day

For the day chosen (day 165th of the year 2014), diversity filter values for 1 min., 5 min., and 15 min. time intervals have been calculated. Mentioned below are outcome of these evaluations:

3.3.1. Diversity filter calculation for Δt = 1 min.

Diversity Filter (considering 10 uncorrelated sites with the same variability) = $1/\sqrt{10} = 0.316$.

The theoretical maximum smoothing is achieved for a Diversity Filter of 0.316 i.e., around 68.4% of the variability will be suppressed.

Diversity Filter (considering the site-pair correlation obtained from graph) = 0.341, i.e., almost 65.9% of variability is suppressed. The small difference in the Diversity Filter value indicates that for a time interval of 1 minute the sites are nearly uncorrelated.

3.3.2. Diversity filter calculation for Δt = 5 min.

Diversity Filter (considering the site-pair correlation obtained from graph) = 0.365, i.e. almost 63.5% of variability is suppressed. Again, the small difference in the Diversity Filter value indicates that for a time interval of 5 minutes the sites are nearly uncorrelated.

3.3.3. Diversity filter calculation for Δt = 15 min.

Diversity Filter (considering the site-pair correlation obtained from graph) = 0.392, i.e., almost 60.8% of variability is suppressed. Also for a time interval of 15 minutes, only a slight increase in correlation is observed.

4. Discussion

The analysis that has been done to understand site-pair correlation leads to several points to ponder upon. Firstly, site-pair correlation values decrease with increasing distance between a pair of stations for a specific time interval. This means as the distance between a pair of sites increase, changes in output from PV plants at these locations become less correlated and outputs vary in an independent manner. When solar generation varies independently, maximum smoothing will occur when outputs from these plants are fed to a common grid. Also reduction in site-pair correlation signifies less Diversity Filter value, which indicates higher suppression of variability when the PV plants at sites under study are connected as a fleet. Secondly, site-pair correlation values increase with increasing time interval for a pair of sites. This denotes the significance of selecting the time interval, which actually depends on the concern of the user. For a regional grid operator, solar variability during a time interval of a few seconds may not matter much, but it will be a reason to worry for a small PV plant. So, it is of utmost importance to study the site-pair correlation to estimate solar variability for a group of PV plants, whether clustered over a small area or dispersed over a wider region.

Another important observation has been the effect of spatial smoothing or dispersion-smoothing effect. As an example, the 15-minute time interval from 12.30 PM to 12.45 PM in Fig. 4 shows 'Percentage Change in Generation' values of +110% and +3% for the single site Bagora and for multiple sites, respectively. That is, a significant spatial smoothing for the time interval of 15 minute is observed, when generation from all ten sites is combined. This also means a substantial reduction in ramp rates for a wider control area compared to that for a single site, which can lead to the conclusion that, from better grid management point of view, wider control area holds greater significance compared to a single generator at a site.

We have also evaluated Diversity Filter values on a highly variable day for time intervals 1, 5, and 15 minutes. Here, the Diversity Filter value signifies the percentage by which variability is suppressed when the output from individual sites are fed to a common regional grid. For the 1-minute time interval, almost 66 % of variability was suppressed, while for 5 and 15-minute time intervals, the percentage values by which suppression took place were estimated to be around 64% and 61%, respectively. The values obtained from the sample calculation also denote the importance of considering the effect of smoothing while estimating reserves for balancing operation. Ignoring the same may lead to an overestimation of balancing requirements and hence, to extra costs.

Previously, we discussed several impacts of short term solar irradiance variability on power system. The same can be addressed by strengthening the grid and by efficient control and management of the power network. A strong, reinforced grid will facilitate evacuation of power from areas with high solar resources to locations where there is a power scarcity and will also enable grid operators to access a wide variety of flexible resources to manage ramps. In India, currently efforts are underway in this direction under the 'Green Energy Corridors (GEC)' project to build an advanced, robust grid infrastructure. Under this project, in addition to improved transmission facilities, it has also been proposed to establish, locate Renewable Energy Management Centers (REMCs) along with load dispatch centers where challenges pertaining to system operation, managing variable resources can be addressed through day-ahead forecasting, improved scheduling and ancillary services. Day-ahead solar power forecasting along with real time solar generation information can prepare grid operators for controlling ramps effectively, while ancillary services can compensate for the operating reserves. Also under GEC project, policies are being formulated to bring market reforms and strengthen power market for improving coordination, cooperation along balancing areas.

In the end, commenting about the usefulness of solar radiation data sets measured at SRRA stations, the high resolution 1-min solar irradiance data shows an excellent value and can be used for a Pan-India level solar variability study. If combined with satellite-based resource information and ground-based sky imagers at few selected sites, this could provide an invaluable information source for studying various aspects of solar power grid integration.

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6. References

Bird, R. E., 1984. A simple, solar spectral model for direct-normal and diffuse horizontal irradiance. Solar Energy. 32, 461-471.

CAT Projects & ARENA for public distribution, 2015. Investigating the Impact of Solar Variability on Grid Stability. <http://arena.gov.au/files/2015/03 /150302-Impact-of-Variability-Report-for-public-release.pdf>

Central Electricity Regulatory Commission (CERC), 2011. Suo- Motu Petition No. 127 /2011. <http://www.cercind.gov.in/2011/May/signed_order_in_suo _motu_pet_No_127-2011.pdf>

Hoff, T.E. & Perez, R., 2010. Quantifying PV Power Output Variability. Solar Energy. 84 (10), 1782 –1793.

Hoff, T.E. & Perez, R., 2012a. Modelling PV Fleet Output Variability. Solar Energy. 86 (8), 2177–2189.

Hoff, T.E. & Perez, R., 2012b. Predicting Short-Term Variability of High-Penetration PV. Proc. World Renewable Energy Forum. Denver, CO.

IEA, 2015. Characterization of the Spatio-Temporal Variations and Ramp Rates of Solar Radiation and PV, IEA PVPS Task 14, Subtask 1.3, Report IEA-PVPS T14-05:2015.

Kumar, A., Gomathinayagam, S., Giridhar, G., Mitra, I., Vashistha, R., Meyer, R., Schwandt, M. & Chhatbar, K., 2013. Field experiences with the operation of solar radiation resource assessment stations in India, Energy Procedia 49 (14), 2351 – 2361.

Mills, A., Wiser, R., 2010. Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power. Lawrence Berkeley National Laboratory Technical Report. LBNL-3884E.

MNRE, Govt. of India, 2015a. Programme/ Scheme wise Physical Progress in 2015-16 (During the month of June, 2015). < http://mnre.gov.in/mission-and-vision-2/achievements/ >

MNRE, Govt. of India, 2015b. Tentative State-wise break-up of Renewable Power target to be achieved by the year 2022. < http://mnre.gov.in/file-manager/UserFiles/Tentative-State-wise-break-up-of-Renewable-Power-by-2022.pdf>

Myers, D. R., 2013. Solar Radiation Practical Modelling for Renewable Energy Applications. Energy and the Environment. CRC Press: Taylor & Francis Group.

Perez, R., David, M., Hoff, T., Kivalov, S., Kleissl, J., Lauret, P. & Perez, M., 2015. Spatial and temporal variability of solar energy. <http://asrc.albany.edu/people/faculty/perez/2015/SEVAR.pdf>

Perez, R. & Hoff, T., 2013. Solar Resource Variability. In: Kleissl, J. (ed.). Solar Resource Assessment and Forecasting. Elsevier, pp. 133-148.

Perez, R., Kivalov, S., Schlemmer, J., Hemker Jr., K. & Hoff, T. E., 2012. Short-term irradiance variability: Preliminary estimation of station pair correlation as a function of distance. Solar Energy. 86. 2170–2176.

The World Bank, 2015. Access to electricity (% of population). <http://data.worldbank.org/indicamyerstor/EG.ELC.ACCS.ZS >