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Solar variability of four sites across the state of Colorado

Matthew Lave, Jan Kleissl*

Dept. of Mechanical & Aerospace Eng., University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0411, USA

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ABSTRACT

Solar Global Horizontal Irradiance (GHI) fluctuates on both short (seconds to hours) and long (days to months) timescales leading to variability of power produced by solar photovoltaic (PV) systems. Under a high PV penetration scenario, fluctuations on short time scales may require a supplementary spinning power source that can be ramped quickly, adding significant external cost to PV operation. In order to examine the smoothing effect of geographically distributed PV sites, GHI timeseries at 5 min resolution at four sites across the state of Colorado were analyzed. GHI at the four sites was found to be correlated due to synchronous changes in the solar zenith angle. However, coherence analysis showed that the sites became uncorrelated on time scales shorter than 3 h, resulting in smoother average output at short time scales. Likewise, extreme ramp rates were eliminated and the spread in ramp rate magnitude was significantly reduced when all four sites were averaged. Nevertheless, even for the averaged output, high frequency fluctuations in PV power output are relatively larger in magnitude than fluctuations expected from wind turbines. Our results allow estimation of the ancillary services required to operate distributed PV sites.

1. Introduction

Over the past few years, there has been an increasing interest in harnessing renewable energy sources such as wind and solar power as a supplement to, or replacement for, current carbon-based power sources. However, at high grid penetration, variability of these renewable sources has the potential to affect grid reliability and energy cost. Wind power has thus far been the more popular technology for large-scale implementation, with about 121 GW of wind power installed across the world at the end of 2008 [1]. In areas where a large percentage of the power is provided by wind, fast-ramping of other power sources has been used to counteract wind variability [2].

In comparison to wind power, installed solar photovoltaic (PV) power capacity was relatively small, with only about 13 GW at the end of 2008 [1]. However, PV installation has increased rapidly over the past few years. Since 2002, PV power capacity has increased 48% per year, on average, and is expected to continue to be the fastest growing energy technology in the world [3]. Since PV is growing so quickly, it is pertinent to study high-penetration scenarios.

Geographically dispersing wind power sites is an effective way of reducing wind variability, as power production at different sites typically becomes uncorrelated over a few 100 km [4–6]. In Northern Europe wind power supply from sites more than 1500 km apart is uncorrelated [7]. When aggregated, the output of 1496 widely spread wind turbines in Germany showed maximum variations of 60% in 4 h. Similarly, one would expect that geographic dispersion of solar energy production sites could mitigate solar variability caused by atmospheric transmissivity changes in short timescales (clouds), while being largely ineffective in mitigation of the day-night-solar variability.

Analyzing a month of 1 min radiation data from 11 sites over 75 × 75 km in Wisconsin (a mid-latitude frontal weather regime), Long and Ackerman (1995) determined the correlation of Global Horizontal Irradiance (GHI) and GHI normalized by clear sky radiation [8]. As expected, the correlation coefficients were smaller for the normalized value, as the synchronized occurrence of rising and setting sun at all stations contributes significantly to a high correlation. Large day-to-day differences in correlations were observed indicating limitations for average statistics in describing or modeling insolation. Moreover, for individual days – especially overcast days – there was significant scatter in the correlation versus distance plots for all stations pairs indicating that atmospheric transmissivity is not an isotropic process. Barnett et al. (1998) used Oklahoma Mesonet data from 111 GHI sensors to define spatial correlograms [9]. Subtracting out the diurnal signal, they found that characteristic length and time scales (i.e. the distances and time differences at which correlation goes to zero) were

* Corresponding author.
E-mail address: jkleissl@ucsd.edu (J. Kleissl).

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300 km and 60 min, respectively. Curtright and Apt (2008) examined three PV sites spread across hundreds of kilometers in the state of Arizona and found a reduction in average 10 min step size magnitude and in standard deviation for the sum of all three sites [10]. However, they also found that short timescale variability of large-scale PV power was still significant and that the geographical diversity did not dampen PV variability enough to eliminate the need for substantial supplemental power sources. Wiemken et al. (2001) studied 100 PV systems spread across Germany, and also found a decrease in average step size magnitude and standard deviation for the sum of all systems, but did not present timescale variability analysis [11].

In this paper we study the variability of measured GHI at four different sites across the state of Colorado. This choice is motivated by the fact that the greatest spatial density of 1–5 min resolution irradiance data exists in Colorado. Topographical and meteorological differences between Wisconsin, Oklahoma, Arizona and Colorado also warrant the analysis of variability over different regions. The sharper terrain difference across these Colorado sites may lead to more varied weather patterns and increased geographic variation. Moreover, we extend the existing literature by analyzing shorter time scales (5 min) and examining coherence between the sites and its effect on smoothing average output at different time scales through spectral analysis.

2. Data

While ultimately PV array power output is the relevant variable for variability analysis, 90% of the variability in PV output is explained by variability in GHI. Consequently, here we assume that solar radiation is proportional to PV power output and we use radiant flux density (W m^{-2}) rather than power for this analysis, neglecting the influence of PV panel temperature on panel efficiency. Furthermore, while variability analysis of PV output is more practically relevant, these studies are not as representative, since they depend on the system specifications, and there is generally less publicly available time-resolved data for PV output.

GHI data were obtained from the National Renewable Energy Laboratory's (NREL) Measurement and Instrumentation Data Center (MIDC) [12]. Sites were chosen which were within a few hundred kilometers of one another such that they would typically feed into one utility grid, and had complete data for Jan 1, 2008–Dec 31, 2008. Four sites fit these criteria: the National Wind Technology Center (NWTC), the NREL Solar Radiation Research Laboratory (SRRL), the South Park Mountain Data (SPMD), and the Xcel Energy Comache Station (XCEL, Fig. 1). The distances between sites are shown in Table 1. The NWTC site has an Eppley Laboratory, Inc. Precision Spectral Pyranometer, SRRL data were collected using a Kipp and Zonen CMP 22 pyranometer, and the XCEL site uses a LICOR LI-200 silicon pyranometer. All sites had data at 1 min resolution except for SPMD where a LI-200 was operated at 5 min temporal resolution.

Although a greater geographical wealth of solar radiation data is available through NREL's National Solar Radiation Database (NSRDB), these data are only recorded once per hour, and much of it is not based on GHI measurements. Using 1 h resolution, even if it is an average of data collected at shorter intervals, will filter out the shorter time-scale variability that produce the largest ramp rates (RRs). For example, large RRs caused by clouds occur on scales of seconds to 10 min. Fig. 2 illustrates the difference in RRs between hourly data and 1 or 5 min data, which is the motivation for using the unique collocation of highly time-resolved data in Colorado in this paper.

Visual examination of the timeseries revealed that SPMD tends to be shaded in the morning due to high surrounding terrain. This variability is naturally occurring (i.e. it would be the same for a PV array at the same site), but was eliminated from the dataset by filtering out data at large solar zenith angles (SZAs). We also found that NWTC seems to be shaded at several times of the day, especially around 1400 MST. This unexplained shading in NWTC was difficult to correct for and the realization of the shading will be further discussed in the results section.

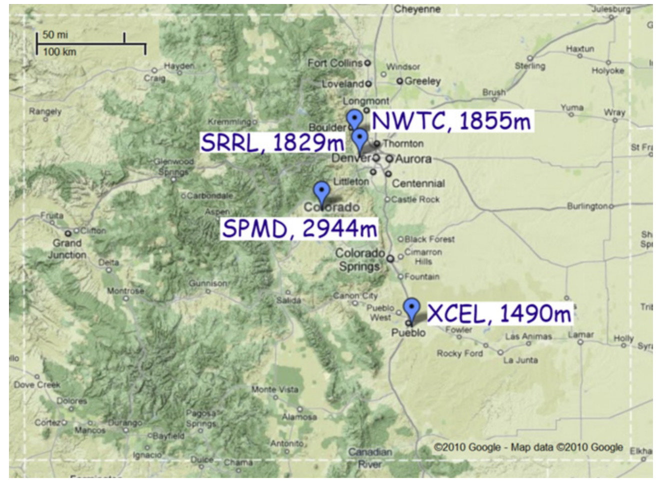

Fig. 1. The sites used for this study on a terrain map with elevations in meters: National Wind Technology Center (NWTC), Solar Radiation Research Laboratory (SRRL), South Park Mountain Data (SPMD), and Xcel Energy Comanche Station (XCEL). Map © 2010 Google - Map Data © 2010 Google.

3. Methods

3.1. Data quality control

Since this paper does not attempt an assessment of the mean solar resource, but an analysis of the variability in GHI, slight sensor differences in offset and/or gain will not have a significant effect on our results. Nevertheless, we calibrated the sites against each other on clear days in the region, when they are expected to be similar given the small variability of atmospheric composition over short distances. The SRRL site is maintained daily by trained NREL staff and is considered to have the best data. Therefore, the NWTC and XCEL data were corrected using a linear regression against SRRL on nine clear days (Jan 13, Mar 3, Apr 14, Jun 14, Jul 13, Aug 28, Sep 16, Nov 19, Dec 25). The SPMD site was not corrected since higher clear sky atmospheric transmissivity associated with its high elevation (expected transmissivity of about 81% versus 79% for the other sites) would result in a different clear sky GHI.

A linear regression of GHI(SRRL) = A GHI(site X) + B was applied. The regression constants A and B for the XCEL site were nearly constant throughout the year, so an overall linear fit of all nine clear days was applied. The regression constants for NWTC showed a seasonal variation. Consequently, interpolated (time dependent) slopes and intercepts based on regressions from the nine clear days

Table 1
Distance between sites.

From	To	Distance
NWTC	SRRL	19 km
NWTC	SPMD	78 km
NWTC	XCEL	197 km
SRRL	SPMD	65 km
SRRL	XCEL	178 km
SPMD	XCEL	149 km