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Relating solar resource and its variability to weather and climate across the northwestern United States

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ABSTRACT

The spatiotemporal variability of the solar resource has implications for every stage in the development and operation of a photovoltaic power plant from siting and design through grid integration and day-to-day operation. The irregular and relatively unpredictable portion of this variability is primarily caused by the passage of clouds and large-scale weather systems. In this study, we examine the variability of solar irradiance at five locations in the northwestern US at temporal scales ranging from 5 min to 9 days in the context of local and regional weather patterns. The total solar resource in this area exceeded expectations, with values as high as 4.5 kWh/m^2/day. The magnitude of the seasonal cycle of the solar resource at these locations was found to be greater than in other regions of the US due to the strong seasonality of cloudiness. Seasonal differences were also seen in the variability of measured solar irradiance down to sub-hourly time scales. Site-to-site differences in the magnitude of irradiance fluctuations could be traced to local meteorological differences, but also depended on temporal scale, reflecting the contrasting influences of overall cloudiness and the smaller scale spatial characteristics of cloud structure. The degree to which combining irradiance time series from pairs or groups of diverse locations smoothed temporal irradiance variability mainly depended on the magnitude of the variability of the original data at short time scales but on the separation of the sites for daily averages. This distinction can be traced to the negligible/appreciable correlation of sub-hourly/daily irradiance fluctuations measured at these widely separated (250–850 km) sites, which again reflects differences between the spatial and temporal extent of weather systems as opposed to their underlying cloud structure. Each of these results demonstrates how knowledge of local and regional meteorology can provide insights into the character of the solar resource at a particular location.

1. Introduction

Understanding the variability of the solar resource is essential at all phases of the development and operation of a utility-scale photovoltaic (PV) power plant. Accurate information about the annual expected resource is, of course, critical to establishing the feasibility of a project during the siting and financing phases. However, variability on the scales of days to decades also affects plant performance estimates and facility design (Vignola et al., 2012). Estimates of variability down to the scale of minutes are also needed before the plant is constructed in order to investigate potential problems when integrating the generated power into the larger electrical grid system (Mills et al., 2011). Furthermore, once a PV plant is placed in service, variations in production over periods from seconds to days are critical to daily operations. For example, voltage regulation is performed at time scales of seconds to minutes while unit commitment for load following takes place on scales of minutes to hours (Mills et al., 2011).

Because understanding solar resource variability is vital to the success of a PV power plant, many recent studies have analyzed solar irradiance variability at particular geographic locations. For example, Lave and Kleissl (2010) studied observations from Colorado, Hinkelman (2013) analyzed data from Oahu, Hawai'i, Lohmann et al. (2016) examined measurements from two locations in Germany, and Moreno-Tejera et al. (2016) primarily considered data from Seville, Spain. Others selected multiple locations spread over a range of climatic conditions. Rayl et al. (2013) looked at six of NOAA's Surfrad measurement sites spread over the US, and Perez et al. (2011) used data from both the Surfrad and DOE ARM networks in the US. Lauret et al. (2016) treated data from

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20 stations, 14 of which were in the mainland United States while the other six were on tropical islands.

Despite the significant interest in solar resource variability at different locations and the fact that clouds are the single biggest cause of non-astronomical variations in irradiance (i.e., aside from the daily and annual solar cycles), relatively little effort has gone into relating observed irradiance variations to local weather conditions. Rayl et al. (2013) discussed the scales of weather phenomena as they affect different aspects of PV power generation. They also related the temporal scale of irradiance variability to the spatial scales of weather phenomena, such as synoptic scale (1000 s of km) or the size of individual clouds (up to 10 km), and discussed variability as a function of season. However, reference to the specific weather features causing the variability at the locations they studied was limited. In a more recent paper, Lauret et al. (2016) investigated intraday (hourly) variability of the clear sky index in a variety of climatic regions and found that sites with orographically influenced cloud formation had somewhat different variability statistics than other locations. A preliminary study by Hinkelman et al. (2016) also found that differences among the distributions of clear-sky index changes measured at several sites could be linked to local weather conditions. On the other hand, the Perez et al. (2011) study that used data from 24 measurement sites throughout the US (although somewhat dominated by locations in the southern plains) found variability to be similar enough over all the stations to allow them to build a model that predicts short-term clear sky index variability given irradiance values derived from satellite data at any of these stations. Finally, both Reno and Stein (2013) and Hinkelman et al. (2013) analyzed solar irradiance variability as a function of cloud type determined from satellite measurements, but did not attribute the cloud types to specific meteorological conditions.

In this paper, we describe a study of the solar resource and its variability at five sites in the northwestern United States framed in the context of local and regional weather patterns. The typical weather conditions at the stations are first outlined, after which the available resource is computed and compared to that in locations currently hosting utility-scale photovoltaic power plants. The annual cycle of observed solar resource is then explained with reference to both the latitude and cloud conditions at the sites. The variability of the incoming solar irradiance on scales from 5 min to 9 days is characterized using analysis methods in both the temporal and frequency domains, and statistical differences between the variability computed at the individual locations are ascribed to weather patterns. The time series of variations from the sites are then correlated to determine the degree to which weather conditions across the region create similar or different patterns of variability. Finally, the implications of these correlations for the reduction of variability via site diversity are quantified.

2. Data and methods

2.1. Measured data

PV array power output data is difficult to obtain and results computed using this data may not be generalizable due to dependence on the particular configuration of the source power plant (e.g., nameplate capacity, cell composition and size, panel spacing and tilt, and DC-AC conversion efficiency). However, 90% of the variability in PV output is explained by variability in solar irradiance (Lave and Kleissl, 2010; Hoff and Perez, 2012). Thus, for this study, solar irradiance data is used as a proxy for PV power output, with the understanding that system specifications are not accounted for.

Five-minute resolution total or "global" horizontal solar irradiance (GHI) time series were obtained from the University of Oregon Solar Radiation Monitoring Laboratory (UOSRML, http://solardat.uoregon.edu/index.html, Riihimaki et al., 2009) for five sites spread throughout the northwestern United States (see map in Fig. 1). In order to ensure a variety of climate zones along with reliable data, the sites were chosen based on their geographic location, instrument quality, and completeness of record over the years 2004–2013. These sites are equipped with Eppley PSP thermopile pyranometers, which have a manufacturer specified uncertainty of ±3–4% under laboratory conditions. However, we note that, in the field, error tends to be dominated by more practical factors such as siting, soiling, and frequency of calibration. All selected

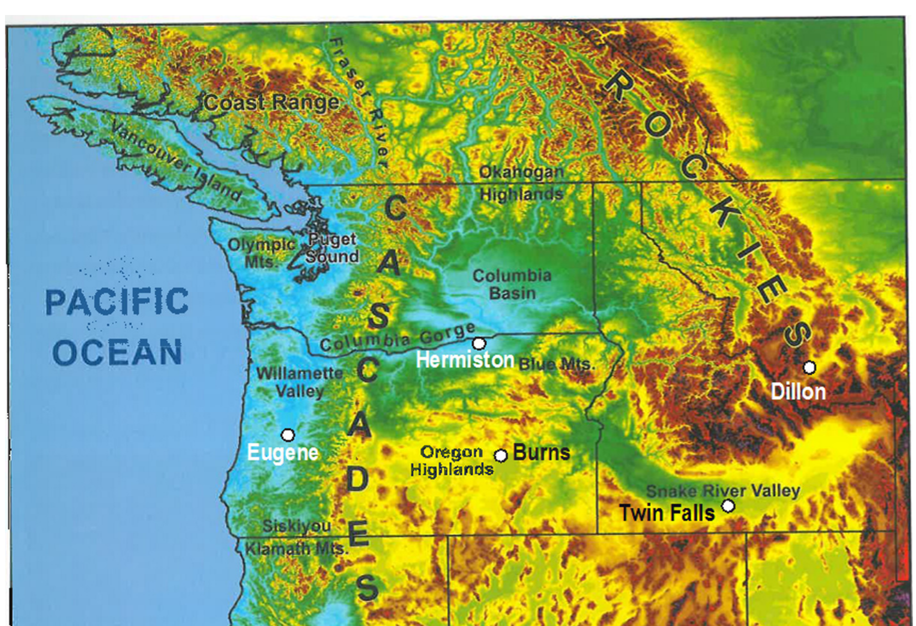

Fig. 1. Map of the northwestern United States showing the locations of the solar irradiance measurement sites. Modified from Mass (2008). Used by permission of the University of Washington Press.