Renewable Energy 86 (2016) 602–610

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Applying the kriging method to predicting irradiance variability at a potential PV power plant

Samuel H. Monger*, Eric R. Morgan, Ana R. Dyreson, Thomas L. Acker

Mechanical Engineering Department, Northern Arizona University, Flagstaff, AZ 86001, USA

A R T I C L E I N F O

Article history:
Received 16 April 2015
Received in revised form
16 July 2015
Accepted 25 August 2015
Available online xxx

Keywords:
Solar resource variability
Kriging
Photovoltaics
Grid operation timescales

A B S T R A C T

One-second irradiance data from forty-five sensors spaced over a one-mile square section of land were analyzed to characterize the short-term (1-s to 1-min) variability of the solar resource in Northern Arizona. The geostatistical interpolation model known as kriging was applied to our data set to better understand the method's strengths and weaknesses in accurately predicting the variations in the irradiance over this relatively small section of land. Of particular interest was to investigate the ability of the kriging method to show the variation in solar irradiance over the section of land as compared to that measured by the sensors. When using data from all the sensors as input to the prediction method, kriging performed very well compared to the sensors. However, because it is unlikely to have a large number of sensors to characterize the variability at a prospective solar site, it was also of interest to investigate how many sensors are required as input to the kriging technique in order to generate a reliable prediction. Solar data from four characteristic periods (related to the four seasons) were analyzed, and different sensor configurations, consisting of subsets of the actual sensor array, were employed using the method to demonstrate the number of sensors required to correctly characterize the short-term irradiance variability at the site. Using four measurement stations as input to the kriging method was shown to reasonably represent the variability in the 1-s to 1-min timescales.

1. Introduction

Solar energy is the most abundant resource available to humankind, and although solar generated power is typically more expensive than some traditional generation resources, costs are decreasing [1] and the technology is in a state of rapid development as societies strive to meet renewable energy goals as part of the effort to slow climate change and become less dependent on finite resources. However there are many valid concerns associated with integrating high levels of solar energy into the transmission and distribution grids due to the rapid changes in power output and voltage from photovoltaic generated electricity due to drops in the solar resource, due to clouds passing by and shading the PV modules [2]. It is well known that as the PV plant size increases, the relative variability decreases, i.e. the percent change in output per unit time decreases [3]. In order to understand this effect, a study was conducted to quantify the variability of solar irradiance at a specific area using a uniform grid of forty-five irradiance sensors as seen in Fig. 1.

Another goal of this study was to determine the minimum number of measurement stations necessary to quantify the variability. In addressing this question, the geostatistical "kriging" method [4] was applied to predict variability on the 1-s to 1-min time frame using a sub-set of the forty-five sensors, with the intention of determining the minimum number of sensors required to reliably predict the short term variability of a utility-scale PV plant (10–30 MW).

1.1. NextEra solar variability project

Previous solar variability studies have used existing data from several meteorological stations that are located relatively far apart considering the size of PV power plants [5–9] . The purpose of those studies was to understand the variability over a local region of a potential or current site for PV power production. However, instead of using existing solar data from meteorological

* Corresponding author.
E-mail addresses: smonger47@gmail.com (S.H. Monger), Eric.Morgan@ll.mit.edu (E.R. Morgan), anadyreson@gmail.com (A.R. Dyreson), Tom.Acker@nau.edu (T.L. Acker).

http://dx.doi.org/10.1016/j.renene.2015.08.058
0960-1481/

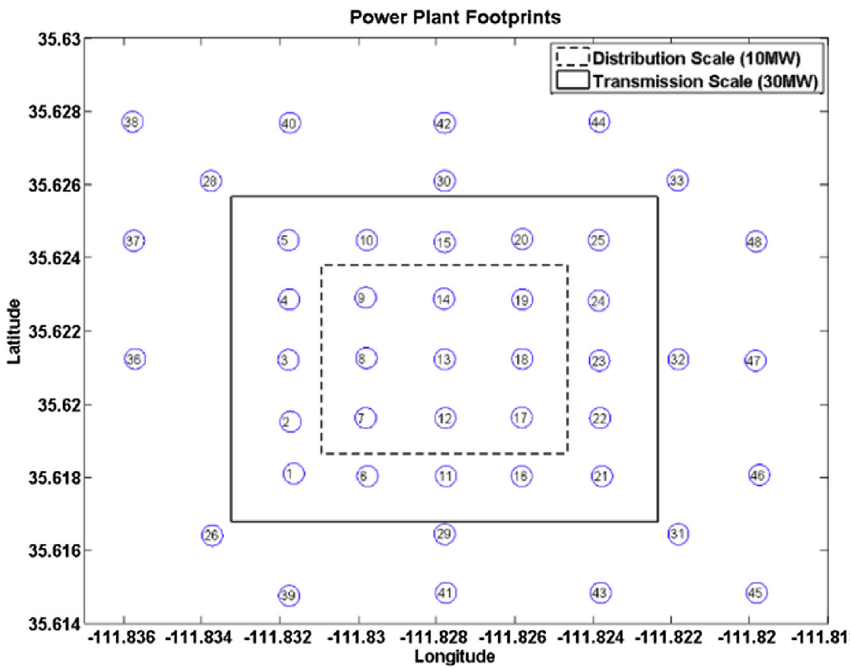

Fig. 1. NextEra project sensor layout.

(MET) towers or other resources, Northern Arizona University in conjunction with NextEra Energy Resources designed an experiment to study the variability of the solar resource by utilizing many measurement stations collecting high frequency irradiance data. The NextEra project was designed to measure the variability of irradiance over an area, and to be able to test models against this unique data-set [10]. The study site was located on a square-mile of land forty miles north of Flagstaff, Arizona. Forty-five irradiance sensors were installed during the winter of 2011 in three increasingly sized grids to roughly correspond to different PV power plant capacities with the goal that 1 sensor would roughly correspond to 1 MW of PV solar power as seen in Fig. 2.

The data loggers at each of these stations recorded 1-s irradiance data. The data collection period began in November 2011 and ended in May 2013. Because the data loggers were subject to the availability of solar irradiance to charge the data logger battery as well as high temperature fluctuations, the final data set does not cover this entire period. The total data recovery rate over the 551 day field deployment period was 44%. The representative periods chosen for detailed analysis were selected from these periods of high data availability. An extensive data quality control process was completed after the network was decommissioned [10].

Although the data collected from this experiment are spatially dense compared to other experiments, the actual percentage of land these sensors are describing is a tiny fraction of the whole area. To most accurately characterize variability, it would be ideal to know the irradiance striking every square meter of each PV panel in a power plant. However, that is not practical. Therefore, the kriging technique was used as a smoothing method that is capable of using existing data to accurately estimate irradiance at any location, and thereby capable of achieving a smoothed irradiance value over the entire site [11].

The data from a single station for a continuous year (May 24th, 2012 to May 19th, 2013) was used as thedata set to narrow our focus to four interesting time periods seen in this area. The data was averaged over a minute and the Sandia Variability Index (VI) [12,13] was computed. In this way a daily VI value was found for each day of the year, and interesting weeks could be further examined. Four representative periods with a range of variabilities were selected to showcase the range of possible values including the extremes. The range of seasonal variability in this region characterizes many areas in the Western United States from arid sunny regions to variable high-elevation mountain regions. Table 1 provides the dates of the VI periods and the average VI value for each week.

1.2. Objectives

The first objective of this study was to quantify the variability of the solar resource in Northern Arizona over the footprint of a utility-scale PV power plant that could be interconnected to either a transmission line or distribution system. This objective was accomplished using the average of the station data (aggregate method) and the geostatistical kriging method on a data-set of forty-five spatially dense, high resolution solar irradiance sensors. For the kriging method, all the available station data was used to estimate a dense grid of irradiance over areas corresponding to two power plant sizes (~30 MW and ~10 MW). A version of block kriging where the estimates at every location are averaged was the method explored to predict the smoothed irradiance values over the power plant footprints. The aggregate method and the estimated data from the kriging method were analyzed and summary statistics were computed on certain metrics to quantify the variability of the site. The comparison of the two methods show how well the kriging method performs, assuming the aggregate method is the closest approximation to the actual smoothing seen.

The second objective of this study was to determine the number of irradiance sensors needed and the accuracy of their capability to capture the variability for these power plants. This was answered by using the same kriging method on combinations of data from fewer stations to estimate the irradiance over the area of the power plants. Considering utilities' concern to provide stable electricity, the regulating reserves required for new variable generation is of greatest importance in integration studies, and therefore the ability to capture the variability on the regulation (and sub-regulation)