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On the spatial decorrelation of stochastic solar resource variability at long timescales

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Abstract

Understanding the spatial and temporal characteristics of solar resource variability is important because it helps inform the discussion surrounding the merits of geographic dispersion and subsequent electrical interconnection of photovoltaics as part of a portfolio of future solutions for coping with this variability. Unpredictable resource variability arising from the stochastic nature of meteorological phenomena (from the passage of clouds to the movement of weather systems) is of most concern for achieving high PV penetration because unlike the passage of seasons or the shift from day to night, the uncertainty makes planning a challenge. A suitable proxy for unpredictable solar resource variability at any given location is the series of variations in the clearness index from one time period to the next because the clearness index is largely independent of the predictable influence of solar geometry. At timescales shorter than one day, the correlation between these variations in clearness index at pairs of distinct geographic locations decreases with spatial extent and with timescale. As the aggregate variability across N decorrelated locations decreases as $1/\sqrt{N}$, identifying the distance required to achieve this decorrelation is critical to quantifying the expected reduction in variability from geographic dispersion.

Using 10 years of satellite-derived daily-interval solar resource data across the world, we demonstrate that the spatiotemporal behavior of unpredictable solar resource variability is mirrored at longer timescales. We do so by examining over 1.4 million unique pairs of sites across the Western hemisphere and quantifying the influence each pair's geographic separation and bearing has on the correlation between the variability of each pair's clearness indices at timescales of one, two, four, seven, fifteen and thirty days. Expected pair-decorrelation distances are estimated by fitting exponential trends to the data using nonlinear least-squares regression and are presented as a function of timescale and pair orientation.

Reflecting the predominant direction in which meteorological phenomena propagate at each of these timescales, we find that pairs of sites require considerably shorter distances to decorrelate when they are oriented north to south versus when they are oriented east to west. As at shorter timescales, these decorrelation distances are shown to increase with both timescale and with geographic extent.

Keywords: Correlation; Variability; Solar energy; Photovoltaics

1. Introduction

With the rapid recent growth of the solar photovoltaic (PV) industry, it is of utmost importance to address the principal barrier to achieving its high-penetration across global electrical grids: the inherent variability of the solar resource. Variability of the solar resource is a result of largely unpredictable or stochastic meteorological phenomena and from the predictable rotation of the earth around the sun and about its own axis. To achieve very high PV

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Nomenclature

Kt	also known as the clearness index. The ratio of Global Horizontal solar radiation (downward shortwave radiative flux) to Top-of-Atmosphere solar radiation (downward shortwave radiative flux)
Cartesian bearing	the bearing in degrees based on an equirectangular projection of the earth. Important because true geodesic bearing can change significantly along a given straight-line path, especially over long distances
TOA	TOA irradiance stands for downward shortwave radiative flux at the Top of the Atmosphere
Gh	Gh irradiance stands for Global horizontal radiation or the downward shortwave radiative flux at the surface of the earth

penetration, the imbalance between the variable supply of sunlight and demand must be alleviated.

Overcoming the effects of unpredictable resource variability poses the greatest challenge as the uncertainty in PV output it drives makes it a challenge to plan for. This unpredictable variability occurs on every temporal scale: from second-to-second variations driven by individual passing clouds to year-to-year variations driven by periodic large-scale phenomena such as El-niño and variations in volcanic activity. If high penetration PV is to be achieved, a balanced portfolio of solutions for coping with these imbalances is required on both the supply and demand side.

The widespread geographically distributed deployment and electrical interconnection (geographic dispersion) of PV is one of three primary supply-side solutions to solar variability—which do not rely on support from other generation sources—that can minimize the cost of electricity generated therefrom. The other two primary supply-side solutions are storage (where excess solar generation is stored when it exceeds demand and is released when it does not meet demand), and smart curtailment (where solar capacity is oversized and excess generation is curtailed at key times to minimize the need for storage).

While conventional electricity market structures and regulatory frameworks remain suboptimal for the optimized development of these aforementioned solutions, an understanding of the nature of solar resource variability is critical for an informed discussion about the relative merits of each. In these conventional electricity markets, variations in PV output introduced by fluctuations in the solar resource on the minute-to-minute and second-to-second timescales drive increased unit governor response and load frequency control requirements while influencing economic dispatch. Solar resource variability on the timescale of minutes to hours impacts load following requirements, while day-to-day variability and longer variations in the solar resource influence day-ahead requirements and long-term regional infrastructure planning, especially at higher penetrations (Mills and Wiser, 2010).

The object of this research is to understand the way in which unpredictable solar resource variability is affected by geographic distance, bearing and timescale for timescales greater than one day. In so doing, we help frame and inform the discussion surrounding the relative effectiveness of geographic dispersion as a solution for achieving high penetration PV.

The series of variations in the clearness index from one time period to the next constitute a suitable proxy for unpredictable variations in the solar resource at any given location because the clearness index is largely independent of the predictable influence of latitude. At timescales shorter than one day, the correlation between these variations in clearness index at pairs of distinct geographic locations decreases with spatial extent and with timescale (Hoff and Perez, 2010, 2013; Perez et al., 2012). As the aggregate variability across N decorrelated locations decreases as $1/\sqrt{N}$ according to the central limit theorem, identifying the distance required to achieve this decorrelation is critical to quantifying the expected reduction in variability from geographic dispersion.

Herein, we examine 1.4 million unique pairs of sites across the Western hemisphere and quantify the influence of each pair's geographic separation and bearing on the correlation between the variability of each pair's clearness indices at timescales of one, two, four, seven, fifteen and thirty days. We then estimate the pair-decorrelation distances for each combination of timescale and pair orientation (pairs separated north-to-south or east-to-west) by fitting exponential trends to the data using locally weighted polynomial regression.

Much research has been performed over the past several decades surrounding the nature of solar resource variability, including its spatial and temporal characteristics (Perez et al., 2011a,b,c; Hoff and Perez, 2010; Gueymard and Wilcox, 2011; Lave et al., 2011; Perez and Hoff, 2011; Skartveit, 1992; Vignola, 2001; Woyte et al., 2007), the effect of distance on pair correlation (Hoff and Perez, 2010, 2013; Perez et al., 2012), its spatially anisotropic nature and relation to cloud-speed (Hinkelman et al., 2011; Hoff and Norris, 2010; Kleissl, 2014; Lave and Kleissl, 2013), the nature and implications of spatial smoothing (Mills and Wiser, 2010; Perez and Fthenakis, 2012;