ABSTRACT

Solar irradiance has both short-term (less than 12 hour) and long-term (seasonal) variations. Understanding these fluctuations is crucial for improving solar resource forecasting and evaluating co-production strategies for solar-fossil power technologies. Six USA sites are selected from the Integrated Surface Irradiance Study (ISIS) and Surface Radiation (SURFRAD) budget network. To assess the long-term variations, the data is analyzed in seasonal periods: winter, spring, summer, and fall. Power spectral density is used to analyze the short term and long term variations in DWS. The inter-site coherence and phase analysis allows geographic dispersion of the solar resource to be evaluated. Results indicate that understanding long-term periodic oscillations are useful to optimize the co-production of solar/fossil power. Seasonal analysis of short-term variations suggests that the ability of a regionally dispersed network of PV to dampen the intermittency of solar power production is dependent upon the climatic regime.

1. INTRODUCTION

While the quantity of energy generated solar energy technologies is rapidly increasing, the intermittancy of power output and need for complementing fast ramping energy generation technologies are key concerns for increased grid-connected photovoltaics. Curtright and Apt have shown that knowledge of the characteristics of both short term and long term variations in PV power can be used to minimize the cost of energy [1]. Therefore, research to assess and understand both the short-term (less than 12 hour) and long-term (seasonal) variation of the available solar resource is essential to addressing this concern.

This research will show that a combined approach of power spectral and co-spectral analyses can provide much more information than through traditional modeling techniques. The assessment will be beneficial for both regionally distributed solar power and solar-fossil fuel co-production schemes. Recent work by Lave and Kleissl has demonstrated that a network of PV systems spaced less than 200km apart in Colorado dispersed over the region has a smoothing effect on the annual combined output power from photovoltaics and that the average of the sites are less likely to experience large fluctuations [2].

Even though annual irradiation for the continental USA is high, within ~14-21 MJ/m^2, seasonal variations will be different for each locale. As such, each locale will be affected by the variable synoptic, mesoscale/microscale, and diurnal patterns from prevailing meteorological conditions, leading to fluctuations in irradiance (incident shortwave solar radiance, W/m^2). It has been suggested by Guemard that 3 years or more of data are recommended to validate a solar resource model [3]. This study focuses on several pairs of locations around the continental United States using three-minute,
time-averaged downwelling shortwave solar irradiation data from the ISIS and SURFRAD networks for a three year period. The sites were selected as representative of various geographic regions in the US.

2. METHODS

2.1 Data Collection

The raw shortwave solar irradiation data were collected from ISIS level 1 and Surface Radiation Budget (SURFRAD, ISIS level 2) networks. The ISIS level 1 stations monitor incoming radiation only while the ISIS level 2 SURFRAD stations more completely monitor the surface radiation balance and several other meteorological parameters[4] [5]. Both networks report irradiation in three-minute averaging from one second sampling with Eppley black and white model 8-48 pyranometers. Three regional dispersed location-pairs were selected. The three location-pairs included in this study are Fort Peck, MT and Bismarck, ND, and Rock Springs, PA and Sterling, VA, and Desert Rock, NV and Hanford, CA. Table 1 lists the locations from north to south, their longitudes and latitudes, and the distance between them.

2.2 Data Processing

Both the ISIS and SURFRAD networks use the same methodology of reporting flawed solar irradiation data. For all reported parameters, if the sensor malfunctioned at a point of time, hence missing data, the reported measurement is -9999.9. For this study, erroneous values are corrected by interpolating between the surrounding correct data. Gaps in the data of a day or more were omitted for this study. The radiation parameters are flagged as errors if there is any negative data present that is outside the range of noise of the measurement device; these values are set to zero. Additionally, in 2009 the SURFRAD network switched to reporting one-minute data which were converted to three-minute averages.

The downwelling solar irradiation data were compiled into arrays of three consecutive years: 2007, 2008 and 2009. The years were divided by season, with Winter spanning December, January and February, Spring spanning March, April and May, Summer spanning June, July and August and Fall spanning September, October and November.

2.3 Power Spectral Density

The power spectral density is a measure of the strength of variation of the power contained in a signal as a function of frequency. The power spectrum of a signal is defined as the square of the magnitude of the Fourier transform shown in equation 1.

\[ S_x(\omega) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-j\omega n} \] \[ \text{[6]} \] \[ (1) \]

Where \( S_x(\omega) \) is a real valued number. Once PSD was plotted, linear best fit slopes were evaluated for each spectra in both the synoptic-scale and meso-/microscale weather regions. For the synoptic-scale, a 90% confidence interval was used, while a 95% confidence interval was used for the meso-/microscale data regions.

2.4 Coherence and Phase Spectra

The cross power spectral density between two arrays of data is also called the co-spectrum, the measure of similarity between the respective power spectral densities. The co-spectrum is a product of the complex valued phase spectrum, a measure of the phase offset, lagging or leading, between the two arrays and the cross amplitude spectrum or coherency spectrum, a measure of the similarity of the magnitudes of the frequency components. The co-spectrum is defined by the relationship shown in equation 2.

\[ S_{xy}(\omega) = \frac{1}{N} \left( \sum_{n=0}^{N-1} x(n) e^{-j\omega n} \right) \left( \sum_{n=0}^{N-1} y(n) e^{-j\omega n} \right)^* \]

\[ \alpha_{xy}(\omega) \cdot e^{j\phi_{xy}(\omega)} \] \[ \text{[6]} \] \[ (2) \]

Where \( x(n) \) is the first time-series and \( y(n) \) is the second time-series, and \( S_{xy}(\omega) \) is a complex valued number whose magnitude is the coherency spectrum (\( \alpha_{xy}(\omega) \)) and angle is the phase spectrum (\( \phi_{xy}(\omega) \)).
3. RESULTS

3.1 Power Spectral Density

The monthly power spectral densities were calculated and averaged into intra-seasonal plots. The plots show a 30 day average sampled at three months for three years, a total of nine months averaged.

Figure 1 shows a cartoon of the weather types over a sample PSD plot. The x-axis shows the periodicity in terms of days rather than hertz (seconds\(^{-1}\)). This normalizes the period around the diurnal cycle. All seasons and locations show peaks around one day and 12 hours that correspond to the cyclic nature of the solar geometry. These and the subsequent harmonic peaks are also indicative of the diurnal cycle.

Information with periods greater than one day

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Fig. 1: Cartoon illustrating the weather scales and diurnal phenomena on a frequency plot of power spectral density (PSD).
correspond to large-scale meteorological phenomena spanning 1000-2500 km termed *synoptic-scale weather* [7]. The synoptic scale weather is described by a best-fit line from 15 days through 2 days. Information with periods less than one day through the very high frequency (or low period) is termed *meso- and micro-scale weather*. These scales correspond to meteorological phenomena that spans hundreds of kilometers and up to one kilometer respectively. The best-fit line for the high frequency spans from 9 hours to 1 hour.

Figure 2 illustrates the power spectral densities for Rock Springs, Pennsylvania and Sterling, Virginia. The slopes of the best fit lines are shown in the legend for each plot as well as described in table 2 and 3 with the intercepts and confidence intervals. The slope takes the form of $f^{-\beta}$. The confidence intervals show are percentages of the exponent for the intercepts. The synoptic weather in both Pennsylvania and Virginia show very low slopes in the winter of $f^{-0.19}$ and $f^{-0.18}$ respectively. The steepest slopes occurred in the summer in PA ($f^{-0.85}$) and the fall in VA ($f^{-0.77}$). The steepness of the slopes in the synoptic weather range is indicative of the change in the magnitude of variations on longer time scales. The least steep, closer to zero, the slope is the smaller synoptic variation in irradiance is expected to be. These results indicate that the synoptic variations are smaller in the winter and larger in the summer and fall in the mid-Atlantic region.

The power spectral densities for North Dakota and Montana during the winter and fall were averaged from 8 months rather than 9 due to large sections of missing data. The steepest and shallowest slopes for the mid-continental region occurred in the summer ($f^{-0.60}$) and spring ($f^{-0.32}$) respectively for Montana and in the winter and spring ($f^{-0.85}$) and fall ($f^{-0.40}$) respectively for North Dakota. Winter, spring and fall all showed similar slopes on the synoptic-scale from $f^{-0.8}$ to $f^{-1.0}$ in the southwestern region. Summer showed the shallowest slopes of $f^{-0.64}$ in Nevada and $f^{-0.41}$ in California.

The diurnal pattern in the mid-Atlantic and mid-continental regions generally showed much fewer harmonics during the spring and summer than during the winter and fall. The main harmonics occur at 8, 6, 4.8, 4 and 3 hours. The magnitude and width of the harmonic peaks also vary throughout the seasons. The southwest locations showed the most prominent harmonics of the diurnal pattern with additional peaks at 8, 6, 4.8, 4 and 3 hours during all four seasons with the exception of winter which lost the 3 hour harmonic peak.

The steepest and shallowest slopes for the meso- and microscale weather in both Pennsylvania and Virginia occurred in the winter (PA:$f^{-1.43}$ and VA:$f^{-1.59}$) and summer (PA:$f^{-1.25}$ and VA:$f^{-1.18}$) respectively. This indicates that the magnitude of the high frequency variations in the summer are the largest and the winter variation are the smallest. Both of the mid-continental sites had the largest variation between the high frequency best fit slope.

The winters had the largest slopes (MT:$f^{-1.59}$ and ND:$f^{-1.61}$). The summers had the smallest slopes (MT:$f^{-1.18}$ and ND:$f^{-1.25}$). The change between the high and low slopes throughout the year for Montana was a 25% and 22% for North Dakota.

The intra-seasonal changes of the slope of the best fit line in the high frequency is much less for the southwestern sites. Winter showed the steepest slope of

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**Table 2: SLOPES AND CONFIDENCE INTERVALS OF PSD FOR ROCK SPRING, PA.**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syn Int</td>
<td>$10^{10.06}(±0.079)$</td>
<td>$10^{10.10}(±0.233)$</td>
<td>$10^{10.06}(±0.211)$</td>
<td>$10^{0.86}(±0.177)$</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-0.19(±0.119)</td>
<td>-0.84(±0.347)</td>
<td>-0.85(±0.313)</td>
<td>-0.73(±0.265)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{10.06}(±0.020)$</td>
<td>$10^{10.05}(±0.0195)$</td>
<td>$10^{10.21}(±0.019)$</td>
<td>$10^{0.83}(±0.019)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.43(±0.001)</td>
<td>-1.35(±0.001)</td>
<td>-1.25(±0.009)</td>
<td>-1.3(±0.010)</td>
</tr>
</tbody>
</table>

**Table 3: SLOPES AND CONFIDENCE INTERVALS OF PSD FOR STERLING, VA.**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syn Int</td>
<td>$10^{10.06}(±0.214)$</td>
<td>$10^{10.18}(±0.197)$</td>
<td>$10^{10.06}(±0.187)$</td>
<td>$10^{0.77}(±0.148)$</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-0.03(±0.322)</td>
<td>-0.71(±0.294)</td>
<td>-0.62(±0.279)</td>
<td>-0.77(±0.222)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{10.00}(±0.020)$</td>
<td>$10^{11.06}(±0.019)$</td>
<td>$10^{10.23}(±0.019)$</td>
<td>$10^{0.97}(±0.096)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.59(±0.011)</td>
<td>-1.24(±0.010)</td>
<td>-1.18(±0.009)</td>
<td>-1.35(±0.011)</td>
</tr>
</tbody>
</table>
3.2 Coherence and Phase Spectra

The weather types correspond to the same period bands as with the power spectral density. All of the locations become nearly incoherent at periods shorter than a few hours. Figure 3 illustrates the coherence and phase spectra for the mid-Atlantic region. The winter synoptic scale weather shows several peaks around 2 and 10 days and become nearly incoherent at periods longer than 10 days. Spring and summer show high coherence from 4 and 5 days to 10 days. Fall has high coherence from 1 to 2 days and from 3 to 5 days. Spring shows the highest monthly coherence of 0.74 and winter shows the lowest at 0.25. The high coherence in the spring and summer and close to zero phase lag from 30 days to the diurnal cycle indicates that networked solar production between the two sites would be less effective at smoothing the intermittency of irradiance on the synoptic-scale. The diurnal cycle is visible at 1 day and 12 hours year-round with coherent and in phase peaks. The 8 hour harmonic is visible at 8 hours in the winter, spring and fall. Spring and fall also show 6 hour and 4.8 hour peaks with smaller magnitudes.

The mid-continental region is nearly incoherent in the spring and fall in the synoptic scale. Winter and summer have moderate coherence around 5 and 6 days. The monthly coherence is highest in the spring at 0.61 with winter, summer an fall being nearly incoherent. The magnitude of the phase lag between the sites is very large throughout most of the year with the exception being summer which is in phase from 30 to 4 days. The other seasons are out of phase until the diurnal pattern. The harmonics of the diurnal cycle are visible at 8 hour, and 6 hours year-round. A few lower harmonics are visible in winter and fall but have much smaller magnitudes.
The southwest region is nearly incoherent and out of phase year-round from 1 to 3 days with the exception of a peak at about 2.5 days in the spring. Winter shows moderate coherence and is in phase at 3 to 4 days and 6 to 8 days but becomes nearly incoherent at longer periods. Spring, summer, and fall are moderately coherent and in phase over a 30 day period at 0.55, 0.62, and 0.59 respectively. Fall also shows the most harmonics in the diurnal pattern at 8 hours, 6 hours, and 4.8 hours. The 8 hour and 6 hour peaks are also visible in the spring and summer diurnal pattern.

4. CONCLUSIONS
Analyzing the character of both the power spectral density and co-spectrum of shortwave solar irradiance in geographically dispersed regimes of the USA gives further insight to the variation of the available solar resource. The power spectral densities for mid-continent, mid-Atlantic, and southwest regimes suggest that character of synoptic weather behavior has an impact on the meso- and micro-scale variation trends.

The analysis of the solar irradiance in terms of the climate regimes, in seasonal terms, inform the analyses in complement with simple annual characters. Knowledge of these periodic seasonal changes in climate regimes can help to optimize system design and deployment as well as and improve integration with networked solar and solar-fossil co-production.

It can be observed that the seasonal succession of climate regimes reflects the lateral changes in air masses, and therefore the quality and character of downwelling solar irradiance. Information on the characteristics of the irradiation with periods longer than one day is relevant to slow ramping technologies for long term forecasts. Information on the character of the irradiation with periods shorter than one day is relevant to fast ramping technologies. A highly coherent and in phase period on long time scales (the sites are either both receiving sunlight or both not receiving sunlight) will require additional, non-solar energy, technologies to offset the intermittancy that will be visible at both locations. A lowly coherent and/or out of phase period will benefit from networked solar between the two locations and a smoothing effect on the total downwelling shortwave irradiance would be expected.

5. REFERENCES