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November 15, 2019

Mr. Walter L. Thomas, Jr.
Secretary
Alabama Public Service Commission
RSA Union Building
100 North Union Street, Suite 950
Montgomery, Alabama 36130

Re: Docket No. U-4226
Errata and Substitutes to the Direct Testimony, Reply Testimony and Exhibits of Alabama Power Company

Dear Mr. Thomas:

On June 15, 2018, Alabama Power Company submitted the Direct Testimony and Exhibits of Ms. Natalie Dean in the above-referenced docket. On December 13, 2018, Reply Testimony and Exhibits of Ms. Dean were filed. The following errata relate to those submittals:

1. Direct Testimony of Ms. Dean:
   a. Page 2, line 19 – replace "$5.42" with "$5.41"
   b. Page 18, line 12 – replace "$610" with "$609"
   c. Page 18, line 19 – replace "5,362 kWhs" with "5,358 kWhs"
   d. Page 18, line 22 – replace "$280" with "$279"
   e. Page 19, line 6 – replace "$280" with "$279"
   f. Page 19, lines 7, 9, 11 and 18 – replace "$5.42" with "$5.41"
   g. Page 19, line 10 – replace "$23.30" with "23.26"
   h. Page 19, line 18 – replace "$4.88" with "$4.87"
   i. Page 20, line 14 – replace "$262" with "$258"
   j. Page 20, line 16 – replace "535 kWh" with "521 kWh"
2. Revised Exhibit ND-3 to be substituted for Exhibit ND-3.
3. Revised Exhibit ND-5 to be substituted for Exhibit ND-5.
4. Revised Exhibit ND-6 to be substituted for Exhibit ND-6.
5. Revised Exhibit ND-7 to be substituted for Exhibit ND-7.

6. Revised Confidential Exhibit NDReply-4 to be substituted for Confidential Exhibit NDReply-4.

7. Revised Exhibit NDReply-8 to be substituted for Exhibit NDReply-8.

By way of explanation, the revisions identified address an error that Alabama Power has identified in one of the files underlying the Company's calculations. Specifically, solar production data for ten (10) days (out of 366 days) has been determined to be out of sequence with the corresponding hours for that production. (The total daily production levels themselves are correct.) As the errata show, the resulting impact of the correction is minor, but nonetheless proper for revision. Also, revised Confidential Exhibit NDReply-4 (which are workpapers) is being provided to the parties to this proceeding and to the Commission's Legal Division.

In addition, the Company is submitting substitute pages 18-21 for Ms. Dean's Reply Testimony and a non-confidential version of Exhibit NDReply-7. The contents of these materials have not changed; however, the Company has determined that an assertion of confidentiality over that exhibit (and the references to it in Ms. Dean's Reply Testimony) is no longer necessary and these materials may reside in the public record of proceedings.

If there are any questions or if there is anything further we need to do, please do not hesitate to contact me.

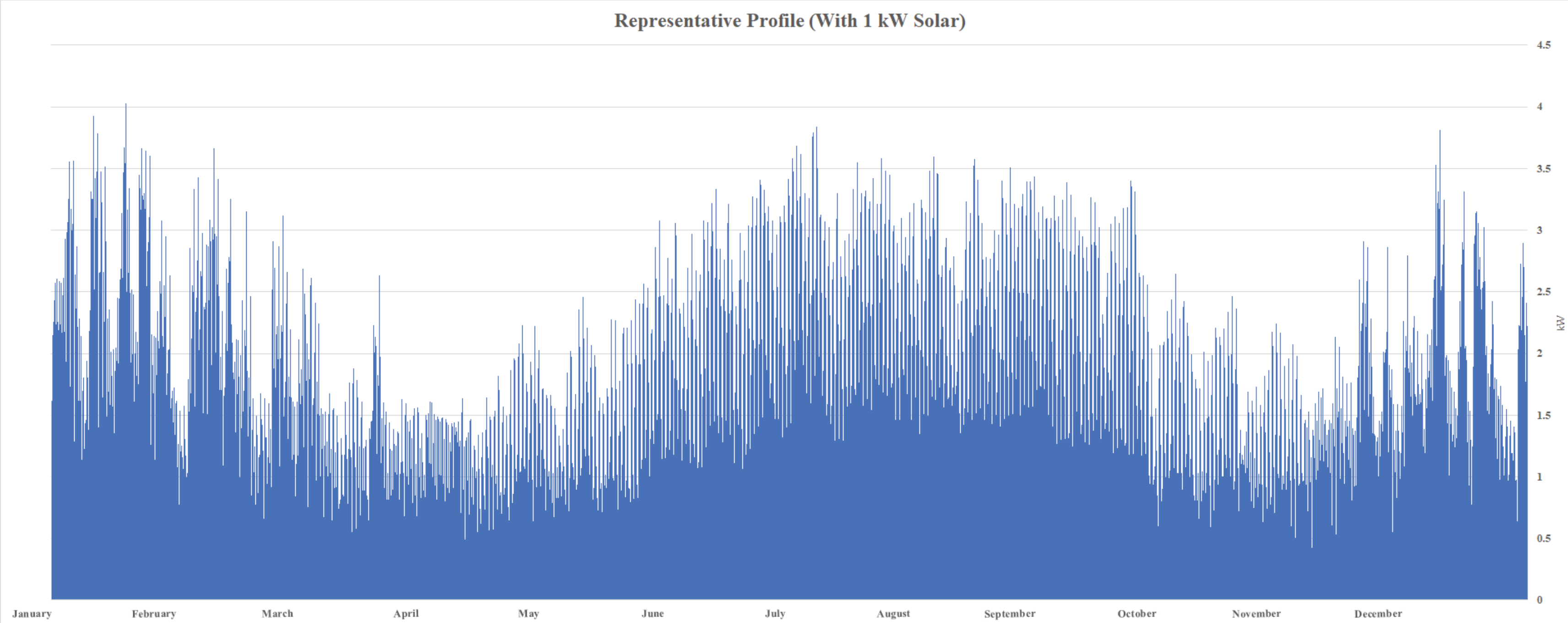
Sincerely,

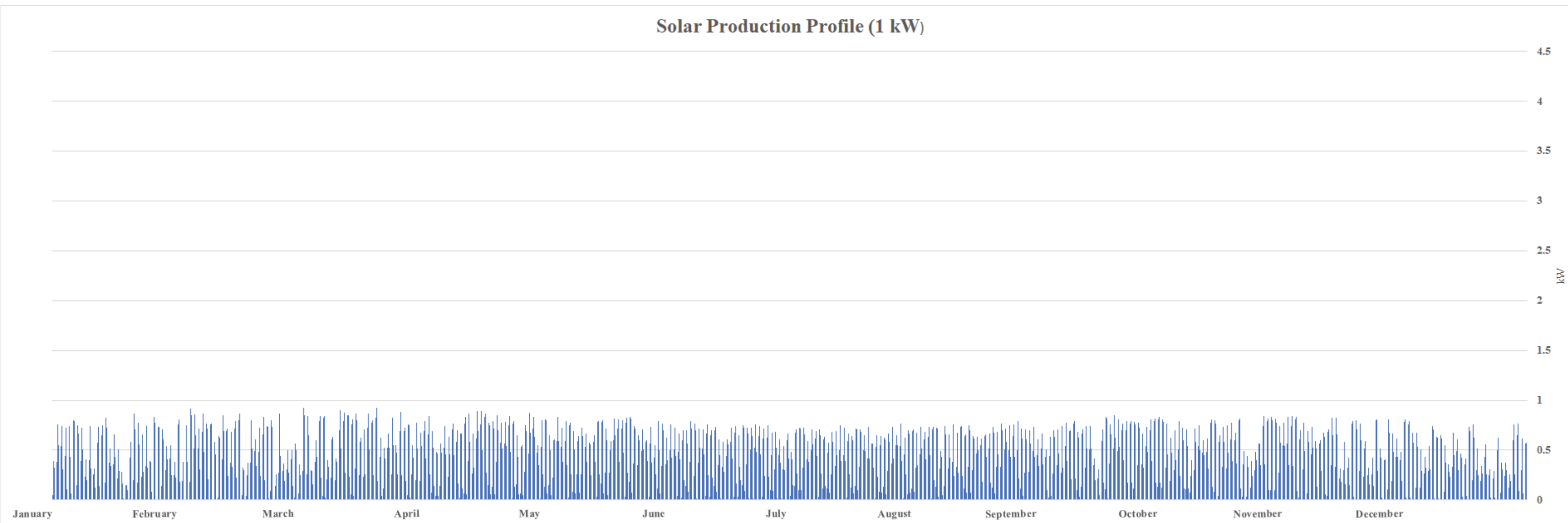
Scott B. Grover

cc: (w/enclosures)
Legal Division
Service List

Testimony of Natalie Dean

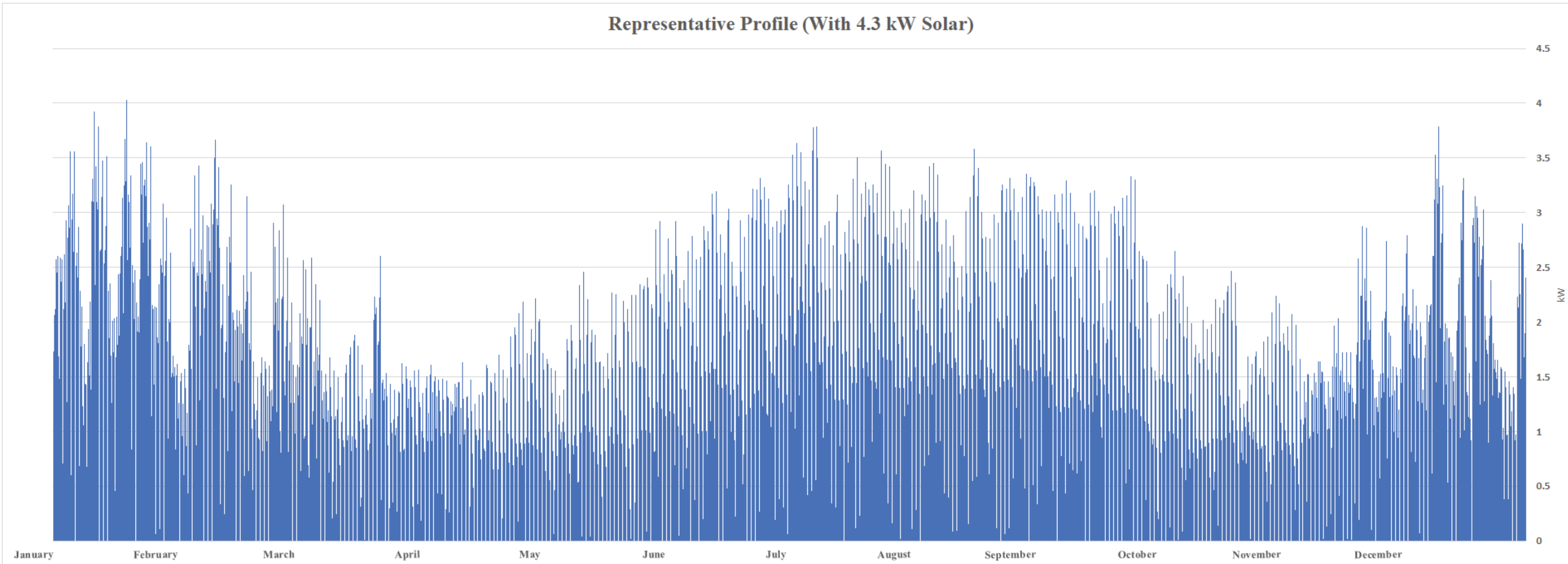
Revised Exhibit ND-3

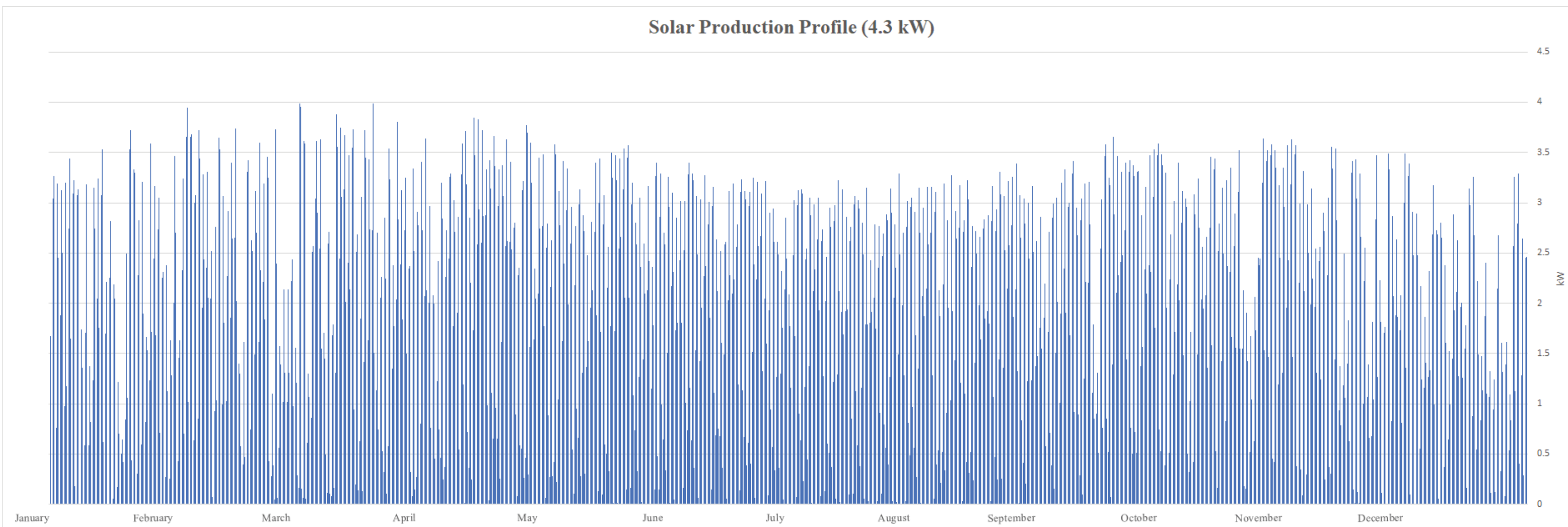

Representative Profile (With 1 kW Solar)
kW
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
January
February
March
April
May
June
July
August
September
October
November
December


Solar Production Profile (1 kW)
kW
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
January
February
March
April
May
June
July
August
September
October
November
December

Testimony of Natalie Dean

Revised Exhibit ND-5


Representative Profile (With 4.3 kW Solar)
kW
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
January
February
March
April
May
June
July
August
September
October
November
December


Solar Production Profile (4.3 kW)
kW
4.5
4
3.5
3
2.5
2
1.5
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0.5
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January
February
March
April
May
June
July
August
September
October
November
December

Testimony of Natalie Dean

Revised Exhibit ND-6

Rate FD Cost Recovery Calculation

Month	Representative Profile (Without Solar) Billed kWh	Representative Profile (Without Solar) FD Billing	Representative Profile (With 4.3 kW Solar) Billed kWh	Representative Profile (With 4.3 kW Solar) FD Billing
January	1,635	$ 194.98	1,238	$ 153.70
February	1,235	$ 153.41	876	$ 116.06
March	971	$ 126.03	599	$ 85.38
April	872	$ 115.72	495	$ 73.23
May	1,071	$ 136.36	605	$ 86.10
June	1,500	$ 196.00	924	$ 125.86
July	1,772	$ 229.26	1,140	$ 152.14
August	1,679	$ 217.91	1,078	$ 144.45
September	1,452	$ 190.20	940	$ 127.83
October	990	$ 127.98	609	$ 86.55
November	965	$ 125.36	639	$ 90.07
December	1,343	$ 164.67	984	$ 127.34
Total	**15,485**	**$ 1,977.88**	**10,127**	**$ 1,368.71**

Energy Reduction (kWh)	**5,358**
Cost Recovery Difference (Rate FD)	**$ 609**

Capacity Reservation Charge Calculation

Cost Recovery Difference	**$ 609**	
Annual Cost Reduction		
Energy (2.53 ¢/kWh @ 5,358 kWh)	$ 136	
Demand ($129 /kW* 35% @ 4.3 kW)	$ 194	
Total Annual Cost Reduction	**$ 330**	
Annual Net Unrecovered Costs	**$ 279**	
Required for Monthly Recovery ($279/4.3 kW/12 months)	$ 5.41	
Capacity Reservation Charge	**$ 5.41**	**per kW**

Testimony of Natalie Dean

Revised Exhibit ND-7

Rate RTA Cost Recovery Calculation

	Representative Profile (Without Solar)		Representative Profile (With 4.3 kW Solar)	
Month	**Billed kWh**	**RTA Billing**	**Billed kWh**	**RTA Billing**
January	1,635	$ 172.68	1,238	$ 136.45
February	1,235	$ 135.38	876	$ 102.47
March	971	$ 109.41	599	$ 74.85
April	872	$ 97.13	495	$ 63.27
May	1,071	$ 116.32	605	$ 74.25
June	1,500	$ 220.25	924	$ 141.08
July	1,772	$ 245.16	1,140	$ 163.22
August	1,679	$ 242.35	1,078	$ 161.05
September	1,452	$ 210.73	940	$ 142.35
October	990	$ 108.26	609	$ 74.16
November	965	$ 109.14	639	$ 78.95
December	1,343	$ 145.60	984	$ 112.35
Total	**15,485**	**$ 1,912.41**	**10,127**	**$ 1,324.45**

Energy Reduction (kWh)	**5,358**
Cost Recovery Difference (Rate RTA)	**$ 588**

Rate RTA Super-Peak Energy Charge Calculation

Cost Recovery Difference	**$**	**588**	
Annual Cost Reduction			
Energy (2.53 ¢/kWh @ 5,358 kWh)	$	136	
Demand ($129/kW* 35% @ 4.3 kW)	$	194	
Total Annual Cost Reduction	**$**	**330**	
Annual Net Unrecovered Costs	**$**	**258**	
FD Energies (kWh) in 3:00-5:00PM Super-Peak Period Required		521	
for Recovery during Super-Peak Period ($258/521 kWh)*	$	0.49	
Rate RTA Peak Period Charge (per kWh)	$	0.221822	
Total Required for Recovery during Super-Peak Period ($0.49+$0.221822)	$	0.71	
Rate RTA Super-Peak Energy Charge	**$**	**0.71**	**per kWh**

*Summation variances due to rounding approximations.

Testimony of Natalie Dean

Revised Exhibit NDReply-8

Rate RTA Cost Recovery Calculation

	Representative Profile (Without Solar)		Representative Profile (With 4.3 kW Solar)	
Month	**Billed kWh**	**RTA Billing**	**Billed kWh**	**RTA Billing**
January	1,635	$ 172.68	1,238	$ 136.45
February	1,235	$ 135.38	876	$ 102.47
March	971	$ 109.41	599	$ 74.85
April	872	$ 97.13	495	$ 63.27
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Total	**15,485**	**$ 1,912.41**	**10,127**	**$ 1,324.45**

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Rate RTA Super-Peak Energy Charge Calculation

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Annual Cost Reduction			
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Rate RTA Super-Peak Energy Charge	**$**	**0.71**	**per kWh**

*Summation variances due to rounding approximations.

associated with the capacity held available for its back-up power service requirements. Thus, FERC makes clear that as part of a diversity determination, weather variability and performance data are relevant considerations, above and beyond the mere mechanical availability that Mr. Rábago prefers.

Q. Did the Company rely on this information in developing the modifications?

A. As I discussed, these and other factors shaped the Company's judgment. That being said, after Mr. Rábago prompted the Company to review Order No. 69 more closely, the Company endeavored to see if additional data might be available to further inform the diversified capacity requirements.

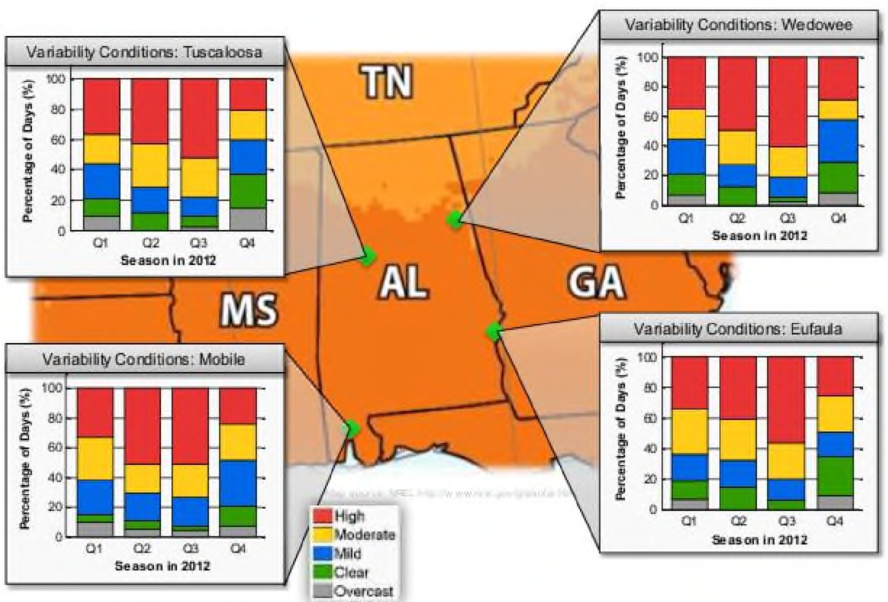
Q. Did Alabama Power identify any such information?

A. Yes. EPRI has undertaken an analysis of distributed solar photovoltaic performance data in Alabama. Specifically, EPRI has taken metered production data from six clusters of single-module solar monitoring systems deployed across various cities to characterize solar system operability across the state. As part of the study, EPRI quantified the delivered energy and power profiles of the systems, evaluated their overall performance, and measured their variability at multiple ramp rate time intervals. The results of this work, included in a 2015 report, were intended to help utilities like Alabama Power better understand and plan for distributed solar generation sources.[31]

Q. What did you find notable in the report?

[31] *See Southern Company Distributed PV Monitoring in Alabama: Analysis of Field Data from Six Clusters of Single-Module Solar Monitoring Systems during 2011-2012,* EPRI, Palo Alto, CA (April 2015, 3002006371) (attached as NDReply-7, and designated as confidential).

A. I would first call attention to the report's discussion of solar resource variability, as it relates to daily clearness.[32] The report elaborates on the different types of days measured: overcast, clear, mild, moderate and high. With regard to Alabama, "[b]oth spring and summer seasons experienced 'moderate' or 'high' solar resource variability during at least 65% of the days within each quarter in all locations. The prevalence of partly-cloudy days is expected for Alabama, given the typical weather patterns experienced in the Southeast."[33] The maps bear out this observation, with the vast majority of days experiencing high, moderate and overcast variability.[34]



Also noteworthy is the report's discussion of irradiance profiles and the charts showing the effects on solar output in Tuscaloosa and Mobile during August 2012.[35]

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[32] *See id.*, page 2-3 through 2-5.

[33] *Id.*, page 2-5.

[34] *Id.*

[35] *See id.*, pages 2-1 through 2-3.

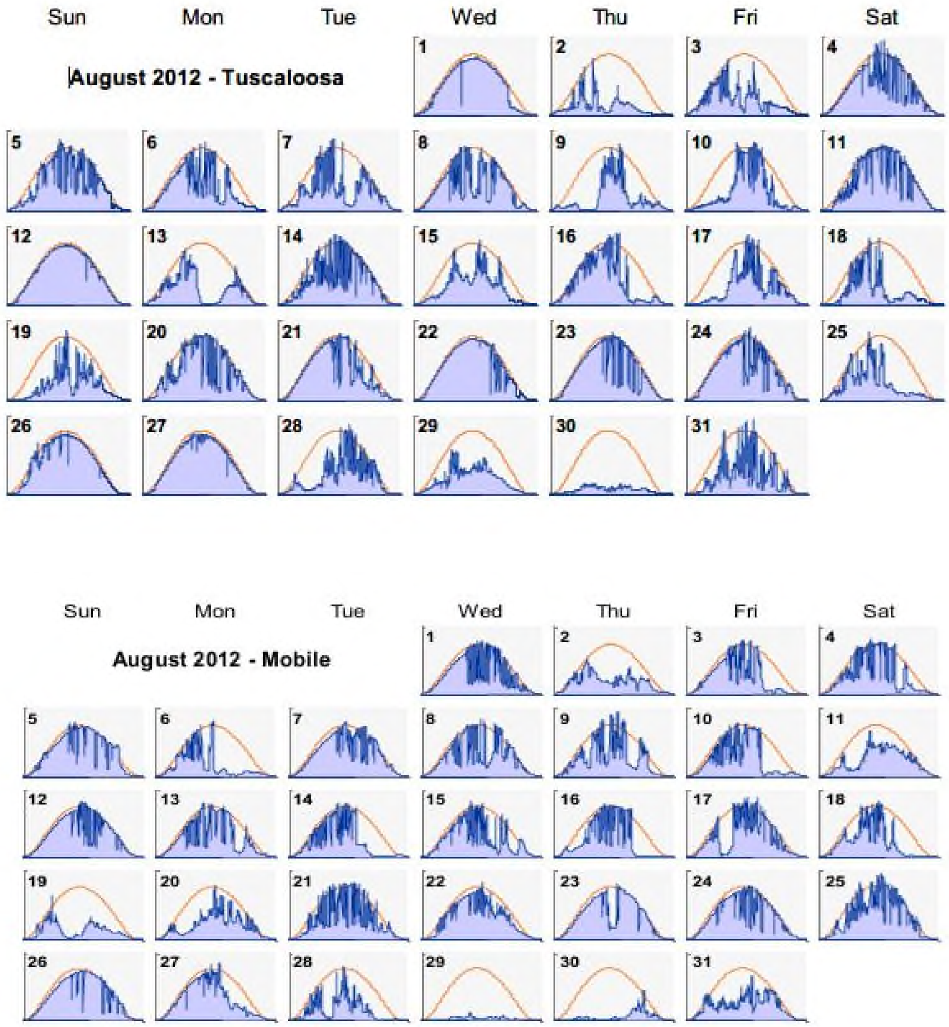

Figure 2-2
Daily solar irradiance profiles (blue areas) and clear sky irradiance (orange lines) in plane-of-array for August 2012

These charts show how solar irradiance (and thus production) changes quickly, frequently, and often dramatically, as compared to optimum (i.e., clear sky) conditions. These irradiance fluctuations are independent of customer demand; however, as customer demand cannot be expected to disappear with the loss of sunlight. The charts also show commonality between locations. That is to say, irradiance fluctuations in Tuscaloosa and Mobile often overlap, requiring the Company to be prepared to provide back-up power service in both locations simultaneously.

Q. Are you saying the report calculates a diversity requirement of 65 percent?

A. No. The solar resource variability percentage I noted above is coincidental. The importance of the report is that the irradiance data, which is informed by solar resource variability, demonstrates that solar resources in Alabama often are unavailable and can be expected to be unavailable in multiple regions simultaneously. As such, the Company remains confident in its judgment that utilizing 65 percent to represent diversity is reasonable.

Q. Mr. Rábago also expands his criticism to other parts of Rate Rider RGB. Did any of his comments raise concerns to you?

A. No. His claim that the supplementary service rate constitutes an overcharge is predicated on his false assumption that the Company realizes fixed cost "savings"[36] associated with customers with on-site generation—yet another application of his flawed "supplied vs. available" predicate that I have thoroughly addressed. He also criticizes the language in the rate as unclear and confusing. Customers do contact the Company from time to time regarding Rate Rider RGB, but the Company (and the Commission's Staff) also receives inquiries on countless other service-related matters, including but not limited to the Company's rate schedules and its service regulations. The fact that people periodically have questions does not mean that a rate or regulation is unreasonable. Electricity supply is not a simple undertaking,[37] and if the absence of questions proved the standard for reasonableness, very little ratemaking would get accomplished.

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[36] *See* Rábago Testimony, page 38, line 16 through page 39, line 2.

[37] To this end, the decision by a customer to operate a generator in parallel with the Company's system presents significant risks. This is partly why the Company maintains a detailed set of special rules respecting such parallel operations—rules that Mr. Rábago does not challenge. *Cf.* Special Rules Governing Application of Rate Rider RGB, available at https://www.alabamapower.com/content/dam/alabamapower/Rates/SP-RGB.pdf.

Reply Testimony of Natalie Dean

Exhibit NDReply-7

Southern Company Distributed PV Monitoring in Alabama

Analysis of Field Data from Six Clusters of Single-Module Solar Monitoring Systems during 2011-2012

3002006371

Final Report, April 2015

EPRI Project Manager
C. Trueblood

ELECTRIC POWER RESEARCH INSTITUTE
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Electric Power Research Institute

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ACKNOWLEDGMENTS

The Electric Power Research Institute (EPRI) prepared this report:

Principal Investigators:
S. Coley
L. Rogers
C. Trueblood

This report describes research sponsored by EPRI. EPRI would like to acknowledge the support of Southern Company and Alabama Power.

This publication is a corporate document that should be cited in the literature in the following manner:

Southern Company Distributed PV Monitoring in Alabama: Analysis of Field Data from Six Clusters of Single-Module Solar Monitoring Systems during 2011-2012. EPRI, Palo Alto, CA: 2015. 3002006371.

ABSTRACT

In 2010 the Electric Power Research Institute (EPRI), along with several utilities, began collecting high-resolution field data on distributed solar photovoltaic (PV) systems throughout the United States. Included in this monitoring data are multiple single-module solar monitoring systems located along selected distribution circuits. Utilizing data from installed monitoring systems in Alabama, this report will focus specifically on characterizing the solar resource, quantifying delivered energy and power profiles, evaluating overall performance, and examining measured variability at multiple ramp rate time intervals. The results of this work may help utilities better understand and plan for distributed PV generation sources, especially when significant penetrations of PV systems are connected to the same distribution circuit.

Keywords
Circuit
Distributed
Distribution
Feeder
Monitoring
Photovoltaic
PV
Solar
Variability

Reply Testimony of Natalie Dean
Exhibit NDReply-7

EXECUTIVE SUMMARY

In 2010 the Electric Power Research Institute (EPRI), along with several utilities, began collecting high-resolution field data on distributed solar photovoltaic (PV) systems throughout the United States. Included in this monitoring data are multiple single-module monitoring systems located along selected distribution circuits. Utilizing data from monitoring systems installed in Alabama, this report will focus specifically on characterizing the solar resource, quantifying delivered energy and power profiles, evaluating overall performance, and examining measured variability at multiple ramp rate time intervals. The results of this work may help utilities better understand and plan for distributed PV generation sources, especially when significant penetrations of PV systems are connected to the same distribution circuit.

Approach

Six clusters of single-module solar monitoring systems deployed across Alabama are used for analysis. Each of the clusters is instrumented with 8 small, 0.2-kW PV monitoring systems mounted on utility poles for collecting high-resolution solar resource data. These monitoring systems were placed along specific distribution circuits to cover the entire geographic footprint. The six clusters range in area from 0.08 km^2 to 5.9 km^2. The clusters were chosen in various cities throughout Alabama in an effort to characterize solar across the state.

The analysis and results of this report are based on measurement data collected during 2011-2013. EPRI's analysis utilizes the dataset to study the following:

- Solar resource;
- Seasonal variability;
- Energy;
- Power output and performance;
- Daily variations in ramping;
- Up/down ramp rates;
- Ramp rates across entire feeders; and
- Correlations between pole-mount solar sites within each feeder.

The layout of solar monitors throughout the distribution feeders are not symmetric or equally spaced, but are distributed throughout the feeders based upon each specific feeder's geographic layout. From a purely theoretical standpoint, a symmetric layout would yield results that are less dependent upon the direction of cloud movement; however, actual distribution systems aren't laid out in such a manner. Many distribution systems have irregular footprints, and the results shown throughout this report illustrate this fact (e.g., PV systems equally distanced apart but along different vectors show different correlation and variability statistics).

Key Findings

This report presents an assessment of PV performance and solar variability at several locations throughout Alabama. This report has also shown several examples of the extent that geographic location and spatial diversity has on solar variability throughout the state of Alabama. Some of the key findings discovered throughout this analysis are summarized here:

- **Insolation:** Measured annual insolation in 2012 ranged from 4.16 to 4.62 kWh/m²/day, while seasonal insolation varied from 3.69 to 5.54 kWh/m²/day across the state.
- **Solar Resource Variability:** Variability, due to partly cloudy conditions, was common across Alabama. Few days were completely cloudless during spring and summer, and the greatest number of clear days occurred in the fall. Both spring and summer seasons experienced "moderate" or "high" solar resource variability during at least 56% of the days within each quarter in all locations.
- **Capacity Factor:** Measured monthly capacity factors in Tuscaloosa and Eufaula in 2012 ranged from 0.1 to 0.22. The highest capacity factors occurred during spring, due to longer periods of daylight and cooler operating temperatures, which increase PV system efficiency.
- **Power Output:** PV systems across the state generated at least 20-30% of their rated output for 55% of all daytime hours and generated at least 76% of their rated output for 10% of all daytime hours. The spring and summer seasons have a greater number of hours spent operating at higher power output (as a % of dc rating) than the fall and winter.
- **Permanent Object Shading:** Shading from any object that covers even a small portion of a PV module, such as cross arms and power lines, can have a severe adverse effect on PV output.
- **Using Irradiance measurements as a substitute for single PV module output to assess solar variability:** The magnitude of changes in irradiance compared to changes in PV power output from a single PV module differed at most by 11% across multiple time intervals and percentiles. This allowed for adversely-affected power data to be replaced with irradiance data for successful variability analysis.
- **Symmetry in Up/Down Ramping:** Feeder-wide PV system ramping at multiple time intervals has general symmetry in both ramp-up and ramp-down directions.
- **Severity of Ramp Rates:** The fastest ramp rates observed were found to have approximately 30% change in output across a 5 second window (6% per second). The largest magnitude ramps were observed to have changes in output of approximately 70% change over 10-minute to 1-hour time intervals.
- **Frequency of Occurrence of High Ramp Rates:** The most extreme ramp rates did not occur often, even given that the region is characterized by high variability. The largest changes in output across clusters (changes in output of roughly 60% or greater ramping over a 10-minute window) only occurred 0.01% of the time, or roughly 3 occurrences per year.

- **Impact of Feeder Footprint (Area) on Ramp Rates:** Minor variation was observed in ramp rates between the largest cluster (5.9 km^2) and the smallest cluster (0.08 km^2).
- **Correlation of Ramping between Sites:** As expected, as distances increase, the correlation between changes in output for pairs of PV systems decreases. Little to no correlation was observed at the 5-second to 1-minute time intervals. Weak correlations are found at 10-minute intervals, and 1-hour ramp rates are highly correlated. Correlation coefficient for 1-minute ramp rates did not exceed 0.5 for distances of more than 0.3 km.

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1
INTRODUCTION

The main objective of this distributed photovoltaic (PV) evaluation in six cities throughout Alabama is to assess the performance characteristics of solar in different geographical locations throughout the state and along multiple distribution circuits. Each of the six cities has a cluster of 8 single-module solar monitoring systems that consist of a 0.2-kW PV module, microinverter, pyranometer, and data acquisition components mounted on utility poles. Data from these units, collected for 3 years beginning in 2010, are used to illustrate the metrics needed to characterize PV power, energy performance, and variability. Some metrics are traditional; others are new and were created to address the challenge of measuring variable generation resources.

Six Clusters

Along selected feeders in Hoover, Wedowee, Tuscaloosa, Wetumpka, Eufaula, and Mobile, multiple single-module solar monitoring systems were installed on utility poles in Alabama, such as the one shown in Figure 1-1, which is located in Wedowee.

Figure 1-1
Single-module solar monitoring system installation in Alabama (source: Alabama Power)

Six clusters across Alabama are used for analysis. Table 1-1 provides a short summary of the clusters considered. The monitoring systems were placed throughout each feeder to cover the entire geographic footprint. The six feeders range in area, from 0.08 km^2 to 5.9 km^2. The clusters were chosen in various cities throughout Alabama in an effort to characterize solar across the state.

Table 1-1
Clusters of single-module solar monitoring systems

Cluster	# of Sites	Area (km²)	Installation Date
Hoover	8	0.08	August 2011
Wedowee	8	5.89	November 2011
Tuscaloosa	8	0.95	August 2011
Wetumpka	8	0.59	April 2011
Eufaula	8	2.76	May 2011
Mobile	8	5.65	April 2011

Data Acquisition System

EPRI selects available data acquisition hardware components to meet the project's objectives and budget. Several core data acquisition components are described below to explain how data is recorded in the field and transmitted to EPRI.

Data Logging

The data logger records data at 1-second resolution by regular polling of devices, maintains time synchronization, and performs automatic data uploads to EPRI (when connected to the internet). To enable 1-sec data recording, the data logger polls meters and sensors sending and receiving Modbus messages via an RS-485 serial port or Ethernet port. The typical round-trip response time to read a power meter and several analog sensors is generally 100-150ms.

While data is recorded at 1-sec resolution, it is uploaded to EPRI at 15-minute intervals. The data logger retains data logs in its non-volatile flash memory until they are successfully uploaded and verified on EPRI's server. If one or more uploads fail, the data logger will resend all pending data logs on the next connection. If several days pass without successful uploads, cached 1-sec data logs may be deleted if the data logger's memory reaches capacity. Oldest data logs are purged first to free space for new logs. Field sites can typically sustain 4-5 days offline without losing data.

Maintaining time synchronization is important to correctly align datasets from multiple sites and other data sources (i.e. utility load data and local weather stations). The data logger synchronizes its internal clock several times per day with a dedicated timeserver via the internet. Accuracy is quite precise because the data logger uses Network Time Protocol (RFC-1305). Each row in the data logs is time stamped using Coordinated Universal Time (UTC), and multiple data loggers are expected to be accurate within 500ms of each other.

Meters and Sensors

All single-module solar monitoring systems use an ac power meter to measure PV system output, a pyranometer to measure plane-of-array solar irradiance, and a temperature sensor to measure PV module back surface temperature.

EPRI's Version 2 systems, having an improved framing design over Version 1, were deployed to all locations in Alabama.

Measurements

Table 1-2 shows the measurement types EPRI receives for a single-module monitoring system. For each measurement channel, EPRI designates a unique identifier, a system name, a channel type detailing the measurement, and the units associated with each channel.

Table 1-2
Example measurement channels for single-module monitoring system

System	Channel	Channel Type	Units
Pole #1	1	AC Current	A
Pole #1	2	AC Energy Net Total	kWh
Pole #1	3	AC Power	kW
Pole #1	4	AC Reactive Energy Net Total	kVARh
Pole #1	5	AC Reactive Power	kVAR
Pole #1	6	AC Voltage	V
Pole #1	7	Data Logger Error Code	
Pole #1	8	Data Logger Enclosure Temperature	°C
Pole #1	9	Irradiance, Plane of Array	W/m^2
Pole #1	10	PV Module Temperature	°C

Other Considerations

Often site analysis is based on a PV system's dc rating, which is obtained from the PV module manufacturer's published rating. That power rating has a specific tolerance, typically within 5% of its nameplate. Considering these known module tolerances and the accuracy of ac readings and pyranometers, analyses showing differences within 5% may be considered inconsequential.

Report Approach

The following chapters outline specific PV metrics that can be used to characterize performance based on measured available resource and measured ac output of the distributed PV monitoring clusters:

- **Solar Resource:** annual, seasonal, and monthly insolation, irradiance profiles, and resource variability – measured in the plane of array (30° fixed tilt, facing true south) using pyranometers mounted on each PV module;
- **Delivered Energy:** annual, seasonal, and monthly capacity factors and performance ratios, as well as related production summaries – normalized to each system's dc array rating;

- **Power Output:** seasonal peak powers, time-of-day profiles, and related statistics – normalized to each system's dc array rating; and
- **Ramp Rates:** quantify the magnitude, rate, and number of occurrences of observed ramp events across the clusters.

Selecting a Representative Site

To analyze the solar resource, energy, and power output for a cluster of sites, a single site is selected to represent the cluster. By selecting a single representative site, we are able to apply strict screening criteria to the cluster so that the solar resource, energy, and power output analyses are accurate and have minimal anomalies, which can be common to pole-mounted monitoring systems.

Representative site selection is done by applying a screening process and selecting the sites with the highest median monthly solar insolation. The screening process identifies sites that are not inhibited by permanent shading issues such as overhead power lines, telecommunications lines, street lights, etc., and do not have significant amounts of missing data. In some instances, a cluster of sites did not have any sites that passed the strict screening criteria, and the site with the least amount of shading and missing data was selected. Results for periods of time with significant amounts of missing data have been removed, as they would not have been representative of the solar resource, energy, or power output of PV for that location.

2
SOLAR RESOURCE

The solar resource at a given location is dependent on weather and time period examined. *Irradiance* and *insolation* are two common, and well defined, measures of solar resource. To characterize solar resource, pyranometers located on each single-module monitoring system were used to contrast differences in total resource as well as variability of the resource. The plane-of-array pyranometers are located on the bottom edge of the PV module as shown in Figure 2-1 (within the red circle).

Figure 2-1
Pyranometer installed for plane of array irradiance measurements (Source: EPRI)

Irradiance is a measure of solar power on a given plane, e.g., horizontal or in the plane of array (POA) and is usually expressed in W/m^2. The power output from a PV plant is generally proportional to the incident irradiance across the plant's footprint. For this reason, variability in irradiance is useful in determining variability in plant output power. Site irradiance was measured using typical pyranometers with aperture of roughly one square centimeter.

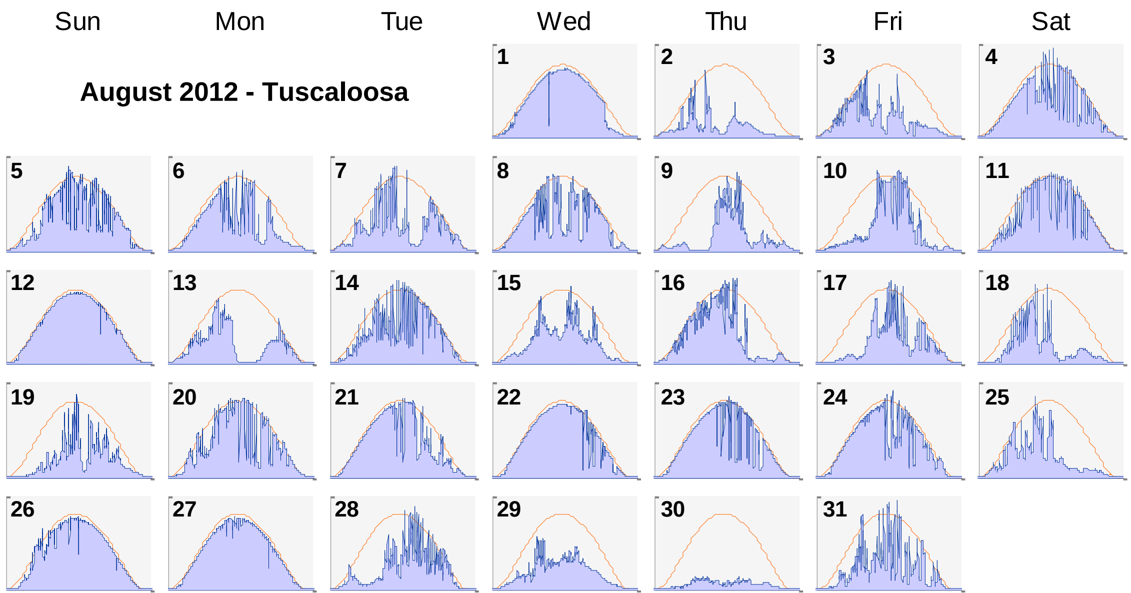
Insolation, meanwhile, is defined as solar energy received over time, i.e., the integration of irradiance. Typical values range from 2 to 7 $kWh/m^2/day$ depending on location, array tilt, time of year, and weather.

Irradiance Profiles

Figure 2-2 shows examples of site irradiance: a solar irradiance calendar based on plane-of-array irradiance averaged for each minute throughout August 2012 in Tuscaloosa and Mobile. The reference curve (thin orange line) shows modeled clear sky irradiance (plane-of-array) as calculated by the Ineichen clear-sky model implemented in Sandia National Laboratory's PV Performance Modeling Toolbox for MATLAB (https://pvpmc.sandia.gov/).

As expected, the resource follows the pattern of the sun rising and falling over the course of a day. Perhaps not expected, however, is that the resource can be highly variable from minute to minute as seen in the calendar, changing quickly with passing clouds. In August, clouds appear almost every day.

The measured irradiance profile shows good alignment with clear-sky modeled irradiance (measured is within 10% of clear sky value at mid-day under clear conditions). Some days are highly variable with fast ramping throughout the day (e.g., August 4 in Tuscaloosa, August 21 and 24 in Mobile). However, the calendars show that across the two locations, daily profiles can vary quite a bit. For example, on August 27, Tuscaloosa has a mostly clear day, while Mobile experiences significant cloud cover in the afternoon.



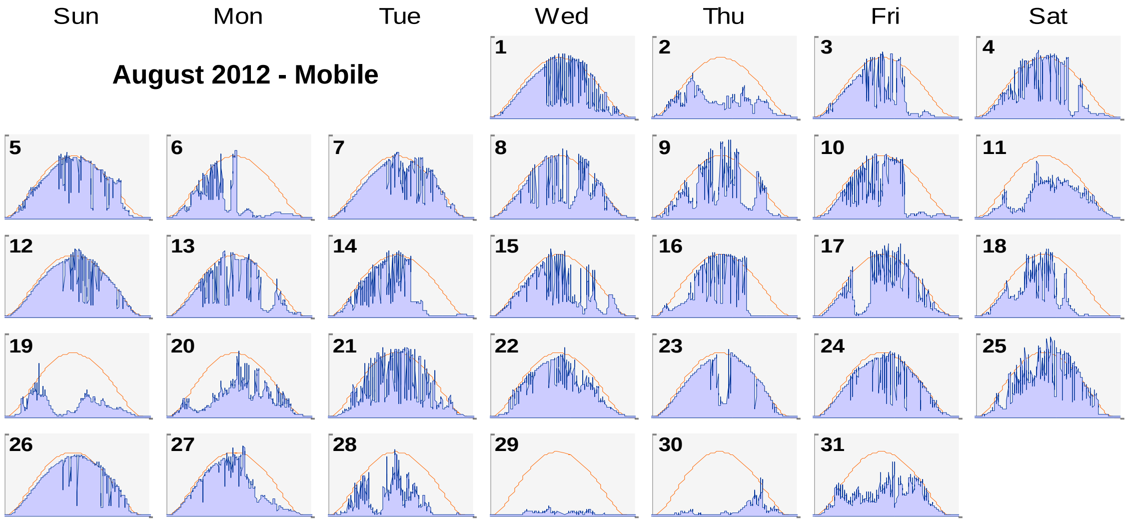


Figure 2-2
Daily solar irradiance profiles (blue areas) and clear sky irradiance (orange lines) in plane-of-array for August 2012

Solar Resource Variability

Looking at the solar resource on a day-to-day basis offers some perspective on the variation for a particular location or region. A method for classifying days as more or less variable uses a combination of the classic "daily clearness index" and newer "daily variability index," defined by Sandia National Laboratories.[1] Research is ongoing to determine if distinguishing variability in this manner can be used by utility generation planners and grid operators in decision making.

Clearness Index

Daily clearness index is the ratio of solar energy measured on a given surface to the theoretical maximum energy on that same surface during a clear sky day.

$$Daily\ Clearness\ Index = \frac{Measured\ Solar\ Insolation}{Calculated\ Clear\ Sky\ Solar\ Insolation}$$

Calculated clear sky solar insolation can be obtained from a number of clear-sky models.[2] Typical values for daily clearness index range from 0.0 to 1.1. Values greater than 1.0 are obtained in practice because clear-sky models may not be exact for every hour at any given location.

Variability Index

Daily variability index is the ratio of the length of the measured irradiance change (blue line in Figure 2-2) to the calculated clear sky irradiance change (orange line), each quantified by summing the length of the line segments in the irradiance plot between time steps. When

[1] J. Stein, et al, The Variability Index: A New and Novel Metric for Quantifying Irradiance and PV Output Variability (ASES 2012 VI, SAND2012-208).
[2] M. Reno, C. Hansen, J. Stein, "Global Horizontal Irradiance Clear Sky Models: Implementation and Analysis", Sandia National Laboratories SAND2012-2389, 2012.

irradiance is variable, the length of the measured irradiance will be greater, and thus higher variability corresponds to greater index values. Typical values range from 1 to 30 for plane of array irradiance at 1-minute time steps.

$$Daily\ Variability\ Index = \frac{Length\ of\ measured\ irradiance\ plot}{Length\ of\ clear\ sky\ irradiance\ plot}$$

Daily Variability Conditions

Using combinations of the daily clearness index and variability index, categories of day types are created as shown in Figure 2-3. Five variability conditions or day types are defined: high variability, moderate variability, mild variability, clear, and overcast. Classifying daily variability conditions in this way provides another metric to examine measured data.

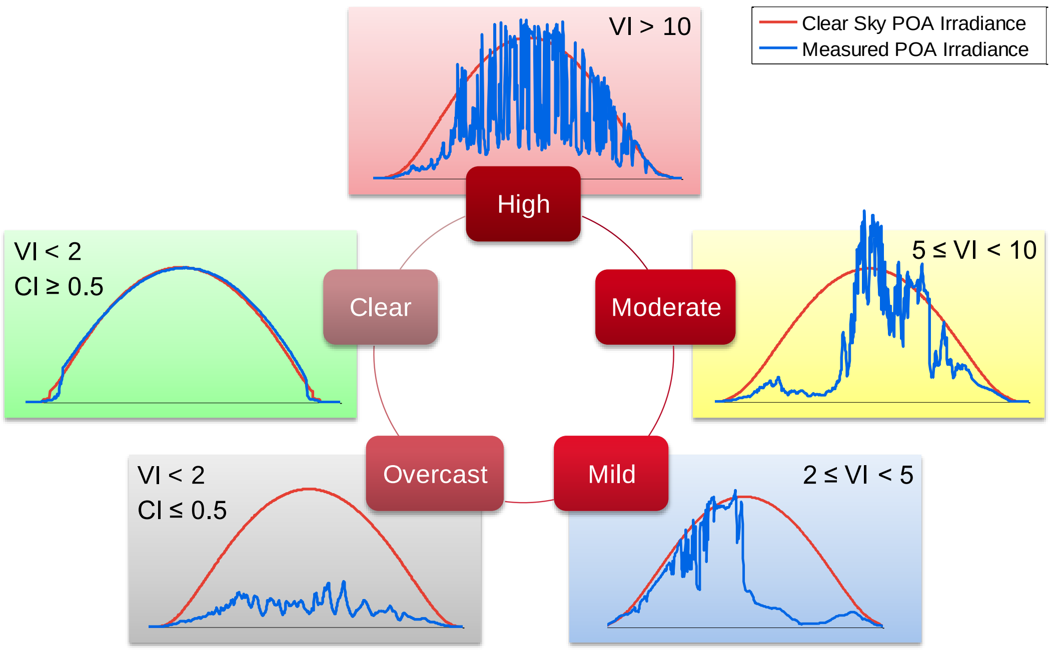


Figure 2-3
Categories for daily variability conditions, based on clearness index (CI) and variability index (VI)

Establishing a solar resource variability and clearness metric allows for comparison of weather in different regions and its potential effect on PV output. Figure 2-4 illustrates this variability metric to show conditions measured across the state of Alabama for four seasons in 2012. Each day in the season is classified as one of the five daily variability conditions in order to show the relative frequency of occurrence of each day type within the season.

Variability due to partly cloudy conditions was common across Alabama for every season in 2012. Few days were completely cloudless during spring and summer, and the greatest number of clear days occurred in the fall. In most locations, the spring and summer had mostly high or moderate variability. The greatest number of overcast days in most locations occurred during the fall months with the exception of Mobile, which saw the greatest number of overcast days during winter.

Both spring and summer seasons experienced "moderate" or "high" solar resource variability during at least 65% of the days within each quarter in all locations. The prevalence of partly-cloudy days is expected for Alabama, given the typical weather patterns experienced in the Southeast.

It is noted that while strict limits have been used to define day types for computational purposes, the nature of defining day types is subjective at these limits. Due to the subjective nature at the limits and the presence of line shading at several representative sites, the number of mild variability days may be overestimated as several of those days may have been clear.

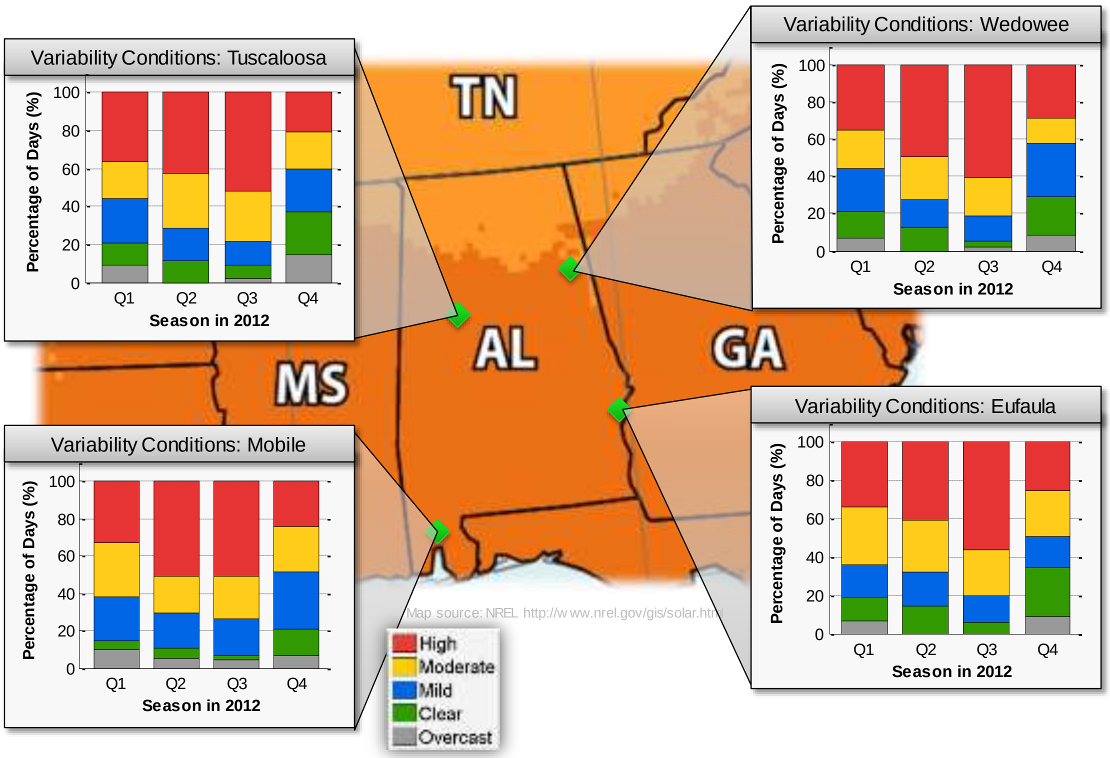


Figure 2-4
Daily variability conditions for four clusters in 2012

Solar Insolation

The solar insolation quantifies solar energy over a period of time; it is roughly proportional to the expected plant electrical energy output for the same period. This section will look at the annual and seasonal insolation for all locations in Alabama, and the monthly insolation for three locations of interest in Tuscaloosa, Eufaula, and Mobile.

Annual Insolation

Figure 2-5 shows the average annual insolation for each Alabama cluster for 2012. In total, the Wedowee cluster had the highest annual insolation (4.62 kWh/m²/day), and the lowest occurred in Hoover (4.16 kWh/m²/day) due to permanent object shading. Aside from the shading issues at Hoover, solar insolation across the state of Alabama is relatively steady, with no significant changes from location to location; neglecting Hoover, the other 5 sites' annual insolation values were within 2.4% of one another.

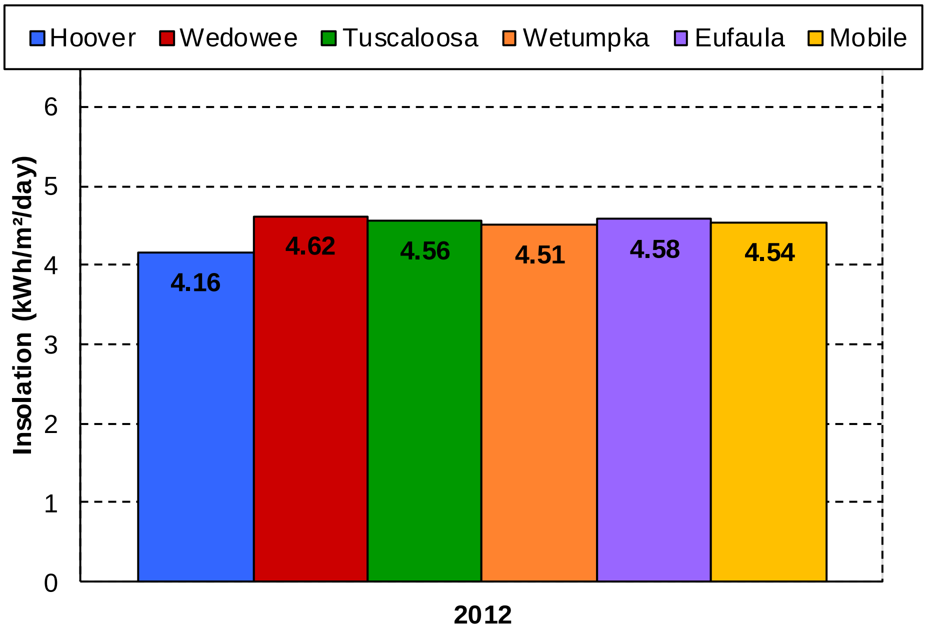


Figure 2-5
Annual solar insolation for six clusters in 2012

Seasonal Insolation

Another way to look at insolation is the seasonal variation. Figure 2-6 shows the seasonal insolation for each cluster in 2012. The insolation measured in each season is similar from location to location. Tuscaloosa had the highest measured insolation in Spring (5.54 $kWh/m^2/day$), while Wedowee had the highest insolation in Winter and Summer (4.09 $kWh/m^2/day$ and 4.89 $kWh/m^2/day$, respectively). Overall the seasonal variations between locations remain within an 11% difference for winter, spring, and summer, and within a 20.3% difference for fall. Neglecting Hoover's shading issues, the seasonal difference between the other five clusters is never greater than 9.5%.

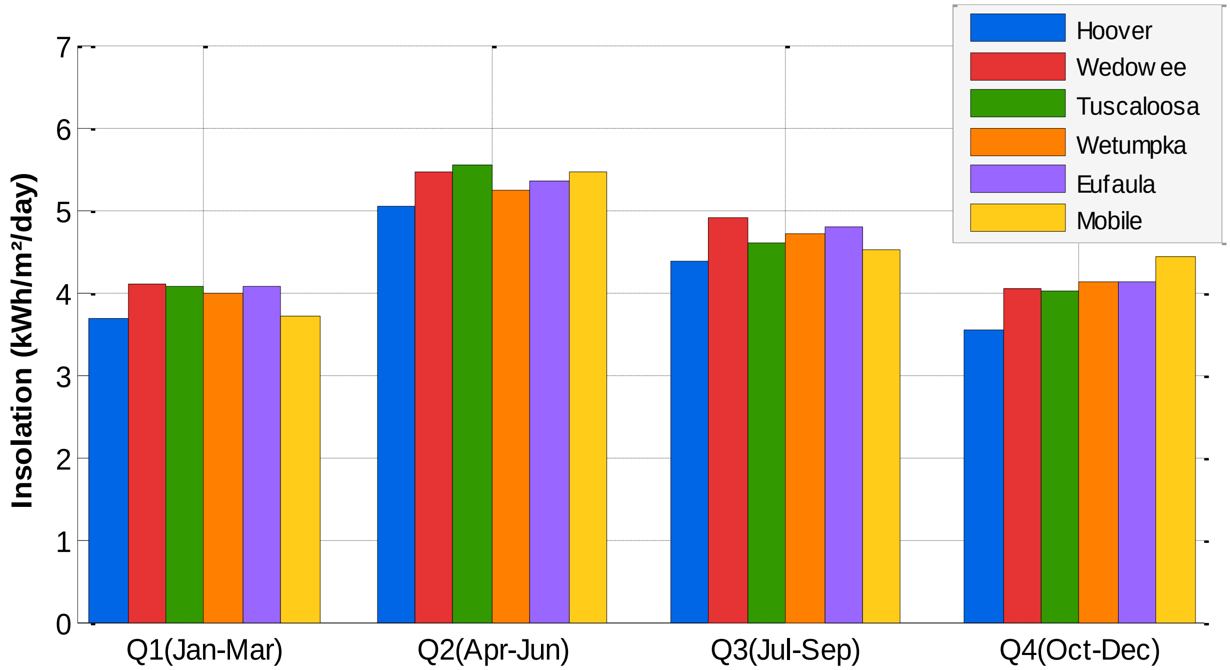


Figure 2-6
Seasonal solar insolation for six clusters in 2012 (values provided in Table A-1)

Monthly Insolation with PVWatts

Figure 2-7 depicts the measured monthly plane-of-array insolation at select Alabama sites (vertical bars) compared to calculated values (filled area in background). The vertical bars represent the average measured insolation from pyranometers at the sites. Calculated values are monthly outputs obtained from NREL’s PVWatts. They are based on site design details entered into the online calculator and a solar prediction for the site based on hourly weather history data in a typical meteorological year (TMY) from the National Solar Radiation Database. While TMY data can be useful for planning purposes, actual measured insolation will often differ from calculated values. Three locations are highlighted to show differences across Alabama. As seen in Figure 2-7, February and December had the largest variation in insolation across the three sites examined at 24% and 20% differences, respectively.

Solar Resource

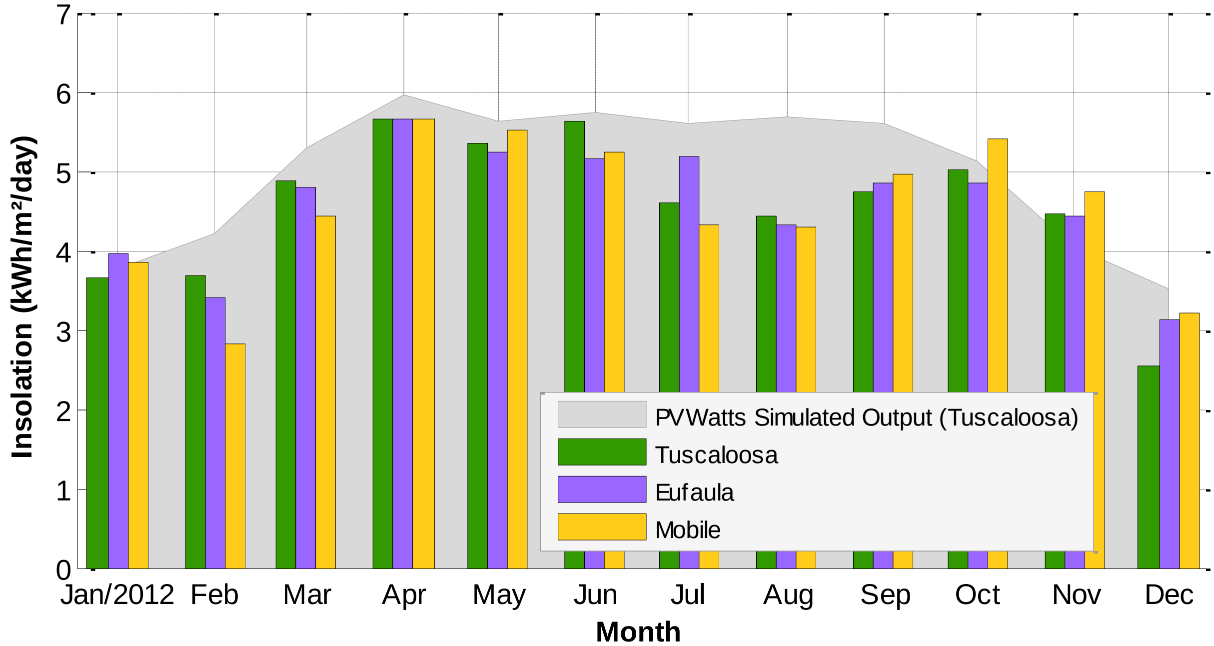


Figure 2-7
Monthly solar insolation and PVWatts predicted insolation for 2012 (values provided in Table A-2)

3
DELIVERED ENERGY

Energy, or power output integrated over a time period, is a primary measure of plant productivity. For PV systems the solar resource should also be considered during the same time period to form a baseline to which the delivered energy can be compared. If done carefully, insolation measurements can also provide a reference for determining degradation of plant output over time.

Capacity Factor

Capacity factor is defined as the ratio of actual output of a plant over a period of time relative to rated output if operating at nameplate capacity over the same period.

$$Capacity\ Factor = \frac{Total\ Energy\ Produced\ (kWh)}{System\ Rating\ (kW)\ \times\ Time\ Interval\ (hours)}$$

For PV plants the annual capacity factor depends on many elements, including: location, weather, array tracking, balance of plant efficiencies and inverter sizes.

Several issues must be addressed to more consistently calculate a PV plant's capacity factor. The first such issue surrounds the choice of system rating. The utility industry uses the generator (inverter) ac rating when calculating capacity factor, while the PV industry has traditionally used the collector (array) dc rating. For the purposes of this analysis, the dc rating was used because the primary focus of this evaluation is to assess PV modules, not inverters. A second issue is the decision to either over or undersize the inverter rating (i.e., dc array size relative to ac inverter size); either approach can significantly affect the capacity factor. New standards may help with these issues.

Monthly Capacity Factor

Figure 3-1 shows monthly capacity factors for two clusters in 2012. The average daytime hours for each season are included in the background to show capacity factor relative to daytime hours (sunrise to sunset at a given geographical location). Monthly capacity factors are higher in the spring, reaching nearly 0.22 for the single module systems in April. Similar to insolation, Tuscaloosa had significantly lower capacity factors in December due to more frequent overcast conditions in that month.

Delivered Energy

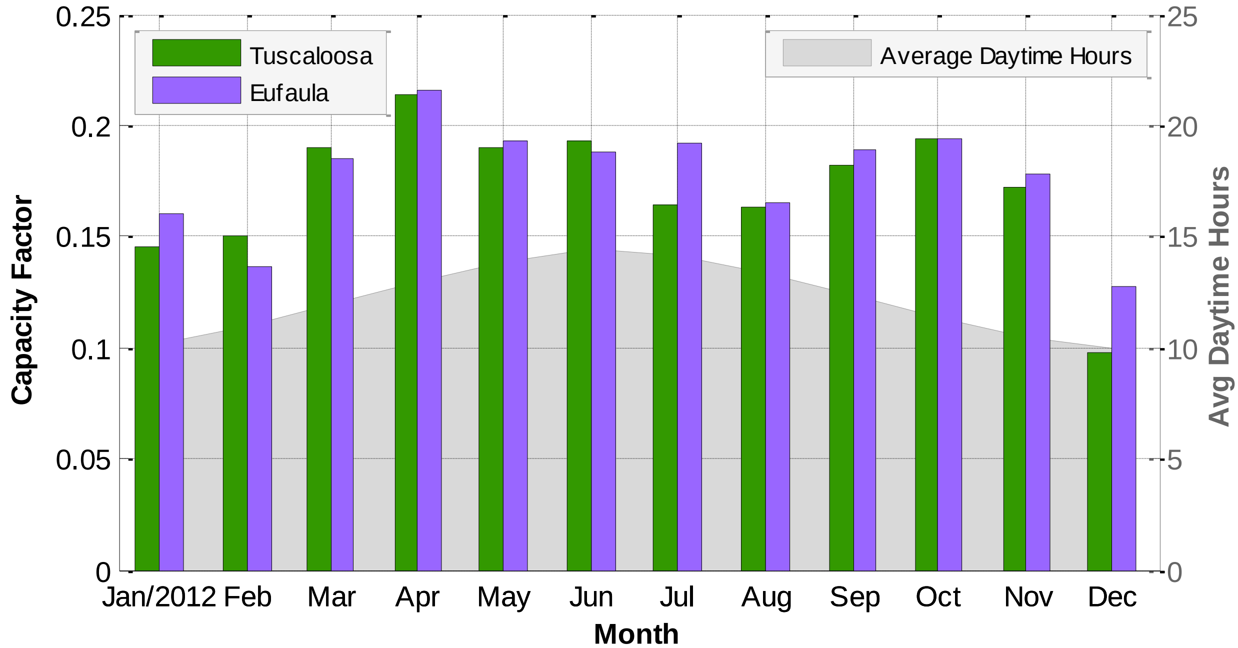


Figure 3-1
Monthly capacity factor per cluster for 2012 (values provided in Table A-3)

Performance Ratio

A different way to observe energy performance specific to PV plants is to normalize delivered energy based on the solar resource (plane-of-array insolation). This idea has been researched by several organizations. For example, production and solar insolation ratios, identified as *yields*, have been used by NREL to define a PV plant energy performance ratio since 2005.[3] Evolving from this concept, a PV plant's daytime performance ratio is defined below. This ratio is dimensionless and can be used to compare performance with PV systems of varying sizes and locations.

Performance Ratio is defined as a ratio of a production factor and a sun factor:

$$Performance\ Ratio = \frac{Production\ Factor}{Sun\ Factor}$$

Production Factor is the total energy produced divided by the rated capacity and total hours in a day. The plant's rated capacity can be in terms of the inverter (ac rating) or the array (dc rating). *Sun Factor* is the daytime insolation—in the plane of the array (POA)—normalized to a value representing direct normal clear-sky irradiance (1,000 W/m^2) multiplied by daytime hours.

More specifically, a *Performance Ratio* is defined as:

$$\frac{Total\ Energy\ Produced\ (kWh)\ \times\ 1000\ (W/m^2)}{System\ Rating\ (kW)\ \times\ Daytime\ POA\ Solar\ Insolation\ (Wh/m^2)}$$

The performance ratio is dimensionless, and typical values may range from 0.6 to 1.0, where 1.0 indicates optimal performance. Lower values indicate a lower performing system. A

[3] NREL, "Performance Parameters for Grid-Connected PV Systems", Golden, CO, NREL/CP-520-37358, 2005.

performance ratio can be computed over any time period, usually over month, quarter, or annual periods. The solar resource measurements used in this report are based on the spectral response of silicon. Non-silicon PV module technologies may have a different spectral response and may affect their performance ratio values.

Monthly Performance Ratio

A monthly performance ratio in 2012 for two clusters, including an average module temperature from Tuscaloosa, is shown in Figure 3-2. This figure provides some insight into balance of system losses, and in particular sheds light on apparent temperature effects. For each of the two locations, the performance ratio is very similar from month to the month, ranging from 0.83 to 0.97 over the year. The highest performance ratios occur in January and February, and the lowest in June. As temperature increases, the performance of the panels generally decreases due in large part to less-efficient performance of modules operating in higher temperatures. It is seen that in the colder months, it is possible to have a performance ratio above 1.0, meaning the module was producing power above its nameplate rating.

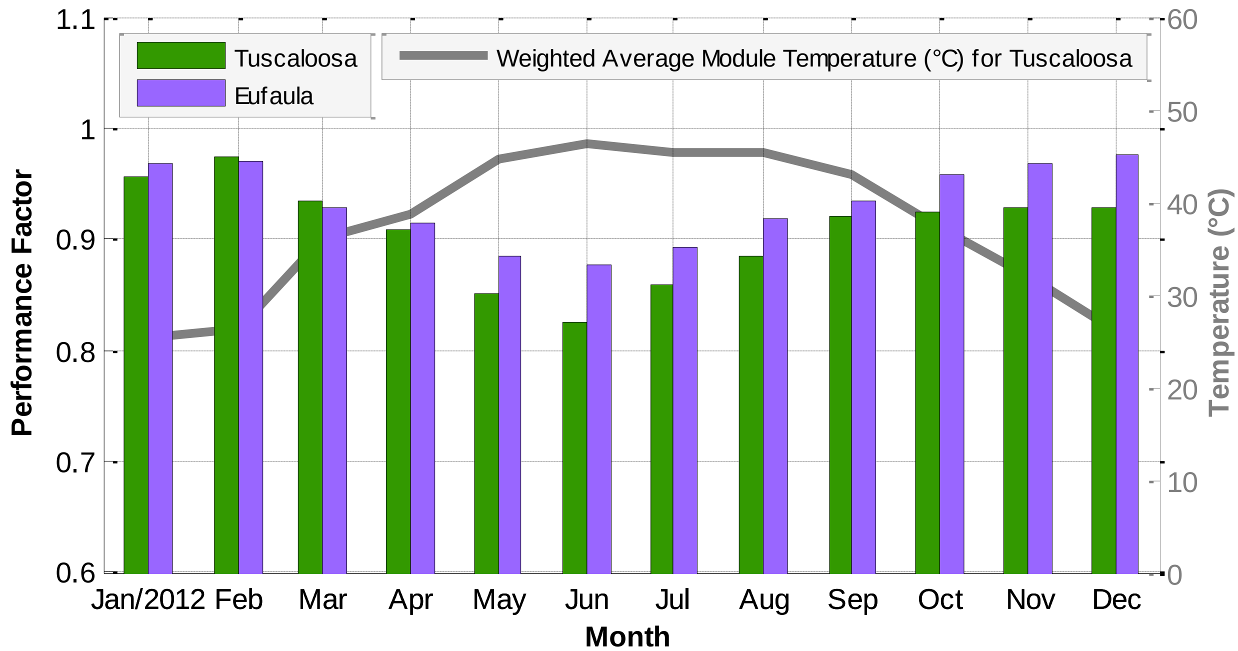


Figure 3-2
Monthly daytime performance ratio per cluster and weighted average module temperatures (gray line) in 2012 (values provided in Table A-4)

4
POWER OUPUT

Plant output power is normalized to show relative output during a given time period, such as 15-minute, hour, day, or month intervals. Depending on the application, output power can be computed using the raw data (e.g., 1-second measurements) or averaged data. An example is peak generation either based on the 15-minute or 1-hour averages of the raw data. Metrics computed from power output are useful to characterize plant impacts on the electric system.

Annual Power Duration

Figure 4-1 shows a duration curve for the combined ac output power of the six PV clusters as measured in 2012. It is based on 15-minute interval averages, and is shown as a percent of daytime hours, which occur between sunrise and sunset. In 2012, at the six representative sites, there were between 4,297 and 4,443 daytime hours with adequate power data. For the figure, the maximum daytime hours at any location is shown.

Daytime power duration shows that each of the six representative systems is generating at least 20% of rating between 55-60% of all daytime hours. In general the power duration profile is similar in each location in Alabama. Power exceeded between 20-30% of the system rating only 50% of total daylight hours in 2012, while only exceeding approximately 76% of its rating for 10% of the total daytime hours (about 44 hours for the entire year). Modules in Hoover, Mobile, and Wetumpka were partially shaded during parts of the year from overhead power lines. Wetumpka modules were partially shaded during midday (higher power output), and Mobile and Hoover in the morning and evening hours (mid to low level power output).

Power Ouput

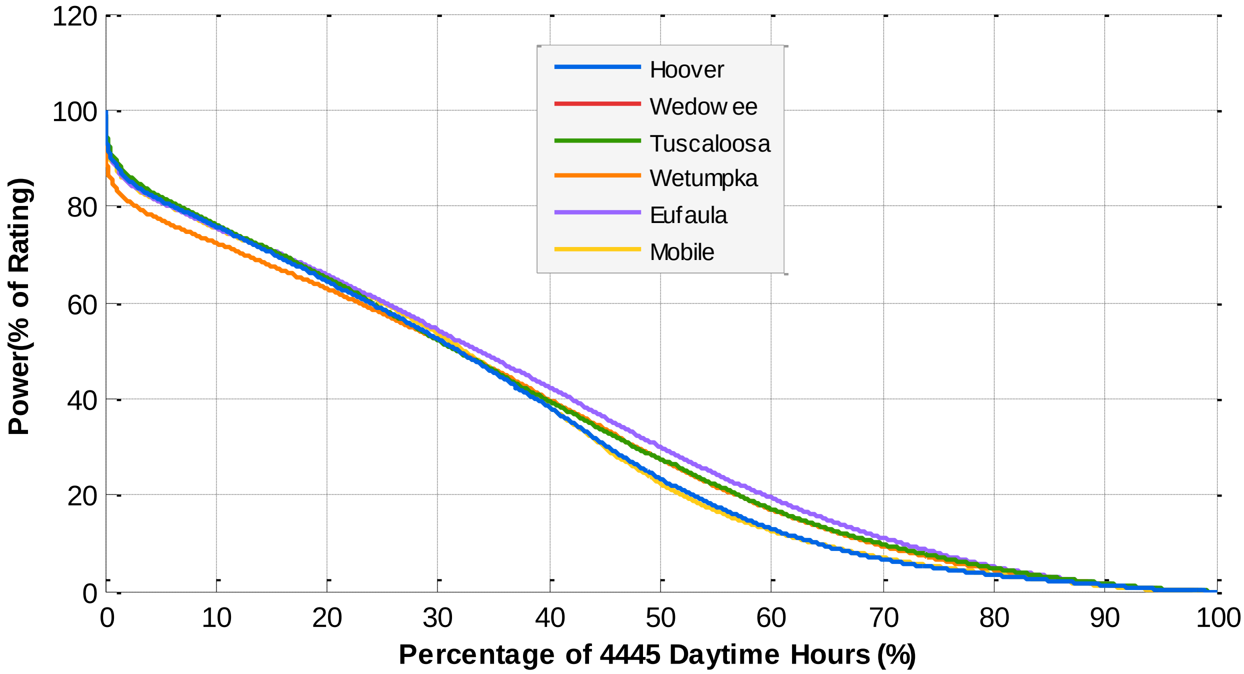


Figure 4-1
Annual power output duration during daytime in 2012

Time-of-Day Power Profiles

Daily power output profiles for a given location are primarily dependent on the sun's path across the sky, local cloud cover, and array tilt. Figure 4-2 shows selected daytime power profiles for Tuscaloosa and Eufaula in 15-minute intervals for three types of day during each season in 2012: clear day, overcast day, and median day. Each day is classified based on the amount of energy produced by the representative pole.

The clearest day is the day within the season having the highest amount of energy produced (tall green bars); the most overcast day is the day with the least amount of energy produced (short red bars); and a median day is the day that has the median amount of energy produced (yellow line). The array tilt, shade, terrain, Daylight Saving Time, and time of year all affect the system start and stop times, which are plotted using local time (Central prevailing time). Using prevailing time may cause a time-shift in the median-energy daily profile for Q4 and Q1 because Daylight Saving Time changes during those quarters.

The views shown in Figure 4-2 can be used to characterize the range of power output profiles observed by season. During clear days in the winter, spring, and fall (Q1, Q2, and Q3), power output is higher than during clear days in the summer, partly due to the higher efficiency of the PV panels at lower temperatures. The median day shows that power output from PV can be variable throughout the day, mostly due to cloud movement overhead.

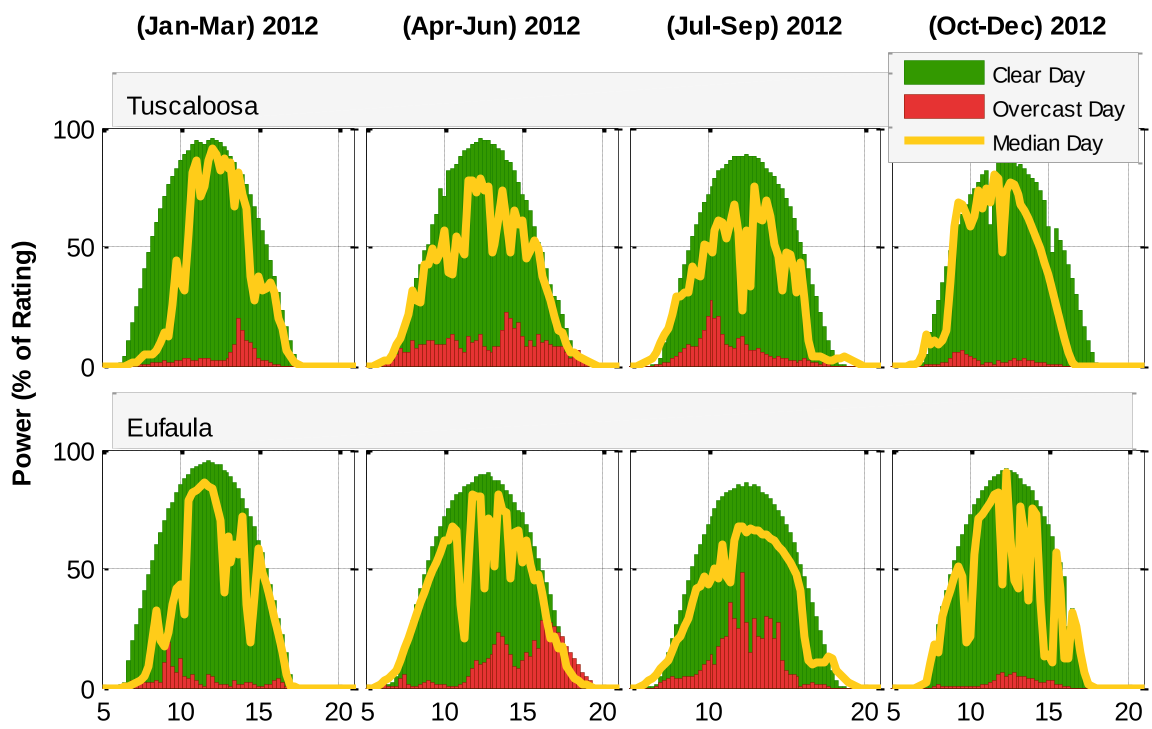


Figure 4-2
Sample power output profiles for the clearest, most-overcast, and median energy days per season for 2012

Hourly Distribution Power Profiles

Also of interest may be the hourly power output distributed statistically by time of day. Figure 4-3 shows a plot by season for each hour of the day for two clusters in 2012. Maximum and minimum values are black lines, the inner quartile range is the blue box, and the median value is a red line. The maximum and minimum values for all seasons typically correspond to clear sky and overcast conditions, respectively.

Spring and summer have a greater percentage of higher power values in both locations, shown by the higher and narrower inner quartile ranges. This is reflective of the higher seasonal and monthly insolation and capacity factors for these seasons. The wider inner quartile ranges in winter and fall show there is more variation in power output during these seasons. The jagged line in Tuscaloosa during early morning hours in the fall is most likely a result of early morning shading from nearby trees.

Power Ouput

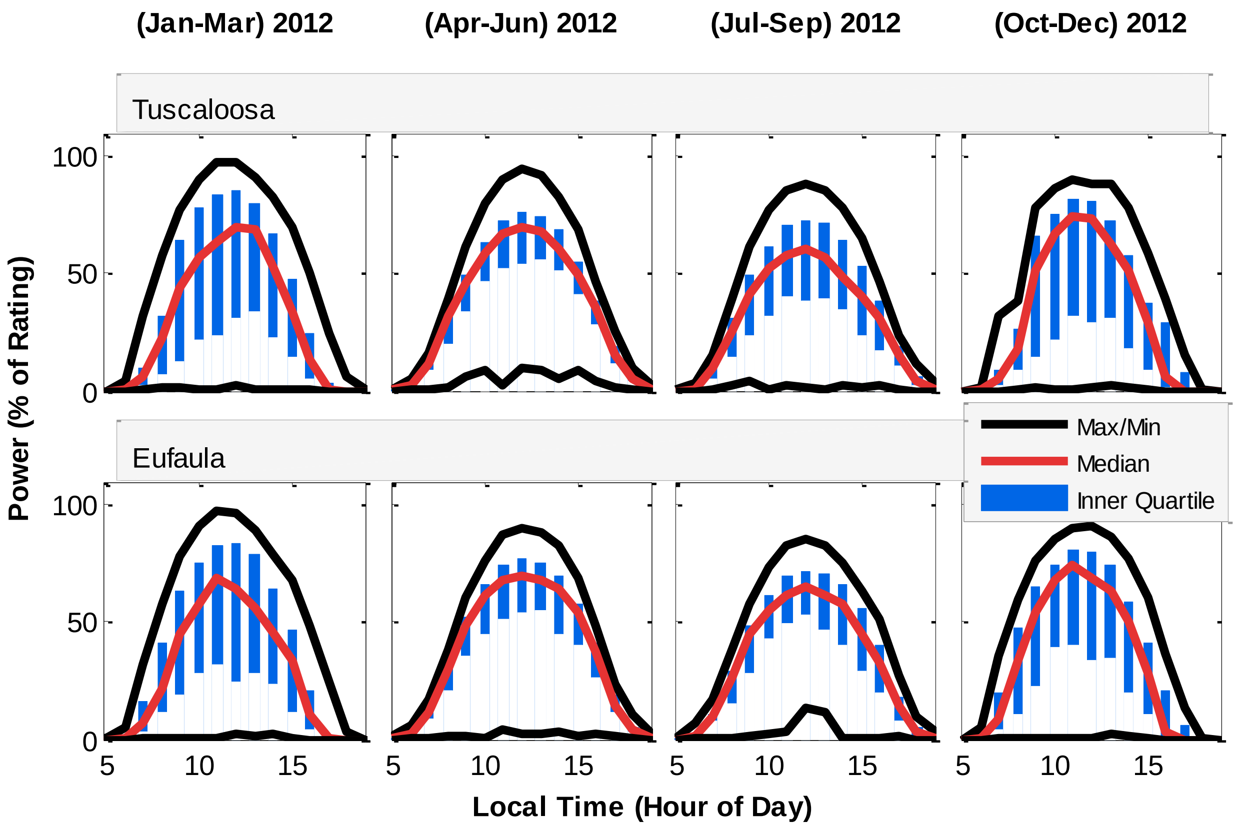


Figure 4-3
Statistical distribution of hourly power output per season in 2012, showing min and max (black lines), inner quartile (blue bars) and median (red lines)

5
RAMP RATE DATASET

Characterizing PV system output variability is important for electric utilities (their engineers, operators, and planners) to understand how solar PV generation sources may affect the utility system. The primary consideration for the distribution system is the extent that additional PV variability impacts feeder voltage regulation and the duty on the regulation equipment. Since this potential impact is localized, the presence of a single PV plant, if large enough and connected at a particularly weak point on the feeder, could adversely affect a given distribution circuit. Additionally, since distribution regulation equipment, such as voltage controlled capacitor banks and regulators, operates with lag times on the order of 30-60 seconds, the PV variability time intervals of interest are generally on the order of seconds to minutes timeframes.

While PV variability can also result in local voltage impacts on the bulk transmission system, the potential adverse impacts of PV variability at that level tend to be related to how the aggregate variability of many PV plants impact frequency regulation and load following requirements over a wider range of time intervals. This range, typically from 1 minute to several hours, is associated with bulk system automatic generation control (AGC), dispatch, balancing, and other services that consider the aggregate variability of all sources and loads within an operating region.

PV system output variability may be quantified by computing sequential changes in measured ac power output between block averages over multiple time intervals. These time-based changes form a ramp rate dataset that enables researchers to characterize ramp rates statistically, by describing “how often” and “to what extent” output ramping occurs. The ramp rate datasets only include changes that occur when the PV system is operating during daytime. Changes in power and rates of change in this dataset can be closely related to the solar resource variability index presented in the previous chapter[4].

Establishing a Ramp Rate Dataset – Looking at a Single Day

A sample daytime power profile for one of the 190-W PV monitoring system in Alabama is shown in Figure 5-1. Variations in normalized power measurements indicate partly cloudy conditions starting around 11am, with significant output variability between 1-3pm.

[4] J. Stein, et al, The Variability Index: A New and Novel Metric for Quantifying Irradiance and PV Output Variability (ASES 2012 VI, SAND2012-208)

Ramp Rate Dataset

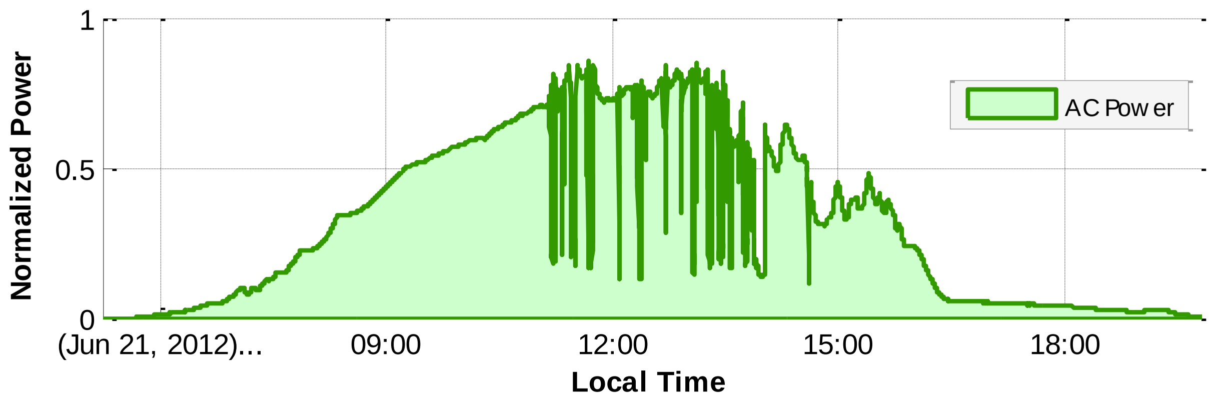


Figure 5-1
Daytime power profile from a single-module PV system in Alabama (June 21, 2012)

To begin investigating output variability on this day, a ramp rate dataset based on 10-second and 1-minute changes in power output is created.

Ramp rates are computed for each interval using differences between consecutive block averages, offset by the interval of interest (in this example, 10-seconds and 1-minute). Each sequential ramp rate is computed by shifting forward by the interval amount and repeating the process. While this method can average out variability, especially at larger time intervals, it is the preferred method to determine the number of ramping occurrences and the total time or percent of time spent ramping at a certain rate.

Plotting time-based changes for each ramp rate interval allows the magnitudes of change for all ramp-up and ramp-down occurrences to be visualized, as shown in Figure 5-2. On this day 1-minute changes (orange line) are noticeably more extreme than 10-second changes (blue line). This plot can also be used to verify the significance of changes that occurred between 11am-3pm.

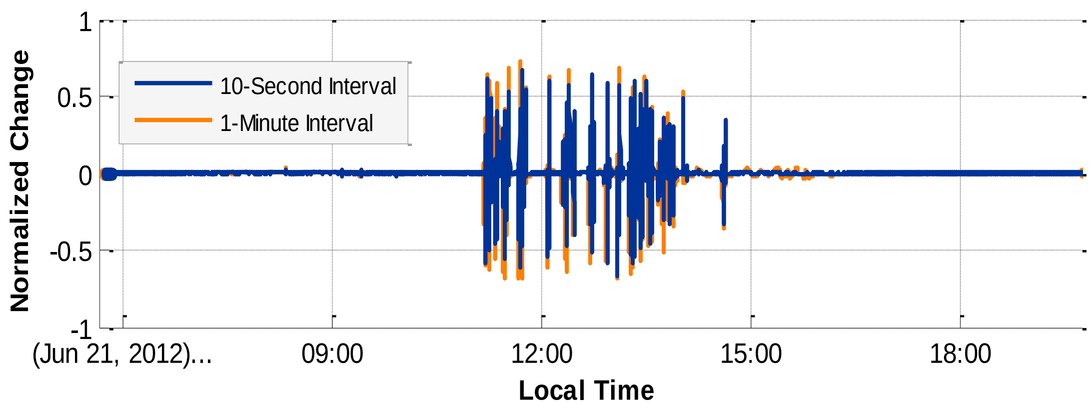


Figure 5-2
Changes in output power from a single-module PV system in Alabama (June 21, 2012)

On this day, the largest 1-minute change is over +60% just before 12pm, while the largest 10-second change occurs at the time and is of slightly smaller magnitude. While a plot of time-based changes may offer some insight into PV system variability it does not directly answer this question:

"How often and to what extent does PV output ramping occur?"

Figure 5-3 shows distributions of change in the output of a single-module monitoring system in Tuscaloosa during 2012. Of the 6 ramp rate intervals shown, higher-magnitude changes occur more often for 5-minute and 1 hour intervals because power output has a longer time to change more drastically and thus larger changes occur more frequently. Also, the directions of changes are separated to illustrate similarities between ramp-up and ramp-down observations. The relative frequency, which is the count of ramps at a certain magnitude divided by the total number of ramps at each time interval, is scaled quite low, cropped to 5%, to emphasize that the most significant changes occur infrequently. The remaining values (not shown) approach zero change in output at higher frequencies. What is of primary interest to the utility industry are ramping events having extreme changes, even if they rarely occur.

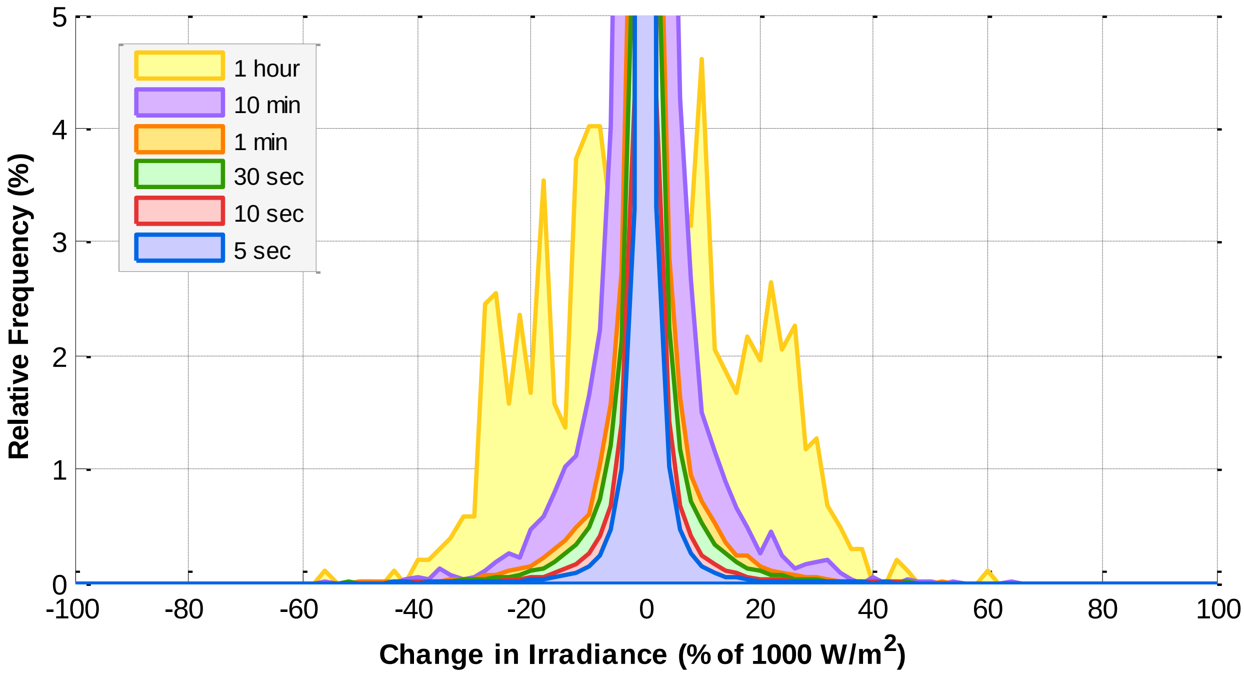


Figure 5-3
Ramp rate distribution for Tuscaloosa during Jan-Mar 2012; relative frequency of changes in averaged power for 6 ramp rate intervals: 5 seconds, 10 seconds, 30 seconds, 1 minute, 5 minutes, and 1 hour

Permanent Object Shading – Every Rose Has Its Thorn

When establishing a ramp rate data set for the Alabama clusters, power output measurements revealed permanent object shading at multiple sites within each cluster. The extent of this phenomenon was not fully understood until after sites were installed and data was being analyzed. Permanent object shading is most commonly caused by a cross arm or overhead line shading a portion of the panel during the day causing the power output to be affected. Often in these cases, the pyranometer remains unobstructed or minimally affected compared to power output, allowing for accurate irradiance measurements. Figure 5-4 below shows an example of shading from a street light in Wedowee, Alabama. The figure shows normalized power and irradiance for June 27, 2012. Just before noon, the power significantly drops below the irradiance measurements due to an overhead street light. Power output varies drastically between 17-70%

of the module's power rating for roughly 3 hours, while irradiance shows clear sky conditions. The irradiance measurement is clearly a better representation of the solar resource and expected PV output given shade free conditions.

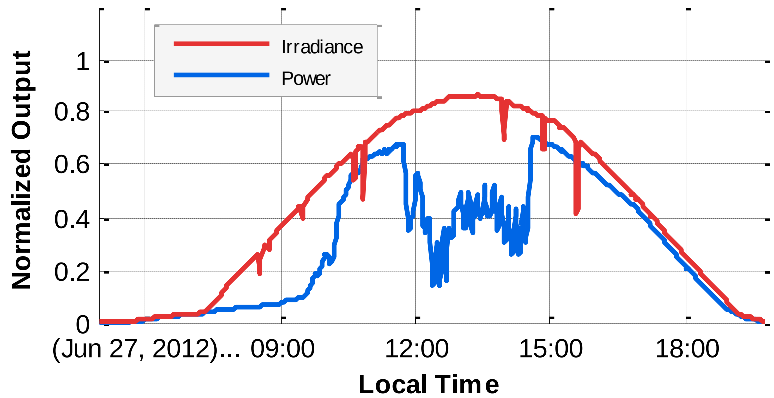


Figure 5-4
Normalized power and irradiance on June 27, 2012 in Wedowee

The extent and effect of this type of shading varies drastically depending on the size, shape, and location of the shading obstruction relative to the PV module. Another example is shown in Figure 5-5 for the representative pole in Hoover on the same day where shading from four overhead lines is affecting the power output. While not as drastic as the example in Wedowee, it is seen that power output is more affected by line shading than irradiance. This shading can be seen in the irradiance profile from the 3 dips in output between 2pm and 3pm, but is clearly not as drastic as the normalized power output, which drops below the irradiance line for the entire afternoon.

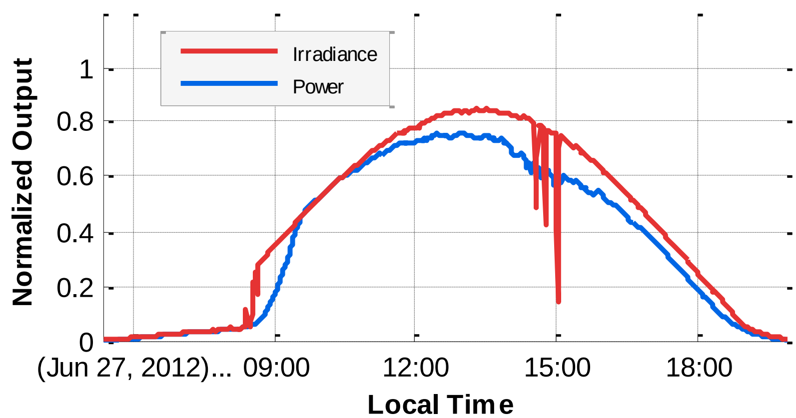


Figure 5-5
Normalized power and irradiance on June 27, 2012 in Hoover

Using power output measurements with permanent object shading would incorrectly characterize the ramp rates in Alabama. In order to accurately quantify the variability in the presence of permanent object shading, using irradiance instead of power should be considered. To gain confidence in the similarities between the power and irradiance measurements, two histograms are plotted below. Figure 5-6 shows a histogram of the relative frequency (up to 1%) of changes in power and irradiance for the seven representative sites in Alabama at 10 second intervals.

These sites had the least amount of, and often no, permanent object shading issues and accurately portray how irradiance and power output variability from a single module differ. As can be seen by the overlapping plots, the changes in power and irradiance are virtually the same at 10 seconds.

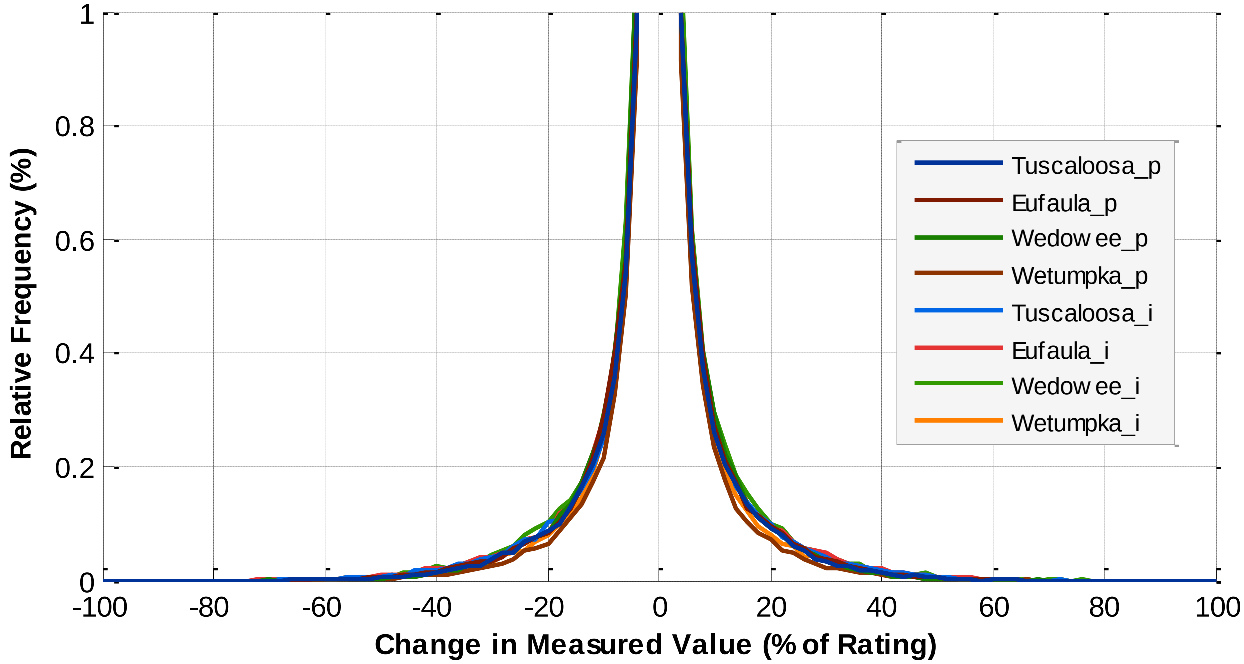


Figure 5-6
Relative frequency of 10-second changes in power and irradiance for all six Alabama sites

While the histogram shows that changes in power and irradiance generally are closely aligned, it is also important to look at ramping events with extreme changes. Looking at the upper percentiles for both ramp-up and ramp-down magnitudes of power and irradiance offers insight into the extreme cases. To illustrate the occurrence of extreme changes, Figure 5-7 shows the change in power and irradiance for upper percentiles (rare events) at six time intervals in every season for two of the clusters of PV units in Alabama that have no permanent object shading. Percentiles are distinguished between up (>=0) and down (<=0) ramp events. For example, the top of the dark red box indicates the magnitude of the 99.99th percentile of ramp-up events while the bottom indicates the magnitude of the 99.99th percentile of ramp-down events.

In Tuscaloosa and Eufaula, the extreme events for both power and irradiance are of similar magnitudes across ramp rate intervals and percentiles for 2012. The magnitudes of changes in irradiance are slightly larger than changes in power for each percentile and ramp interval, with an absolute difference of at most 11% of rating. In general, this indicates that the extreme ramp events for an entire year are similar in occurrence and magnitude for both power and irradiance measurements at sites with no shading problems. These results give confidence that using irradiance to quantify PV output variability is acceptable. It is important to remember that PV output has a temperature dependence, but irradiance output does not, as was seen in Figure 3-2. Due to the temperature dependence of PV output, it is likely that on a monthly and even seasonal basis, the difference in magnitudes of the changes in power relative to irradiance can vary. For example, it is possible that the magnitudes of changes in power could be lower in summer months and higher in winter months relative to irradiance.

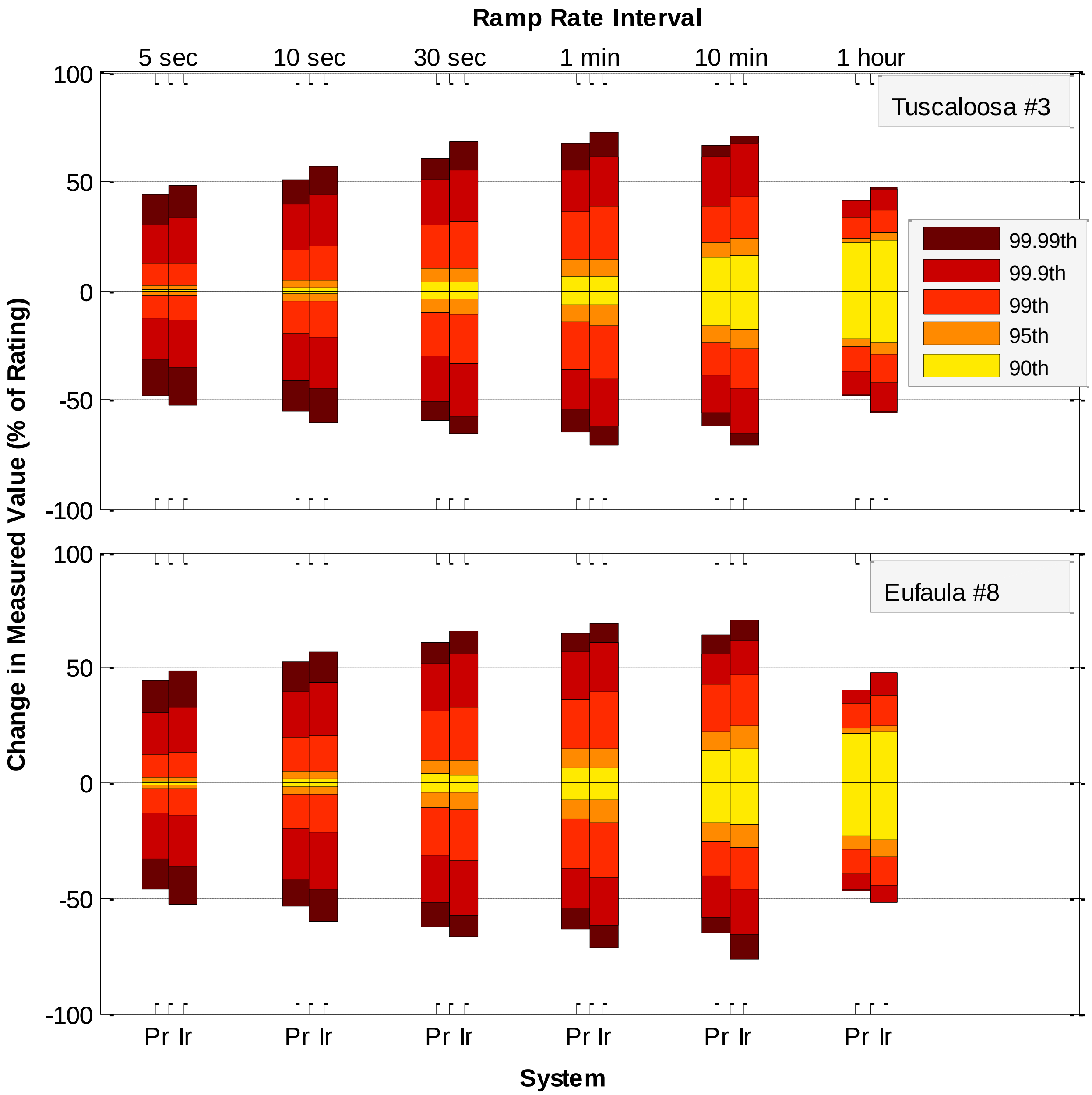


Figure 5-7
Ramp rate percentiles for two clusters with no shading for July-Sep 2012; changes in power and irradiance for all ramp rates at the two clusters

Figure 5-8 shows the same plot, but for two poles with permanent object shading. Wetumpka pole #1 shows large differences in the magnitude of ramp rates at each time interval with irradiance exceeding power by up to 12% of rating at equivalent ramp interval and percentile. This is caused by the diminished power output for an extended period of time due to the overhead light, which decreases the potential of large ramp rates from cloud induced variability. Wedowee Pole #8 shows a similar trend, but not as severe as Wetumpka pole #1, and is more similar to the shade free poles in Figure 5-7. The magnitude of irradiance changes still exceeds power changes, but only by at most 5%. It is seen that irradiance measurements capture slightly more variability than power, but only by at most 5% in the case of a shade free site, which is within the uncertainty of measurements. It is also seen that irradiance more accurately quantifies expected PV output variability in cases of permanent object shading.

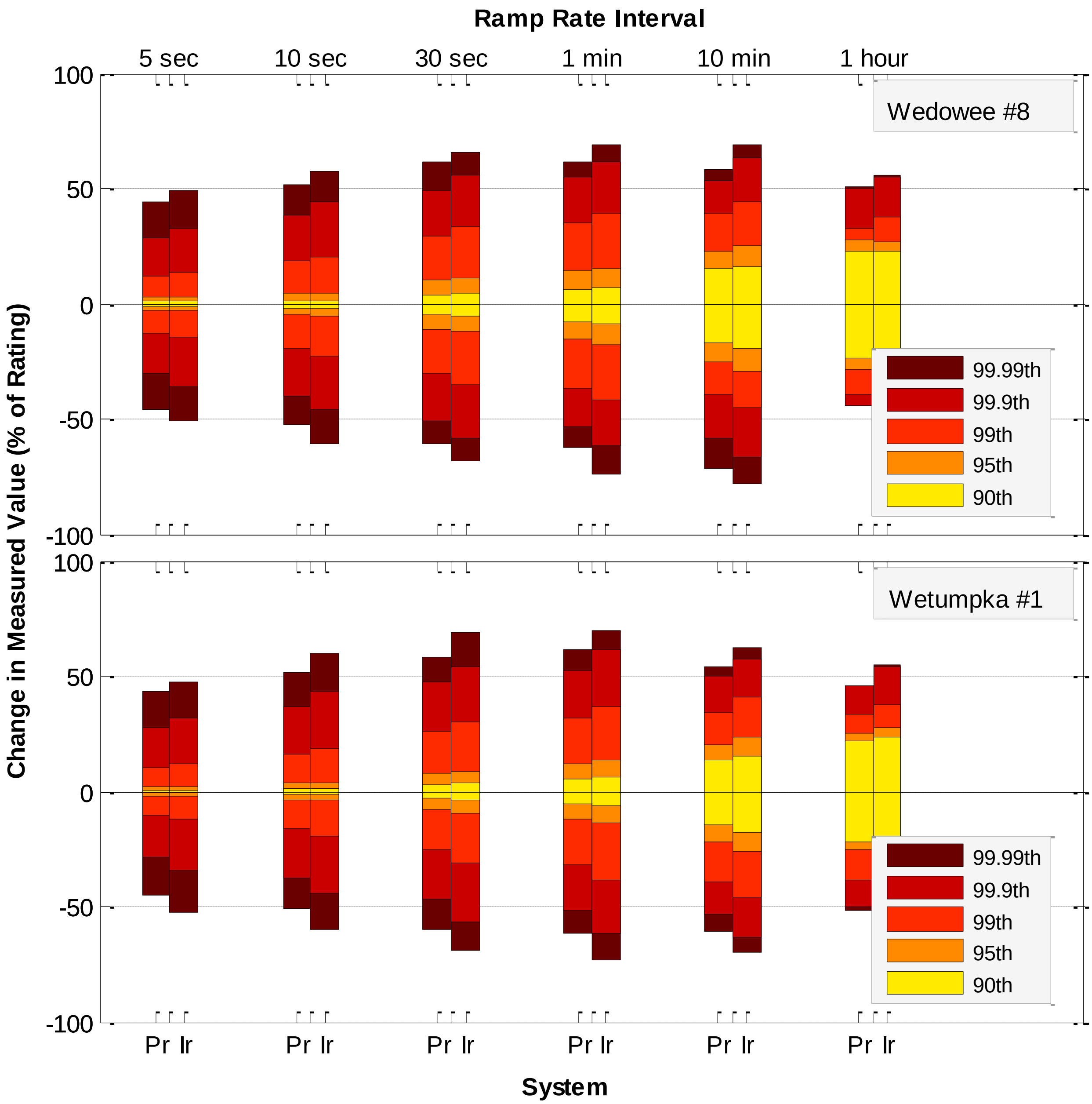


Figure 5-8
Ramp rate percentiles for two clusters with permanent shading for Jul-Sep 2012; changes in power and irradiance for all ramp rate intervals at the two clusters

Final Ramp Rate Dataset

Given the number of sites affected by permanent object shading, and having validated the use of irradiance instead of power output, a final ramp rate dataset was established. Table 5-1 shows the six clusters in Alabama, number of sites in the cluster, and number of sites with good irradiance that will be used for ramp rate analysis. In addition, area, minimum distance, and maximum distance between sites within each cluster are shown.

Table 5-1
Ramp rate dataset characteristics by cluster

Cluster	# of Sites	# of Sites for Variability	Area (km^2)	Min Distance (km)	Max Distance (km)
Hoover	8	3	0.08	0.51	1.23
Wedowee	8	4	5.89	0.63	5.09
Tuscaloosa	8	5	0.95	0.30	4.89
Wetumpka	8	6	0.59	0.33	1.27
Eufaula	8	6	2.76	0.43	9.20
Mobile	8	3	5.65	3.07	5.71

6
RAMP RATE CHARACTERISTICS

Using the ramp rate dataset established in Chapter 5 (Ramp Rate Dataset), the upper percentiles for both ramp-up and ramp-down magnitudes of changes offers insight into the extreme cases of ramping events. Figure 6-1 shows the upper percentile ramp events from the aggregate output of three Alabama locations: Mobile, Eufaula, and Tuscaloosa, for seven seasons at six ramp intervals. Aggregated output from multiple single module pole mount PV units is computed by the weighted average to the geometric mean of all locations considered. This evenly distributes the output across the covered area. In general, the changes in irradiance for each ramp rate interval are similar across locations. This type of figure is useful in answering many of the questions posed previously regarding the aggregated output of PV spread over the area of a distribution feeder such as how fast the aggregated output ramps, the magnitude of those ramps, how often those ramps occur, and if there is any seasonal or geographic difference in ramp events.

By examining the magnitudes of changes in output of the aggregation of sites in Figure 6-1 in comparison to those of an individual module in Figure 5-7, it is seen that the aggregation of multiple locations diminishes the magnitudes of changes in output, particularly at shorter time intervals. As seen in Figure 5-7, an individual module will ramp at near 57% of its rating in 10 seconds (5.7%/sec), 0.01% of the time or about 160 times per year. When aggregated across the area of a feeder, ramp magnitudes diminish to roughly 32% of rating in 10 seconds (3.2%/sec) at the 99.99th percentile. The magnitude of 1 minute ramps at the 99.99th percentile, occurrences of about 26 times per year, diminish from about 72% of rating (1.2%/sec) to 47% of rating (0.78%/sec).

Directionality

It is also important to note that directionally, the change in irradiance is roughly symmetric meaning PV generally ramps up and down at the same rate and frequency. There are a few instances in single seasons at higher time intervals where the larger percentiles of ramp rates are not symmetrical. However, the symmetry of the distribution is inconsequential in these instances as they are very rare, often the single largest event. For example, in the fall season of 2011 in Mobile, the 99.9th percentile of 1 hour ramp up events which is the single largest for the aggregation of sites, was about 60% of rating, where the ramp down event was about -40% of rating.

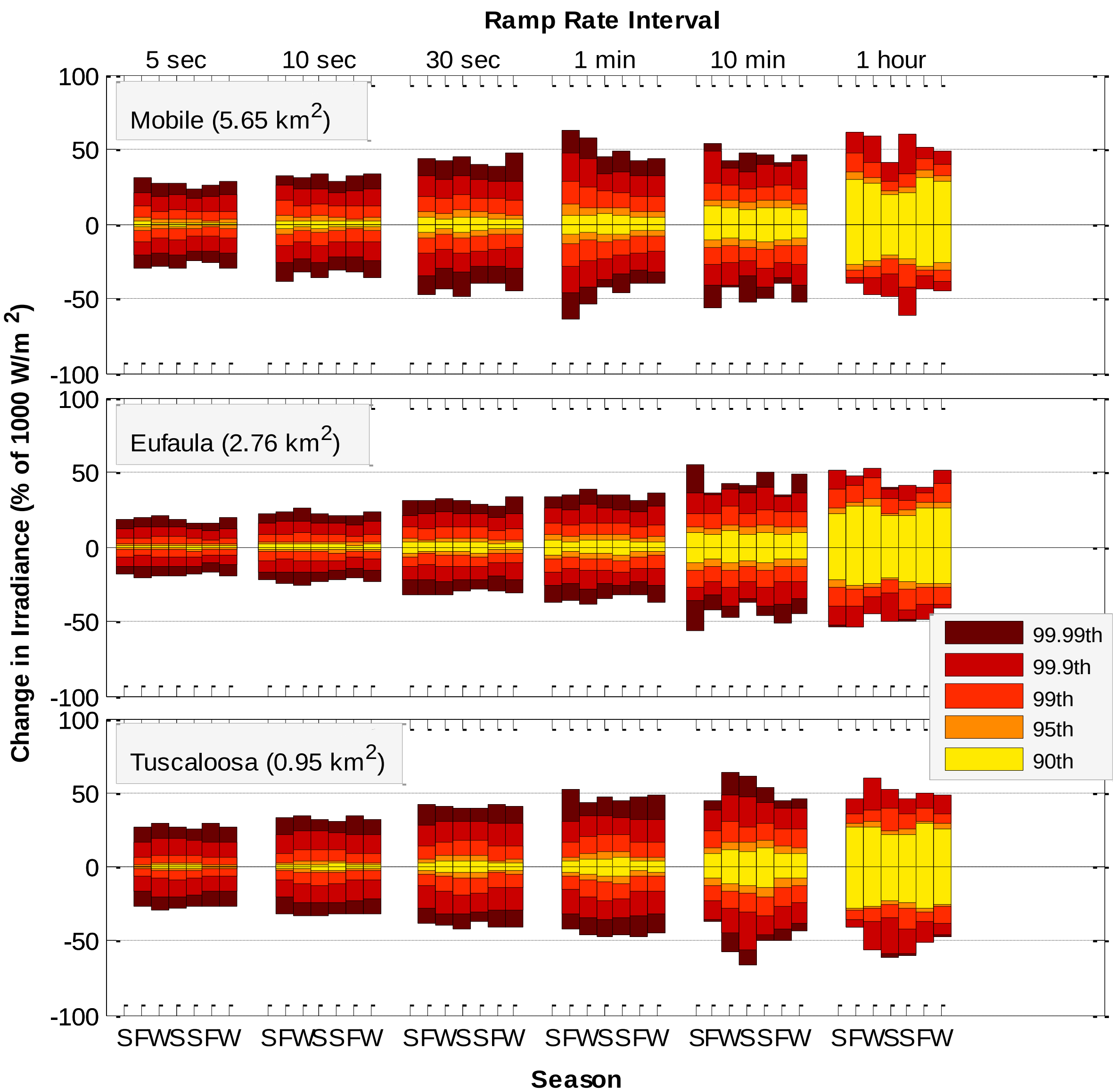


Figure 6-1
Ramp rate percentiles for three clusters for Jul 2011-Mar 2013; changes in power for all ramp rate intervals and seasons at the three clusters

Distribution regulation devices are directionally neutral, meaning that they are triggered regardless of the directional change in voltage. It has been shown that PV generally ramps up and down at the same rate and frequency; therefore it is sufficient to consider only the magnitude of changes ($|\Delta P|$) instead of directional changes.

How Fast Do Distributed PV Sites Ramp?

To take a closer look at the magnitude of ramps, Figure 6-2 shows the six ramp rate intervals for all percentiles during seven seasons in 2011, 2012, and 2013 for each of the six clusters in Alabama. This figure helps answer many of the questions posed regarding the variable nature of PV across the state of Alabama including, how fast does PV ramp, what is the magnitude of those changes, how often do those changes occur, is there a seasonal difference, and is there a difference across the state?

Of the time intervals and percentiles examined, the fastest ramps occur in the 5 second ramp intervals. At the largest percentile, 99.99th percent, the fastest ramps observed within a season ranged from 3.6%/sec to 6.0%/sec. It is possible that the aggregated change in irradiance exceeds these rates, however, these would occur at larger percentiles that could be considered statistical anomalies or at shorter time intervals such that the magnitude of changes is greatly diminished.

What are the Magnitudes of the Fastest Ramp Rates?

As Figure 6-2 shows, the magnitude of changes in irradiance across a feeder area increase at longer time intervals for equivalent percentiles. The faster 5 second ramps had changes in magnitude ranging from 18% of rating to 30% of rating at the 99.99th percentile within a season. 10 second ramps ranged from 25% to 37% of rating, and 30 second ramps ranged from 32% to 47% of rating. One minute ramps ranged from 39% to 64% of rating, 10 minute ramps ranged from 50% to 66% of rating, and 1 hour ramps ranged from 54% to 72% of rating. There were instances within the same season where magnitudes of ramp intervals decreased from 10-minute ramps to 1-hour ramps at larger percentiles. This shows that changes in 10 minute averages can be larger than changes in 1 hour averages.

How often do Ramping Events Occur?

Because ramp rate data sets were created from block averages irradiance, the number of occurrences of each ramp rate that equal or exceed the specified magnitude differs with each ramp rate interval. Computation of the number of occurrences at each percentile level can be easily computed given the duration of time examined, roughly 1,100 daytime hours per season in the case of Figure 6-2, the ramp rate interval, and the percentile level. To ease comprehension of Figure 6-2, Table 6-1 lists the number of ramp rate occurrences that equal or exceed the specified magnitude in each season for each percentile.

Table 6-1
Number of ramp rate occurrences that equal or exceed the specified magnitude per season at each percentile and time interval; based on 1,100 daytime hours per season

Percentile	Time Interval					
	5 sec	10 sec	30 sec	1 min	10 min	1 hr
99.99th	79	40	13	7	< 1	< 1
99.9th	792	396	132	66	7	< 2
99th	7,920	3,960	1,320	660	66	11
95th	39,600	19,800	6,600	3,300	330	55
90th	79,200	39,600	13,200	6,600	660	110

Seasonal Variation in Ramping Events

As seen in Figure 6-2, there is not a consistent or significant seasonal variation in the distribution of ramping events at the six locations across Alabama. Unlike the seasonal variation in variability conditions, as seen in Figure 2-4, the statistical representation of ramp rate percentiles does not yield a particular season as being the most variable in regard to the highest number of significant ramping events. It is, however, important to realize that there can be a difference in the magnitudes of ramp rates at similar percentiles between seasons.

Geographic Differences in Ramping Events across Alabama

When comparing regional differences across multiple clusters, it is important to remember that there are other variables which may contribute to differences in results, specifically the size and shape of the areas being considered for ramp rate analysis. Similar to seasonal variations, there is not a consistent or significant difference in the magnitudes of the upper percentiles of ramping events across the state of Alabama.

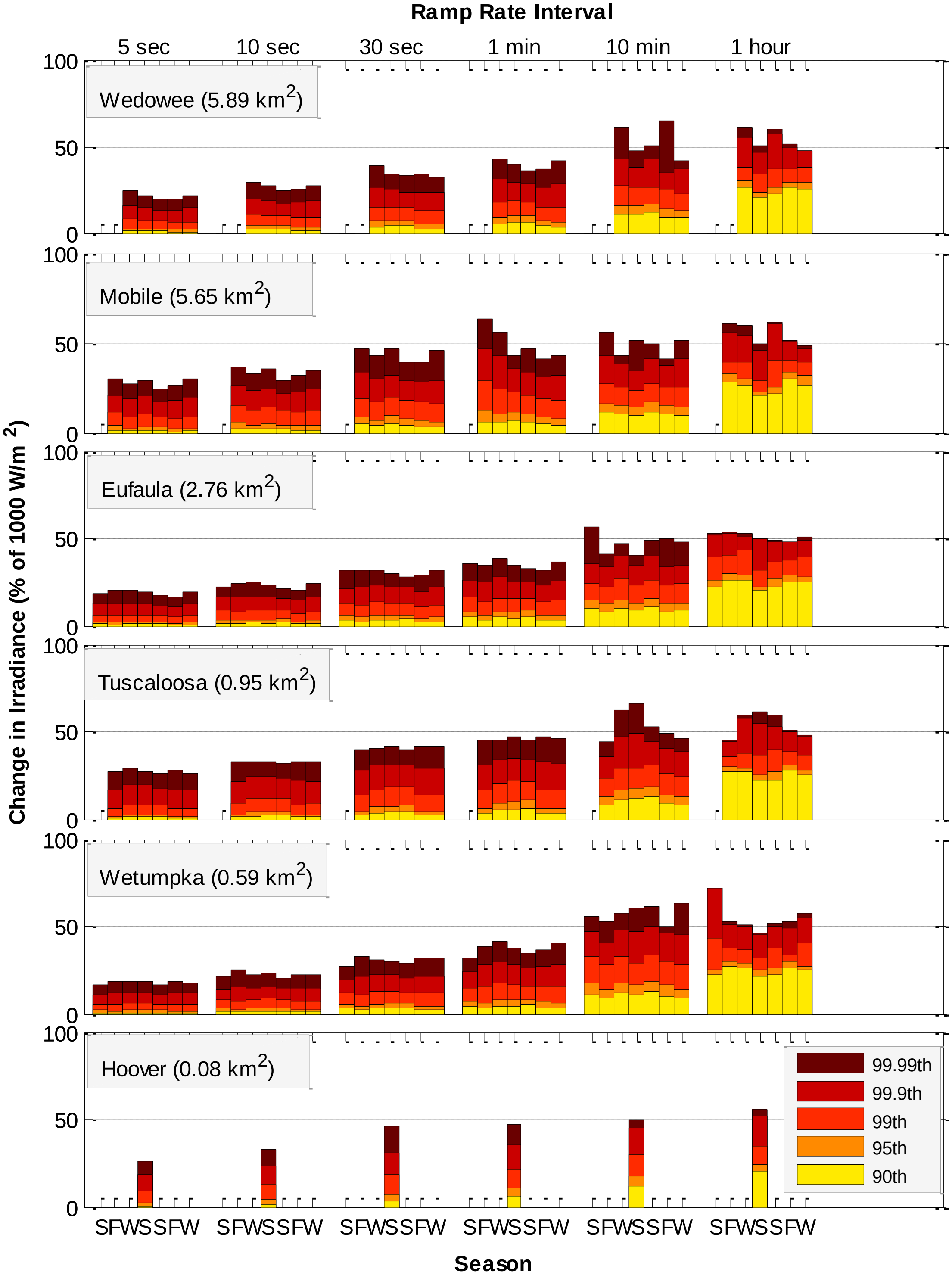


Figure 6-2
Changes in irradiance for six ramp rate intervals, magnitude only for seven seasons during Jul 2011-Mar 2013

Geographic Area of Distributed PV Deployments

It is also of interest to understand the effect that spatial diversity has on solar output, its variability, and the frequency with which large ramping events occur. It is reasonable to assume that increasing the area in which solar power is aggregated will dampen its variability due to time lagged cloud induced ramping. Figure 6-3 provides perspective on the effect that increasing area has on specified percentiles of ramp magnitudes. For four of the clusters, 1-minute ramp rates are plotted as a function of increasing area along the feeder during 4 seasons in 2012. Areas are calculated for all possible combinations of three or more single module pole locations within each cluster on a feeder. The aggregated power output of the combination is then calculated based on the weighted average to the geometric mean location of the coordinates contributing to that location. Each area is calculated as the area of the smallest convex region that contains all the latitude and longitude coordinates of that combination. For example, if there are three locations that contribute to the combination, the area is calculated as the area of the triangle made between the three coordinates. If a fourth location is added in the middle of that triangle, the area remains the same but the geometric mean and aggregated power is recalculated. Some seasons show less data points because some sites were removed from the analysis due to permanent object shading during those seasons.

As shown in Figure 6-3, the clusters cover different size areas with some overlap, the Wedowee cluster being the largest and the Tuscaloosa cluster being the smallest. In general, at all percentiles, increasing area has little effect on the magnitude of ramping events. Even at the less frequent, higher percentile ramping events, the magnitude only decreases by 27% at most from the smallest area to a coverage of 0.95 km^2 in Tuscaloosa. There does not seem to be any general trend for the entirety of Alabama. Eufaula and Tuscaloosa had steeper trends at smaller areas than Mobile and Wedowee. Lastly, it is noted that across all clusters, the change in output barely exceeded much more than 60% for 1-minute ramping, only for very small areas, near 0.02 km^2 and only for rare occurrences, in the case of 99.99th percentile, for an aggregation of 3 or more locations.

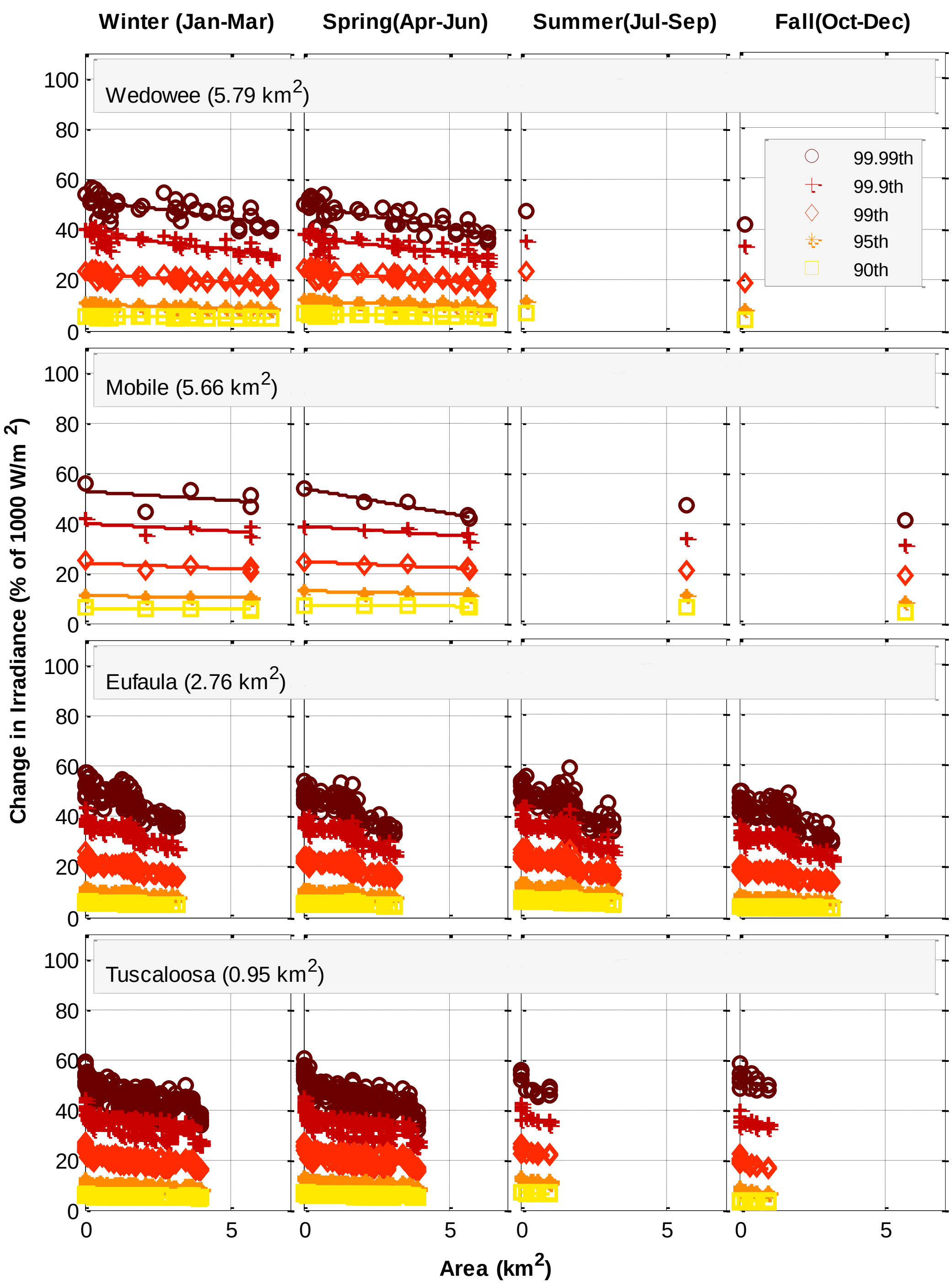


Figure 6-3
Changes in irradiance over increasing areas for 1-minute ramp intervals during Jan-Dec 2012

Correlation of Ramping Events between Distributed PV Sites

Another important aspect of understanding the variable nature of solar is the correlation of ramping events with increasing distance between sites. Correlation across distance helps understand how often power output from solar plants moves at the same time and the same speed. Figure 6-4 shows the correlation of ramp rates for each interval with increasing distance. In all locations, the correlation at shorter time intervals drops to zero as distance increases.

Figure 6-4 illustrates that at longer time intervals, ramping events are well correlated, even at farther distances, due to the suns movement. At the shorter ramp rate intervals of 5 and 10 seconds, across all locations, there is virtually no correlation in ramping events at any distance. In Wedowee, Eufaula, and Tuscaloosa, the 30-second, 10-second, and 1-minute intervals show some correlation at small distances but decreases drastically to no correlation as the distance increases. In the case of all locations, Figure 6-4 would suggest that at close distances, ramp events at 10-minute intervals are well correlated; however, ramping becomes less correlated, around 0.4, at distances further than 5 km. This indicates that clouds don't move fast enough over that distance to produce similar solar power output.

An important note is that for time scales relevant for distribution level regulators, less than 1-minute, there is virtually no correlation in ramping events at any distance. However, even if correlation in all ramping events is very low at these shorter time scales, it is still possible for significant feeder wide ramping events to occur, although they occur very infrequently, as seen in the previous area charts (Figure 6-3).

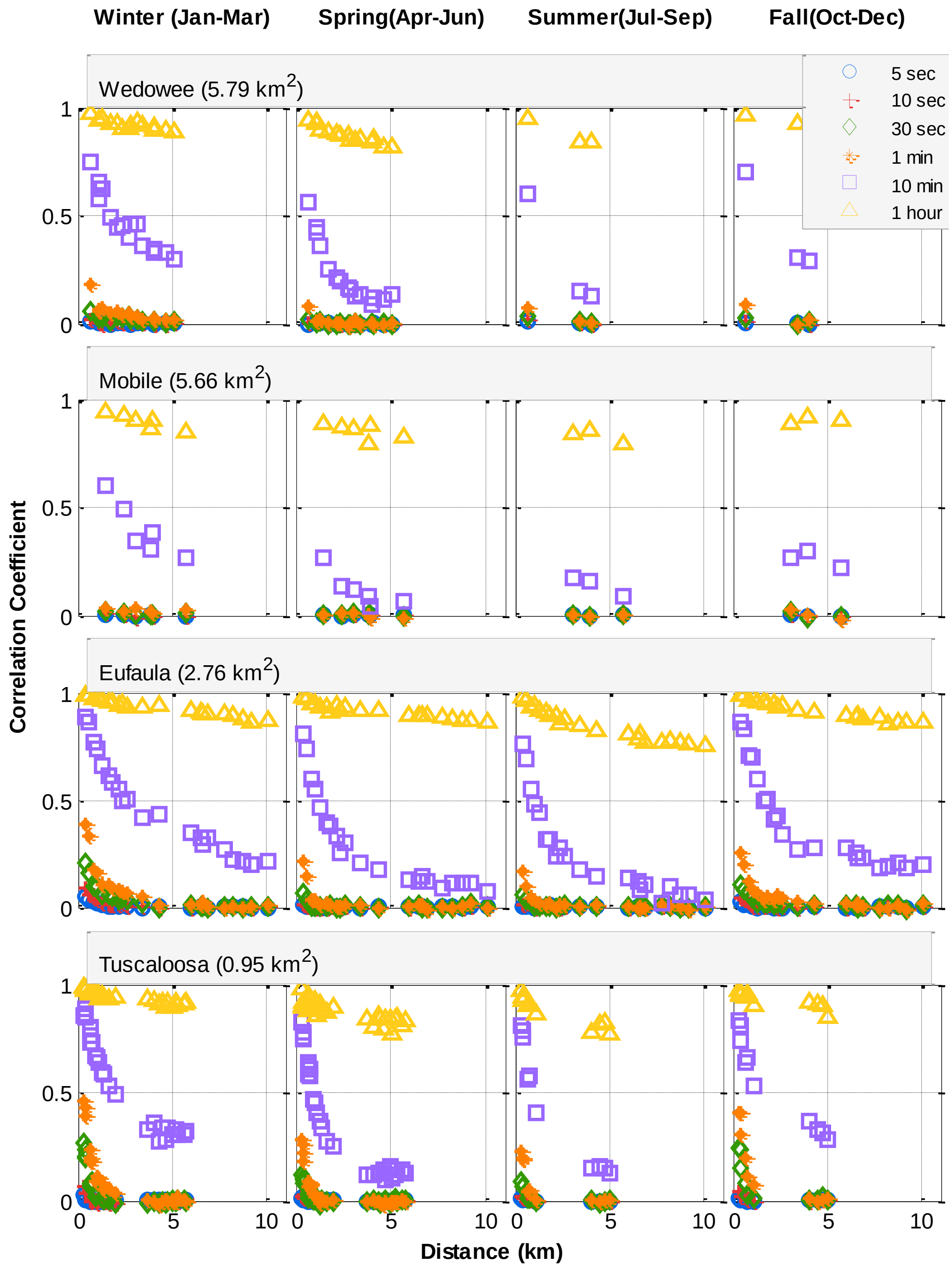


Figure 6-4
Correlation of changes in irradiance over increasing distances for Jan-Dec 2012 for four clusters

Closing Remarks

The results present an analysis of distributed PV performance and variability at the distribution level. While 6 different clusters in Alabama Power's territory have been considered, several trends may be extensible to other circuit locations. However, as these results are location-specific, care must be used when drawing generalized conclusions.

Research organizations and utilities are expected to continue analysis of PV plant variability as more PV systems are interconnected to the grid. There is more work to be done to analyze the relationships between plant size, distance between plants, and density of distributed systems to better understand the behavior of distributed PV. With increased deployment, we expect greater need for standardized metrics to characterize this unique generation resource and enable utilities to fully utilize it.

A
TABLES OF VALUES

Below are tables of values that correspond to several figures in this report.

Table A-1
Seasonal insolation values (kWh/m²/day) for 2012 referenced in Figure 2-6

	Seasonal Insolation			
	2012			
Technology	Q1	Q2	Q3	Q4
Hoover	3.69	5.04	4.36	3.54
Wedowee	4.09	5.45	4.89	4.03
Tuscaloosa	4.08	5.54	4.59	4.02
Wetumpka	4.00	5.22	4.70	4.14
Eufaula	4.07	5.34	4.78	4.13
Mobile	3.72	5.47	4.52	4.44

Table A-2
Monthly insolation values (kWh/m²/day) for three sites in 2012 referenced in Figure 2-7

	Monthly Insolation - 2011											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	2012											
Tuscaloosa	3.64	3.69	4.88	5.66	5.36	5.62	4.59	4.42	4.75	5.02	4.45	2.55
Eufaula	3.96	3.41	4.79	5.66	5.23	5.15	5.19	4.32	4.85	4.84	4.43	3.13
Mobile	3.77	2.80	4.42	5.64	5.56	2.28	4.35	4.29	4.89	5.35	4.67	3.16

Table A-3
Monthly capacity factors for three sites in 2012 referenced in Figure 3-1

	Monthly Capacity Factor - 2012											
Technology	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tuscaloosa	0.15	0.15	0.19	0.21	0.19	0.19	0.16	0.16	0.18	0.19	0.17	0.10
Eufaula	0.16	0.14	0.19	0.22	0.19	0.19	0.19	0.17	0.19	0.19	0.18	0.13
Mobile	0.16	0.12	1.79	0.23	0.22	0.21	0.17	0.17		0.14	0.19	0.18

Tables of Values

Table A-4
Monthly performance ratios for three sites in 2012 referenced in Figure 3-2

	Monthly Performance Factor - 2012											
Technology	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tuscaloosa	0.96	0.97	0.93	0.91	0.85	0.83	0.86	0.88	0.92	0.92	0.93	0.93
Eufaula	0.97	0.94	0.93	0.91	0.89	0.88	0.89	0.92	0.93	0.96	0.97	0.98
Mobile	0.97	1.00	0.97	0.96	0.95	0.96	0.97	0.93			0.94	0.96