




High Resolution PV Power Modeling for Distribution Circuit Analysis

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Clean Power Research
Napa, California

NREL Technical Monitor: Barry Mather

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Subcontract Report
NREL/SR-5D00-60476
September 2013

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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High Resolution PV Power Modeling for Distribution Circuit Analysis

Benjamin L. Norris

John H. Dise

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“Analysis of High-Penetration Levels of PV into the Distribution Grid in California”

Prepared by:

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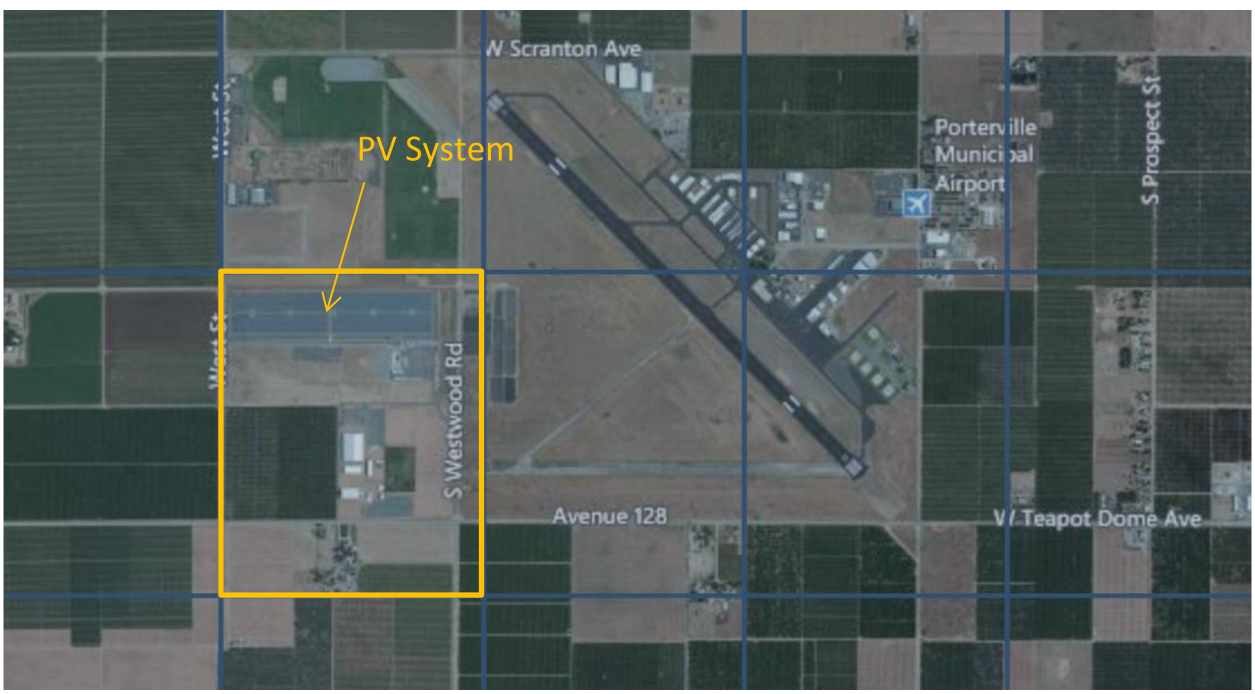
Executive Summary

NREL has contracted with Clean Power Research to provide 1-minute simulation datasets of PV systems located at three high penetration distribution feeders in the service territory of Southern California Edison (SCE): Porterville, Palmdale, and Fontana, California. The resulting PV simulations will be used to separately model the electrical circuits to determine the impacts of PV on circuit operations.

The 1-minute simulations incorporate satellite-derived irradiance data with a spatial resolution of nominally 1 km x 1 km and a temporal resolution of 30 minutes. The special resolution is the highest available through existing satellite imagery, and is shown in Figure ES- 1 for the Porterville site relative to the size of the modeled PV system.

To obtain the 1-minute data, inter-image interpolations are generated with a “cloud motion vector” method by translating the previous image over time using wind speed and direction. The resulting irradiance data is fed into a PV simulation model to produce power output.

Figure ES- 1. Satellite resolution at Porterville



An example of the 1-minute data is shown for Fontana in Figure ES- 2 for the day having the highest variability of 2011, May 29. Of greatest interest is the highest variability observed on the distribution line, so additional analysis of ramp rates was warranted.

As shown in Figure ES- 3, the number of significant ramping events is very small, but the magnitude of the highest events is significant. The number of ramping events higher than 50% of PV system rated output per minute is taken as a metric of “significant” ramping, and this is shown for the Fontana site to be 37 events per year. The highest such event is shown in Figure ES- 4 with an increase in PV output (caused by a departing cloud) of 2.20 MW per minute, or 75% of the systems rated output.

Through methods such as the one described in this report and demonstrated through the datasets delivered under this project, utility engineers will be able to better predict the impacts of high penetration PV on their distribution circuits.

Figure ES- 2. Highest variability day at Fontana, 2011 (May 29).

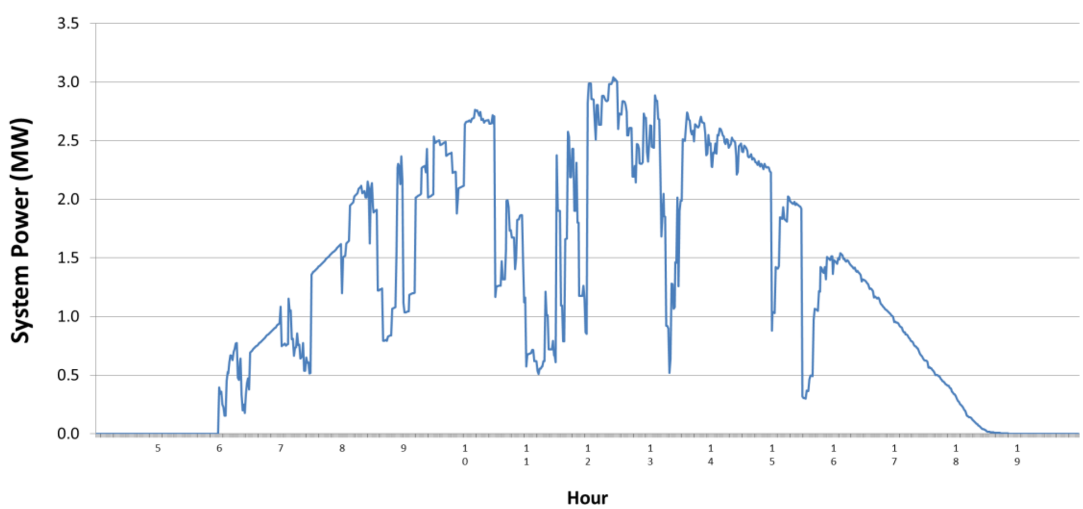


Figure ES- 3. Ramp rate duration curve (Fontana, 2011)

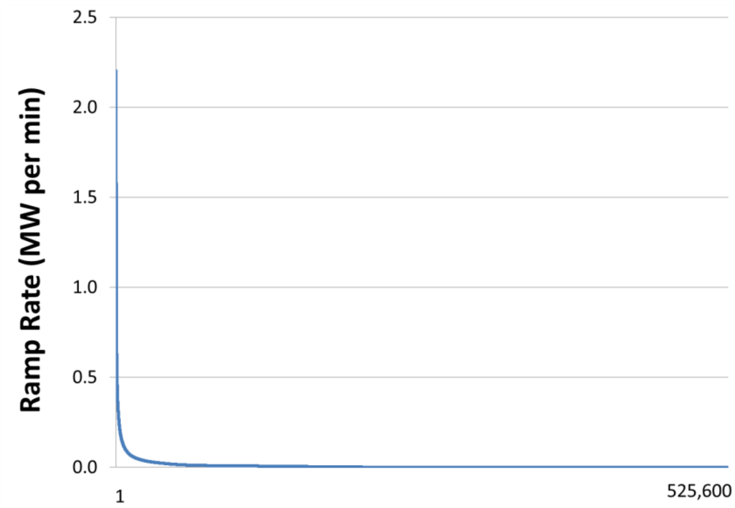
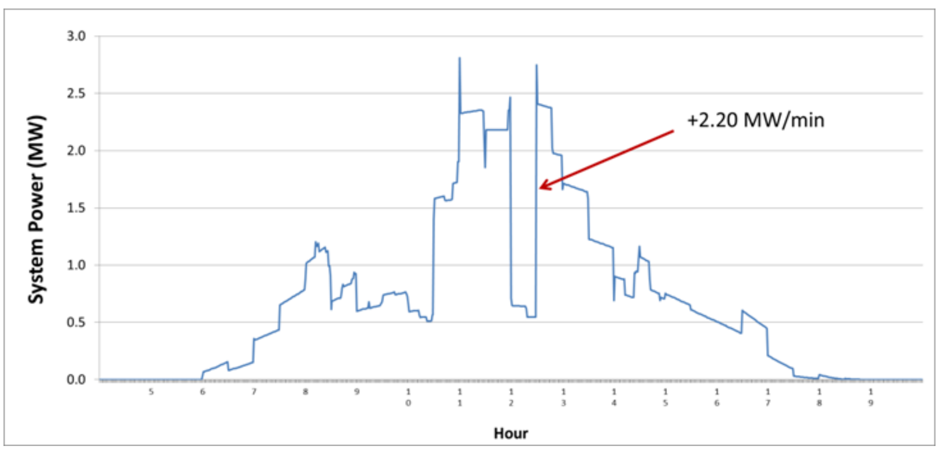


Figure ES- 4. Maximum ramping event at Fontana, 2011.



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Background

SolarAnywhere is the premier solar irradiance time-series source for all locations within the continental US, Hawaii, Mexico, the Caribbean and parts of Canada. Irradiance estimates are generated using NOAA GOES visible satellite images processed using the most current algorithms developed by Dr. Richard Perez at the University at Albany (SUNY). These algorithms extract cloud indices from the satellite's visible channel using a self-calibrating feedback process that is capable of adjusting for arbitrary ground surfaces. The cloud indices are used to modulate physically-based radiative transfer models describing localized clear sky climatology. SolarAnywhere irradiance estimates have several advantages over ground based measurements including longer histories, lower costs, faster time to market, and the ability to directly produce solar power and variability forecasts.

Clean Power Research works with Dr. Perez and SUNY to capture the latest advances in methodology and improvements to consistently provide the highest quality estimates across the widest variety of site conditions. The models have, to date, provided irradiance estimates for specific sites hourly on a 10 km x 10 km ("Standard Resolution") or half-hourly on a 1 km x 1 km ("Enhanced Resolution") basis that extend from 1998 to the present hour plus seven day advance forecasts. Recent research advances have enabled the creation of 1-minute interpolated data from the 1 km images.

This new data, with a resolution of 1 km x 1 km x 1 minute is referred to as "High Resolution," and under this project is used as the key input to 1-minute PV simulations.

Dr. Perez's model was originally verified by the National Renewable Energy Laboratory (NREL) against 31 US locations with varying climates before being selected to create updates of the US National Solar Radiation Data Base (NSRDB). This independent validation[1] found that the average hourly mean bias error of the model was 0.2 W/m^2 for GHI and 16.5 W/m^2 for DNI. The latest version of the model in Standard Resolution continues to be used to provide updates to the NSRDB, as well as serve as the resource database of choice for major energy agencies, such as the California Solar Initiative (CSI) and New York State Research and Development Authority (NYSERDA).

[1] Wilcox, S., R. Perez, R. George, W. Marion, D. Meyers, D. Renné, A. DeGaetano, and C. Gueymard, (2005): Progress on an Updated National Solar Radiation Data Base for the United States. Proc. ISES World Congress, Orlando, FL

One-minute irradiance data such as SolarAnywhere High Resolution and the associated PV simulation model could enable utility engineers to model PV resources on the electric distribution system. With the temporal resolution corresponding to the approximate timeframe of distribution voltage regulators, the data could be used to determine impacts of PV on distribution operations.

Introduction: Three High Penetration Study Feeders

Under the current project, NREL has contracted with Clean Power Research to provide PV simulation support for three high penetration distribution feeders under study in the service territory of Southern California Edison (SCE). The three study feeders, located in Porterville, Palmdale, and Fontana, California, and are mapped in Figure 1.

Figure 1. Study feeder locations and SCE service territory[2].

At each location a large PV system is interconnected to the SCE feeder. Using the High Resolution irradiance data, ambient temperature data, PV plant specifications, and PV simulation methods,

[2] Google Earth.

minutely PV power generation data can be calculated. The datasets can in turn be used, along with physical component and load data, as inputs into electrical circuit modeling tools. The datasets provide PV output, in MW, for each minute of 2011. This report documents the creation of these datasets and characterizes the systems in terms of ramp rates.

Methods

SolarAnywhere High Resolution data is derived from the same satellite image processing algorithm that generates both the SolarAnywhere Standard and Enhanced Resolutions. However, the High Resolution data uses an added method of temporal interpolation between half-hourly satellite images to create minute-by-minute solar irradiance estimates in SolarAnywhere's current geographic coverage area.

Satellite Images

SolarAnywhere satellite image processing occurs using the most recent version of the Perez model. In general, satellite images are obtained for coverage area in the western and eastern halves of the continental US and Hawaii on half-hourly increments from the Space Science and Engineering Center (SSEC) at University of Wisconsin – Madison. Following image transfer, irradiance measurements are made using the Perez model by ranking pixel brightness on clear sky conditions. Half-hourly measurements of global horizontal irradiance (GHI) and direct normal irradiance (DNI) are derived from the model which is then used to calculate residual diffuse irradiance (DHI).

Cloud Motion Vector Method

To generate the 1-minute irradiance measurements, SolarAnywhere first calculates a wind vector for every Standard Resolution tile using consecutive satellite images. The wind vectors are then applied to the Enhanced Resolution irradiance map to predict movement on a minute-by-minute basis. For forecasting purposes, the prediction is calculated forward up to 60 minutes. For historical generation, the prediction occurs between half-hour segments of retrieved satellite images.

PV Simulations

SolarAnywhere High Resolution data can further be used to simulate PV system generation through Clean Power Research's PV Simulator engine. PV Simulator uses a version of the PVForm model to simulate production from a series of parameters, including irradiance, wind, temperature, installation and equipment specifications.

The simulation process starts by passing in the location and time series weather data to the Perez irradiance model found in SolarAnywhere. The selected weather data source provides time series GHI, DNI, wind and temperature data, while the location is used to define the latitude and longitude of the PV system. Using the Perez irradiance model, PVSimulator then calculates the circumsolar diffuse irradiance, isotropic diffuse, and horizon band diffuse irradiance components. These calculations start with determining the declination of the sun and equation of time. Then the solar zenith angle is calculated based on the declination of the sun, equation of time, and latitude. The airmass is then estimated as a function of the solar zenith angle. Based on these values the Perez model then produces the circumsolar diffuse irradiance, isotropic diffuse, and horizon band diffuse irradiance components.

After the irradiance model has broken down GHI and DNI into componentized irradiance values, PVSimulator then uses the PV array geometry in order to calculate the Plane of Array Irradiance (POAI). The POAI calculations begin by calculating the solar time taking into account the local time, time zone, longitude and the previously calculated equation of time value. The solar azimuth angle is then calculated based on the zenith angle, latitude, and declination of the sun. The Plain of Array (POA) Angle of Incidence (AOI) is then calculated based on previously calculated values taking into account the tracking capabilities of the PV System. The components of the POAI (POA beam, circumsolar diffuse, isotropic diffuse, horizon band diffuse, and reflected irradiance components) are then calculated based on the output of the Perez model in conjunction with the tilt of the PV modules, the calculated AOI, and the specified albedo of the surrounding area. The shading model then adjusts the previously calculated POAI to account for shading as a consequence of obstructions as well as row on row shading.

The POAI values are then passed into the selected power output model in order to estimate the energy production of the PV system. Before calculating estimated energy production the temperature of the PV modules are estimated based on the POAI as well the time series wind speed, ambient temperature data provided by the weather data source. Then the 1-minute power output of the PV system is calculated based on the estimated PV module temperature and POAI along with model parameters defining the behavioral characteristics of the PV system as provided in the PV system specification. The model parameters depend on the selected power output model but for example in the case of PVForm the model parameters will consist of quantities such as the module PTC rating and efficiency reduction per degree C as well as inverter average efficiency and kW AC rating.

Once all this processing has been completed the primary output of the simulation is then the estimated 1-minute power of the PV system. In addition to this each stage or processing may also output 1-minute intermediate calculated results (such as POA and AOI).

Delivered Data Sets

1-minute production data

Using the methods described in the foregoing, four data sets of 1-minute PV system power generation were prepared and delivered[3] to NREL. Data files included four columns:

- Time stamp, start of interval
- Time stamp, end of interval
- Power (MW)
- Observation Type

Observation Type[4] includes keys (A) "Archived," (D) "Day," (N) "Night," and (M) "Missing."

Hourly irradiance and temperature data

SolarAnywhere Standard Resolution (version 2.2) data was also provided for Fontana and Porterville, including hourly measurements of GHI, DNI, DHI, wind speed and temperature. This data was used for related circuit modeling work.

Data for these two locations was provided between the dates of January 1 2002 through December 31 2011. The 10-km gridded tile centered at 34.05 north, 117.55 west and 36.05 north, 119.05 west was selected for the Fontana and Porterville sites, respectively.

Data Validation

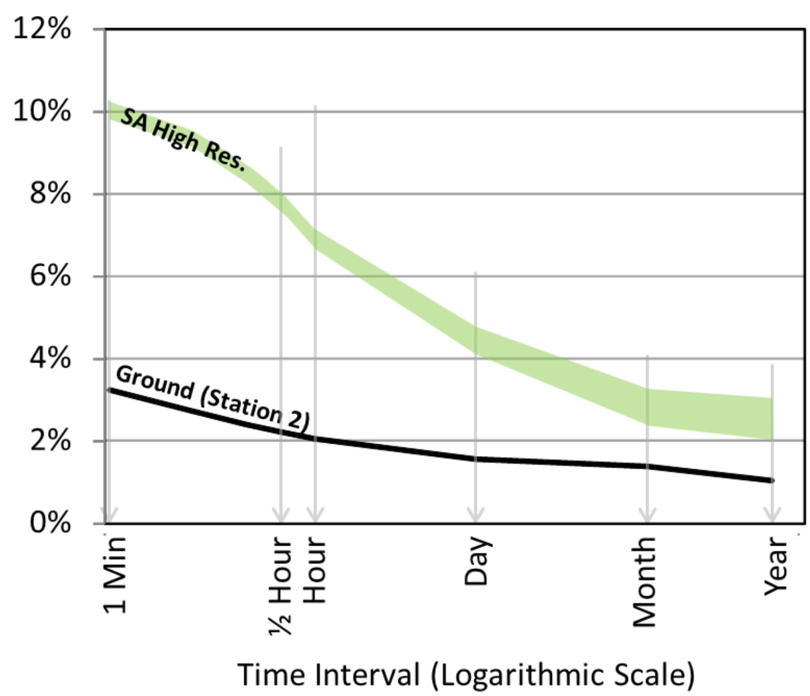
Following the implementation of 1-minute data in SolarAnywhere, studies to validate the model accuracy were conducted. In collaboration with organizations in California, California ISO (CAISO) and Sacramento Municipal Utility District (SMUD), 1-minute data accuracy was validated against high-accuracy, well-maintained ground mounted irradiance sensors throughout the state of California. This validation work falls outside of the current project, but is provided here for completeness.

[3] Results were prepared on 3/5/2013 and made available on an FTP server.
[4] All data was marked as (A) archived because 2011 contains only historical data older than one month. A complete list of observation types is available at www.solaranywhere.com.

CAISO stations

Using ground data from four CAISO ground stations, the relative mean absolute error (%MAE) was calculated comparing the SolarAnywhere 1-minute High Resolution GHI data. When comparing the four locations on an individual basis, as seen in Figure 2, the %MAE decreases from roughly 10% at a 1-minute interval of comparison to a range of 2-2.5% when compared annually. Additionally, the black baseline, marked "Ground (Station 2)", represents the relative error between the second, redundant ground sensor at the same location. This reflects ground measurement error at each location. Having two co-located ground measurement devices also accounts for the shaded green region reflecting the %MAE, as SolarAnywhere 1-minute data was compared to each of the two ground sensors thus creating the high and low accuracy boundaries.

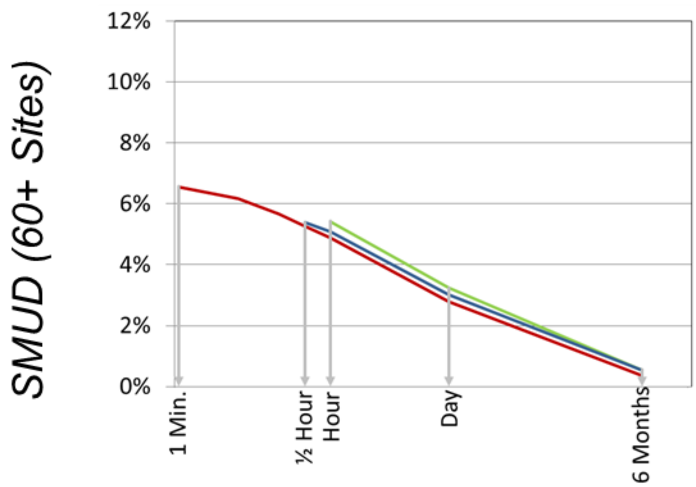
Figure 2: Average %MAE of four CAISO locations versus time interval of comparison



SMUD stations

Additional validation of the SolarAnywhere High Resolution model was conducted using a network of over sixty pole-mounted pyranometers maintained by the Sacramento Municipal Utility District (SMUD) throughout their service territory. Similarly, GHI measurements from the ground stations were compared individually with the corresponding SolarAnywhere High Resolution location. Figure 3 represents the %MAE average for all stations included, as compared by time interval of comparison. The red curve represents the accuracy of the High Resolution data. The blue and green lines represent accuracy measurements of Enhanced and Standard Resolution, respectively. The result comparing SolarAnywhere High Resolution to the SMUD ground sensor GHI measurements resulted in a similar accuracy assessment, with 1-minute SolarAnywhere data falling within roughly 7% of %MAE of the corresponding ground measurement and with an overall bias of either plus or minus 1-2%.

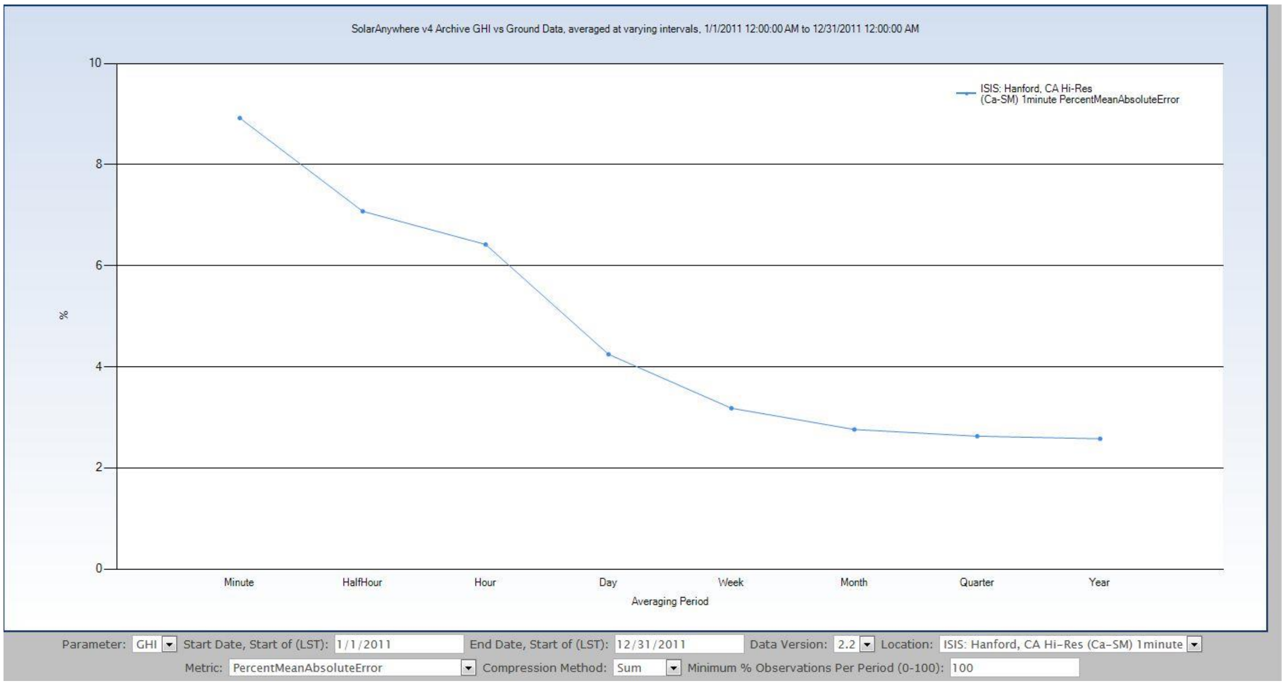
Figure 3: Average %MAE versus time interval of comparison for over sixty locations in SMUD territory



Additional comparisons to ground sensors

An accuracy summary of SolarAnywhere High Resolution compared to the ground collected GHI data from the Hanford ISIS station for the year of 2011 is presented in Figure 4.

Figure 4: %MAE versus time interval of comparison for the ISIS station in Hanford, CA



Analysis

The description of the analysis that follows uses only the Fontana data for simplicity in describing the process. Results for each of the locations are shown in the Appendices.

Missing data

Ramp rates (defined as the absolute change of power output[5] per unit time) were calculated for every minute of the year. By inspection, and it was discovered that some of the highest ramp rates were based on data that appeared to be invalid. This required further investigation.

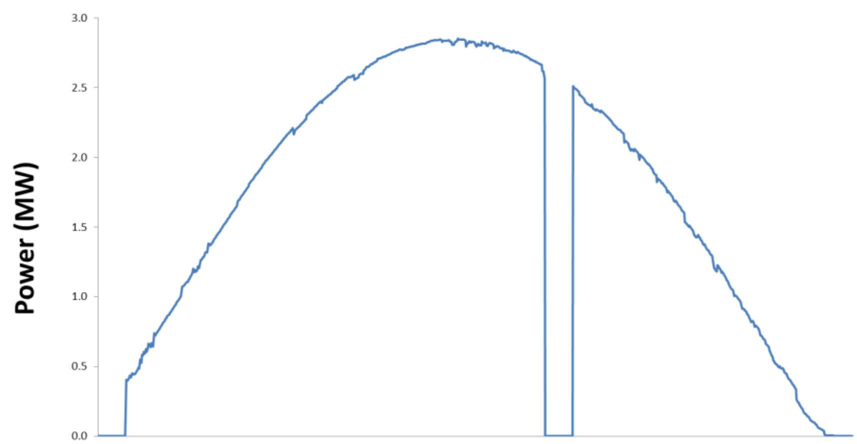
Figure 5 shows the Fontana 1-minute data for the day having the highest ramp rate (the "drop in power" from near full power output to zero). While this behavior is possible in practice—for example due to an inverter malfunction resulting in complete power loss—it is not possible to see a zero output in the middle of the day due only to the presence of clouds. There is always some diffuse radiant energy

[5] For example, if the power output for one interval were 2.5 MW, and the power output for the next interval were 2.3 MW, then the change in power is -0.2 MW and the absolute change in power is 0.2 MW. Finally, since the intervals are 1 minute in duration, the ramp rate is 0.2 MW per minute.

available, even in the darkest of overcast days. Therefore, this data is clearly missing and should not be included in the analysis[6].

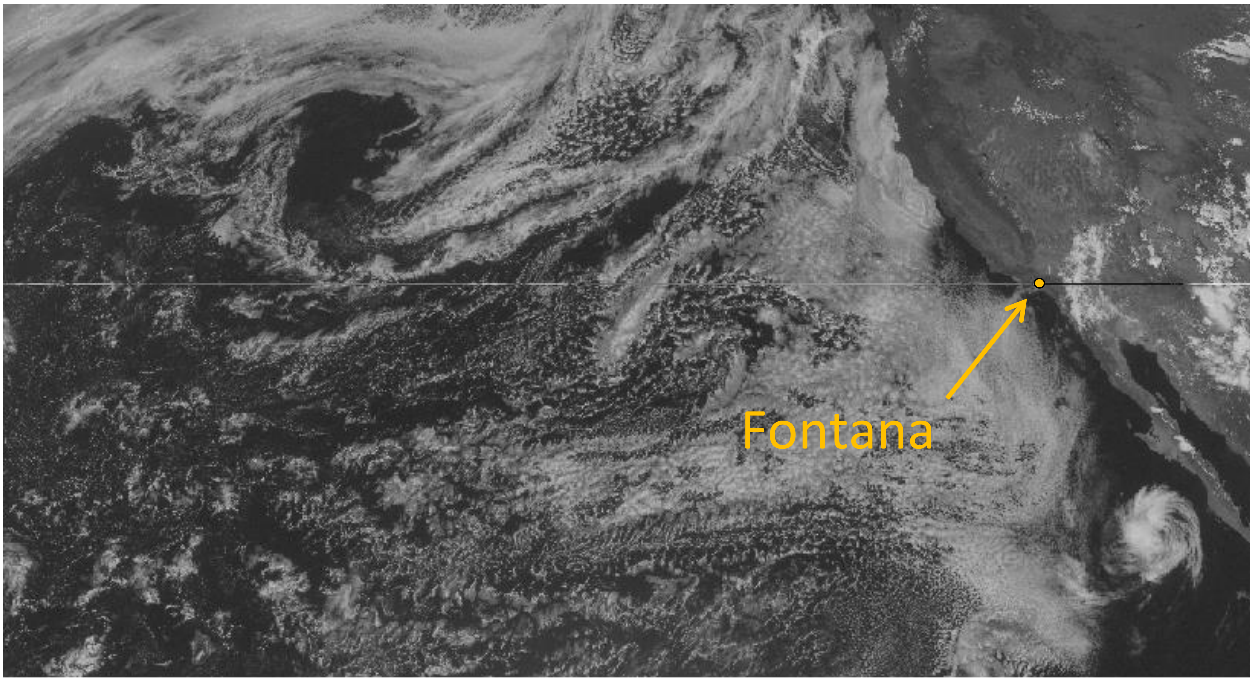
Upon further investigation, the cause of this error was found to be an aberration in the raw satellite image. As shown in Figure 6, the image associated with the missing data includes a streak across the image, and Fontana happens to lie directly along the aberrant line. Therefore, in the 30-minute period following this image, the calculated 1-minute data is missing. The images taken in the half hour before and the half hour after this image were not distorted, and the missing data is confined to only this 30-minute period.

Figure 5. Missing data at Fontana, February 24, 2011 from 13:29 to 13:58.



[6] The dataset includes an "M" flag in the observation type if the data is missing. The problem described here was not flagged as missing because the underlying satellite images do exist. The issues identified here resulted in removal of selected images, hence the "M" flag would show up were the datasets to be re-generated. However, the search for such anomalies was limited to only those resulting in the highest ramp rates.

Figure 6. GOES-west satellite image, July 24, 2011 (21:30:00 UTC), showing error streak.



Analysis of data from each location showed similar cases of zeroed data. The search for such data was not exhaustive and satellite images were not consulted each time. Rather, only the data affecting the highest ramp rates were identified. In each case, two or three of the highest ramp rates were identified as being caused by this problem, and this data was manually excluded from the analysis. The highest ramp rates that that follow for each location reflect data that appears to be correct and unrelated to missing data.

Variability

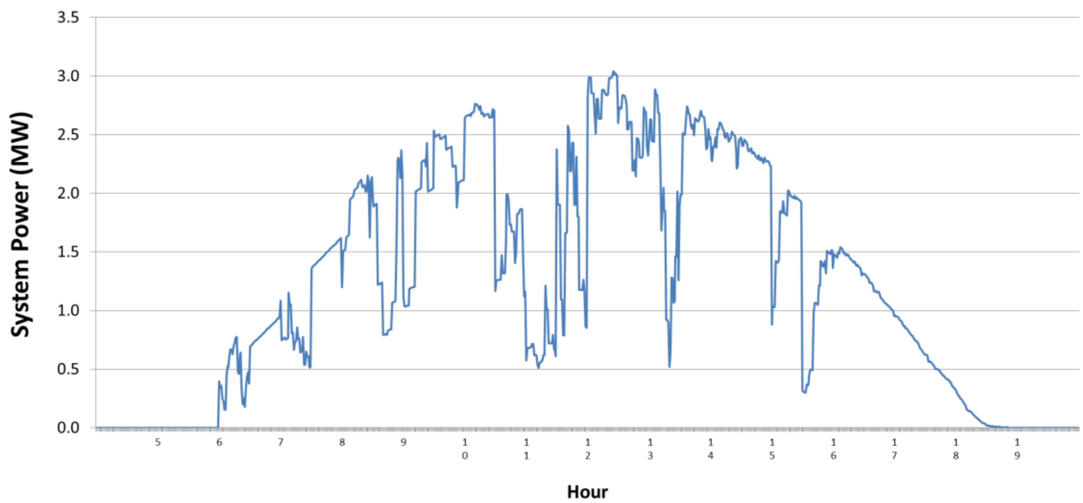
Daily variability is defined as the standard deviation of the population of one-minute ramp rates during the day, and is calculated as:

$$Variability = \sqrt{\frac{\sum_{i=1}^{N}(r_i - \bar{r})^2}{N}}$$

Where N is the number of minutes in each day, r_i is the ramp rate for the i^{th} minute, and $\bar{r}$ is the average ramp rate over the day.

Daily variability was calculated for every day, and the day with the highest variability, May 29, is shown in Figure 7.

Figure 7. Highest variability day at Fontana 2011 (May 29).



Ramp Rate Duration Curve

Figure 8 shows the ramp rates at Fontana for each of the 525,600 minutes of 2011. From this we can get a sense of the magnitude of the highest ramping events. The "normal" periods of ramping are difficult to discern, however, so this data is sorted by magnitude and presented as a "ramp rate duration curve[7]" in Figure 9.

[7] This term is used to parallel a similar ranking of loads in electric utility planning, the "load duration curve."

Figure 8. Absolute 1-minute ramp rates at Fontana, 2011.

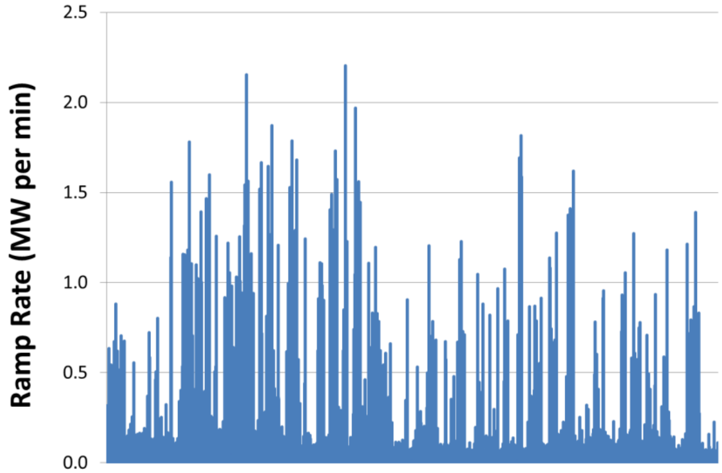
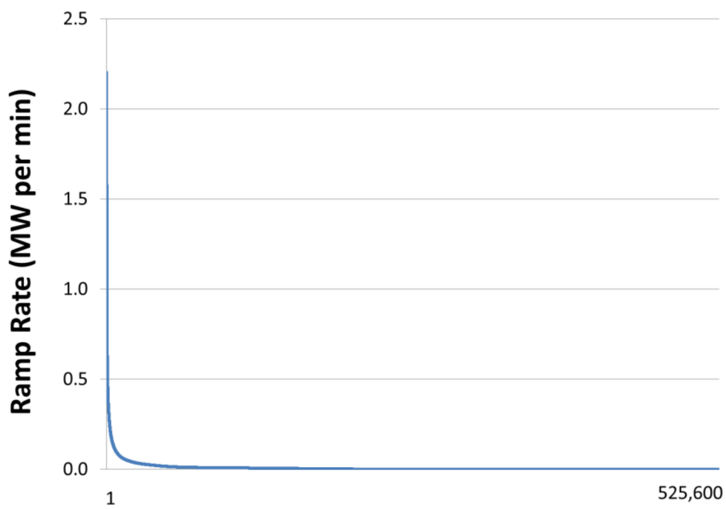


Figure 9. Ramp rate duration curve, Fontana, 2011



This sorting illustrates that the number of significant ramping events is quite small. To further examine and quantify the ramping, we magnify only the top 100 minutes of the year (the top 1% of the year) and normalize ramping as a percent of rated PV system output. Figure 10 shows these minutes, and further defines a "high ramping region" of the curve, arbitrarily selected as covering those ramping events that correspond to an excess of 50 percent of PV system rating. There are 32 such high ramping events, and the largest of these is 2.20 MW per minute, or 75% of the PV System's 2.95 MW-AC rating per minute. This event is shown in Figure 11.

Figure 10. Highest 100 ramp rates at Fontana, 2011.

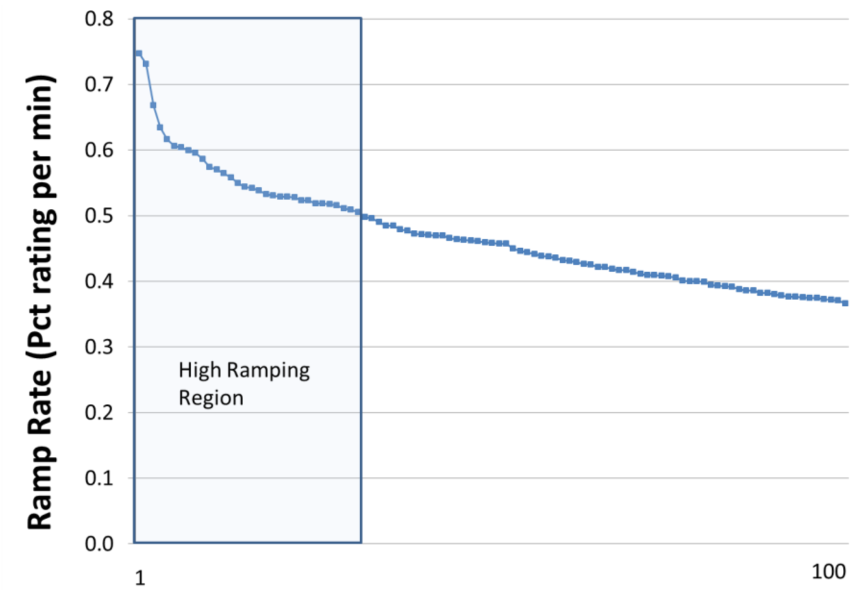
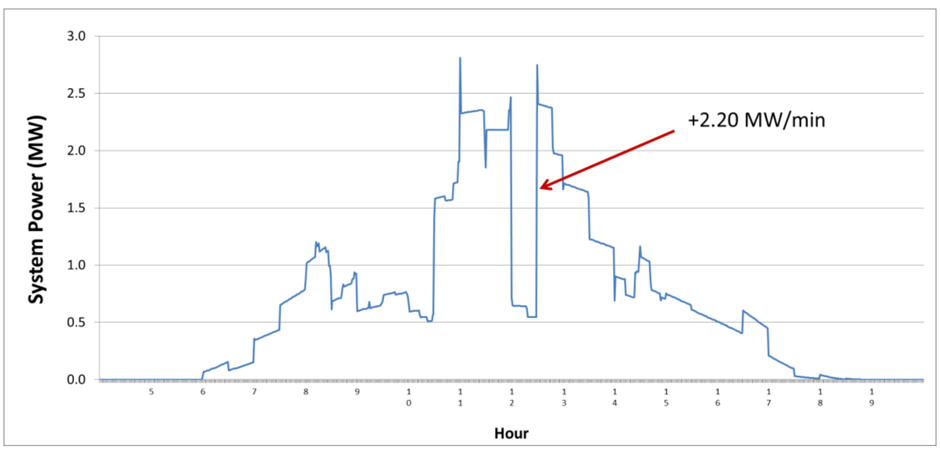


Figure 11. Maximum ramp event at Fontana, 2011 (2.20 MW/min).



An inspection of Figure 11 also reveals an artifact of the high resolution irradiance data generation process. With the raw image data available in half-hour intervals, the "interpolation" between two images is actually based on a given set of wind vectors and the first image corresponding to a specific time. The second image at the end of the half hour period is not used. Hence the computations can result in a disjoint between the last minute of one period and the first minute of the next. A future improvement to the 1-minute data creation might be to use both images to ensure a smooth transition.

Finally, the ramping statistics for Fontana are summarized in Table 1. Similar ramping statistics are presented for each location in the Appendix.

Table 1. Fontana ramping statistics, 2011.

System rating (MW)	2.95
Max. power ramp (MW per min)	2.20
Max. power ramp (% per min)	75%
High ramping events (no. per year)	32

Appendix 1: Fontana (Study Feeder 1)

Figure 12. Fontana PV system.

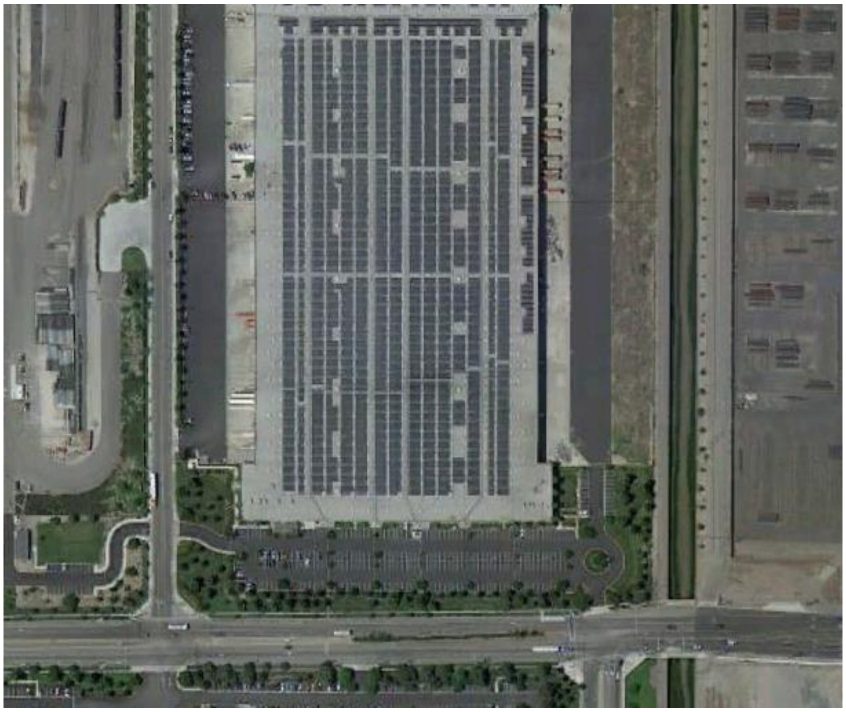


Figure 13. Satellite resolution at Fontana.

Table 2. Specifications for Fontana

Coordinates	34.080, -117.517
Inverters	Quantity: 4 Manufacturer: SatCon Technology Model: 500.0 kW (Model AE-500-60-PV-A) EfficiencyRating 95%
Modules	Quantity: 33,700 Manufacturer: First Solar Model: 72.5W (Model FS-272) Nominal Rating (kW DC): 0.07250 PTC Rating (kW DC): 0.06980
Array Configuration	Quantity: 33,700 Manufacturer: First Solar Model: 72.5W (Model FS-272) Nominal Rating (kW DC): 0.07250 PTC Rating (kW DC): 0.06980
Solar Obstructions (shading)	None

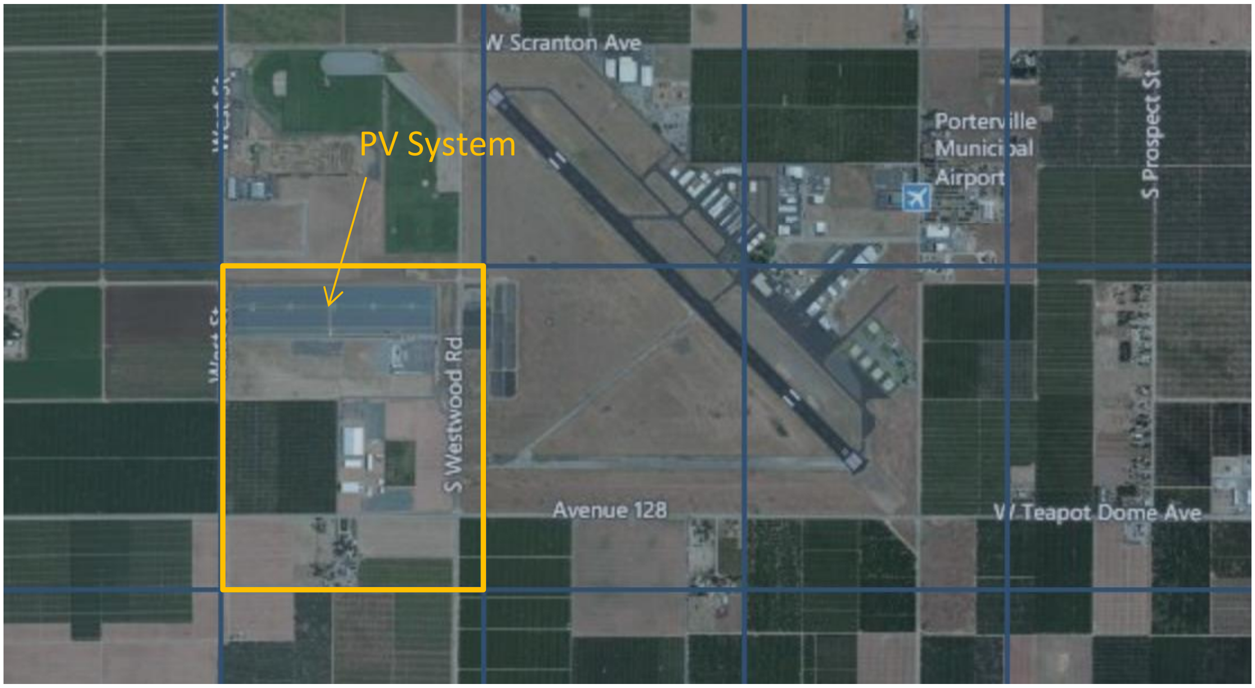
Table 3. Fontana ramping statistics, 2011.

System rating (MW)	2.95
Max. power ramp (MW per min)	2.20
Max. power ramp (% per min)	75%
High ramping events (no. per year)	32

Appendix 2: Porterville (Study Feeder 2)

Figure 14. Porterville PV system.

Figure 15. Satellite resolution at Porterville.



Specifications for Porterville

Coordinates	36.028738, -119.075886
Inverters	Quantity: 7 Manufacturer: SatCon Technology Model: 1000.0 kW (Model EPP-1000-0600-32060-200X-U-x) Efficiency Rating 96.5%
Modules	Quantity: 29,428 Manufacturer: Trina Solar Model: 230W (Model TSM-230PA05.10) Nominal Rating (kW DC): 0.230 PTC Rating (kW DC): 0.2089
Array Configuration	Azimuth Angle: 0.000 (south) Tilt Angle: 25.000 Tracking: Fixed Array
Solar Obstructions (shading)	None

Table 4. Porterville ramping statistics, 2011

System rating (MW)	4.783
Max. power ramp (MW per min)	4.31
Max. power ramp (% per min)	90%
High ramping events (no. per year)	53

Appendix 3: Palmdale (Study Feeder 3)

Figure 16. Palmdale PV system.

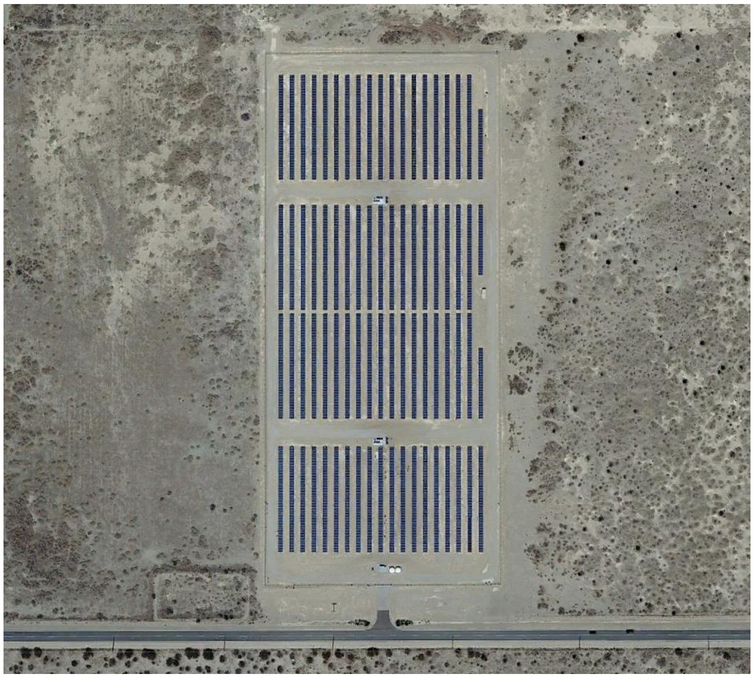


Figure 17. Satellite resolution at Palmdale.

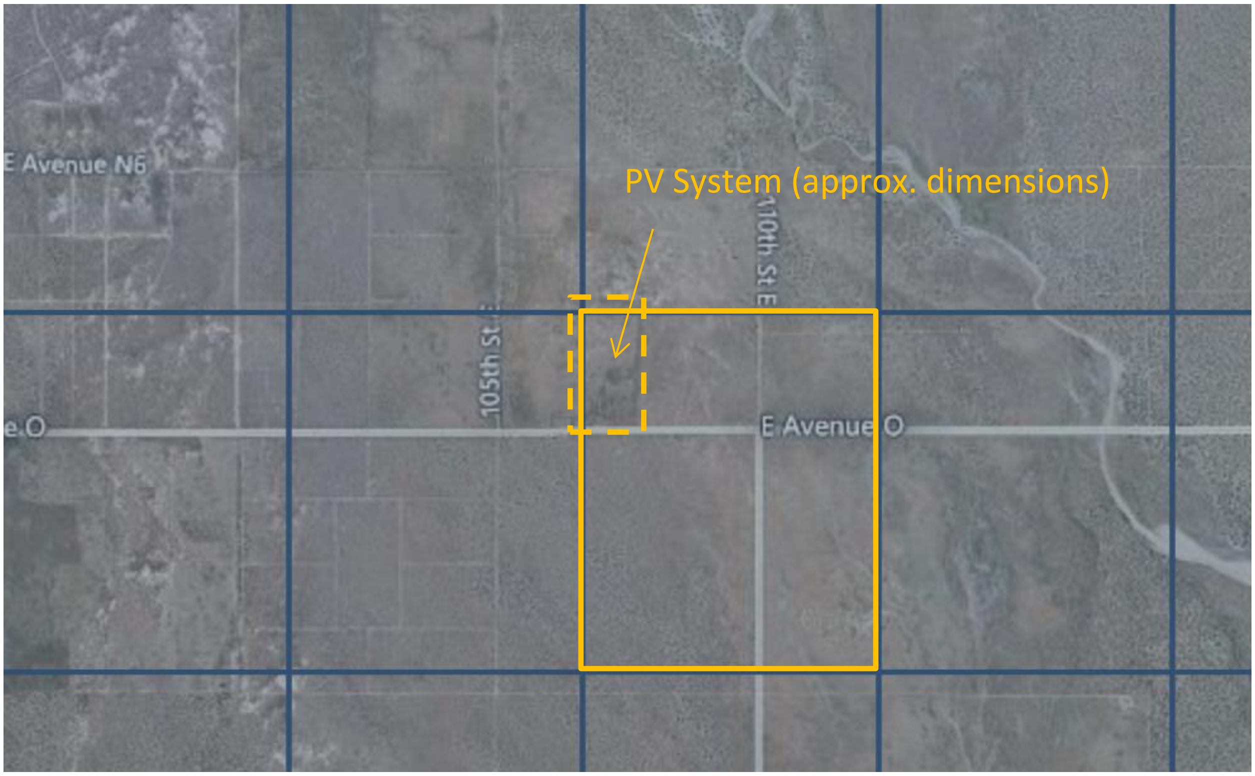


Table 5. Palmdale ramping statistics, 2011

System rating (MW)	1.437
Max. power ramp (MW per min)	1.33
Max. power ramp (% per min)	93%
High ramping events (no. per year)	186