



REDUCING UNCERTAINTY IN SOLAR ENERGY ESTIMATES

Mitigating Energy Risk through
On-Site Monitoring

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SUMMARY

With solar photovoltaic (PV) projects, a major area of risk is quantifying the expected annual energy production and uncertainty. One of the most significant drivers is the uncertainty in solar irradiance data. With more financial stakeholders becoming aware of the risks of using modeled data alone to estimate energy and project cash flows, the collection of on-site measurements is coming to the forefront as a critical area for project planning and evaluated in project due diligence.

Historically, the industry has relied on modeled data to estimate the on-site solar resource; however, in most cases modeled reference data sources lack the accuracy to sufficiently mitigate the energy production risk for larger projects. Similarly, directly using publicly-available measured data may not be suitable at many projects due to the spatial diversity of reference networks and lower quality resulting from poor station maintenance. Because of these risks, it is expected that most financial stakeholders will expect site-specific measurements to demonstrate that the solar resource has been thoroughly evaluated.

Uncertainty in energy estimates can be significantly reduced by on-site monitoring programs that apply best practices to reduce uncertainty in the measurements and support high quality data collection. Best practices include a well-designed measurement plan, careful documentation at system commissioning, regular site maintenance to inspect, clean, and level sensors, and regular data validation and quality assurance procedures.

To demonstrate how solar irradiance data affects uncertainty in energy production estimates, a case study was conducted for 11 sites in the U.S. to show how energy estimates using only modeled data compared to those derived from on-site measured data correlated to a long-term reference. The study used three metrics for comparison:

1. Annual global horizontal irradiation (GHI).
2. Uncertainty estimates for irradiance.
3. Energy estimates 90% confidence, known as the P90.

The results of the case study demonstrated the impact of on-site monitoring, as shown by the three metrics:

1. The long-term GHI from modeled data differed from the GHI estimate derived from on-site data by 2.8% on average, with one site differing by as much as 6.2%. When translated to energy, this difference has a corresponding impact on the projected energy output.
2. On average, on-site monitoring reduced the overall uncertainty from 9.2% to 5.7%, or approximately 3.5%. This is a significant reduction when considering the application to probability-of-exceedance energy estimates.
3. The difference in uncertainty resulted in an even a greater impact when applied at higher confidence intervals. The results showed that on-site monitoring can increase the P90 by over 5% and the P99 by over 10%. The P90 is a common metric used by financial stakeholders to evaluate the relative risk of solar PV projects.



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Part 1 INTRODUCTION

Risks are part of any energy project in the development stage, including legal risks from project contracts, permitting, site control, equipment risks, and system performance. These risks influence the ability for a project to obtain financing. With solar photovoltaic (PV) projects, a major area of risk is quantifying the expected annual energy production. An accurate preconstruction energy estimate offers insight into the risk of a solar PV project, which is quantified through the amount of uncertainty associated with the energy estimate. While there are several areas of uncertainty, one of the most significant drivers is the uncertainty in solar irradiance data. While the industry has historically relied on modeled data to estimate the on-site solar resource, uncertainty in energy estimates can be significantly reduced by on-site monitoring and an in-depth analysis of all available data sources. Since project capital structure is tied to the energy estimates derived from solar resource estimates, accurately quantifying the on-site radiation is important.

This report outlines the sources of solar resource data and demonstrates the benefit of on-site monitoring in reducing uncertainty in energy estimates. This is illustrated in a case study comparing energy production uncertainty for two scenarios: with and without on-site solar data. The case study confirms that on-site monitoring supports high confidence energy estimates (i.e., P90, P99) for bankable energy assessment.

Part 2 BACKGROUND

Purpose of this Study

As the solar industry matures, lessons learned from the wind industry can be applied to increase the financial success of solar projects. Like in the solar industry, early wind projects were less reliant on on-site meteorological data, and many projects suffered through overly optimistic performance expectations and unrealized revenue streams. Early wind practices were improved with more sophisticated methods, specifically the use of on-site measurements to estimate energy production with much higher accuracy.

As with the wind industry, the need for site-specific data to accurately characterize solar energy production is emerging as a necessary component of the analysis needed to reduce risk perceived by those who may eventually have a financial stake in the project. A percent difference in solar resource approximately translates to the same percent difference in energy production. Since project capital structure is tied to energy estimates which are derived from solar resource estimates, accurately quantifying the on-site radiation is important. In most cases, publicly available measured and modeled reference data sources lack the accuracy to sufficiently mitigate the energy production risk for larger projects. The goal of this case study was to more accurately quantify the reduction in uncertainty achieved by using on-site monitoring to estimate a solar energy project's long term energy production.

It is expected that most financial stakeholders will expect site-specific measurements to demonstrate that the solar resource has been thoroughly evaluated to mitigate energy production risk. This is confirmed by ratings agencies such as Fitch Ratings, which states the importance of on-site solar data to obtain a favorable credit rating.¹

“Fitch looks for a minimum of one year, hourly, well-maintained, onsite data for a complete solar resource supply assessment. Shorter data periods than one year will not capture the full seasonal and diurnal characteristics of solar irradiance at a particular site, and would be considered either midrange or weaker.”

With more financial stakeholders becoming aware of the risks of using modeled data alone to estimate energy and project cash flows, the collection of on-site measurements is coming to the forefront as a critical area for project planning.

Solar Resource Components

Atmospheric solar radiation is broken into three fundamental components, shown in Figure 1. Direct normal irradiance is the solar radiation available directly from the sun and normal to the sun's position. This component is important for development of concentrated solar power systems and is most directly influenced by cloud cover and atmospheric aerosols. Diffuse horizontal irradiance is the solar radiation scattered by the atmosphere as collected on a horizontal surface. The sum of the direct and diffuse components, or the total solar radiation available, is the global horizontal irradiance. Energy estimates for PV projects primarily rely on GHI, which will remain the focus for the analysis described in the remainder of this report.

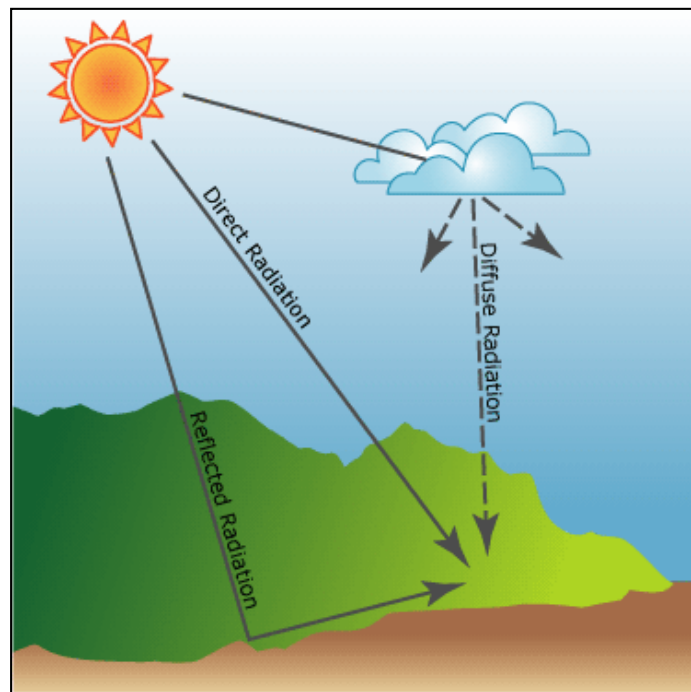


Figure 1: Solar Radiation Components²

Part 3 SOURCES OF SOLAR DATA

To assess the solar resource to determine energy potential, measured and/or modeled data can be used. An optimal energy assessment includes a thorough evaluation of all reference data available. Evaluation of multiple data sets allows for the most appropriate data source(s) to be selected to estimate the long-term irradiation at the site.

On-Site Measurements

The collection of high-quality on-site measurements at the project site is important for understanding site-specific meteorological characteristics. These data, collected through a solar monitoring program, can be used to in conjunction with longer period-of-record data sources to estimate the long-term solar irradiation while minimizing the uncertainty associated with this estimate.

The quality of on-site solar measurements is affected by the level of diligence taken in the design and implementation of the solar monitoring program. Best practices for on-site monitoring help to reduce uncertainty in the measurements. General recommendations for on-site monitoring best practices can be separated into four categories, described below.

Measurement Plan: A well-designed measurement plan, including proper instrumentation, sampling rates, station design, and program length is recommended to meet the primary objectives of the monitoring program. For solar resource assessment to support solar energy estimation, this may include collection of all three solar radiation components as well as collection of meteorological data such as temperature, wind speed, and precipitation.

Installation and Commissioning: Pre-installation due diligence and careful documentation support high quality measurements. Site selection, verification of solar instrumentation with secondary standard reference sensors, and careful documentation of sensor and remote communications information allows for more efficient troubleshooting and is valuable information during data quality control.

Site Maintenance: A regular site maintenance routine to clean and level solar sensors, verify site security, and inspect equipment is necessary to achieve the lowest measurement uncertainty and allows for responsiveness in addressing on-site issues. Site maintenance is essential factor contributing to data quality and reduced uncertainty and therefore is recommended for all solar monitoring programs.

Data Validation and Quality Assurance: Data validation improves data recovery and eliminates suspect values from biasing results from the on-site monitoring program. Regular screening of on-site data and

error-checking protocols help to identify potential issues quickly. Comparison of on-site data with reference data sources helps to validate results. These validation steps, conducted by an experienced analyst, are recommended to assure data quality.

Modeled Data

Multiple sources of public and private modeled solar data exist. Although model-based irradiance data may have lower accuracy compared to other sources and are limited by grid cell resolution, modeled data sets are advantageous in that they are available for any location. Modeled data sets are also more likely to have a longer period of record.

A common source of publicly available modeled solar data in the U.S. is the National Solar Radiation Database (NSRDB). This database consists of numerical and satellite-modeled data across the U.S. in addition to TMY3 data sets, which provide an annual time series of hourly solar data at over 1,400 specific locations. Although TMY3 data sets have been used by the solar industry for site prospecting, they have limited value for directly estimating the long-term solar resource since the data sets are comprised of a combination of satellite-modeled, numerically-modeled, and back-filled data, which increases their overall uncertainty. As a result, the National Renewable Energy Laboratory (NREL) states

“NSRDB meteorological data may not be suitable for climatological work. The meteorological fields in the NSRDB should be used only as ancillary data for solar deployment and sizing applications.”³

Despite NREL’s statement, the accessibility and public nature of the NSRDB has made it a commonly used data source throughout the solar industry. Some users have used NSRDB data for purposes beyond prospecting, such as solar energy estimation to support project financial analysis. Since the quality of energy estimates for financial analysis is directly related to the quality of the solar data used in the analysis, results from an analysis relying on NSRDB data may have a greater amount of uncertainty than an analysis relying on higher quality solar data sources.

Surface Reference Stations

Several international, nationwide, regional and statewide measurement networks collect solar radiation data as surface-based measurements with various periods of record and varying degrees of data quality. While much of this data is publicly available and can have greater accuracy than modeled data, it is rare to find high-quality solar data near a project site due to the spatial diversity of reference networks and poor station maintenance.

Using Solar Data for Resource Assessment

Table 1 shows the types of solar data available, advantages and disadvantages of each, and an overview of applicable uses. An evaluation of all available data sources in the vicinity of the project area is useful to gain insight into regional trends and helps in the selection of the most appropriate data source(s) for characterizing on-site long-term solar conditions.

Table 1: Reference Data Source Selection Details

Data Source	Advantages	Disadvantages	Intended Use
On-Site Measurements	<ul style="list-style-type: none"> ◆ Site-specific data ◆ Customized for project needs ◆ Station details and management well-known ◆ Reduced uncertainty 	<ul style="list-style-type: none"> ◆ Shorter period of record 	<ul style="list-style-type: none"> ◆ High-confidence resource and energy estimates ◆ Bankable-grade reports ◆ In-depth characterization of seasonal and diurnal climate
Modeled Data	<ul style="list-style-type: none"> ◆ Grid-cell specific ◆ Publicly available ◆ High data recovery 	<ul style="list-style-type: none"> ◆ Grid resolution ◆ Regional biases ◆ Greater uncertainty 	<ul style="list-style-type: none"> ◆ Initial prospecting ◆ Smaller projects ◆ Correlation with on-site data
Surface Reference Stations	<ul style="list-style-type: none"> ◆ Higher accuracy ◆ Period of record may be longer ◆ Publicly available 	<ul style="list-style-type: none"> ◆ Sparsity of sites ◆ Proximity to project site ◆ Uncertainty due to O&M, instrumentation and inconsistencies in the data 	<ul style="list-style-type: none"> ◆ Confirm trends ◆ Identify regional biases ◆ Correlation with on-site data

In order to obtain a high-confidence estimate of the solar resource, multiple data sources are often analyzed in ensemble. This allows the analyst to leverage the relative advantages of multiple data sources. For example, the measure-correlate-predict (MCP) approach is a common method for adjusting on-site data with a short period of record to represent the long-term mean. Using this approach, solar irradiance data measured during the monitoring program is adjusted to a long-term value by correlating the on-site measurements with long-term reference data. This allows for the value of the high-confidence on-site measurements to be combined with the value of the reference data source's longer period of record, resulting in a high confidence long-term solar resource estimate. Analysis techniques utilizing multiple data sources, such as MCP, have the potential to reduce the uncertainty in solar resource estimates.

Sources of Uncertainty

Statistical uncertainty is defined as the estimated amount or percentage by which an observed or calculated value may differ from the true value.⁴ There are a multiple factors contributing to uncertainty in solar energy production estimates, which are outlined below.

Measurement Accuracy: This uncertainty addresses the accuracy of measured or modeled data used to represent the project site. Factors considered include the sensor types and counts used for on-site measurements, sensor non-stability, preventative site maintenance, and sensor calibration. Uncertainty associated with measurement accuracy was the focus of the case study described in this paper.

Inter-Annual Variability: This uncertainty addresses natural differences in the solar resource from year to year. Inter-annual variability is calculated from multiple years of high-quality reference data and varies by region.

Representativeness of Monitoring Period: This uncertainty addresses how well the period of record represents the long-term historical average. Considerations for this uncertainty include the measure of correlation between the on-site and reference data, their periods of record, on-site data recovery, and the inter-annual variability.

Spatial Variability: This uncertainty addresses the spatial variation in the solar resource across the region of interest. The effect of spatial variability on energy production is related to the total land area to be used by the solar PV project.

Transposition to Plane of Array: This uncertainty addresses the accuracy of the transposition of the horizontal radiation components to the plane of the photovoltaic array.

Simulation & Plant Losses: This uncertainty addresses the performance simulation and derived plant loss factors, including losses for effective irradiation, photovoltaic conversion, electrical systems, plant operation, and annual degradation.

Impact of Uncertainty

Although there are multiple areas of uncertainty during a project's development process, uncertainty in the solar resource estimate is one of the most significant sources of the overall energy production uncertainty (Figure 2) making the selection of an appropriate reference data source critical for reducing uncertainty in the solar resource estimate, which in turn increases the confidence in the project's energy estimate.

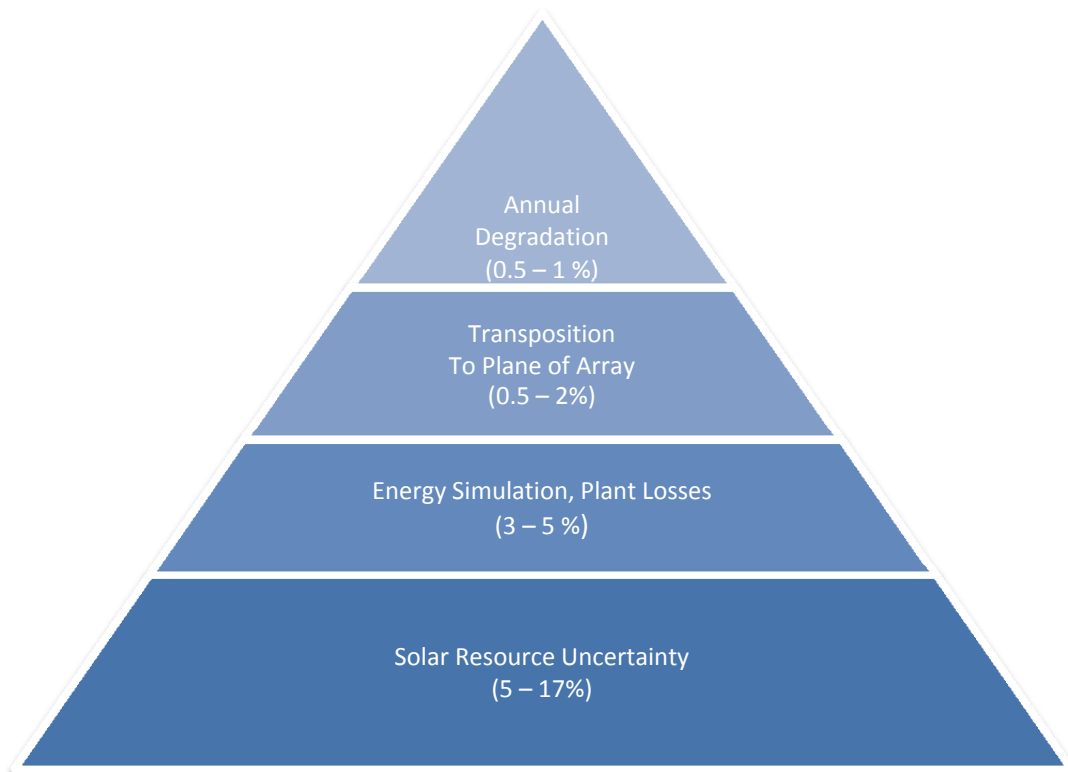


Figure 2: Components of Project Energy Uncertainty

Solar resource uncertainty can be broken down into four categories, shown in Figure 3. The measurement component of solar resource uncertainty is often the greatest contributor, and can range significantly depending on the data source used. Modeled data sources have measurement uncertainties in the 8 to 15% range. On-site measured data has much lower measurement uncertainty, depending on the quality of instrumentation and the frequency of on-site maintenance: a regular schedule for leveling and cleaning solar sensors is necessary to achieve the lowest measurement uncertainty.

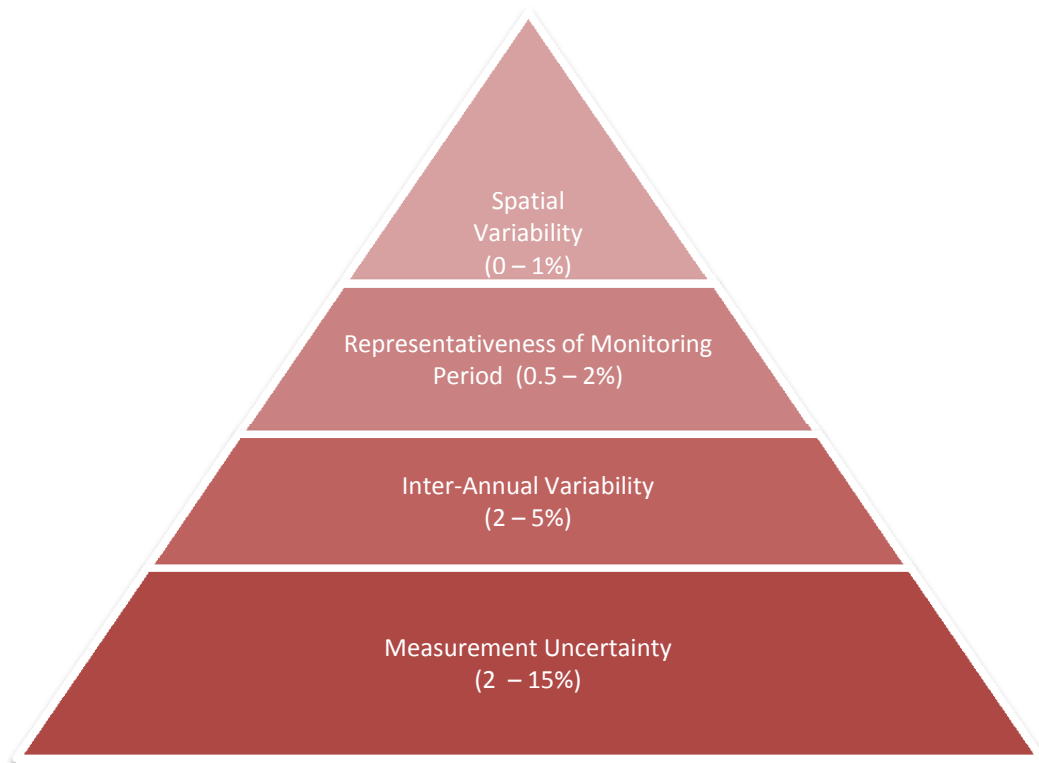


Figure 3: Components of Solar Resource Uncertainty

Probability of Exceedance

To quantify the energy risk for a project, financial stakeholders rely on the concept of probability of exceedance, or the level of confidence that a project's actual energy production will achieve at least a certain value based on the energy production uncertainty. The 50% confidence estimate, known as the P50, represents the best estimate of the solar project's expected energy production. Theoretically, there is an equal likelihood that actual generated production will be either higher or lower than the P50. Using the P50 as a baseline, investors and lenders calculate more conservative energy estimates that have a higher probability of being generated (or exceeded) during any given year of plant operation. For example, the energy value that can be expected with 90% confidence is called the P90. Actual energy generation is expected to match or exceed the P90 estimate 90% of the time. Figure 4 is provided to help to demonstrate the concept of the difference between the P50 and P90.

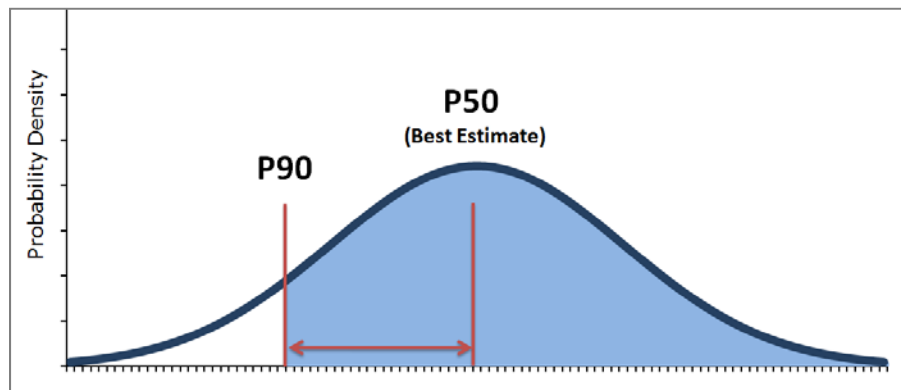


Figure 4: Characterization of a Project's Uncertainty and Probability of Exceedance

The value of the P90, P95, and P99 are directly related to the amount of uncertainty in the energy production estimate. The higher the uncertainty, the lower the P90 compared to the P50. Therefore, reducing uncertainty is a priority for project stakeholders to maximize the P90 energy and minimize project risk.

According to Fitch Ratings, Moody's Investors Service, and Standard and Poor's, P90, P95, and P99 confidence intervals are commonly used to evaluate the relative risk of solar PV projects.

Approach

To demonstrate how solar irradiance data affects uncertainty in energy production estimates, a case study was conducted for 11 sites in the U.S. using modeled and measured data. On-site data was collected with LI-200 pyranometers with each site having a period of record of a year or more, while the satellite-modeled data with a 13-year period of record was selected as the long-term reference data source. At 9 of 11 sites, regular on-site maintenance was conducted and in doing so increased the confidence in the measurements from these sites.

Annual GHI was evaluated from each data source to show how results from modeled data may differ from on-site data. For the modeled data, the long-term mean was calculated directly from a 13-year period of record. For the on-site data scenario, the shorter period of record was adjusted using a long-term reference data source and the MCP methodology. Since a percent difference in solar resource approximately translates to the same percent difference in energy production, the difference from these data is useful to understanding the impact of the selected data source on energy production estimates.

In addition to comparing the magnitude of the solar resource from different data sources, two uncertainty estimates were developed, one using satellite-modeled data and the other using on-site data. A comparison of the resulting uncertainty was conducted to show how confidence can be increased by using on-site measurements. The P90 energy estimates were compared for typical modeled data and on-site data scenarios to show how site-specific measurements influence the results.

Comparison of the Magnitude of the Solar Resource

For the 11 sites evaluated, the estimate derived using on-site measurements was compared to the satellite-modeled long-term irradiation estimate. The results in Figure 5 and Figure 6 show a mean difference of 2.8% between the satellite model and on-site estimates, ranging from 0.1 to 6.2%. When translated to energy, this difference has a similar percentage impact on the projected energy output.

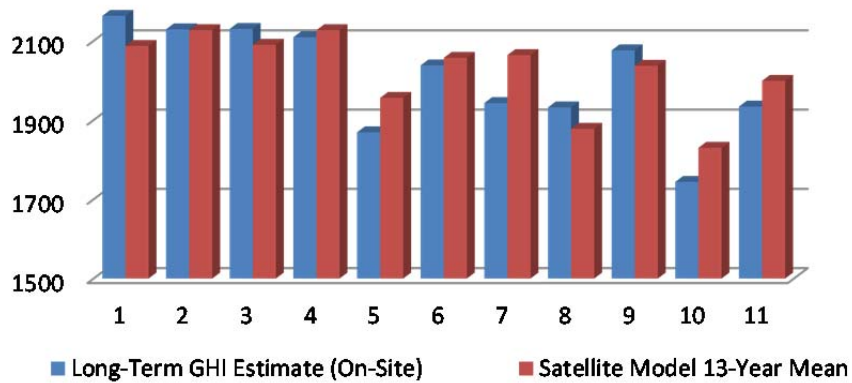


Figure 1: Annual GHI Estimate from Satellite-Modeled Data and On-Site with MCP

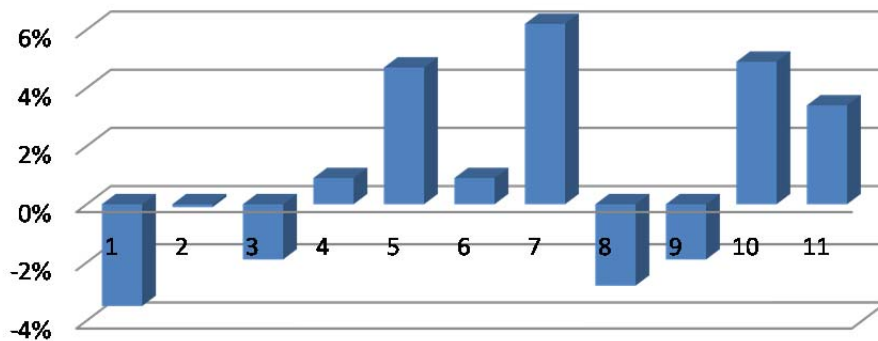


Figure 6: Percent Difference of Satellite-Modeled GHI vs. GHI from On-Site Data with MCP

Comparison of Uncertainty Estimates

A comparison of the resulting energy uncertainty estimates shows how confidence can be increased and uncertainty decreased by incorporating data from on-site instrumentation. For both scenarios, combined energy uncertainty was calculated by combining the following uncertainties in quadrature:

- ◆ Measurement uncertainty
- ◆ Inter-annual variability
- ◆ Representativeness of the monitoring period
- ◆ Spatial variability

For both the on-site data and satellite-modeled data scenarios, uncertainties were applied uniformly with the exception of the measurement component. Based on published model uncertainties and experience with various satellite models, a measurement uncertainty of 8.5% was assigned for the satellite data. This led to a combined uncertainty range of 8.7% to 9.5% for the 11 sites, with a mean uncertainty of 9.2%. Based on the instrumentation installed on-site and the frequency of site maintenance, measurement uncertainties between 4% and 6% were assigned for the assessment using on-site data. Each site's measurement uncertainty was. This led to a combined uncertainty range of 4.5% to 7.3%, with a mean uncertainty of 5.7%.

Figure 7 shows the difference in uncertainty from the two scenarios. On average, on-site monitoring reduced the project's expected uncertainty from 9.2% to 5.7%, or approximately 3.5%. Two of the 11 sites (10 and 11) exhibited poor or undocumented maintenance practices, which increased measurement uncertainty by 2% for these sites. Excluding these two sites as outliers, the mean reduction in uncertainty was 3.9%.

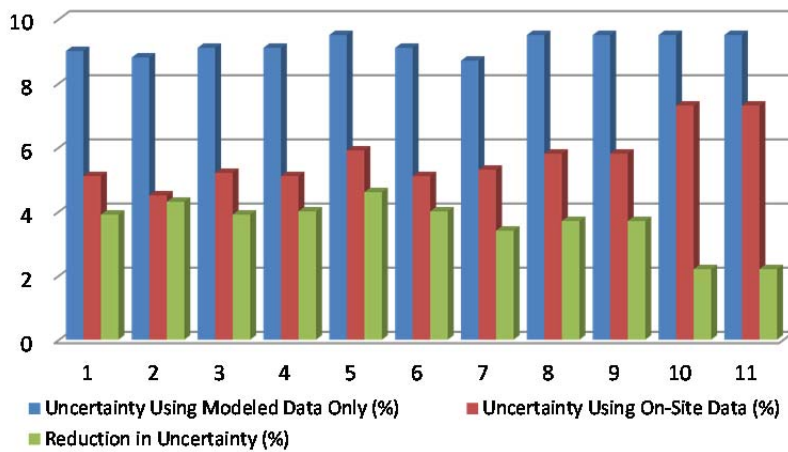


Figure 7: Difference in Energy Production Uncertainty using Modeled Data and On-Site Data

Comparison of Probability of Exceedance

The combined uncertainty for each case can be used to generate higher confidence solar resource and energy estimates. As shown in the probability density plots in Figure 8, the greater uncertainty associated with modeled data results in a wider distribution curve, with greater distance between the P50 and P90 estimates. Having on-site measurements results in a tightening of the curve, and the P50/P90 difference becomes smaller to coincide with a higher confidence estimate.

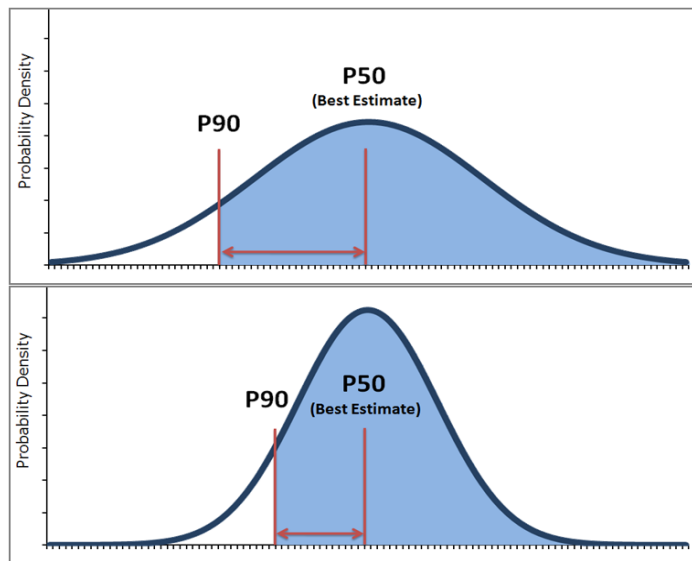


Figure 8: P90 Comparison of Satellite-Modeled Data (Top) and On-Site Data with MCP (Bottom)

A greater solar resource uncertainty has a greater impact when applied at higher confidence intervals, shown in Figure 9. When calculated as a percent of the P50, the difference between modeled and on-site measurements at higher confidence intervals results in a greater difference between the two. At the P90 confidence interval, a difference of approximately 5% was observed, while a difference of almost 10% was observed at the P99 confidence level. Figure 9 helps to show how having on-site measurements with lower uncertainty results in a higher confidence resource and energy estimate.

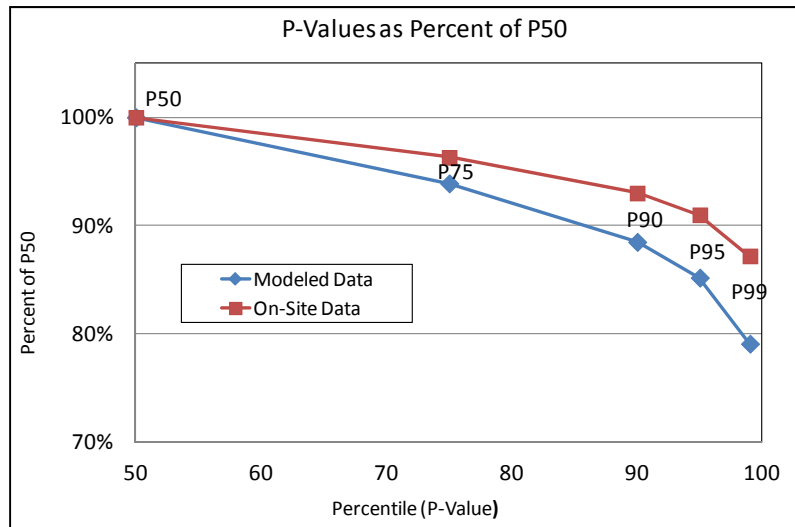


Figure 9: Impact of Uncertainty on Higher Confidence Levels as Percent of P50

Part 6 CONCLUSION

With the increasing size of solar projects in recent years, site-specific measurements have become increasingly important to accurately characterize solar energy production. Site-specific measurements generally help to reduce risk perceived by those who may eventually have a financial stake in the project. This may improve the financeability of projects when being evaluated by potential investors.

To demonstrate the potential uncertainty reduction that may be achieved by collecting site specific measurements, a case study was conducted at 11 locations in the United States Desert Southwest. The case study evaluated the difference in solar magnitude between site-specific measurements and commonly used modeled data sets. The percent reduction in uncertainty was evaluated and its impact on probability-of-exceedance energy estimates was assessed.

The case study of 11 sites in the United States demonstrated the importance of on-site data collection in the following ways:

- ◆ **Magnitude of the Solar Resource.** The long-term GHI calculated from modeled data differed from the long-term GHI estimated using on-site data by 2.8% on average, with one site differing by as much as 6.2%. When translated to energy, this difference has a corresponding impact on the projected energy output.
- ◆ **Impact of Uncertainty.** On average, on-site monitoring reduced the overall uncertainty from 9.2% to 5.7%, or approximately 3.5%. This is a significant reduction when considering the application to probability-of-exceedance energy estimates.
- ◆ **Value of On-Site Maintenance.** Lack of regular on-site maintenance to clean and level instrumentation can increase measurement uncertainty by as much 2%. *For sites with regular on-site maintenance, the average uncertainty reduction over modeled-data was 3.9%.*
- ◆ **Impact on Probability-of-Exceedance Energy Estimates.** A greater solar resource uncertainty results in an even a greater impact when applied at higher confidence intervals. Using typical uncertainty estimates, on-site monitoring can increase the P90 by over 5% and the P99 by over 10% as shown in Figure 8.

Endnotes

¹ Quote from *Rating Criteria from Solar Power Projects*, Fitch Ratings, 02-2011.

² Source: ESRI, Inc.

³ National Solar Radiation Database 1991-2005 Update: User's Manual, pg 8. National Renewable Energy Laboratory. 04-2007.

⁴ Source: www.thefreedictionary.com/uncertainty, definition 3.



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Other Resources

AWST presented a webinar on this topic, which is available at www.awstruepower.com.

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