
APPLICATION NOTE

PREDICTING AND MONITORING PV ENERGY PRODUCTION

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SUMMARY

The measurement and prediction of photovoltaic energy production is a fundamental sub-discipline in PV system science and engineering. Measurement and monitoring, as compared to prediction, is generally simpler. Prediction, because it is dependent upon weather, is more challenging. Measurement and prediction of PV can be used to compute revenues based upon electricity tariffs, or to create construction contract terms for bonuses or liquidated damages, for utility grid management, or for system owners' warranty and O&M, or many other applications. Whatever the goal, the processes and methods are critical to the physical and financial viability of PV technology and its integration into the utility grid. Though they are described separately in this application note, prediction and monitoring are frequently done simultaneously. This results in a performance ratio. This ratio is a metric which quantifies the expected vs. delivered system production. This application note provides a broad overview and introduction to the topic.

Monitoring PV production has much in common with the monitoring of energy production from conventional energy generating systems such as gas turbines or reciprocating engine generators. As with conventional generators the PV system has a physical plant with technologies and method for monitoring the state of the system. Incident irradiance, module cell temperature, dc and ac currents and voltages, and other parameters are typical PV system and environmental states which are monitored. Of these parameters, solar irradiance is the prime mover and by far the most influential. Ambient temperature is the second most influential factor following by an order of magnitude. The irradiance hitting the array is the "fuel" and primary input to the system. Similar to conventional energy generating plants, PV systems have an electrical output which is monitored and/or metered for the revenue derived from the creation of that energy. The output is also monitored to detect failures and defects in the plant. In both cases – whether monitoring the status of the plant or metering its output – the data are collected through direct physical measurements.

Simulation or prediction of PV energy production differs from monitoring. The input may be either measured or calculated. The output is not measured; it is calculated. Simulation is a two part process entailing use of a set of input parameters and a model or transfer function of the physical plant used to calculate the production of a PV system. Those input parameters typically include incident irradiance and temperature data and other third and fourth order parameters, such as wind speed and direction, which form the generating system prime movers. Models of the physical plants for PV systems and their constituent components – panel characteristics, inverter efficiency, wire losses, shading impacts, thermal behavior, etc.—are very well understood. The accuracy of these models is generally limited largely by the geometric complexity of the system being modeled and by the skill of and investment in time by the person modeling the system. The data sources for the prime mover model inputs may include historical meteorological databases, forecasts of irradiance derived from numerical weather prediction models, satellite data, measured ground level irradiance and cloud cover data or combinations of any or all of the above. Predicting or forecasting the environmental inputs for PV production models is, in many ways, the science of weather prediction. In particular for near term predictions it is the practice of cloud cover forecasting.

This application note will provide an overview of the current state of the art in prediction and monitoring for grid connected PV system energy production. "Off-grid" or "stand-alone" PV systems with energy storage require a different type of analysis than will be covered here. Similarly the fields of study in micro-grids and "smart grid" applications, which incorporate PV along with demand response, energy storage, and other forms of distributed generation, are beyond the scope of this application note. And so too is the emerging practice of bulk energy storage as it relates to prediction and mitigation of PV system variability. Though these practices will not be reviewed in detail, all of them which include PV require, as a starting point, the prediction, simulation, monitoring and modeling capabilities which we will focus on here.

THE SOLAR RESOURCE: PV'S PRIME MOVER

"Law, say the gardeners, is the sun, Law is the one All gardeners obey, To-morrow, yesterday, to-day."¹

For PV technology the sun is the prime mover. The prime input to the PV system is the solar irradiance incident upon the surface of the modules. Measured in units of Watts per square meter (W/m^2), that incident irradiance is a power density. It is the fuel of the PV plant. Integrated over time incident irradiance becomes Watt-hours per unit area. And when the commercial output is considered, it is in units of Watt-hours or kilowatt-hours (kWh) in the form of electrical energy.

The solar irradiance which PV converts to electrical energy is a form of electromagnetic radiation. It is part of the spectrum which we refer to broadly as sunlight. That radiation is an unvarying value outside of the earth's atmosphere, known as the solar constant, of $1,370\text{W}/\text{m}^2$. On the earth's surface the value varies with latitude, season, altitude, and micro-climates. As with other forms of radiation, solar irradiance can be blocked and scattered by obstructions between the source and the array surface. Obstructions can include local items such as nearby trees and building and more distant features such as hills or mountains. Particulates, water vapor and other aerosols in our atmosphere block and scatter the sunlight. Aside from the impact of latitude and geographic location, cloud cover is a principal factor impacting ground level irradiance. The three most commonly measured forms of irradiance studied for their impact on PV production are direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and global horizontal irradiance (GHI). Direct normal irradiance is the unobstructed beam component of irradiance, measured on a plane facing normal to the rays of the sun. This is most evident on clear days when the sun's light casts sharp and distinct shadows. Diffuse horizontal irradiance is the component of sunlight, measured on a horizontal surface facing up into the dome of the sky, which is scattered by clouds and hazy skies. Under conditions of high diffuse irradiance shadows can be imperceptible. Global horizontal irradiance is the total irradiance, measured on a horizontal surface facing up into the dome of the sky, which combines both the beam and scattered components. Global horizontal irradiance is the simplest and most common irradiance measurement made and recorded.

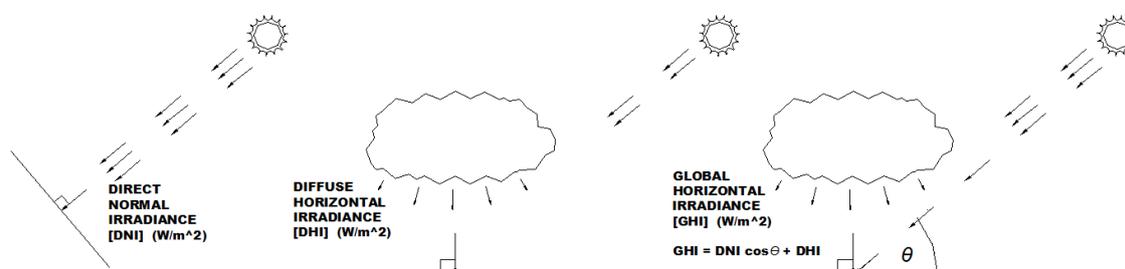


Figure 1 – Direct normal and global and diffuse horizontal irradiance.

These irradiance components, DNI, DHI, and GHI, together describe the solar resource of a region or site (1). Together, in an instant in time or over a historical period, these parameters provide the information needed to determine the incident irradiance on the surface of a PV system. A common expression of that incident sunlight is “plane of array” or POA irradiance². POA irradiance, whether measured or simulated, is the dominant input to any PV production model. If direct normal and diffuse horizontal irradiance are known, and

¹ Law Like Love, W. H. Auden.

² Another common expression of incident irradiance is “global tilt irradiance” GTI.

if the location, date, time and surface orientation of a PV array are known then, using a process known as “transposition,” plane of array irradiance can be calculated for any array orientation.

Solar irradiance is, on average, on an annual basis, periodic and predictable. However, on an hourly basis, on the earth’s surface, solar energy is fundamentally intermittent. PV system owners, PV investors, energy market participants, and electric utility grid operators all have a financial interest in predicting and monitoring the energy production of these systems. Technologies and methods to do this are well established but are under continual improvement in a highly competitive research and development environment. The history of assessing the solar resource for its commercial value for agriculture or energy production starts with ground based measurement technology and progresses to weather modeling and satellite observations. Similarly does the practice of prediction and modeling of PV production. What follows is an overview of technologies and approaches for predicting and monitoring photovoltaic production currently used in the industry.

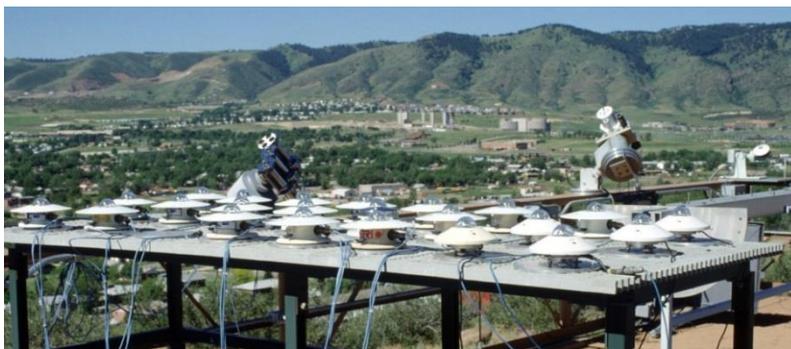
GROUND BASED MEASUREMENT DATA

GROUND BASED METEOROLOGICAL STATIONS

Ground based solar monitoring stations range from simple plane of array (POA) irradiance measurements using a silicon pyranometer for a PV system to highly sophisticated installations measuring direct normal, diffuse horizontal and global horizontal irradiance (DNI, DHI, GHI) with high accuracy instruments. Most commercial PV installations larger than 500 kW have some level of irradiance monitoring capability for performance verification. Broadband thermopile pyranometers are within about 3% uncertainty and are often preferred over silicon-based photodiode devices which have about 5% uncertainty. When employed at a PV installation or when used by an electric utility, the irradiance data can be integrated into the host SCADA data stream. Ground-based instrumentation is used



for long term assessment and characterization of the solar resource of a region. This type of assessment is done in Europe by the EU’s Joint Research Centre’s Photovoltaic Geographical Information System (PVGIS) and in the United States by the National Renewable Energy Laboratory (NREL), Sandia National Laboratory, the National Oceanic and Atmospheric Administration (NOAA), and by the National Aeronautics and Space



Administration (NASA) [2]. In the private sector, ground based irradiance instrumentation is often used for solar resource prospecting when considering a major investment in a PV installation. Irradiance instrumentation is also used for performance verification at the time of commissioning or throughout the life of a solar plant.

Figure 2 – Irradiance measurement instruments. Rotating shadowband radiometer (upper right). Thermopile pyranometers being calibrated at NREL (lower left).

SKY IMAGING CAMERAS

Ground-based measurements which use the wide angle cameras or other sky imaging technology infer ground level irradiance over a region from the projected cloud movement and estimated sunlight at the top of the atmosphere. The sky imager approach requires a ceilometer to determine cloud height because the imager’s “field of vision” and thus effective area of coverage varies with cloud height. As is the case with any ground-based irradiance measurement system, sky imaging approaches are susceptible to errors caused by soiling of

the device lenses. These systems are being developed for short horizon forecasting of irradiance –in the range of minutes to hours (2).

AGGREGATED GROUND BASED SENSORS

A novel approach to continent level solar resource assessment which is being done in North America is the aggregation of sets of existing sensors from a wide variety of unrelated industries. Irradiance sensors from agricultural monitoring stations, university R&D, government agencies, and weather monitoring networks are being aggregated, filtered and synchronized to form a patchwork of ground-based measurement coverage. A company called JHtech provides a broad irradiance resource service called Solar Data Warehouse which covers most of the United States. The service is based upon a network of over 5000 publicly available irradiance measuring stations (3).

WEATHER DATA MODELS & FORECASTS

Numerical weather prediction (NWP) models are being used to model and predict cloud patterns which, when combined with projections of cloud shadows based upon cloud height and irradiance at the top of the atmosphere, yield ground level irradiance patterns. Firms specializing in solar resource assessment use NWP to provide commercial irradiance mapping. National weather services in the United States and Europe provide forecasts of a range of parameter, including sky cover, which can be converted to ground-level irradiance estimates using transmittance models (4).

HISTORICAL IRRADIANCE & WEATHER DATABASES

Historical databases of irradiance and weather parameters are key inputs for models which are used to calculate PV generation. These databases contain various combinations of direct normal, diffuse horizontal and global horizontal irradiance, as well as ambient temperature, humidity, cloud cover, and a host of other environmental variables. These data are used to model the incident irradiance on PV arrays and thus the output of the systems. Because of the heavy influence of weather these resources are essential for predicting PV system production.

TYPICAL METEOROLOGICAL YEAR (TMYx)

In the United State NREL has created the Typical Meteorological Year (TMY) database of irradiance and meteorological parameters for 1020 locations across the USA, Guam, Puerto Rico, and US Virgin Islands for use in solar and building energy modeling. Currently in its third version, the TMY3 data are based upon a period of record from 1976 to 2005 for a portion of the sites and from 1991 to 2005 the remainder. Each data set for each of the 1020 locations provides 8760 one hour values of direct normal, diffuse horizontal and global horizontal irradiance, along with over a dozen meteorological parameters. Best described in the TMY3 User Manual itself, “A typical meteorological year (TMY) data set provides designers and other users with a reasonably sized annual data set that holds hourly meteorological values that typify conditions at a specific location over a longer period of time, such as 30 years.” Each data set is comprised of 12 specific months from different years which are judged to be “typical” and which are then concatenated into a representative year. The intent of the nominal thirty year period of record is to address issues of inter-annual variability in the climate record. These data provide inputs to models for multi-year production estimates for photovoltaics, concentrating solar power, solar water heating, and building thermal modeling (5).

METEONORM

A commercial irradiance and meteorological database similar to the TMY data sets is the Meteonorm product. Meteonorm is a global weather database and is used by simulation programs to model PV production, solar thermal applications and building modeling programs (6).

SATELLITE DATA

Much of the weather data cited previously is derived in part or entirely from satellite data. Imagery from geostationary weather satellites has been adapted from their original weather applications to use for estimation of ground-level irradiance. The specific irradiance estimating applications range from continent scale annual resource assessment to high resolution (5 km² pixel resolution) assessment, to near-real-time cloud motion vector forecasts. Satellite based approaches infer ground level irradiance from the projected cloud movement and characteristics. Presently the images from satellite based systems update no more frequently than every 15 minutes. In North America the primary platforms are the GOES weather satellites. In Europe, the Sat24 supplies data for these applications (7).

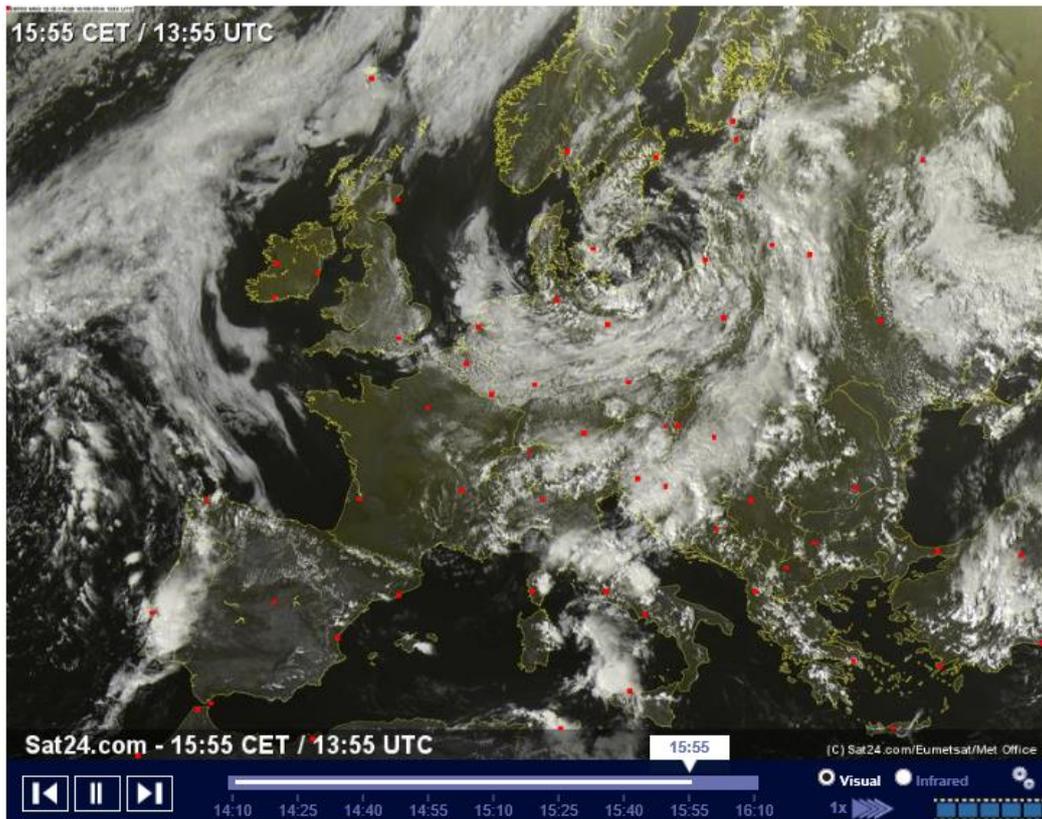


Figure 3 – sat24 satellite image of cloud cover over Europe.

PRODUCTION ESTIMATION METHODOLOGIES

All PV production estimation and prediction utilizes some form of model of the PV system or plant. That PV production model is a transfer function converting an irradiance input to electricity output. The model can characterize the PV cell level, the module level, the string or inverter level, or an entire PV plant. The methods vary and may use measured or simulated irradiance input data. Common to all of these modeling methods is the calculation of an output based on irradiance input and a set of system characteristics.

Any discussion of the PV production methods and models must start with the definition of the industry's key metric, the peak Watt (W_p) or Watt STC (W_{STC}) or simply the Watt (W). This is the power rating of a PV cell or module measured under controlled laboratory conditions known as "Standard Test Conditions" or STC. This parameter is a standardized, measured value for any PV module and is the "rating" of the module. The standardized conditions under which these measurements are performed are: 1000 W/m² irradiance, 25°C cell temperature, and air mass of 1.5³. The power output value measured under these laboratory/factory controlled conditions becomes the STC rating or nameplate rating of the module. Although these conditions rarely occur together in nature, they form the industry reference for manufactured products. This reference is used in one manner or another in most modeling approaches.

COMPONENT MODELING

Two approaches to modeling the conversion efficiency of a photovoltaic system include *the single diode model and the PV module model*. In the single diode model, the fundamental factory-measured characteristics of a single PV cell makes up the module in question for the active PV system. In the module approach –here we cite the Sandia Photovoltaic Array Production Model-- the module in question is characterized through empirical field measurements (8).

SINGLE DIODE EQUIVALENT CIRCUIT MODELS

This approach models the behavior of a single PV cell as an equivalent photodiode circuit and then concatenates the output up to module level with series and parallel strings of cells. Using this approach, the full module is characterized from its constituent cells. In PV system simulation models which employ this approach, strings of modules are then modeled in successive series and parallel combinations to form arrays. Arrays of modules are combined to form full systems (9).

SANDIA PV ARRAY MODEL

In the 1990s' Sandia National Laboratories developed a new model for PV production. In the Sandia PV Array Performance Model the equations are developed at the cell level, but the input parameters are empirically derived from test of specific modules. The electrical and thermal effects are characterized in the model and captured in the sample module outdoor data collection. Solar spectral and optical characteristics of the tested modules are captured and reduced to an effective incident irradiance value (E_e) at the cell level. The model has been thoroughly validated and its basic equations are used as the computational engine of a number of widely used simulation models such as the US National Renewable Energy Laboratory's PVWatts.

PV MODULE EFFICIENCY

PV module efficiency is a measure of the rate of conversion of incident solar power to dc electrical power at the terminal of the module. It might surprise some who are new to the industry but module efficiency is not a

³ The air mass affects the spectral distribution of sunlight.

common parameter on commercial specification documents (it does appear on some manufacturer’s literature, but generally only those whose products are at the higher end of the commercial continuum). What does appear on specification sheets is the module’s STC rating. Typically a single specification sheet will list between three and six versions of a PV module with different STC ratings. These different versions are a consequence of variation in the manufactured product quality and “binning” of the final yield⁴. Module ratings will typically increment by a value of 5 W_{STC} between versions of a single model. All versions of a product model within a specification will share the same mechanical characteristics and thus the same physical area. Module efficiency is the ratio of the module’s STC rating, divided by the STC irradiance reference of 1000 W/m² and the area of the module:

$$eff = \left[\frac{\text{Module Power Rating}(W_{STC})}{\text{Module Area}(m^2)} \right] \div \left(\frac{1000W}{m^2} \right)$$

Equation 1: PV module efficiency.

In algorithms which model PV plant production and performance, the differences in module efficiency are embedded in the calculations. It is a multiplier value less than 1.

PV INVERTER EFFICIENCY AND RATING

Inverter efficiency is a loss in the model of the physical plant of a PV system. This value is the conversion loss from the dc electrical input to the ac electrical output. In recent years, manufacturers have pushed the bounds of inverter efficiency to within a few percentage points of 100%. There are different methods for measuring and modeling inverter efficiency. That discussion is beyond the scope of this application note. Inverters typically reach their peak efficiency after about 40% of their nameplate capacity.

Another factor that has to be taken into consideration when modeling PV production and performance on a system level, is the power rating of the inverter in relationship to the power rating of the PV array. This is generally referred to as the DC/AC ratio. For example, if a PV system had an array of modules whose combined STC rating was 130kW and a single inverter with a nameplate rating of 100kW, would say that the system had a DC/AC ratio of 1.3. For inverters their nameplate power rating is a fixed upper limit on their ability to convert dc power into AC electrical output. If the instantaneous dc power available to the inverter exceeds its rating the ac output will simply limit or “clip” at the nameplate rating. It is typical for the dc capacity of a PV system to be designed larger than the ac rating of its inverter to achieve a more efficient utilization of the inverter during those times in the daily cycle –mornings and evenings—or times in the annual cycle –winter months—when irradiance levels are low. In recent years, with declining module prices, PV system designers have been increasing DC/AC ratios. Because of this, this clipping behavior can often be seen in the modeled output of PV plants on days with high irradiance.

PLANT CAPACITY MODELING

PV systems are different from most of the electrical equipment because their performance is intrinsically linked to the unique details of their site and the specifics of their installation. We can be confident that 5 horsepower motor will develop the rated power when connected to a grid source because the grid is maintained at a constant nominal voltage. With a photovoltaic system the performance is dependent upon

⁴ As with other semiconductor manufacturing there is variability in the performance of PV cells. Manufacturers test the cells and categorize or “bin” them into different power performance classes. This binning results in a range of power ratings for any given model of PV module.

the solar resource at its particular latitude and the daily variations in cloud cover and temperature. The shading experienced by any PV array is a consequence of the physical details of the installation such as the proximity to buildings and trees, and the tilt and azimuth angles of the array. Two PV systems with identical nameplate ratings, located in the same latitude and longitude, can have very different output. Differences in environmental shading must be precisely modeled to insure accurate simulation of system performance.

BALANCE OF SYSTEM LOSS MODELING

In addition to modeling the inverter losses in a PV plant, an accurate model will account for module soiling, annual power degradation, module mismatch, thermal characteristics, and Ohmic losses in both dc and ac conductors. The loss diagram below provides a breakdown of losses in a PV system (modeled with the software program PVsyst).

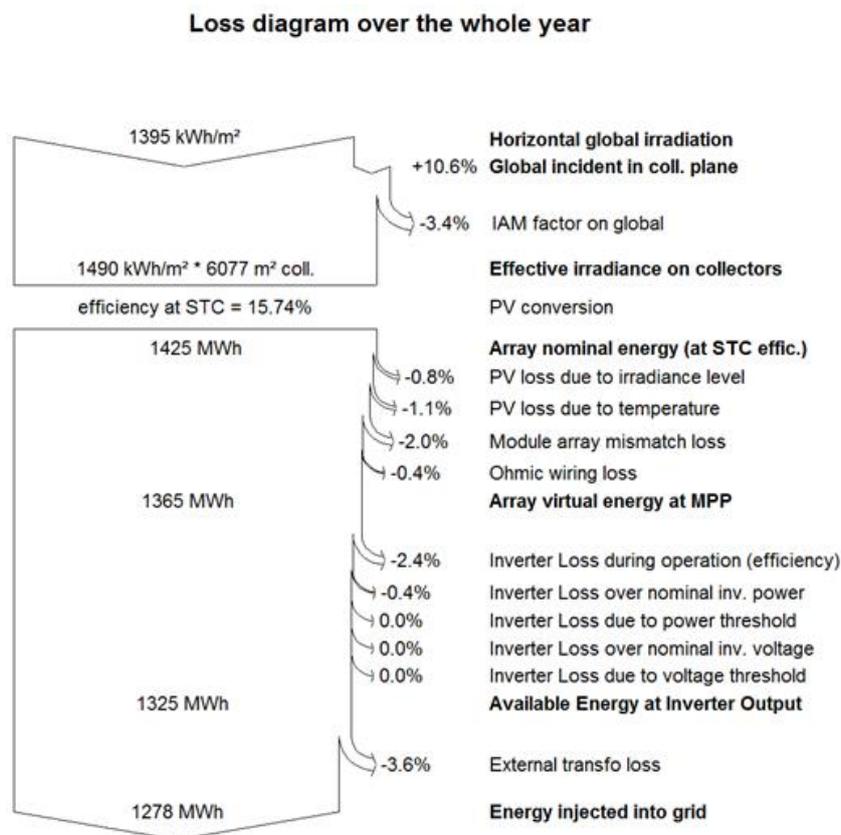


Figure 4 – PVsyst PV modeling software system loss diagram.

PV SYSTEM RATING USING REGRESSION ANALYSIS

The basic dilemma faced by anyone attempting to determine the power rating of a grid-paralleled photovoltaic installation is that they cannot simply use the nameplate-rating of the equipment at face value. The reason is that the sun is moderated by the atmosphere, which is not constant. In addition the characteristics of the installation which are not accounted for by the nameplate rating of the PV array can have a significant influence on the final production capacity of the system. STC specifications were developed to provide PV module manufacturers with a basis for rating and comparing one module with another. Standard Test Conditions rarely occur simultaneously outside of the laboratory.

Regression analysis techniques have been developed as one means of providing the equivalent of an STC rating for PV systems installed in the field, taking into account all of their unique features. One such regression

technique was developed in the 1990's under a program called PV USA (10). The rating method bears the name, PV USA Test Conditions or "PTC". It was initially devised as an empirically derived field rating method for PV systems. Various forms of the method have been implemented over time. In the original version, plane of array irradiance, ambient air temperature, and wind speed data were collected for approximately 30 days. The data set was then filtered for records which were at least 500 W/m² or greater in the plane of array. The system rating was then based upon a regression analysis using these data. The equation used for classic version of the analysis is

$$P_{sys} = Irr \times A + Irr^2 \times B + Irr \times T_{amb} + Irr \times WS \times D$$

Equation 2: PVUSA Test Conditions regression formula.

Where P_{sys} is the system output power in kWac. Irr is the plane of array irradiance in W/m². T_{amb} is ambient air temperature. WS is wind speed. And A , B , C , and D are regression coefficients. Once the coefficients for a particular PV system have been determined through the regression process a simulation of that system's output can be done for any combination of plane of array irradiance, ambient temperature, and wind speed.

SYSTEM RATING USING IV CURVE TRACING TRANSLATED TO STC

Another method for modeling a PV system is to use an IV curve tracing tool to create power curves for each source circuit in a PV array. The IV curve tracer measures string currents and voltages while varying the operating point of the PV string. At the same time the tool measures the plane-of-array-irradiance" and "back-of-module" –temperature. During the measurements and in post processing, the IV curve tracing software "translates" the IV curves taken at the specific irradiance and temperature conditions to the curves at standard test condition (STC), which is a process of normalization. The IV characteristics are recalculated based upon environmental conditions of 1000 W/m² irradiance, 25°C cell temperature, and air mass of 1.5. While this process may not take into account all factors such as shading from near objects it is one method for rating a PV plant. Figure 5 illustrates the IV curve from one string in a PV array at both the actual irradiance level at the time of the measurement and the string's equivalent performance had it been exposed to standard test conditions (the higher curve is at STC).

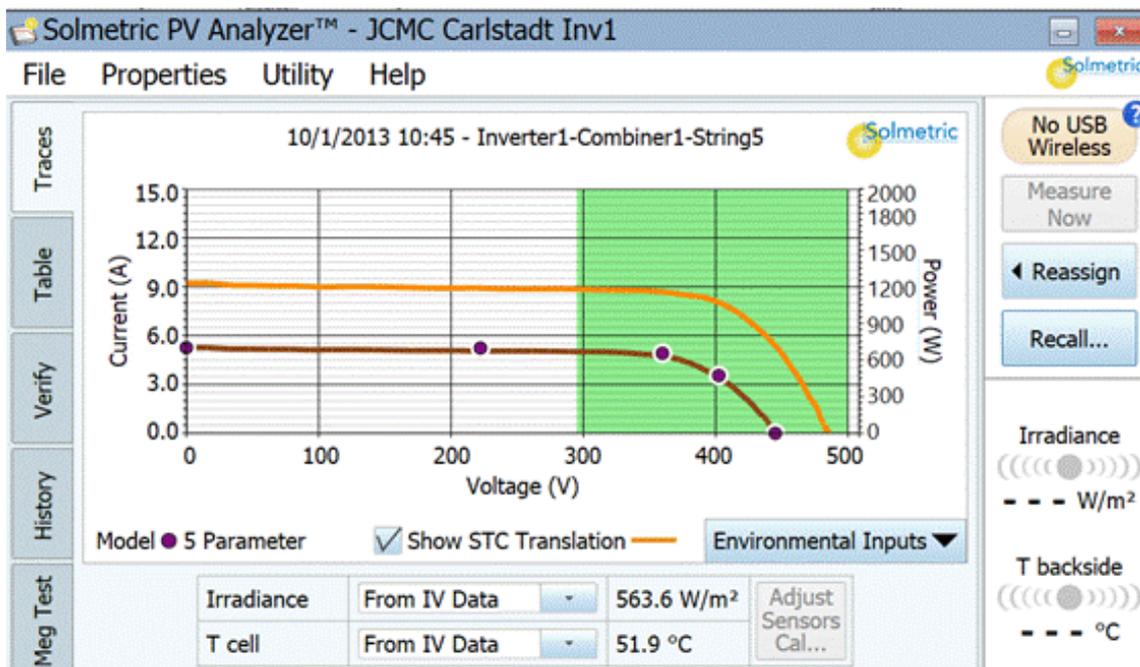


Figure 5 – PV module IV curve translated to its STC rating (Solmetric, Inc.).

MODELING: FEASIBILITY STUDIES, PERFORMANCE VERIFICATION

A PV system feasibility study addresses the question, “Given the expected solar resource, what will a PV system of a particular size and specifications, in a particular location, produce over its useful lifetime?”⁵

A PV system performance verification study addresses the question, “Given the measured solar resource since start up, is a PV system, as it was built and at its particular location, meeting its estimated production goals?”

FEASIBILITY STUDIES (PRE-CONSTRUCTION)

For system owners and financial investors PV feasibility studies mitigate risk by addressing the issue of ROI and the ability of the borrower to service debt. PV system feasibility studies typically begin with a survey of the location being considered for the installation. The survey might begin with an analysis of satellite images from which roof and ground maps are created and follows with a visit to the prospective PV site. The engineer will survey the candidate roof and/or ground locations taking measurements and documenting the existing conditions such as shading obstructions, roof/ground slope, mounting obstructions, and overall dimensions. The electrical infrastructure is also documented with a focus on grid interconnection options. A hypothetical design example may be done for a system based on the available real estate and the recommended electrical interconnection. Typical feasibility studies for a grid-tied PV system will include a technical analysis of the site and a financial analysis based upon the technical findings. The technical analysis will include assessment of the solar resource --annual equivalent sun hours and shading impacts. The potential system size in kilowatts, based upon a range of PV module technologies or the customer's preferred module, will be estimated. Array orientation and fixed vs. tracking mounting options will be reviewed for their costs and benefits with regard to annual production. The solar resource analysis is intended to determine if the location is an appropriate site for a photovoltaic installation. The intent is to provide the client an example of what is possible at his/her site and a prediction of annual energy output.

PERFORMANCE VERIFICATION STUDIES (POST-CONSTRUCTION)

A number of methods have been devised to verify the actual performance of PV systems once they are constructed. These studies are typically done during the commissioning of a system. Performance verification determines if the PV system that was built meets the production estimates of the original design and feasibility study predictions. In other words, given its *real* losses, is the system's energy production higher or lower than the design estimate?

A performance ratio for the system is often attained by measuring the irradiance and other environmental conditions, while at the same time measuring the AC output of the system. Once a sufficiently large data sample is acquired an energy ratio is defined that describes the system performance in terms of the environmental inputs and system outputs. Performance metrics have been created using many different combinations of measured and simulated parameters. Performance verification testing and analysis compares simulated energy production to measured production from the installed system. A typical performance ratio compares measured AC output to the simulated AC production (kWh/kWh).

⁵ There is an important additional step for systems large enough to warrant it. That step is to determine whether or not the solar resource data available from public and private sources for the specific site is as expected. This is done with ground based irradiance, ambient temperature and wind speed measurements.

MONITORING: OPERATIONAL PERFORMANCE

Monitoring and modeling of PV system performance have become essential components of PV plant management. The International Energy Agency Photovoltaic Power Systems (IEA PVPS) Programme makes this central to its task 13 with a focus on analytical monitoring, PV module failure modes and degradation, and long-term system performance (11). Large investments are dependent upon the reliable and optimized performance of these systems. As system size has grown, so has the sophistication with which they are monitored, modeled and operated. Monitoring typically consists of the range of measurement approaches described in Section 1. For larger rooftop or ground mount systems, ground-based irradiance and other environmental measurements are combined with direct power and energy production measurements. Whether it is a simple plane of array (POA) irradiance measurement using a silicon pyranometer, or a higher accuracy thermopile pyranometer, or a direct normal, diffuse horizontal and global horizontal irradiance measurement, PV systems larger than 500 kW typically incorporate a resource solar monitoring system.

Power and energy are measured and metered at the level of total system output. Where central inverters are used (large commercial or utility scale systems) the inverter's internal processor can report system state and energy production. Power levels can also be measured in the form of DC currents and voltages at the array string level. And now, with the emergence of module-scale power electronics which are used for either DC-DC optimization or DC-AC conversion, the internal status and energy production of a system can be polled from each individual module.

Some companies which specialize in third party ownership of residential and commercial systems own and monitor "fleets" of smaller systems. These systems can be spread out over cities, provinces and entire countries covering large geographic regions. Many PV inverters are IP addressable devices and these companies often monitor production remotely. However, monitoring of irradiance and other environmental parameters at every site is generally cost prohibitive. These PV fleet owners typically turn to a variety of irradiance data sources such as national weather services, numeric weather prediction (NWP) models, specialized satellite data services and networks of ground-based as described in Section 1. All of these PV monitoring systems, when combined with an accurate model of system performance, provide actionable data for plant operations.

OPERATIONS AND MAINTENANCE (O&M) DISPATCH

At the operations level the primary purpose of monitoring PV systems and predicting their output is to detect and then remediate system defects and reduce energy production shortfalls. In some cases monitoring systems will detect a component failure which is binary. These are simple cases of a failure of a component or subsystem that results in an integer reduction of plant output. An example of this would be a case where one of 20 inverters in a system shutdown unexpectedly resulting in a 5% reduction in predicted plant output. A more gradual and subtle case might involve progressive system production decline, when compared with predicted output, due to soiling of the panels between rain events. In both cases, the O&M decision to be made is whether or not the decrease in production and impact upon ROI warrants the dispatch of maintenance services. For the first case, the decision is whether or not to repair/reset/replace the defective inverter. In the second case, the management question is whether or not to pay to clean the array. Repair and maintenance services come at a cost and must be calculated into the overall PV system financial analysis.

PREDICTION: ANNUAL, WEEKLY, DAY-AHEAD, HOUR-AHEAD, INTRA-HOUR

“Prediction,” in this Section, is used to mean “forecast.” The term is explicitly temporal in denotation. PV prediction or forecasting is an emerging field. Much of the work is in the early stages of research and development. PV forecasting has temporal, spatial and power dimensions. Standards are only beginning to emerge. This can be seen in the hodgepodge of terminology used to describe time horizons: short-term, medium term, day-ahead, intra-hour, sub-hourly, now-casting, etc. Spatial terminology also lacks standard definitions. The most common spatial terms in the literature are “point” and “regional.” In this context however, “region” could mean an area thousands of square kilometers in size, such as a utility’s service territory, or it could mean just a few square kilometers, such as the area covered by a utility scale solar farm. The forecast of the time and amount of power injected into the electrical grid is the ultimate goal of this type of prediction.

Presently worldwide, solar energy contributes only a small fraction of the electrical energy supplied through the electrical grid. In its present form, many electrical grids, both in their physical structure and market configurations are not designed to incorporate a significant percentage of their daily energy transactions from variable resources such as solar energy. Because, with present technology, large amounts of electrical energy cannot be stored cost effectively⁶, the grid requires constant management to balance energy production with demand. The need for forecasting solar power production, for both grid management and power markets is growing rapidly. As the penetration of PV increases its’ impact on voltage and frequency regulation, operational reserves, unit commitment, energy trading, and a range of other grid management issues grows. Mitigating the impact of PV variability on the grid comes at a cost. Accurate PV forecasts can reduce those costs (11). The standards and definitions for PV forecasting are being driven by grid operators in Germany, Spain, California and elsewhere. The specific time horizons and durations of day-ahead forecasts are, for example, determined by the unit commitment and market schedules of their respective grid management organizations. There are a limited number of commercial firms serving the solar forecasting market at this time. Most of the work being done in this area for periods shorter than day-ahead time horizons, is either still in the category of research, or offered as custom, site specific studies by consulting firms. A list of companies and institutions which are working in this field can be found in a recent report by the US-based Solar Electric Power Association (12).

At their most basic level solar forecasting technologies can be grouped into two major categories. The first of approach is numerical weather prediction (NWP) models. The second approach is projection based upon observed irradiance or cloud cover conditions (13). In the current research environment this second approach is further divided into satellite-based cloud cover observation and ground-based cloud cover or irradiance measurements. Different approaches and technologies perform better and worse with different time horizons and spatial resolution. Generally satellite and ground based measurement forecasting techniques yield greater accuracy in the short term and numerical weather prediction models yield better results in the medium term⁷. A number of researchers are experimenting with “ensemble” approaches which combine elements of both forecasting technologies.

⁶ Hydro power, in the form of pump storage, is an exception to this claim. However this technology is very site dependent.

⁷ In the current literature "short term" or "hour ahead." appears to be no less than 1 hour and up to six hours into the future. “Medium term” is generally used to indicate one to several days into the future. Time horizons shorter than an hour are generally referred to as “intra-hour” or “sub-hourly.”

SINGLE YEAR AND MULTI-YEAR PREDICTION

A number of public scientific agencies and private sector companies have mapped the irradiance levels on the earth's surface. These maps, such as the figure below illustrating Europe's solar resource, depict output of models of the annual average irradiance for the regions. The map in figure 6 illustrates two metrics simultaneously. It shows the average annual solar energy density for global horizontal irradiance expressed in units of kWh/m². The map also illustrates the specific energy for a 1 kWp PV system expressed as energy per unit system power in kWh/kWp. This estimates what the annual per kWp production would be for a well-designed system in any of these areas in Europe. Because of inter-annual variability, resource maps such as this are only approximations or illustrations of averages over extended, multiyear, time frames.

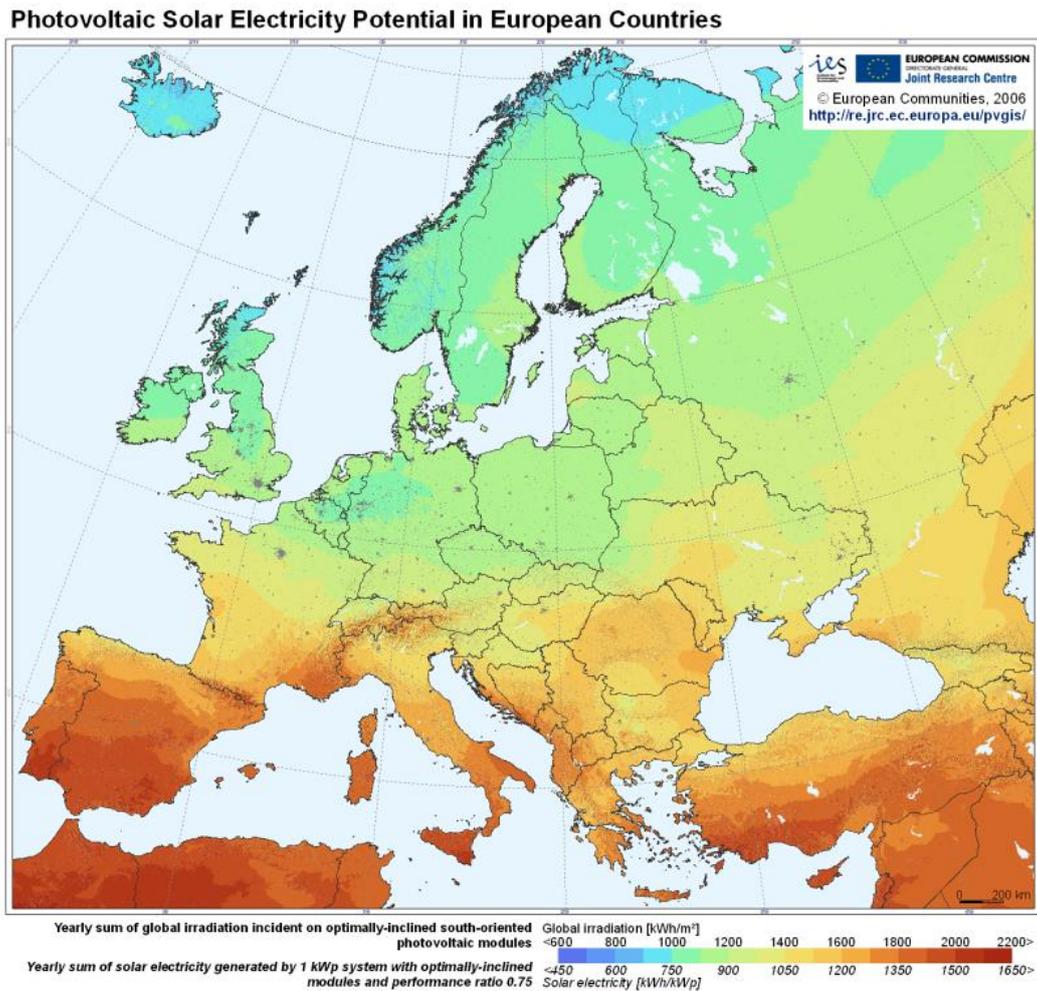


Figure – Solar resource map of Europe.

WEEKLY/DAYS AHEAD PREDICTION

Some firms working in the field of PV forecasting today provide estimated irradiance and PV power production in a multi-day time horizon⁸. Physics-based NWP atmospheric models and statistical techniques are used for time frames from about 6 hours to six days in the future. Some use a combination of NWP models, satellite

⁸ Meteocontrol GMBH, AWS Truepower, LLC, Vaisala/3TIER and other offer solar forecasts of up to a week.

imagery and ground based pyranometer and total sky imager measurements. The most common of the forecast products in this range is the day-ahead forecast which corresponds to utility scheduling and one common energy trading market.

DAY-AHEAD PV POWER FORECASTING

Day-ahead forecasting of PV contribution to the electric utility grid is becoming an important component of overall grid management in regions of the world where solar energy has made large inroads. This solar generation presents challenges to both the management of the physical grid --in terms of unit commitment, frequency regulation, and load following -- as well as to the wholesale electricity market aspects. For the engineers who must manage the dispatch of generation, operating reserves and the transmission constraints of the grid, grid-tied solar energy presents little problem as long as its contribution is a small percentage of the energy flowing into the system. However in Europe and parts of the US PV has already reached levels that must be accounted for in the daily system management (15) (16). Although load demand response, in the form of load shedding, is an effective utility practice, much of the demand is inelastic. Because solar generation cannot be dispatched (but can be curtailed) the difference is made up with dispatch of conventional generation. The dispatch of conventional generation is greatly facilitated by forecasts of the solar contribution. In areas where PV penetration is significant, day-ahead forecasts of solar contribution to the grid are important because they coincide with the daily planning and unit commitment of conventional utility generation resources.

For traders in wholesale energy markets who buy and sell energy and who must anticipate their customer's demand, solar energy generation that is distributed amongst their customers, presents no problem so long as that generation makes up only a small percentage of the total demand. As the percentage of solar generation in a region increases, so does its impact upon the market. As with any market, foreknowledge of other market participants' behavior provides a strategic advantage to the traders. Day-Ahead energy markets are conducted on fixed schedules and those schedules then define the time horizons for day-ahead PV forecasts. California Independent System Operators (CAISO) closes their day-ahead market at 5:30 each morning. The day ahead market covers the period from midnight that day to the following midnight. Accordingly day-ahead PV forecasts in California run from a window 18.5 to 42.5 hours in the future from 5:30. In other locations, the markets and unit commitment schedules may vary and correspondingly so will the time frame for day-ahead PV forecasts (14).

HOUR-AHEAD AND INTRA-HOUR PV POWER FORECASTING

An active area of research in PV forecasting is that of hour-ahead and intra-hour power prediction. These forecast horizons vary depending upon the end use application and forecast technology. But they may range from hourly predictions several hours into the future to fifteen minute intervals reaching an hour or two into the future. One approach that has gained popularity is a sky camera imaging approach being developed at the University of California San Diego and elsewhere. It is specifically designed for short term solar forecasting. One application for very short term PV power forecasts is for mitigation of rapid changes in PV power plant output called "ramps" which can cause unacceptable voltage variations on the grid. Solar ramp events caused by passing clouds can destabilize electrical grids with weak voltage support. In 2012, PREPA, Puerto Rico's electric utility required utility scale generators to limit ramps to < 10%/nameplate/minute (15). These ramp mitigation requirements can be met by incorporating energy storage into the PV plant design. Short term PV power forecasts, combined with intelligent feed forward control algorithms, can reduce the size of costly energy storage units.

PREDICTION AND MONITORING FOR FINANCIAL MODELS⁹

As a financial asset a PV system is similar to a single payment annuity¹⁰, the future returns of which are fixed quantities of energy instead of monetary payments. All system costs are up front (financing is considered separately) with the system returning value to the owner in the form of energy over the course of its useful life. In its most basic form, the calculation of the cost of photovoltaic energy is the financed cost of the system divided by the energy production over that system's productive lifetime. Time dependent debt payments are divided by energy production over the associated time intervals resulting in a value of energy expressed as a monetary value per kilowatt-hour. The price of that energy is determined by the owner's avoided cost for the equivalent energy (including energy, transmission, demand charges, time of use, etc.) from conventional sources. If a state-sponsored incentive such as a feed-in tariff rate exists then that adds to the value the PV energy. The net present value (NPV) of the photovoltaic system is the ratio of the price to cost brought back to a present value. The PV owner's investment internal rate of return (IRR) can only be known if the future price of energy –over the twenty-five to thirty year life of the PV system– is known. If, over the life of the system, the cost of conventional energy decreases, then the IRR for the PV system owner will also decline. If, over the life of the system, the cost of conventional energy increases, PV system owner's IRR will improve. Regardless of the parameters of the financial model, the prediction of ROI for a PV system today is a function of the predicted amount of energy the PV system will produce over its lifetime.

CONTRACT PERFORMANCE CRITERIA

Simulation of energy production plays a major role in contract terms and conditions in the construction of large PV systems. In many cases, bonuses or penalties (liquidated damages) are assessed based upon the energy production of a PV system as compared with some contract benchmark. Typically the performance of larger PV systems is assessed at the time of completion of construction as described in Section 3. A predicted value, based upon measured environmental parameters and a model of the system, is compared with a direct measurement of the system output. The criteria or standard used in the test is typically created in the construction contract. An example of a Performance Guaranty clause of a commercial contract is included in Appendix 1.

⁹ A full financial analysis of PV economics is beyond the scope of this application note, however we present an overview of the uses and impacts of PV energy production prediction and monitoring technologies.

¹⁰ An annuity is a financial product that accepts payments over a fixed period of time (or a single payment as in the example here) with the promise of growing the invested funds and paying out on a schedule at some point in the future.

ACCURACY AND METRICS

The accuracy attainable in ground-based irradiance measurements varies greatly depending upon the measurement technology and the specifics of the setting. In the commercial realm silicon pyranometers and thermopile pyranometers make up the bulk of the measurement devices. The range in accuracy of these devices is about 5% uncertainty for silicon devices to about 3-4% for thermopile devices (16). If the measurement is not in the plane of the array for the PV system being modeled, the transposition of GHI or DNI and DHI to the plane of the array adds further error.

It is difficult to provide a simple comparison of uncertainties associate with different PV power prediction technologies and approaches. The commercial methods which exist are experimental and proprietary. For forecasting methods, accuracy is a function of forecast horizon, spatial resolution and methodology, as was cited in Section 5. The choice of metric for reporting error has a large impact on the level of error reported and is itself an area of research. The US Department of Energy recently funded a research program titled, "*Improving Accuracy of Solar Forecasting*" and the first activity was "Determine Standardized set of Metrics." In a seminal paper on this topic, *Reporting of Relative Irradiance Prediction Dispersion Error*, the authors identify six types of absolute and relative error metrics that can be used, each resulting in different levels of error (17). In any discussion of irradiance forecast accuracy it is critical that the metric be chosen to meet the intended needs of the user. As the authors indicate, for utility applications where PV power is forecasted to be injected into the grid, the relative error (error in relationship to the full nameplate installed PV capacity) is more useful than the absolute error.

In the absence of a widely accepted standard, the single best reference against which to compare forecast performance is a persistence model. A persistence model simply predicts that the irradiance (or PV power) in the next time interval will be the same as in the last. In the aforementioned IEA report on Photovoltaic and Solar Forecasting, for short-term predictions (0-6 hours), the measured persistence models have an absolute Root Mean Squared Error (RMSE) of 6 to 12 W/m². Persistence models which use satellite imagery have RMSE of 8 to 12 W/m² over the same horizon. Ground-based cloud motion forecast systems perform slightly better with an RMSE of 6 to 10 W/m². And the NOAA National Digital Forecast Database (NDFD), an NWP model, has an RSME of 10 W/m² over the entire 0-6 hours. As the time horizon moves out into the multi day range, the persistence model performance degrades to 18 W/m² while the NDFD model stays below 12 W/m².¹¹

¹¹ As a reference, at sea level on a clear day, irradiance levels typically reach approximately 1000W/m².

CONCLUSION

Substantial financial outcomes hinge on the data produced by the prediction and monitoring of PV systems today. Forecast production data can indicate the favorable or unfavorable future financial return of a PV plant being considered for construction. Monitoring and simulation systems can determine that immediate servicing is needed for PV plant to avoid loss of revenue or that it is more cost effective to wait to dispatch maintenance crews. PV system forecasts in day-ahead or hours ahead time frames enable optimization of utility dispatch of conventional generation and informed energy trading. Accurate and timely knowledge of a PV system's performance equates to financial value. And, as PV system penetration into the utility grid increases, that same knowledgebase becomes a critical component of grid planning, operations, and management. The science and art of PV prediction and monitoring has improved markedly over the last two decades and continues to improve. As solar photovoltaic technology continues its transition from the margins of the overall electrical generation mix to take its place alongside conventional generation and other renewable energy technologies, PV prediction and monitoring methods will establish themselves as standard tools in the repertoire of finance, management, planning and utility grid operations.

GLOSSARY

- Diffuse Horizontal Irradiance [**DHI**]: the radiation component that strikes a point from the sky, excluding circumsolar radiation. In the absence of atmosphere, there should be almost no diffuse sky radiation. High values are produced by an unclear atmosphere or reflections from clouds¹².
- Direct Normal Irradiance [**DNI**]: the amount of solar radiation from the direction of the sun¹¹.
- Global Horizontal Irradiance [**GHI**]: total solar radiation; the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and ground-reflected radiation; however, because ground reflected radiation is usually insignificant compared to direct and diffuse, for all practical purposes global radiation is said to be the sum of direct and diffuse radiation only: $GHI = DHI + DNI * \cos(Z)$; where Z is the solar zenith angle¹¹.
- **Meter** (verb): to measure a phenomenon such as electrical energy production or consumption directly, specifically for tariff and revenue purposes. Metering is a form of energy monitoring, typically with accuracy and calibration specifications mandated by a public utilities oversight agency or specified in the terms of a contract.
- **Model** (verb): to create a model or algorithm which describes the behavior of a system in response to an input or set of inputs.
- **Monitor** (verb): to measure a phenomenon, such as solar irradiance or electricity, directly with the use of physical sensors, transducers, or meters. “Monitoring” refers to measurement of energy production for scientific, engineering or operational purposes.
- Numerical Weather Prediction [**NWP**].
- Plane of Array irradiance [**POA**]: the irradiance measured in the geometric plane of a PV array.
- **Predict** (verb): to simulate the output of a system at a future time based upon a forecast input or set of inputs to the system.
- **Simulate** (verb): to calculate the output of a system, such as an energy generating system, based upon a model of the system and upon an input or set of inputs to the system.
- Standard Test Conditions [**STC**]: solar industry test conditions under which photovoltaic cells and modules are tested, comprised of 25° C, 1000 W/m², and air mass of 1.5.
- Watt, Peak [**Wp**]: the STC rating of a photovoltaic cell, module or array (sometimes referred to as the “nameplate rating”)

¹² Solar radiation resource definitions courtesy of NREL Glossary of Solar Radiation Resource Terms, http://rredc.nrel.gov/solar/glossary/gloss_s.html .

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APPENDIX 1: EXAMPLE CONSTRUCTION CONTRACT PERFORMANCE GUARANTY

PERFORMANCE DATA ACQUISITION SYSTEM HARDWARE REQUIREMENTS

- Campbell Scientific data logger-based data acquisition system
- Two Licor 200S series silicon pyranometers, each within one year of its factory calibration date
- Two 0.1% precision sensing resistors
- Back of module surface temperature probe with an accuracy within +/- 2°C
- Ambient temperature probe with an accuracy within +/- 2°C
- Clamp on meter with and accuracy within +/- 0.2 Amps
- Voltage meter probe with and accuracy within +/- 5 Volts

PERFORMANCE RATIO CRITERIA

The performance ratio (the “**Performance Ratio**”) is

$$1 + \left(\frac{M - S}{M} \right)$$

The Performance Ratio guaranty (the “**Performance Ratio Guaranty**”) is that the Performance Ratio shall be equal to or greater than 0.90.

Where M is the measured ac energy value and S is the simulated ac energy value of the PV system production. M is the energy measured in a four hour period spanning two hours before and after solar noon by the PV system ac output kilowatt hour meters used to measure the inverter output. S is computed from three constants and from two inputs measured by the commissioning data acquisition system specified in the performance data acquisition system hardware requirements above. The following formula calculates the AC energy that should be produced in a four hour period by the system based upon the environmental inputs and the estimated system losses or "derate" factor.

$$S = \sum_{n=1}^{14400} (Irr_n \times P_{stc} \div 1000 \times (1 + (Tc - 25) \times \gamma P_{STC} \div 100) \times (1/3600) \times D)$$

In the equation Irr_n and Tc are measured values. P_{STC} , γP_{STC} , and D are constants.

Symbol	Description	Units
Irr_n	POA irradiance measured in field	(W/m ²)
P_{STC}	Rated power of array	(W/1000W/m ²)
Tc	Cell Temperature	(°C)
γP_{STC}	Module Temperature coefficient of Power	(%/°C)
D	PV Watts Derate Factor	()
S	Simulated Electric Energy Value	(Wh)
n	One second measurements during the test	(s)
P_{STC}	STC rated power of array	Site A = 300(kW) and 100(kW) Site B = 250(kW)
γP_{STC}	Module Temp Coeff Power	Coefficient for the chosen module (%/°C)
D	PV system loss Derate Factor	0.85

Global horizontal (GH) irradiance and ambient temperature shall be measured for a baseline reference but is not used in the equation.