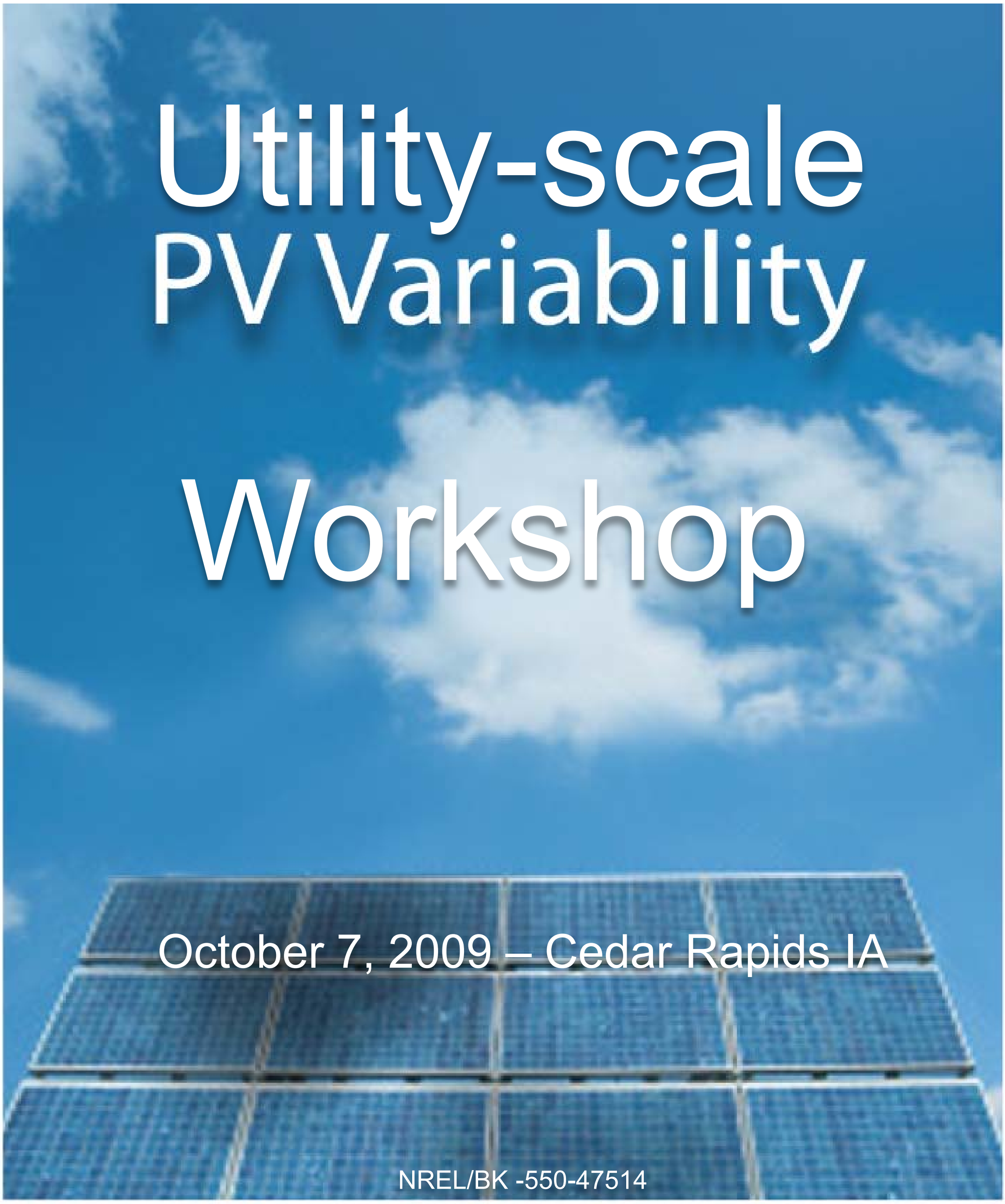

Utility-scale PV Variability

Workshop

October 7, 2009 – Cedar Rapids IA

NREL/BK -550-47514

U.S. DEPARTMENT OF ENERGY | Sandia National Laboratories | NREL National Renewable Energy Laboratory Innovation for Our Energy Future | SEPA solar electric power association | UWIG Utility Wind Integration Group

Prepared by the National Renewable Energy Laboratory (NREL), a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; NREL is operated by the Alliance for Sustainable Energy, LLC.

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Contents

Introduction

Data and analysis are needed to understand the variability of photovoltaic (PV) plants to avoid unnecessary barriers to the interconnection of PV. To address this need, The National Renewable Energy Laboratory, Sandia National Laboratories, the Solar Electric Power Association, the Utility Wind Integration Group, and the Department of Energy hosted a day-long public workshop on the variability of photovoltaic (PV) plants.

The workshop brought together utilities, PV system developers, power system operators, and several experts to discuss the potential impacts of PV variability and uncertainty on power system operations. The workshop was largely motivated by a need to understand and characterize PV variability from the perspective of system operators and planners to avoid unnecessary barriers to the rapid development and interconnection of PV to the electric power system. Understanding PV variability will allow system planners and operators to develop effective measures to manage variability at different levels of PV penetration.

This document contains the papers and presentations developed for the workshop.

Utility-scale PV Variability Workshop

October 7, 2009; 8am – 5pm

Cedar Rapids Marriott, Cedar Rapids, Iowa

Goal: To improve understanding of PV plant variability and its impact on utility planning and operations

Participants: PV developers, utilities, DOE, labs, consultants

Agenda:

7:00 a.m. – 8:00 a.m.
Registration & Breakfast
Location: Pre-Con Area

8:00 a.m. – 5:00 p.m.
Workshop
Location: Hickory

8:00 a.m. – 8:30 a.m.
Welcome, Introductions, and Overview

Welcome and introductions (Charlie Smith – UWIG, Dan Ton – DOE, Christy Herig – SEPA)

- Industry relevance; connection to DOE Renewable Energy and Smart Grid Programs, IEA High Penetration workplan.

Meeting motivation and overview (Benjamin Kroposki – NREL)

- Overview of issues in PV variability, integration, interconnection; overview of agenda.

8:30 a.m. – 9:30 a.m.
PV Interconnection Update

PV interconnection standards (Abraham Ellis – Sandia)

- IEEE, NERC and FERC standards for distributed systems and utility-scale system

Generic PV system models for interconnection and planning studies (Abraham Ellis – Sandia)

- Positive-sequence system planning (PSS/E and PSLF) and distribution planning models

9:30 p.m. – 10:30 p.m.

Integration of PV in Utility Operations

Utility operations and variable generation (Michael Milligan – NREL)

- Overview of utility operations; possible impacts of PV variability and uncertainty; mitigation alternatives

Solar resource forecasting (Mark Alhstrom – WindLogics)

- State-of-the-art, challenges and opportunities for improvement; integration into operations

10:30 – 10:45

Break

Location: Pre-Con Area

10:45 p.m. – 12:00 p.m.

PV Integration Studies

Wind and Solar integration studies (Nick Miller – General Electric)

- Solar integration study purpose, methodologies and data requirements; experience with wind integration studies

Development of data sets for PV integration studies (Ray George – NREL)

- Development of distributed generation and centralized system data sets for integration studies

12:00 p.m. – 1:00 p.m.

Lunch

Location: Oak

1:00 p.m. – 2:30 p.m.

Solar Resource Variability – What do we know?

Modeling the solar resource at higher resolution (Michael Brower – AWS Truewind)

- Mesoscale solar resource modeling methodologies, challenges and opportunities for higher time and space resolution

Short-term variability of the solar resource over wide geographical area (Andrew Mills – LBNL)

- Analysis of ARM data in the Southern Great Plains region; existing solar radiation database

Comparison of PV, CSP, wind variability (Yih-Huei Wan – NREL)

- Analysis of actual system output data to characterize PV variability and effect of geographic diversity, as compared to CSP and wind.

2:30 p.m. – 2:40 p.m.
Break
Location: Pre-Con Area

2:40 p.m. – 4:00 p.m.
Modeling PV Plant Output Variability

Short-term PV output variability in large PV systems (Carl Lenox – SunPower)

- Observed short-term output variability within a single large PV plant

Quantifying PV power output variability (Tom Hoff – Clean Power Research)

- Theory of solar resource variability and impact of geographical dispersion

Characterization of short-term PV variability for large PV systems (Joshua Stein – Sandia)

- Effect of plant size, tracking system and other factors on output characteristics of large and distributed PV systems; static, stochastic and dynamic models for short-term PV output behavior

4:00 p.m. – 4:30 p.m.
Data Collection Needs

Discussion of data collection effort and analysis needs by PV Variability Ad Hoc Group (Travis Johnson – NV Energy)

- Approach to collect high resolution, time-synchronized data; technical challenges; proposed data format and metadata; possible ways to overcome commercial issues

4:30 p.m. – 5:00 p.m.
Open discussion of next steps and priority needs

LBNL-2855E

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System

Andrew Mills[1], Mark Ahlstrom[2], Michael Brower[3], Abraham Ellis[4], Ray George[5], Tom Hoff[6], Benjamin Kroposki[5], Carl Lenox[7], Nicholas Miller[8], Joshua Stein[4], and Yih-huei Wan[5]

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4. Sandia National Laboratories
5. National Renewable Energy Laboratory
6. Clean Power Research, LLC
7. SunPower Corporation
8. GE Energy

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Acknowledgements

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Abstract

Data and analysis are needed to understand the variability of photovoltaic (PV) plants to avoid unnecessary barriers to the interconnection of PV. Several datasets show clouds can cause rapid changes in solar insolation. Smoothing of rapid ramps, however, occurs within PV plants. The degree of smoothing depends on plant size. Smoothing occurs on even longer time-scales between separate plants.

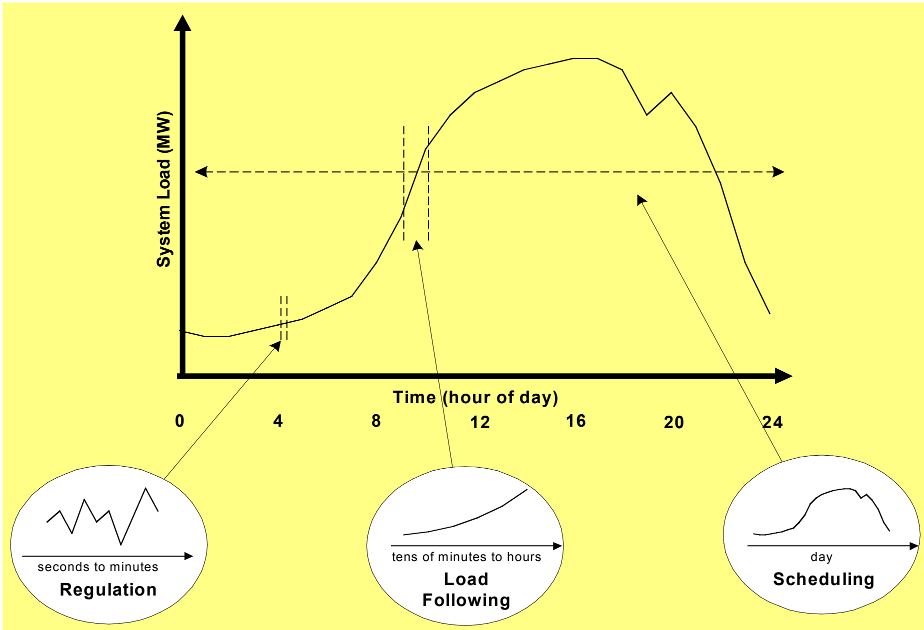
1. Introduction

The National Renewable Energy Laboratory, Sandia National Laboratories, the Solar Electric Power Association, the Utility Wind Integration Group, and the Department of Energy recently hosted a day-long public workshop on the variability of photovoltaic (PV) plants. The workshop brought together utilities, PV system developers, power system operators, and several experts to discuss the potential impacts of PV variability and uncertainty on power system operations. The workshop was largely motivated by a need to understand and characterize PV variability from the perspective of system operators and planners to avoid unnecessary barriers to the rapid development and interconnection of PV to the electric power system. Understanding PV variability will allow system planners and operators to develop effective measures to manage variability at different levels of PV penetration. The workshop generated considerable discussion on the topic and a number of lessons were learned by the end of the day. This paper explores the issue of variability and uncertainty in the operations of the U.S. power grid and presents a number of the findings from the workshop.

2. Managing Variability and Uncertainty in Power Systems

Before focusing on the variability and uncertainty of PV plants, it is important to understand that variability and uncertainty are inherent characteristics of power systems. Loads, power lines, and generator availability and performance all have a degree of variability and uncertainty. Regulations, standards, and procedures have evolved over the past century to manage variability and uncertainty to maintain reliable operation while keeping costs down. There are many different ways to manage variability and uncertainty. Enforceable reliability standards, overseen by the North American Electric Reliability Corporation (NERC), generally focus on minimum performance standards for reliable operation. The standards, however, do not dictate *how* to meet many of the performance requirements. In general, system operators and planners use mechanisms including forecasting, scheduling, economic dispatch, and reserves to ensure performance that satisfies reliability standards in a least cost manner.

The earlier that system operators and planners know what sort of variability and uncertainty they will have to deal with, the more options they will have to accommodate it and the cheaper it will be to mange the system. Planners look years into the future to project needs for generation and transmission capacity, estimate cost effective expansion of supply options, and assess flexibility needs. Flexibility of the generation fleet is characterized in terms of parameters such as minimum start-up and shut-down times, minimum stable generation, and ramp rates. Closer in, planners will schedule units for maintenance or to be available to meet expected loads. These units are committed to generate electricity for a system in the hours to days unit commitment time scale. In the 10-min to hours time scale system operators will change the output of committed units to follow the changes in load throughout the day. More capacity than is needed at any particular time is committed to ensure that errors in forecasts or unexpected events can be accommodated without compromising reliability. In the tens of minutes time scale, system operators schedule adequate regulation reserves to track minute-by-minute changes in the balance between generation and load, Figure 1.



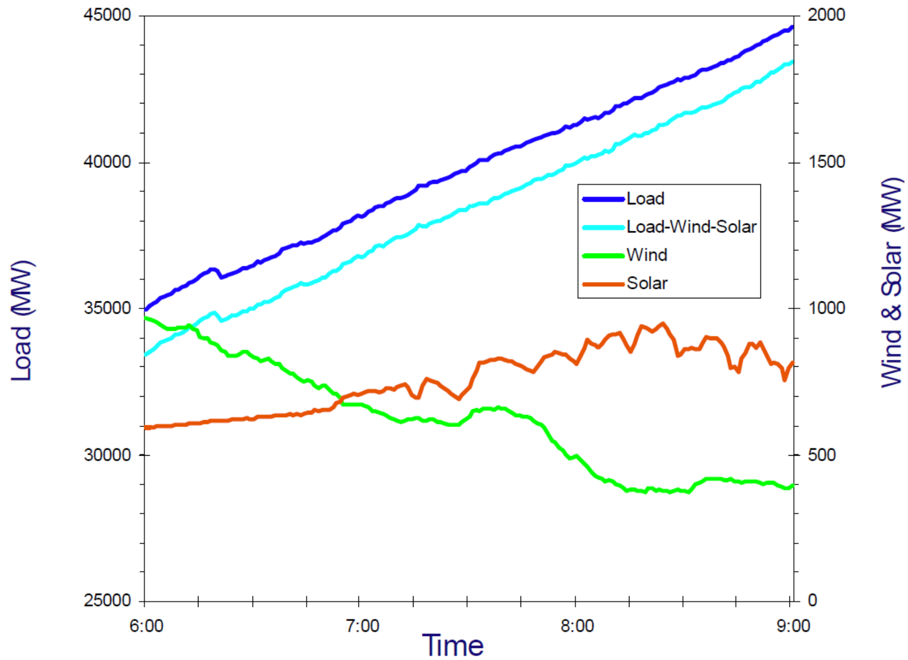
Source: Michael Milligan, NREL, presentation at PV Variability Workshop

Figure 1. Time scales relevant to operating power systems

Managing variability and uncertainty is easier and less expensive when transmission lines are used to aggregate several diverse sources of variability and uncertainty. The daily load shape that system operators use to plan for the real-time operation of the grid is dramatically smoother than the daily profile of an individual residential customer, due to the diversity of load usage among customers. Rather than being concerned with the timing and duration of each individual customer appliance, system operators know that the aggregate of all customers will follow a general trend that can be predicted and managed with relative ease. Similarly, experience with managing wind energy in several countries with high penetrations of wind indicates that aggregation of several diverse wind farms leads to much smoother wind profiles than would be expected from scaling the output of a single wind turbine (Holttinen et al., 2009).

3. Studies are Required to Characterize Additional Variability and Uncertainty of Photovoltaic Plants

The addition of variable generation to meet demand will increase the variability and uncertainty that must be managed by system operators and planners. Figure 2 shows data used in an integration study where flexible conventional generation is used during a morning demand ramp to meet the load or the net-load when integrating wind and solar. Integration studies characterize the additional expected variability and uncertainty in scenarios with high penetrations of variable generation. These studies also focus on strategies that can reduce the challenges and costs of integrating variable generation. A number of integration studies with large amounts of wind and some solar have evaluated the additional reserves required to accommodate the variable generation. The studies found, among other conclusions, that using forecasts of variable generation by system operators and decreasing the time between dispatch schedules for generation can greatly increase access to flexible generation (Kirby and Milligan, 2008). These measures reduce the costs of managing the net increase in variability and uncertainty from adding variable generation (Smith et al., 2007).



Source: Piwko et al., 2007

Figure 2. Detailed analysis of the challenges system operators must be able to manage in the California Intermittency Analysis Project (Piwko et al., 2007). Across all of the time scales identified in Figure 1, system operators use dispatchable resources to manage the combination of the load and the aggregate of all wind and solar plants.

Integration studies separate variability into different time scales as each is associated with different impacts, management strategies, and costs. The following list highlights general issues that are important for different time scales when operating power systems with variable generation:

- Power quality (e.g. voltage flicker) – seconds
- Regulation reserves – minutes
- Load following – minutes to hours
- Unit-commitment and scheduling – hours to days

Aside from the time dimension, it is also important to characterize variability along a spatial dimension. Problems with power quality are often managed within a single distribution feeder. The spatial scales of importance for power quality may be on the order of tens of square kilometers. On the other hand, balancing authorities must balance all generation and load within balancing areas that range from hundreds of square kilometers to tens of thousands of square kilometers. Arrangements that allow balancing authorities to exchange variability in ways that are beneficial to both balancing authorities, such as ACE Diversity Interchange (ADI), require understanding variability on the spatial scale of nearly an entire interconnection or hundreds of thousands of square kilometers.

A fundamental challenge in integration studies is developing projections of the load and variable generation across all of these temporal and spatial scales for expected levels of variable generation that have yet to be experienced anywhere in the world. Integration studies for high-penetration scenarios of PV will require projections of variability from multiple GW of PV generation for both distributed PV and large utility-scale PV plants. Currently, wide-area solar data coverage is available with low time resolution or high time resolution data is available with limited spatial coverage. Solar data covering a large spatial extent is available from satellite images, but this data generally has an hourly temporal resolution. High-time resolution PV data and solar insolation measurements are available from individual points, but there are few networks with multiple time-synchronized PV or solar insolation sites. To develop projections of PV variability for integration studies analysts need to be able to model on the time scale of seconds to hours the output of:

- Large PV plants (~1-10's of sq. km)
- Dispersed PV plants on distribution feeders (~10-100's of sq. km)
- The aggregate of all PV plants that must be managed by system operators (~1,000-100,000's of sq. km)

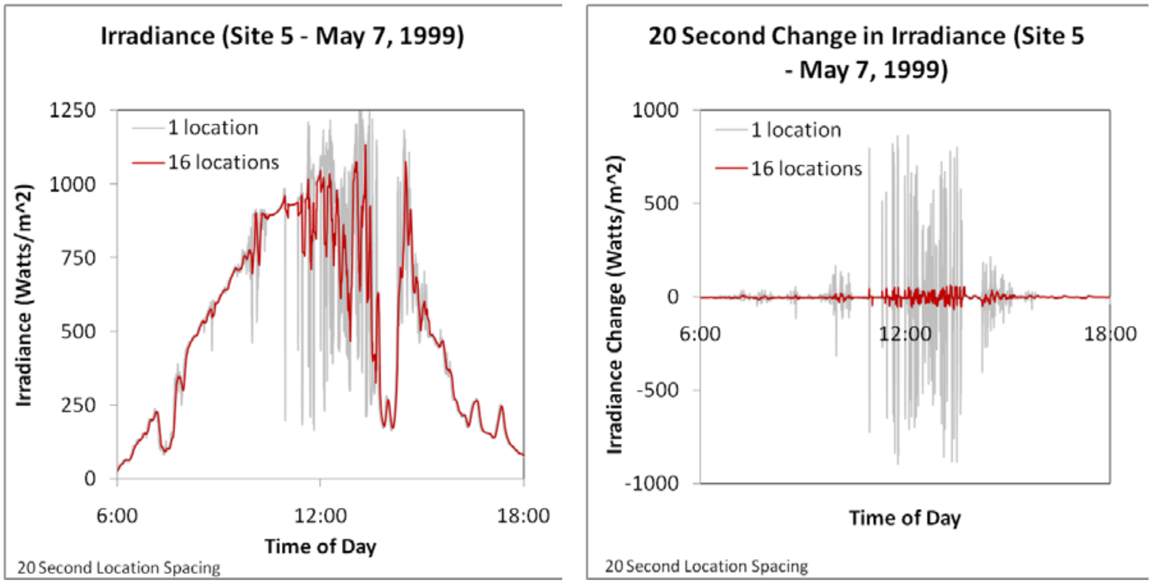
4. Lessons Learned from Analysis of Limited Existing Datasets Managing Variability and Uncertainty in Power Systems

4.1 Clouds can cause significant ramps in solar insolation and PV plant output

The output of PV plants is necessarily variable simply because the sun changes position throughout the day and throughout the seasons. The rising and setting of the sun regularly leads to 10-13% changes in PV output over a period of 15 minutes for single-axis tracking PV plants. Clouds, however, are largely responsible for rapid changes in the output of PV plants that concern system operators and planners. Changes in solar insolation at a point due to a passing cloud can exceed 60% of the peak insolation in a matter of seconds. The time it takes for a passing cloud to shade an entire PV system, in contrast, depends on the PV system size, cloud speed, cloud height, and other factors. For PV systems with a rated capacity of 100 MW, the time it takes to shade the system will be on the order of minutes rather than seconds.

4.2 Clouds are diverse

Unlike changes in the position of the sun which affects the output of all PV plants in a nearly uniform, highly correlated way, changes in PV output due to clouds are not driven by a similar uniform process. Clouds move across plants affecting one part of a plant before another or leaving some parts of plants unobstructed as the cloud passes. Clouds therefore cause diverse changes in PV output across plants and between separate plants. Just as electrical connections are used to aggregate diverse loads and conventional plants, electrical connections aggregate the diverse output of separate PV panels and blocks of PV panels within a plant or between separate PV plants. The degree of diversity between points or plants can be characterized by the correlation of simultaneous changes in the output. Similarly, diversity can be characterized by the relative reduction in the magnitude of ramps for the aggregate of multiple plants relative to a single point, Figure 3.

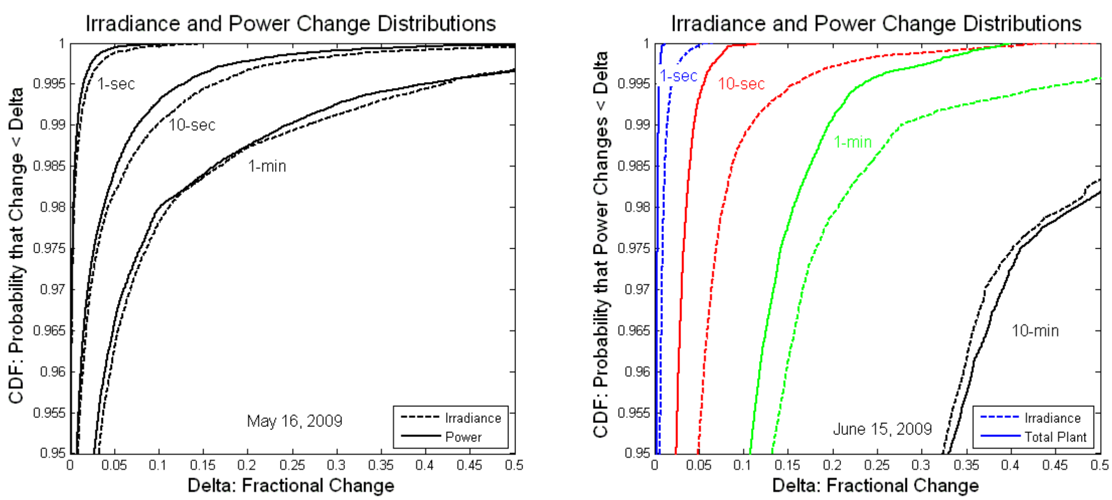


Source: Hoff and Perez, 2009

Figure 3. Aggregating the output of several different solar insolation meters illustrates the reduction in variability of multiple sites relative to a single site. The change in irradiance from one minute to the next (left) is dramatically reduced for multiple sites due to diversity.

4.3 Smoothing occurs within PV plants

Comparison of the variability of a solar insolation meter and a 30-kW PV plant in New Mexico shows that diversity, even within a small PV plant, can smooth rapid ramps relative to the expected ramps from just examining solar insolation. 1-second and 10-second ramps from the 30-kW PV plant are less severe than the ramps in the insolation meter, Figure 4 (left figure). 1-min ramps, however, are nearly identical between the two.



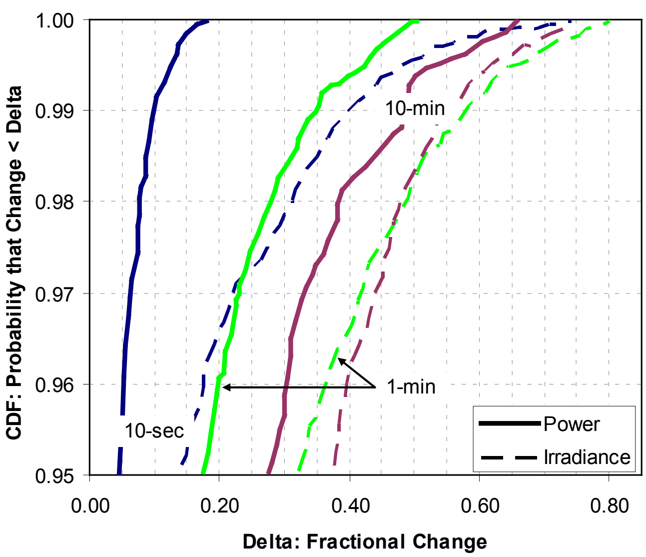
Source: Joshua Stein, Sandia National Laboratories, adapted from presentation at the PV Variability Workshop

Figure 4. Cumulative distributions (95th to 100th percentiles) of irradiance and PV power changes over various time periods during a single day from a 30-kW PV system (left) and a multi-MW PV

system (right) show a reduction in variability between single point measurements (irradiance) and PV plant output (power/ total plant)

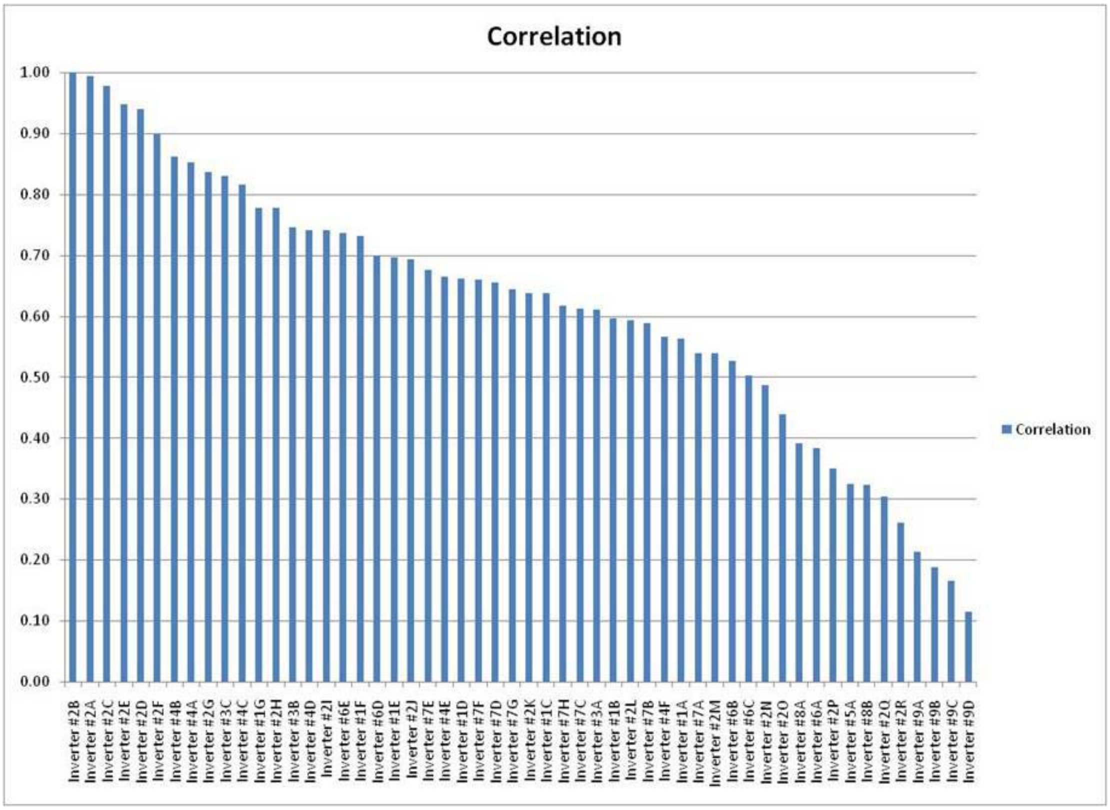
Comparison between variability observed in insolation meters and the output of larger multi-MW plants exhibit more pronounced reductions in variability. For example, output from a multi-MW PV plant of undisclosed capacity (>2 MW) shows the relative difference between ramps observed at a point (irradiance sensor) and power ramps from the entire plant decrease as the ramp duration increases, Figure 4 (right figure). Large 1-sec, 10-sec, and 1-min ramps in the multi-MW PV plant are approximately 60%, 40%, and >10%, respectively, less severe than observed at a point. The ramp distributions are nearly identical for 10-min ramps.

Other large PV plants exhibit similar behavior. A 75% ramp in 10-seconds observed by an insolation meter was associated with only a 20% in 10-second ramp in a different 13.2-MW plant in Nevada. A severe event that changed the output of an insolation meter by 80% in 1-min therefore led to only a 50% in 1-min change in the output of this plant and a 10-min change 65% in 10-min was slightly less severe than the 75% in 10-min change observed in the nearby insolation meter, Figure 5. 1-min changes in output of inverters within this plant were nearly perfectly correlated for close inverters, but inverters far apart within the same plant show correlation coefficients between simultaneous 1-min changes in output that drop as low as 0.1, Figure 6. The magnitude of the reduction in the maximum 1-min change in output therefore depends on the size of the plant. Increasing the plant size increases the relative reduction in 1-min changes in plant output, Figure 7.



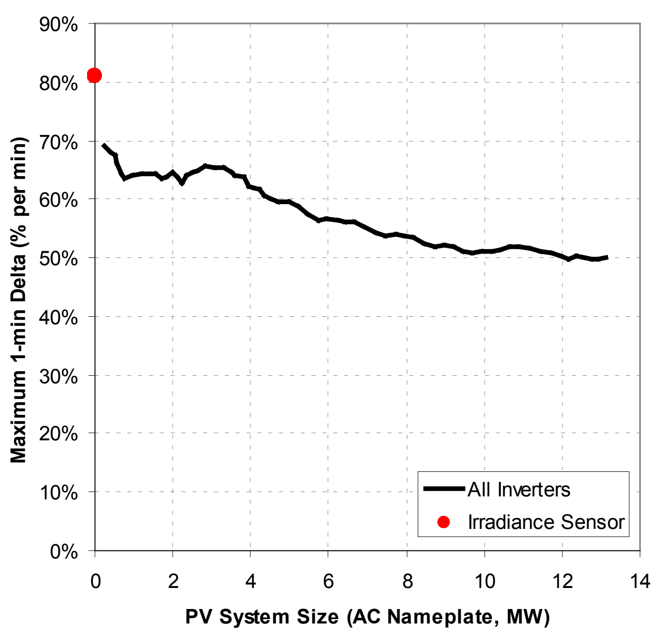
Source: Carl Lenox, SunPower Corporation, adapted from presentation at PV Variability Workshop

Figure 5. Cumulative distributions (95th to 100th percentiles) of irradiance and PV power changes over various time periods during a highly variable day for a 13.2-MW system.



Source: Carl Lenox, SunPower Corporation, presentation at PV Variability Workshop

Figure 6. Correlation coefficient of 1-min step changes in power output between different inverters (relative to Inverter #2B) within a 13.2-MW PV plant in the Southwest on a highly variable day.



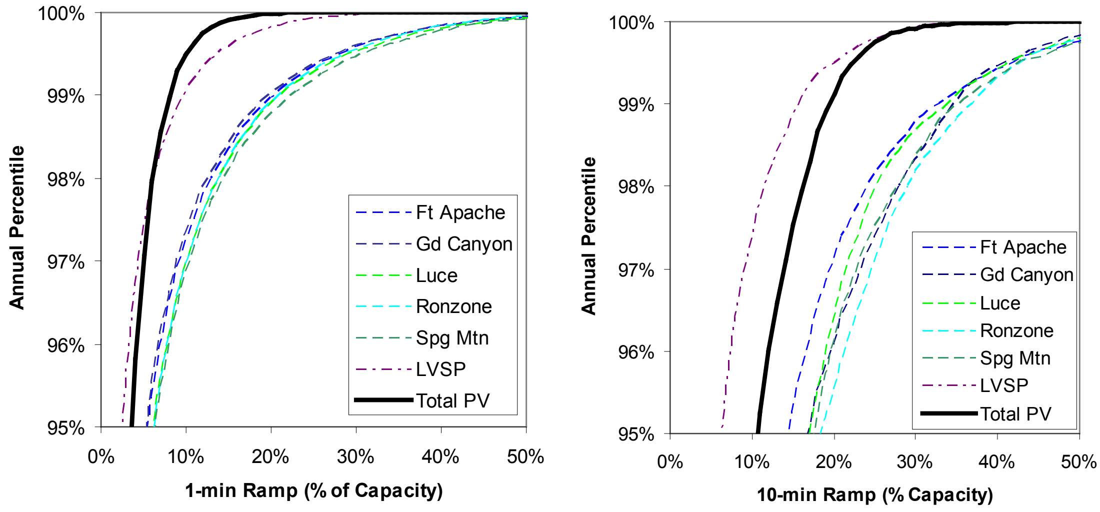
Source: Carl Lenox, SunPower Corporation, adapted from presentation at PV Variability Workshop

Figure 7. Maximum 1-min changes in the output of an irradiance sensor and aggregated blocks of a 13.2-MW PV plant on a highly variable day.

There are two key lessons from this analysis. First, diversity can occur even within plants and the amount of smoothing within a plant depends on the size of the plant. Comparisons of the variability of different technologies need to be done for plants of similar capacity to be meaningful. Second, for plants in the tens of MW scale, the output of an insolation meter will show distinctly more severe ramps in time scales up to about ten minutes than will be observed in the output of the PV plant. Changes in the output of an insolation meter for time scales longer than about 10-min however will be similar to the changes in the output of multi-MW PV plants. These observations are based on a limited sample of data, and should be verified with data from other locations.

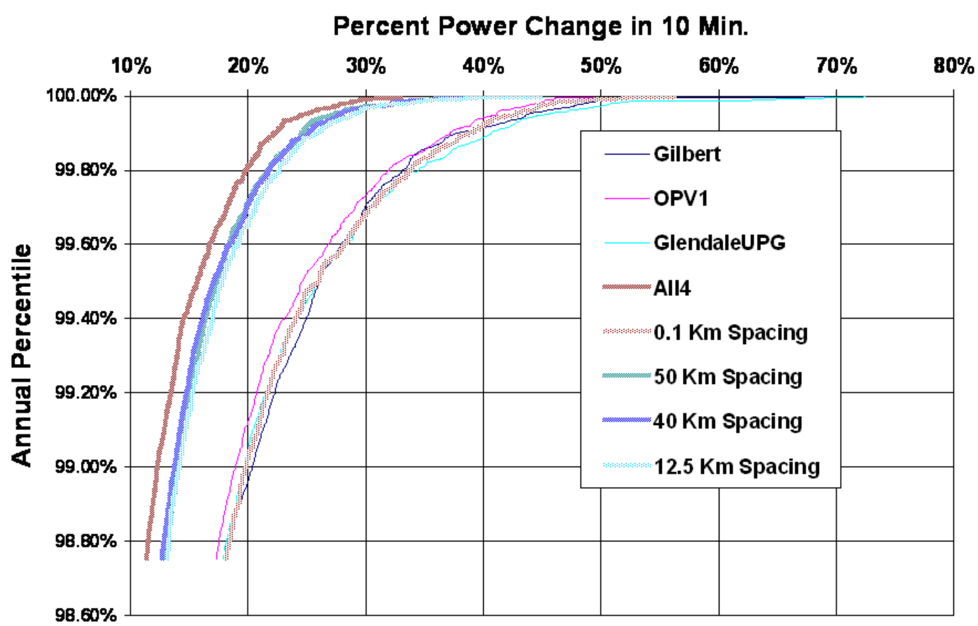
4.4 Diversity occurs between separate PV plants

While diversity over longer time-scales may be limited within multi-MW PV plants, analysis of a network of several time-synchronized solar insolation measurements in the Great Plains region of the U.S., six PV plants in the city of Las Vegas, four PV plants in Arizona, and two PV plants in Colorado indicates that smoothing can occur on even longer time-scales between separate plants. Aggregating six plants within a ~200 square kilometer area in Las Vegas greatly reduced not only the 1-min ramps but also reduced the 10-min ramps relative to the individual plants, Figure 8. Sixty minute ramps were smoothed, but to a lesser degree, with aggregation. Analysis of the 10-min ramps for PV plants located 12.5 km to 50 km apart in Arizona show on the order of a 50% reduction in the 99.7^{th} percentile of the most severe ramps by aggregating any pair of sites, Figure 9. This is the reduction that would be expected if the 10-min ramps at each site were uncorrelated. Aggregating the output of two PV plants in Colorado 8.8 km apart (but along the same mountain ridge) showed a smaller reduction in 10-min ramps indicating that the smoothing benefit of aggregation may vary by region. Data sets from multiple regions need to be analyzed and compared to determine the extent to which local features affect the smoothing benefits of geographic diversity.



Source: Yih-huei Wan, NREL, adapted from presentation at the PV Variability Workshop

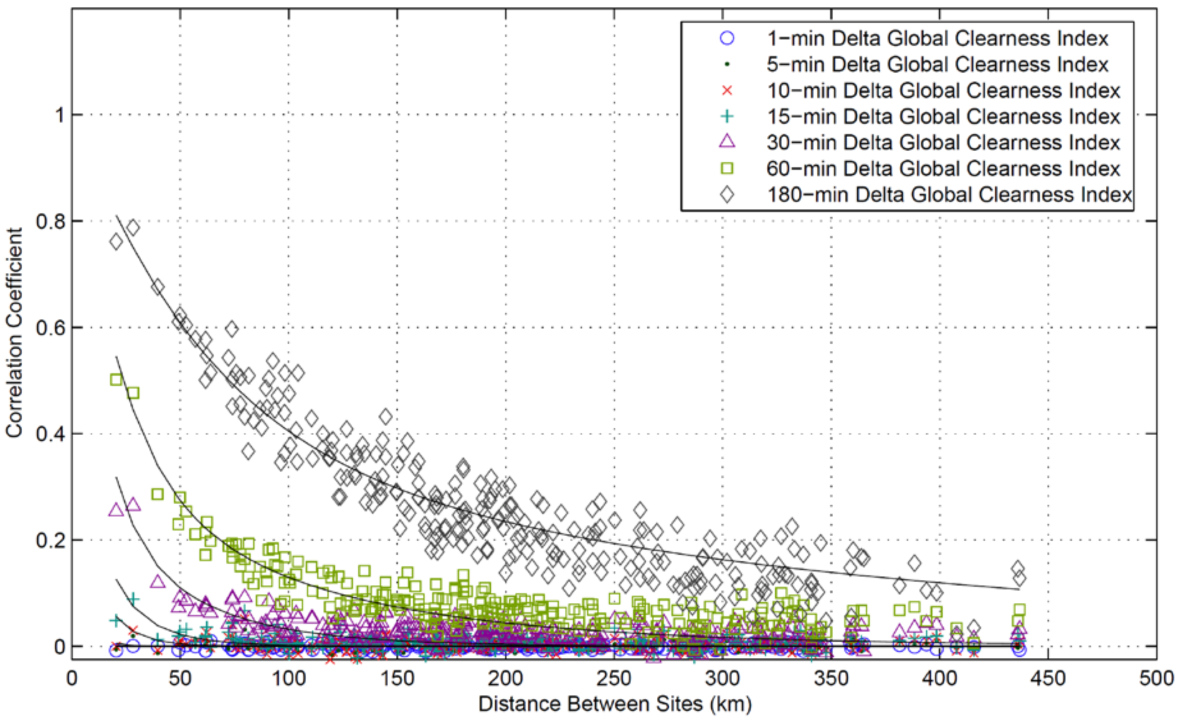
Figure 8. Cumulative distributions (95th to 100th percentiles) of six individual PV plants within a ~200 square kilometer area in Las Vegas and the aggregate of the plants demonstrate that aggregation greatly reduces the magnitude of extreme 1-min (left) and 10-min (right) ramps in the aggregate (Total PV) relative to the individual plants. Note that LVSP is a fixed tilt array while the remaining five plants are single axis tracking plants.



Source: Ray George, NREL, adapted from presentation at PV Variability Workshop

Figure 9. Cumulative distributions (98.6th to 100th percentiles) of ramps from individual PV plants in Arizona, pairs of variously spaced plants, and the aggregate of all plants (All4). Aggregating the output from pairs of PV sites 12.5 km to 50 km apart leads to a reduction in the magnitude of the 10-min ramps (as a percentage of the name plate capacity) relative to the individual site. Ramps are based on one year of 10-min data from one-axis tracking PV systems (courtesy Arizona Public Service Co.).

In the Great Plains, irradiance ramps over time scales of 30-min were uncorrelated for sites that were on the order of 50 km apart. Ramps over time scales of 60-min were uncorrelated for sites on the order of 150 km apart. Ramps over time scales 15-min and shorter were uncorrelated for all distances between sites down to the minimum spatial resolution of 20 km between sites, Figure 10. When ramps over a particular time scale are uncorrelated between all N plants, the aggregate variability is expected to scale with $1/\sqrt{N}$ relative to the variability of a single point. This diversity between multiple PV sites on all sub-hourly time scales needs to be accounted for in projections of variability that must be managed by system operators. Comparison of the variability of multiple solar insolation meters and similarly sited wind anemometers (scaled to create a time series of wind power output) suggests that the variability of several PV plants may be similar to the variability of several similarly sited wind plants for time scales longer than 10-15 minutes.



Source: Andrew Mills and Ryan Wiser, LBNL, presentation at PV Variability Workshop

Figure 10. Correlation coefficient of step changes in the global clearness index (the ratio of the measured insolation to the clear sky insolation) for different distances between sites and different averaging intervals for the step changes (deltas).

4.5 Multiple methods are available for PV forecasting

Forecasts of PV output are required for days ahead down to hours and tens-of-minutes ahead. Forecasts should include information about the expected output and the degree of uncertainty in the expected output to indicate particularly volatile periods. Short-term PV forecasts are aided by the fact that clouds can be observed. Sky imagers near PV plants can be used to indicate approaching clouds and predict the impact the clouds will have on PV output. Successive satellite images have been shown to yield useful information about the direction and speed of approaching clouds. For longer time scales, numerical weather models can be used to predict solar insolation out to multiple days. Forecasts are an important method for managing both the variability and the uncertainty of PV and should be incorporated into system planning and operations.

4.6 Grid events can impact the variability of PV

Step changes in PV output can occur from simultaneous inverter trips within the plant. Although inverter trip events are far less common than cloud-induced ramps, the severity and magnitude of trips exceed the observed severity and magnitude of ramps due to clouds. Currently, these trips are normal operation as inverters are designed to shut off when abnormal events occur on the grid and cause voltage or frequency deviations outside of a tolerance envelope. Tripping is presently required by IEEE Standard 1547 for PV (and other distributed generation) that is embedded on distribution systems. This requirement stems from safety concerns surrounding inadvertent islanding. However, an unintended consequence of these rules is that wide spread tripping of PV will occur for large grid disturbances such as transmission faults that depress voltages below existing tolerances over a wide geographical area in systems with large amounts of IEEE 1547 compliant embedded PV. Preventing large simultaneous inverter trips due to low voltage on the grid will require some reconciliation of rules like IEEE 1547, that mandate low voltage tripping, and FERC Rule 661a, that prohibit low voltage tripping for large scale generation. From a technology perspective, application of low voltage ride through (LVRT) techniques (such as those developed for wind generation) will be needed for PV inverter design. Voltage ride-through standards for PV are already in place in interconnection standards in Germany (Troester, 2009).

In addition to grid events, PV plants are subject to outages due to equipment malfunction or outages inside the plant similar to conventional generators. PV plant outages, like the outages of wind and conventional plants, should be planned for in the normal way that grid operators prepare for grid contingencies.

5. Conclusions

The PV Variability Workshop was the beginning of a dialogue that will need to continue between utilities, PV system developers and owners, and regulators to characterize PV variability and develop effective measures to manage the variability and uncertainty. The initial lessons learned from the workshop include:

- Rapid ramps are important to characterize and understand for PV, but in the end system operators need to maintain a balance between the aggregate of all generators and loads. Understanding the characteristics of aggregate PV output over large areas and correlation to load are critical to understanding potential impacts of large quantities of PV.
- PV variability can drive localized concerns, which typically manifest themselves as voltage or power quality problems. These issues are distinct from grid system level issues of balancing, and ought not to be confused. Management and remediation options for local power quality problems are generally different than options for maintaining a balance between load and supply at the system level.

- The variability observed by a point insolation measurement will not directly correspond to the variability of a PV plant. A point measurement ignores sub-minute time scale smoothing that can occur within multi-kW plants and sub-ten minute smoothing that can occur within multi-MW plants. Extrapolation suggests that further smoothing is expected for short time-scale variability within PV plants that are hundreds of MW, but this needs to be confirmed with field data from large systems.
- Diversity over longer time scales (10-min to hours) can occur over broad areas encompassed by a power system balancing area. Data from the Great Plains region of the U.S. indicates that the spatial separation between plants required for changes in output to be uncorrelated over time scales of 30-min is on the order of 50 km. The spatial separation required for output to be uncorrelated over time scales of 60-min is on the order of 150 km. The assumption that variability on a 15-min or shorter time-scale is uncorrelated between plants separated by 20 km or more is supported by data from at least one region of the U.S. Additional data is required to examine this assumption in other regions with different weather patterns.
- Multiple methods will be used for forecasting solar resources at differing time scales. Clouds are the primary influence in the solar forecast. Over short time scales, it is important to recognize that clouds (and their rate and direction of movement) are visible to satellites and ground-based sensors. Over longer time scales clouds can change shape and grow or dissipate, so numerical weather modeling methods may prove necessary. As with wind forecasting, solar forecasting will benefit from further development of weather models and datasets.
- Photovoltaics fall under the broader category of variable generation. The experience with managing wind variability and uncertainty will benefit solar integration efforts. Where appropriate, unified approaches for managing variable generation will ease integration issues.

The most important lesson from the workshop, however, is that the dialogue regarding PV variability requires, above all else, additional time-synchronized data from multiple PV plants and insolation meters over spatial scales ranging from sq. km to greater than 10,000 square kilometers. The data will need to cover at least a year and should be synchronized with comparable load data in order to understand the net impact on the variability that must be managed by the system operators. Certain questions, particularly questions concerning power quality and regulation reserves, will require data with as high of a time resolution as multiple seconds. Analysis of data from multiple time-synchronized PV plants will allow detailed evaluation of the degree to which rapid ramps observed in point measurements will be smoothed by large PV plants and the aggregation of multiple PV plants. Such studies will help remove unwarranted barriers to interconnection and provide the basis for setting appropriate interconnection standards that will allow solar energy from PV plants to reach significant penetration levels.

Additional Reading and References

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http://www.uwig.org/pvworkshop-presentations.html

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Vitae

Andrew Mills is a Principal Research Associate in the Electricity Markets and Policy Group at Lawrence Berkeley National Laboratory, where he conducts research on issues in the electricity industry related to renewable energy markets and grid integration.

Mark Ahlstrom is CEO of WindLogics, a leading company in the assessment, forecasting, operations and integration of renewable energy. WindLogics became a subsidiary of NextEra

Energy Resources (formerly FPL Energy) in 2006, allowing it to expand its role as an applied R&D center and provider of services to utility, wind and solar energy clients.

Michael Brower is a founding partner and Chief Technical Officer of AWS Truewind, LLC. AWS Truewind is an international renewable energy consulting firm providing wind and solar resource assessment and mapping, plant design and assessment, performance evaluation, due diligence, and grid integration services.

Dr. Abraham Ellis is Technical Lead of Renewable Energy Grid Integration at Sandia National Laboratories. His work concentrates on impacts of high penetration PV and wind on power systems planning and operations.

Ray George is a Senior Scientist at the National Renewable Energy Laboratory where he specializes in meteorology and GIS

Dr. Thomas E. Hoff founded Clean Power Research in 1998. Clean Power Research provides consulting and software services to evaluate the economics of clean energy investments. Dr. Hoff holds a Ph.D. in Engineering Economic Systems from Stanford University and has 20 years of experience in the area of photovoltaic and other clean energy technologies.

Dr. Benjamin Kroposki is a Principal Group Manager at the National Renewable Energy Laboratory. Dr. Kroposki leads a group of scientist and engineers in that focus in the area of integration of renewable and distributed energy into the electric power system.

Carl Lenox is a Principal Engineer at SunPower Corporation. He leads a cross-functional team that is addressing the challenges of integrating photovoltaic power plants into the utility system.

Nicholas Miller is Director, Energy Applications and Systems Engineering at GE Energy in Schenectady, NY. He has been a principal contributor to several major renewables integration studies and has provided consultation on renewables integration to governments and institutions in more than two dozen countries.

Joshua Stein is a Principal Member of Technical Staff and member of the Photovoltaic Systems and Grid integration Department at Sandia National Laboratories. He conducts research aimed at better understanding the performance characteristics of fielded PV systems and develops models that accurately predict the performance of systems in diverse climates of variable designs, and over variable time periods.

Yih-huei Wan is a Senior Engineer at the National Wind Technology Center in the National Renewable Energy Laboratory.

U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability

DOE Programs Addressing PV Integration into Utility Planning & Operations

Presentation at:
Utility-Scale PV Variability Workshop

Dan Ton, Program Manager
Smart Grid Research & Development

October 7, 2009 Cedar Rapids, Iowa

PV Integration – A Collaborative Area between EERE/OE

U.S. DEPARTMENT OF ENERGY | Electricity Delivery & Energy Reliability

U.S. Department of Energy | Energy Efficiency and Renewable Energy

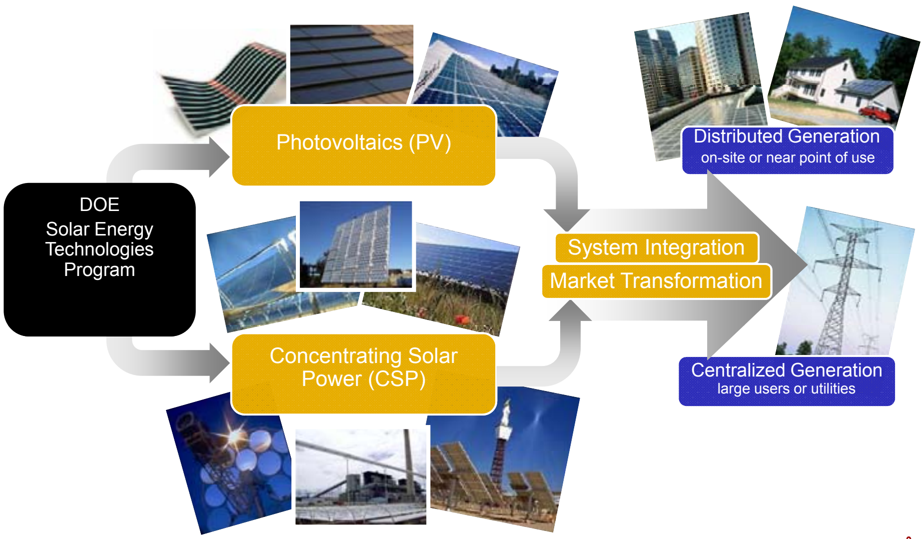
DOE EERE/OE jointly developed and identified five strategic areas for RSI to realize a significantly larger share of the nation's energy consumption from renewable energy (wind, solar, geothermal, tidal wave) and renewable fuels (biomass, biofuels)

- High-resolution renewable energy resource characterization
- Advanced operational strategies with integrated renewables, energy storage, and load management
- Advanced communications and controls for interconnection and interoperability
- Comprehensive regional infrastructure planning and coordination
- Education and workforce development

2

U.S. Department of Energy
Energy Efficiency and Renewable Energy

The Program is implementing four key activities to reduce technology cost and achieve high market penetration



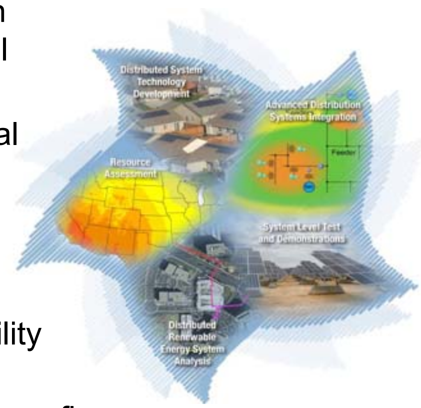
3

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Challenges: System Integration

High-penetration solar electricity into the grid affected by variability of solar resources & outdated electric delivery infrastructure

- Resources characterization with inadequate temporal and spatial resolutions
- System planning and operational tools inadequate to manage uncertainty from renewable energy generation
- Lack of system flexibility to accommodate additional variability introduced by renewables
- Limited capacity for two-way power flow

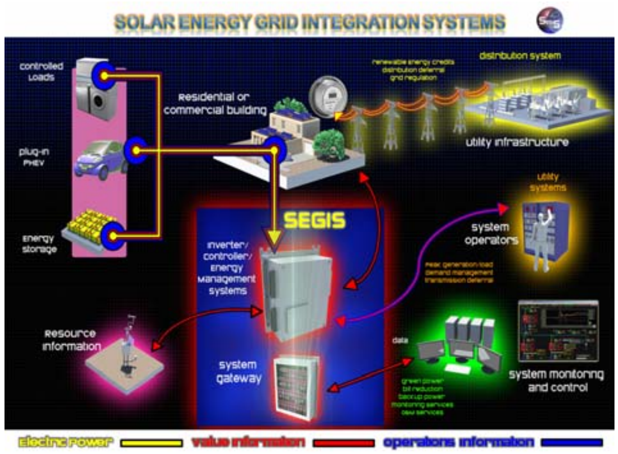


4

Addressing System Integration Challenges

U.S. Department of Energy
Energy Efficiency and Renewable Energy

SEGIS focuses on developing intelligent hardware that interconnects PV to evolving "Smarter" electrical grid



Addresses integration application needs for:

- ✓Communication portals
- ✓micro-grids
- ✓demand response
- ✓zero-energy buildings
- ✓PHEV integration
- ✓PV system sizes, <1kW to >100kW

Five industry awards downselected for prototyping, testing, and pilot production

5

Addressing System Integration Challenges

U.S. Department of Energy
Energy Efficiency and Renewable Energy

High Penetration PV Development

- Industry workshop held in February 2009 with over 120 participants
- Workshop report documenting high-priority needs, RD&D activities, and performance requirements
- Up to $37.5M DOE investment over 5 years (FY10-14), selection for award announced in September 2009:
  - Modeling tools development
  - Field verification of high-penetration levels
  - Modular power architecture
  - Demonstration of PV and energy storage for smart grids

http://www1.eere.energy.gov/solar/pdfs/pv_grid_penetration.pdf

6

Office of Electricity Delivery and Energy Reliability

Office of the Assistant Secretary

Corporate Business Operations

Research & Development (R&D)*

- Clean Energy Transmission and Reliability
- Smart Grid Research and Development
- Energy Storage
- Cyber Security for Energy Delivery Systems

Permitting, Siting, & Analysis (PSA)

- Modeling and Analysis
- Electric Markets Technical Assistance
- Electricity Exports/ Presidential Permits
- Power Marketing Administration Liaison

Infrastructure Security & Emergency Response (ISER)

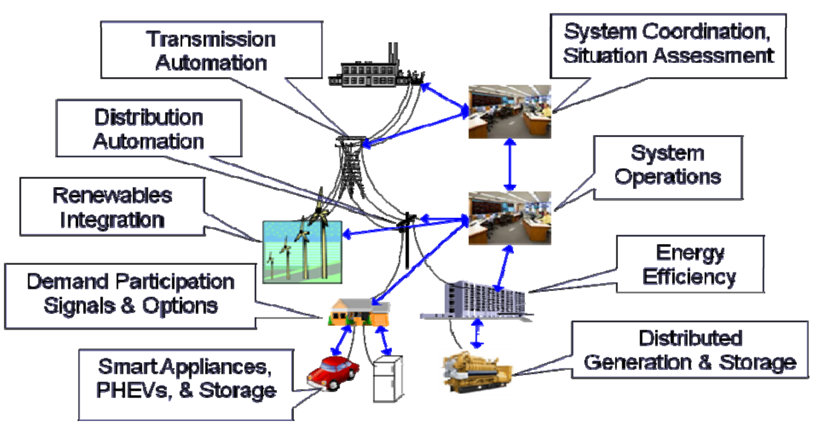
- Energy Infrastructure Protection
- State/Local Gov't Partnerships
- Training and Exercises
- Visualization
- Critical/Vulnerability Assessment
- Emergency response support

** FY10 Budget Line Items*

7

Smart Grid Research and Development

Smart Grid R&D focuses on developing next generation smart grid technologies for integration into the nation's electric delivery network to enhance operational intelligence and connectivity throughout all application areas .



Key SG Application Areas

8

Defining Smart Grid Characteristics

Electricity delivery network modernized using latest digital/information technologies to meet key defining functions

- Enabling Informed Participation by Customers
- Accommodating All Generation and Storage Options
- Enabling New Products, Services, and Markets
- Providing the Power Quality for the Range of Needs in the 21st Century
- Optimizing Asset Utilization and Operating Efficiently
- Addressing Disturbances – Automated Prevention, Containment, and Restoration
- Operating Resiliently Against Physical and Cyber Attacks and Natural Disasters

7 smart grid characteristics reaffirmed through the Smart Grid Implementation Workshop held June 2008

9

Smart Grid R&D Planned Activities for FY10

Smart Grid R&D Multi-Year Program Plan (FY10-14)

- Working groups being assembled to plan for development of each of the defined R&D areas to include the goal, objectives, challenges, tasks, and milestones
- Two-stage development process
  - Meeting in October involving all WGs
  - Industry Workshop in December
- MYPP to guide Smart Grid R&D investments, including a planned FY10 solicitation in February 2010

10

Recovery Act Smart Grid Funds: $4.5 Billion

Office of Electricity Delivery and Energy Reliability	$ Millions
Smart Grid Investment Grant Program; ≤3 years	**$3,400**
Smaller projects, $300K-$20M; 40% of funding	
Larger projects, $20M-$200M; 60% of funding	
Smart Grid Demonstrations; 3-5 years	**$615**
Regional Demonstrations, up to $100M per project	
Grid-scale Energy Storage Demonstrations	
Interoperability Framework Development by NIST	**$10**
Resource Assessment and Interconnection-Level Transmission Analysis and Planning	**$60**
State Electricity Regulators Assistance	**$46**
Enhancing State Government Energy Assurance Capabilities and Planning for Smart Grid Resiliency	**$39.5**
Local Energy Assurance Planning (LEAP) Initiative	**$10.5**

11

Contact Information

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For more Information:

OE: www.oe.energy.gov

Smart Grid: www.oe.energy.gov/smartgrid.htm

Systems Integration:
www1.eere.energy.gov/solar/systems_integration_program.html

12

U.S. Utilities & Solar And IEA-PVPS High Penetration PV Workplan

Utility Scale PV Variability Workshop

Cedar Rapids, Iowa

Oct. 7, 2009

Christy Herig
Solar Electric Power Association

About SEPA

- Mission is to facilitate utility use & integration of solar electric power
- Non-profit membership organization
- Reliable source of unbiased information about solar technologies, policies, and programs
- Bridge between utility & solar industries

SEPA Program Areas

About SEPA

Research Projects

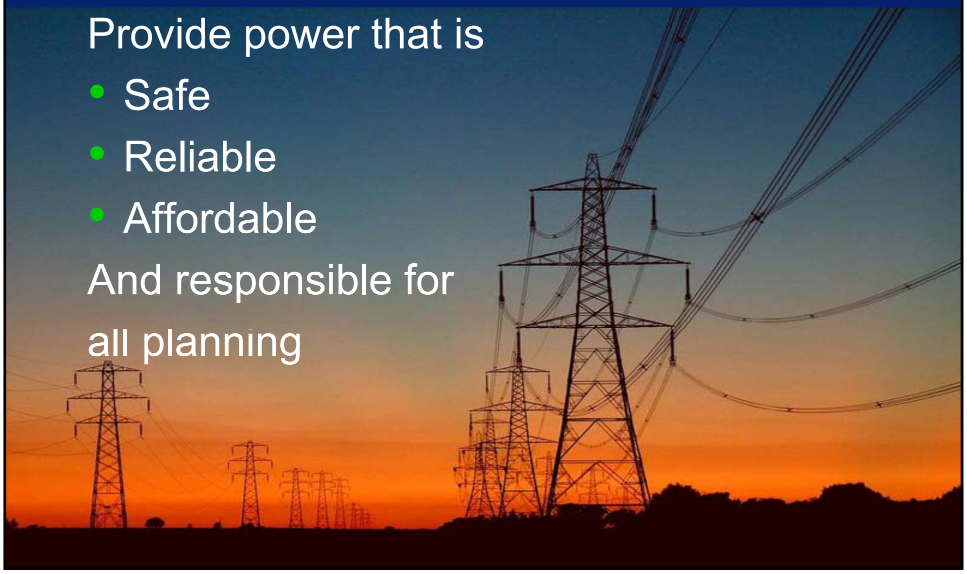
- Solar Incentive Program Survey
- Solar Capacity Methodology Project
- Utility Metering and Interconnection Survey
- Decoupling White Paper
- Utility Solar Case Studies
- Utility Solar Year in Review
- Utility Business Models
- Utility Integration Tracking

Ongoing Activities

- One-on-One Utility Support
- Solar Power International Conference and Expo w/Utility and Regulator Travel Scholarships
- Utility Solar Conference
- Online Resource Library
- Monthly Phone Seminars
- Bi-Weekly Electronic Newsletter and Email Alerts
- Membership Directory
- Fact finding missions to Germany, Spain, and……

Utility "Charter"

SEPA
solar electric power association



Provide power that is
- Safe
- Reliable
- Affordable

And responsible for all planning

SEPA
solar electric power association

Solar Industry

Utility Industry

IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

"High-Penetration of PV Systems in Electricity Grids" (working Title)

Prepared by:

Roland Bründlinger, IEA-PVPS Task 1, roland.bruendlinger@arsenal.ac.at
Christoph Mayr, IEA-PVPS Task 11, christoph.mayr@arsenal.ac.at
arsenal research, Electric Energy Systems, Vienna, Austria
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fechner@technikum-wien.at

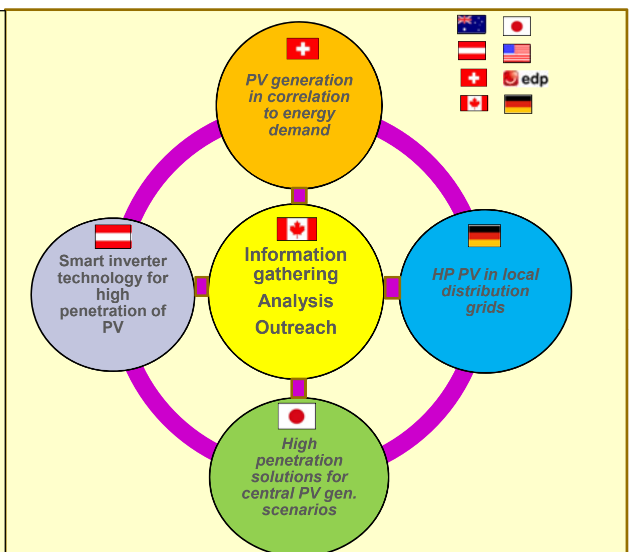
In collaboration with:

Task 14 definition group participants
Dan Ton, U.S. DOE; Ben Kroposky, NREL; Kazuhiko Ogimoto, University of Tokyo;
Konrad Mauch, OA Task 11; Christy Herig, OA Task 10;

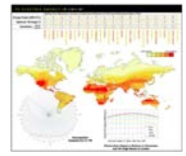
IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS Task 14

High-Penetration of PV Systems in Electricity Grids



IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME



Subtask 1

„How to characterise and react on the fluctuating PV characteristics“ and make it more valuable for the Power System“

- Characterisation of the fluctuating nature of PV
  - Data for further applications
- Definition of Requirements for Forecast prediction
- Definition for Energy Management Systems including storage solutions
- Case studies
- Target Group: Industry, Utilities, Researchers

IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Subtask 2

„Requirements for HP PV and Benefits of PV in the distribution system“

- „Ancillary Services, Impact on energy management on the grid, Benefits for the network. Reactive and active Power Balancing, Change from distribution to supply grids, …

- Target Group: DNO, (TSO), Regulators, System operators

Subtask 3

The electrical Power system with high Penetration PV

- Power system wide PV generation forecasting (> Subtask 1?), smoothing effects (Subtask 1),
- Power system operation and incentive generation to Distribution systems, Power system upgrade including PV
- Target Group: Utilities, Energy Planning, Energy Policy

IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Subtask 4

Requirements for Inverters at HP PV

- Smart inverter requirements for grid integration at HP Scenarios
- Technical capabilities and Solutions
- Remote Control and communication for Smart inverters
- Target group: Inverter Industry, DSO, Large System operators

SEPA
solar electric power association

Yesterday: Historical Utility Solar Engagement


A1
B1
C1
C3
C4
B6
A6
W
N
S
E
© Phönix Sonnenstrom AG (presently: Phoenix Solar AG)


World
2008 ~ 7000 MW
Total ~ 12000 MW
SEPA
solar electric power association
Germany
2008 ~1500 MW
Total ~ 5300 MW
Japan
2008 ~ 220 MW
Total ~ 7500 MW
USA
2008 ~ 330 MW
Total ~ 800 MW
Spain
2008 ~ 2500 MW
Total ~ 3100 MW

Thank you!

SEPA
solar electric power association

Christy Herig

cherig@solarelectricpower.org

www.solarelectricpower.org

Electricity, Resources, & Building Systems Integration

Utility-scale PV Variability Workshop

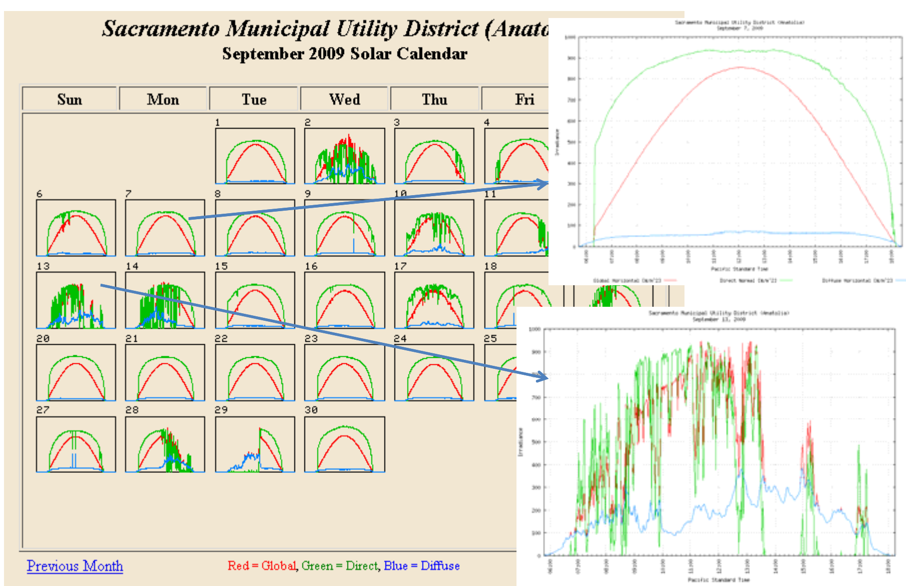
Meeting motivation and overview

Ben Kroposki, PhD, PE

October 7, 2009

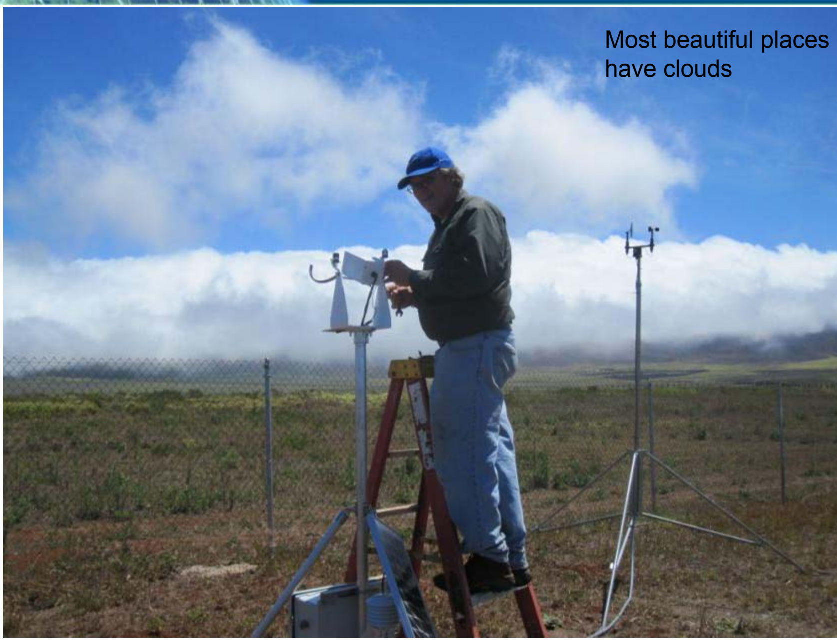
NREL National Renewable Energy Laboratory Innovation for Our Energy Future

NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.



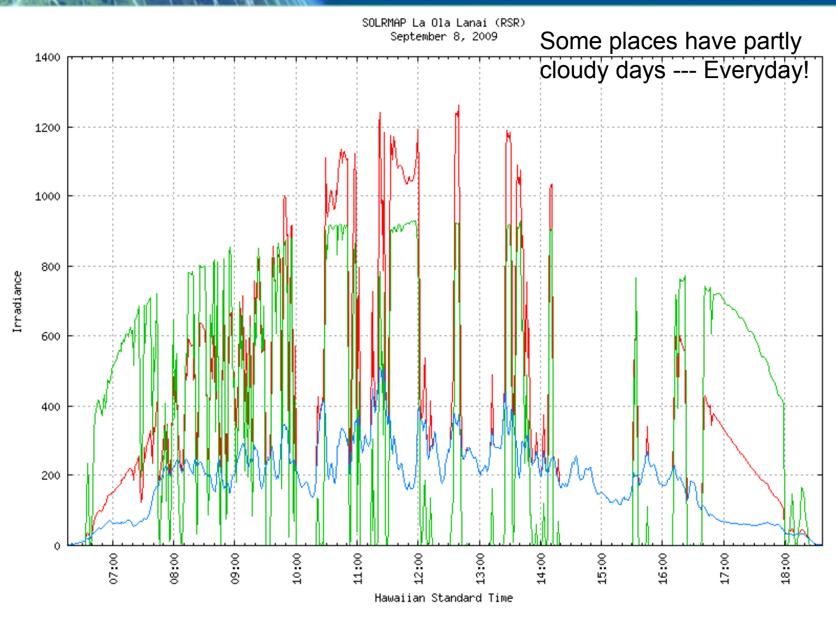
Even places with great sun have cloudy days

Most beautiful places have clouds



Renewable Technology Integration

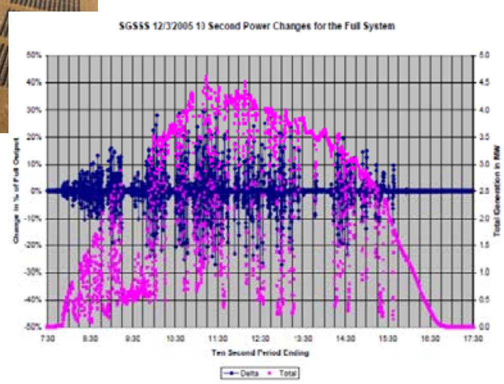
Some places have partly cloudy days --- Everyday!



National Renewable Energy Laboratory | Innovation for Our Energy Future

Why is this important?

- Tucson Electric Power – Springerville Plant (4.5MW$_{dc}$)
- 44 Acres



- 10 sec. data can show tremendous variability
- Ramp rates of PV at high penetration can effect electric power system operations
- Effects of geographical diversity still TBD

Large –Scale PV is Coming!

A 23.3 MW solar park in Trujillo, Extremadura, Spain. Photo courtesy of Suntech.

Solarpark Lieberose (Germany) - 53 MW (photo courtesy Juwi)

Parque Solar Olmedilla de Alarcon (Spain) - **60MW**

What is the industry doing to address this issue?

- Ad-hoc PV Variability Working Group
- Sharepoint site that has relevant papers, presentation and information on this topic.
- email Ben (benjamin.kroposki@nrel.gov) for access
- Starting in January 2009, we have had 5 conference calls on this topic.
- Started to develop a work plan, data requirements, meta data definition, and data collection plan
- This is the first face-to-face meeting to discuss the issues. Thanks to UWIG for allowing us to colocate!
- Presentations will also be posted on UWIG website

8:00 a.m. – 8:30 a.m.
Welcome, Introductions, and Overview

Welcome and introductions (Charlie Smith – UWIG, Dan Ton – DOE, Christy Herig – SEPA)

- Industry relevance; connection to DOE Renewable Energy and Smart Grid Programs, IEA High Penetration workplan.

Meeting motivation and overview (Benjamin Kroposki – NREL)

- Overview of issues in PV variability, integration, interconnection; overview of agenda.

8:30 a.m. – 9:30 a.m.
PV Interconnection Update

PV interconnection standards (Abraham Ellis – Sandia)

- IEEE, NERC and FERC standards for distributed systems and utility-scale system

Generic PV system models for interconnection and planning studies (Abraham Ellis – Sandia)

- Positive-sequence system planning (PSS/E and PSLF) and distribution planning models

9:30 p.m. – 10:30 p.m.
Integration of PV in Utility Operations

Utility operations and variable generation (Michael Milligan – NREL)

- Overview of utility operations; possible impacts of PV variability and uncertainty; mitigation alternatives

Solar resource forecasting (Mark Alhstrom – WindLogics)

- State-of-the-art, challenges and opportunities for improvement; integration into operations

10:30 – 10:45
Break
Location: Pre-Con Area

10:45 p.m. – 12:00 p.m.
PV Integration Studies

Wind and Solar integration studies (Nick Miller – General Electric)

- Solar integration study purpose, methodologies and data requirements; experience with wind integration studies

Development of data sets for PV integration studies (Ray George – NREL)

- Development of distributed generation and centralized system data sets for integration studies

12:00 p.m. – 1:00 p.m.
Lunch
Location: Oak

1:00 p.m. – 2:30 p.m.
Solar Resource Variability – What do we know?

Modeling the solar resource at higher resolution (Michael Brower – AWS Truewind)

- Mesoscale solar resource modeling methodologies, challenges and opportunities for higher time and space resolution

Short-term variability of the solar resource over wide geographical area (Andrew Mills – LBNL)

- Analysis of ARM data in the Southern Great Plains region; existing solar radiation database

Comparison of PV, CSP, wind variability (Yih-Huei Wan – NREL)

- Analysis of actual system output data to characterize PV variability and effect of geographic diversity, as compared to CSP and wind.

2:30 p.m. – 2:40 p.m.
Break
Location: Pre-Con Area

2:40 p.m. – 4:00 p.m.
Modeling PV Plant Output Variability

Short-term PV output variability in large PV systems (Carl Lenox – SunPower)

- Observed short-term output variability within a single large PV plant

Quantifying PV power output variability (Tom Hoff – Clean Power Research)

- Theory of solar resource variability and impact of geographical dispersion

Characterization of short-term PV variability for large PV systems (Joshua Stein – Sandia)

- Effect of plant size, tracking system and other factors on output characteristics of large and distributed PV systems; static, stochastic and dynamic models for short-term PV output behavior

4:00 p.m. – 4:30 p.m.
Data Collection Needs

Discussion of data collection effort and analysis needs by PV Variability Ad Hoc Group (Travis Johnson – NV Energy)

- Approach to collect high resolution, time-synchronized data; technical challenges; proposed data format and metadata; possible ways to overcome commercial issues

4:30 p.m. – 5:00 p.m.
Open discussion of next steps and priority needs

Interconnection Standards for PV Systems

Where are we? Where are we going?

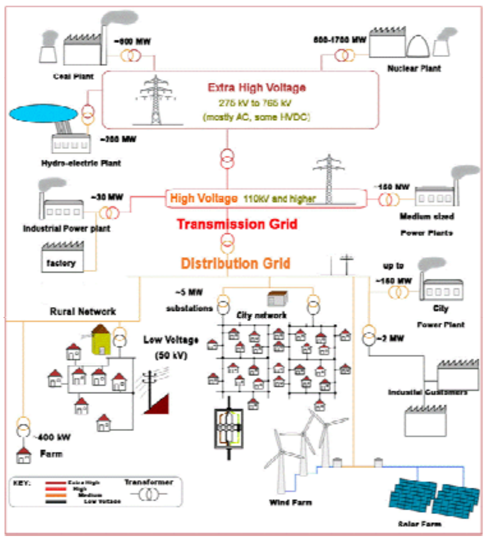
Abraham Ellis
Sandia National Laboratories
aellis@sandia.gov

Cedar Rapids, IA – October 2009

Generator Interconnection Standards

- Establish uniform technical and procedural requirements for interconnection of generation on the electric grid
- Interconnection standards are driven by
  – Safety (people and property)
  – Grid reliability, performance
  Cost considerations
  – Fairness ("…just and reasonable, and not unduly discriminatory or preferential")

What Interconnection Standards and Procedures Apply?



Bulk System Guidelines
NERC, FERC
IEEE, ANSI, IEC
NESC

Plenty of technical and jurisdictional overlap, confusion, contradiction…

Distribution System Guidelines
IEEE 1547, PUC/PRC
IEEE, ANSI, IEC
NEC

Federal-Jurisdictional Interconnection Standards (FERC Order)

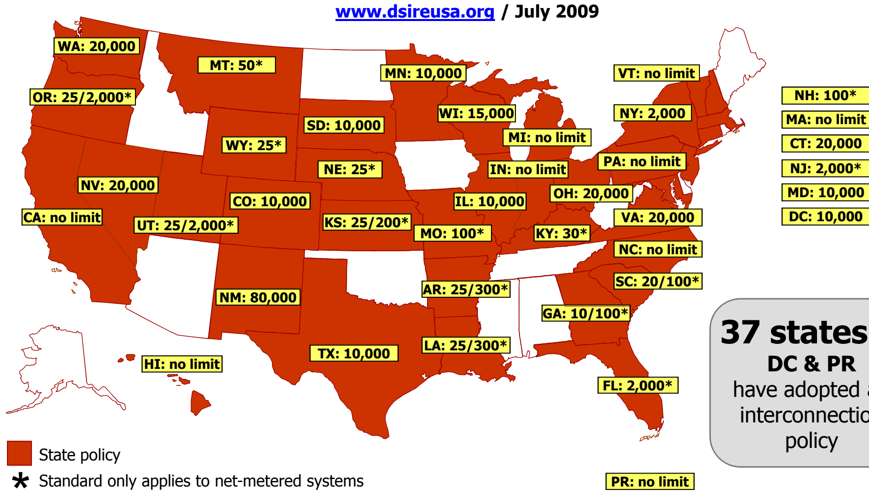
- Apply to generators, participating in wholesale market, regardless of size and interconnection location
  - TSO/DSO follow *pro-forma* procedures via OATT
- Procedures and requirements generally based on size
  - Large Generating Facilities (>20 MW): LGIP/LGIA
  - Small Generating Facilities (SGF) (<20 MW): SGIP/SGIA
- SGIP has streamlined process for smaller DER
  - Fast Track Process for certain generators no larger than 2 MW
  - 10 kW Inverter Process for certified inverter-based generators no larger than 10 kW (SGIP Attachment 5)

State-Jurisdictional Interconnection Standards (PUC/PRC Rule)

- Apply to generators up to a certain size, connected to the grid, but not participating in wholesale market
  - Net Metering, PURPA or similar arrangement for "sale" of electricity to the host utility only
  - Typically cover RE and other DG, all customer classes
- Procedures and standards vary by state
  - Generally conform with FERC SGIP, but some have significant differences
- Technical standards focused on the distribution system and DER

State-Jurisdictional Interconnection Standards

www.dsireusa.org / July 2009



37 states +
DC & PR
have adopted an interconnection policy

State policy
* Standard only applies to net-metered systems

Notes: Numbers indicate system capacity limit in kW. Some state limits vary by customer type (e.g., residential/non-residential)."No limit" means that there is no stated maximum size for individual systems. Other limits may apply. Generally, state interconnection standards apply only to investor-owned utilities.

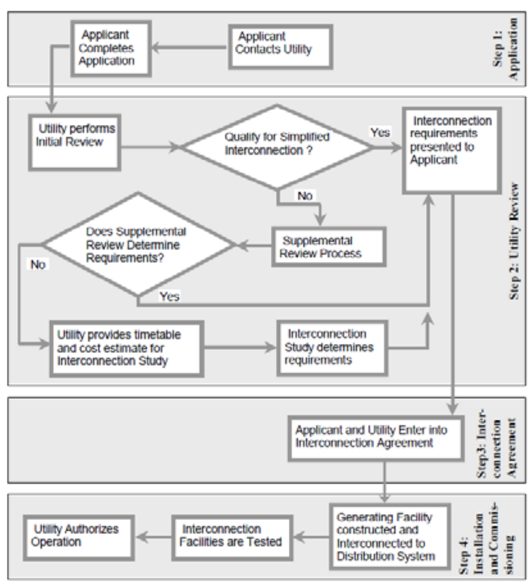
Interconnection Requirements for SGF (FERC Order 2006)

- Fast Track Process for SGF that pass certain “screens”
  - SGF capacity <2 MW
  - SGF meets codes, standards and certification
  - Total SGF capacity <15% of peak load in the circuit
  - If connecting to Spot Network, SGF must be inverter-based, not exceeding 5% of maximum load or 50 kW
  - Total SGF fault current <10% of total fault current
  - Addition of SGF does not cause distribution equipment and protective devices to exceed 87.5% of rating
  - Transformer connection compatible with utility circuit
  - <20kW for single phase, <20%imbalance among phases

Typical DER Interconnection Process

- Example:

CPUC Rule 21 Interconnection Process

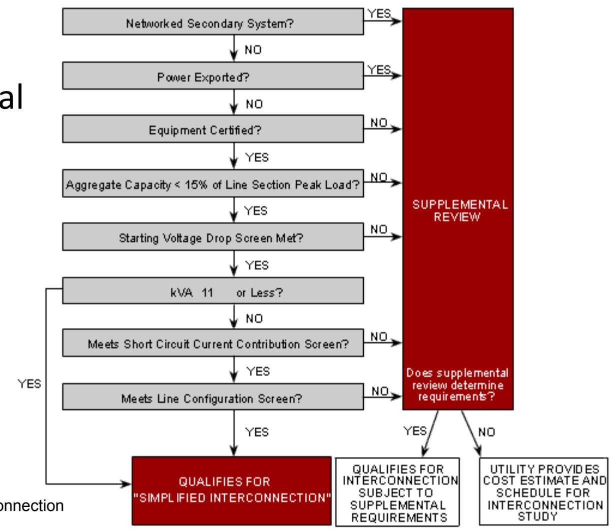


Source: California Interconnection Guidebook
http://www.energy.ca.gov/distgen/interconnection
/guide_book.html

Typical DER Interconnection Process

- Example:

CPUC Rule 21 Initial Technical Review Methodology



Source:
http://www.energy.ca.gov/distgen/interconnection/application.html

IEEE 1547 Standard Family

(Applies to DER no larger than 10 MVA)

No.	Title	Status
1547	Standard for Interconnecting Distributed Resources with Electric Power Systems	2003
1547.1	Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems	2005
1547.2	Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems	2008
1547.3	Guide For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems	2007
1547.4	Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems	Pending
1547.5	Draft Technical Guidelines for Interconnection of Electric Power Sources Greater than 10MVA to the Power Transmission Grid	Pending
1547.6	Draft Recommended Practice For Interconnecting Distributed Resources With Electric Power Systems Distribution Secondary Networks	Pending
1547.7	Draft Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection	Pending

Interconnection Standards for Distributed Energy Resources

- IEEE 1547 Voltage and Frequency Tolerance

Voltage Range (% Nominal)	Max. Clearing Time (sec) *
V < 50%	0.16
50% ≤ V < 88%	2.0
110% < V < 120%	1.0
V ≥ 120%	0.16

(*) Maximum clearing times for DER ≤ 30 kW; Default clearing times for DER > 30 kW

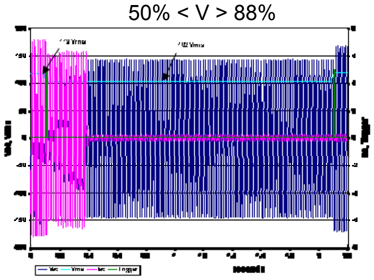
Frequency Range (Hz)	Max. Clearing Time (sec)
f > 60.5	0.16
f < 57.0 *	0.16
59.8 < f < 57.0 **	Adjustable (0.16 and 300)

(*) 59.3 Hz if DER ≤ 30 kW
(**) For DER > 30 KW

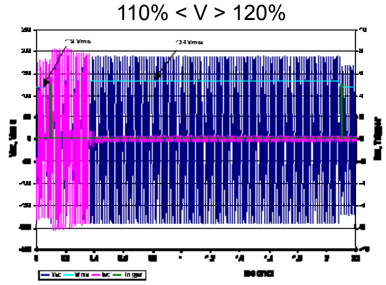
- Additional disconnection requirements
  - Cease to energize for faults on the Area EPS circuit
  - Cease to energize prior to circuit reclosure
  - Detect island condition and cease to energize within 2 seconds of the formation of an island ("anti-islanding")

Interconnection Standards for Distributed Energy Resources

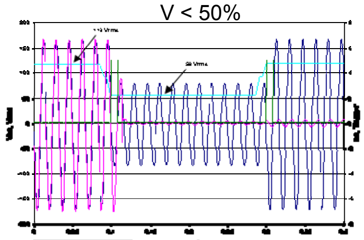
50% < V > 88%



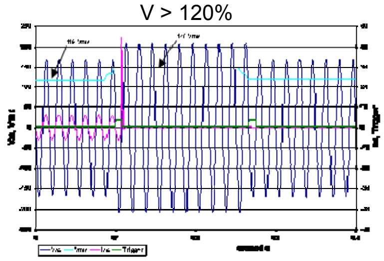
110% < V > 120%



V < 50%



V > 120%



Interconnection Standards for Distributed Energy Resources

- Other applicable codes and standards (not exhaustive)

	Requirement
Voltage Regulation	Maintain service voltage within ANSI C84 Range A (+/-5%)
Voltage control	Not permitted (IEEE 1547)
Flicker	Maximum Borderline of Irritation Curve (IEEE 1453)
Harmonics	<5% THD; <4% below 11th; <2% for 11th – 15th, <1.5% for 17th – 21st; 0.6% for 23rd – 33rd; <0.3% for 33rd and up (IEEE 519)
Power Factor	Output power factor 0.85 lead/lag or higher (equipment typically designed for unity power factor)
Direct Current Injection	<0.5% current of full rated RMS output current (IEEE 1547)
Synchronization and Protection	Dedicated protection & synchronization equipment required, except smaller systems with utility-interactive inverters
Safety	NFPA NEC, IEEE NESC

Interconnection Standards for Transmission-Connected Systems

- Some key differences compared to DER
  - Need to consider some of these for PV as system size & penetration increase

	Requirement
Voltage Tolerance	Ride through 3-phase fault POI for up to 150 ms
Frequency Tolerance	Based on interconnection requirements
Power Factor Capability	+/- 0.95 pf (or higher depending on study results)
Voltage Control	Power factor, reactive power or voltage control at the discretion of transmission operator
Synchronization, Protection	Dedicated switching and protection equipment required for transmission-connected systems
SCADA/EMS integration	Required in all cases
Power Control	Emerging for high penetration wind. May need handle with market instruments in some cases
Other	NERC FAC/TPL/MOD/PRC/VAR standards

Frequency and Voltage Tolerance Standards (Bulk System)

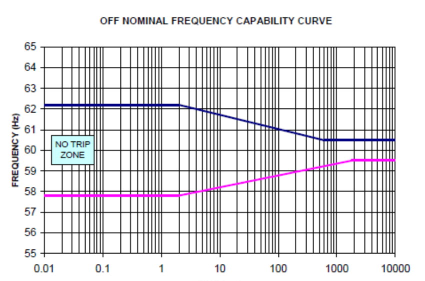
- Voltage Tolerance (LVRT)
  - Tolerate bolted fault (0 volts) at POI for up to 9 cycles (150 ms)
  - FERC Order 661-A: applies to wind generators >20 MVA
  - WECC LVRT criterion: applies to all generators >10 MVA
- Frequency Tolerance
  - For example, WECC ONF standard, which applies to all generators
- Rules still evolving in the US and elsewhere

WECC Off-Nominal Frequency Tolerance

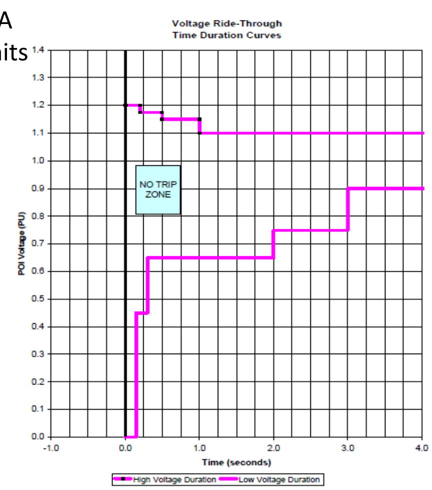
Frequency Range (Hz)	Max. Clearing Time (sec) *
59.4 – 60.5	N/A
59.4 – 58.5 or 60.6 – 61.5	3 min
58.4 – 57.9 or 61.6 – 61.7	30 sec
57.8 – 57.4	7.5 sec
57.3 – 56.9	45 cycles
56.8 – 56.5	7.2 cycles
< 56.4 or >61.7	instantaneous

Frequency and Voltage Tolerance Standards (Bulk System)

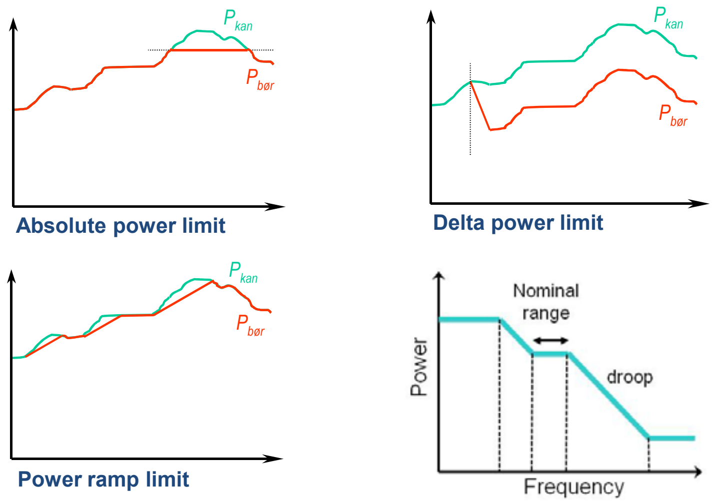
- Proposed NERC PRC-024
  - Would apply to all generators 20 MVA or larger, and stations with multiple units with total capacity of 75 MVA or more



Frequency (hertz)	62.2	60.5	57.8	59.5
Time (seconds)	0 to 2	600 to 10,000	0 to 2	1,800 to 10,000



Emerging Power Control for High Penetration Wind

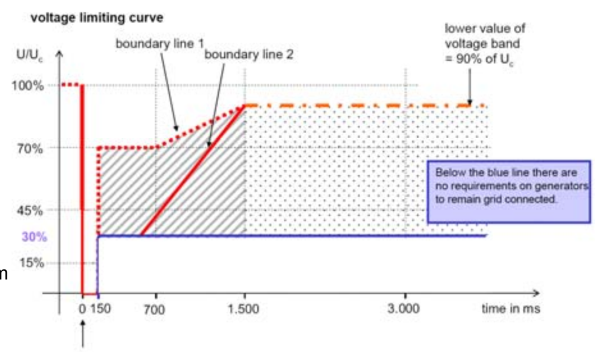


Source: Energinet.dk

Medium Voltage Standard in Germany (10 kV to 110 kV)

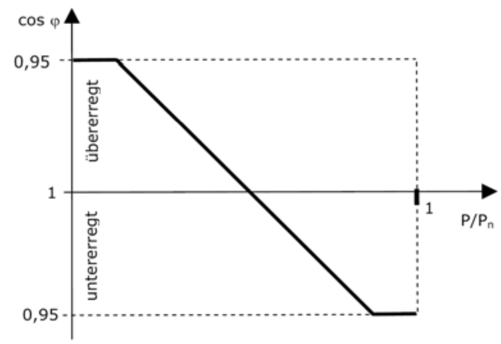
- Fault Tolerance
  - Applies to PV as of 2011
  - Inverters must comply with boundary line 2
  - Must provide reactive support during fault (voltage control)

Source: E. Troester, New German Grid Codes for Connecting PV to the Medium Voltage Power Grid, 2nd International Conference on Concentrating Photovoltaic Power plant



Medium Voltage Standard in Germany (10 kV to 110 kV)

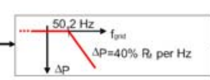
- Static Voltage Support
  - – Provide capability of +/- 0.95 pf at full output (impacts equipment rating)
  - – Dispatch could be constant pf, constant Var, Var support based on power output (see example below) or Var support based on voltage
  - – Applies to PV as of 2010



Source: E. Troester, New German Grid Codes for Connecting PV to the Medium Voltage Power Grid, 2nd International Conference on Concentrating Photovoltaic Power plant

Medium Voltage Standard in Germany (10 kV to 110 kV)

- Active Power Control
  - – Reduce power output when frequency is above 50.2 Hz
  - – Applies to PV as of 2010

f_{grid} →  → ΔP

$$\Delta P = 20\, P_M \frac{50{,}2\text{ Hz} - f_{grid}}{50\text{ Hz}} \quad \text{at } 50{,}2\text{ Hz} \leq f_{grid} \leq 51{,}5\text{ Hz}$$

P_M momentary available power

ΔP power reduction

f_{grid} grid frequency

In the range of 47,5 Hz $\leq f_{grid} \leq$ 50,2 Hz no constraint

At f_{grid} ≤ 47,5 Hz and $f_{grid} \geq$ 51,5 Hz disconnection

Source: E. Troester, New German Grid Codes for Connecting PV to the Medium Voltage Power Grid, 2nd International Conference on Concentrating Photovoltaic Power plant

A Few Observations

- Wind and PV interconnection standards on different tracks, but converging
- North American approach to bulk system standards tends to be "technology neutral"
  - It makes technical sense to apply different requirements to different technologies (e.g., European approach)
  - Difficult to reach consensus, long process
- IEEE 1547 provides great foundation for DER
- Some future capabilities should be mandated by standards; some should be incentivized by markets
  - E.g., primary frequency support

Where are We Going?

- Reconcile distribution/transmission standards
  - Voltage/frequency tolerance
  - Reactive power capability, volt/var control
  - SCADA integration
  - Power/Frequency control
    - Special cases (e.g., islands) or future very high-penetration?
- Harmonization is important for efficiency and cost
- Several active efforts underway
  - IEEE 1547.4, 1547.5, 1547.6, P2030 (Smart Grid) (http://grouper.ieee.org/groups/scc21/1547/1547_index.html)
  - US: NERC IVGTF (http://www.nerc.com/filez/ivgtf.html)
  - Europe: Medium and low voltage grid codes (GR, SP, FR, IT)

Questions and Discussion

Codes & Standards Specific to PV

Source	Documents
IEEE SCC21 – Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage	• IEEE 1547 series (DER up to 10 MVA) • Stand alone PV systems, batteries (several) • P2030 (Smart Grid – New initiative)
Underwriters Laboratories Inc. (UL) PV Standards Technical Panels	• UL 1703 (PV modules) • US 1741 (Inverters, charge controllers)
NFPA	NEC, Article 690 (solar Photovoltaic Systems)
ASTM E44.09 – Technical Committee on Photovoltaic Electric Power Conversion	Several addressing PV module and array testing
IEC TC82 – Solar photovoltaic energy systems	Several addressing measurement, safety, test procedures

PV System Models For System Planning and Interconnection Studies

Abraham Ellis

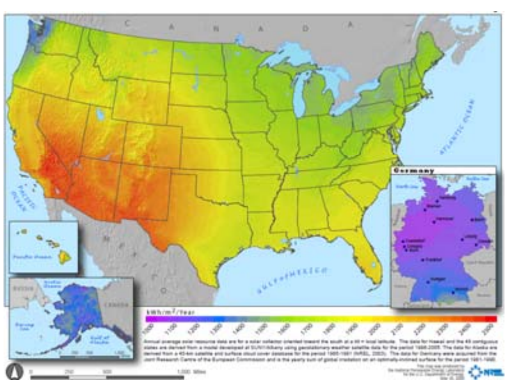
Sandia National Laboratories

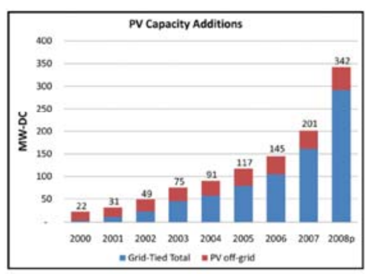
aellis@sandia.gov

Cedar Rapids, IA – October 2009

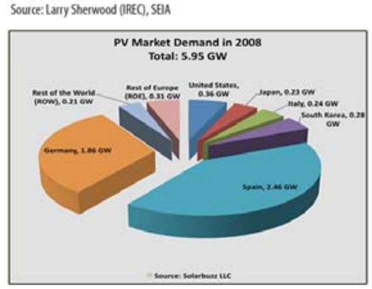
Growth in Grid-Tied PV Systems

- Grid-tied PV as of as of 2008
  - 791 MW total (most in CA)
  - ~1,500 MW "under development"
  - Tendency toward larger systems





p = preliminary
Source: Larry Sherwood (IREC), SEIA



Utility Industry Modeling Needs

- The not-so-distant future

Proposed PV Capacity (MW) Based on LGIP Queue				
Utility	**2010**	**2011**	**2012**	**2013**
SCE	1350	2822	1540	2180
NV Energy South	469	776	484	980

- Reasonable concerns emerging
  - Within a few years, inverter-based PV generation will displace a non-trivial amount of conventional generation
  - Some areas likely to see higher penetration, larger projects
  - NERC reliability criteria are not likely to ease
  - How do we plan for it?

Utility Industry Modeling Needs

- Utility planners need models of these facilities to assess planning and operating impacts
  - Steady-state power flow (thermal, voltage)
  - Dynamic (transient stability)
  - Short circuit (interrupting capacity, system protection)
- With very few exceptions, utility simulation tools don't have standard-library models for PV systems
  - At best, project developers provide insufficiently validated, manufacturer-specific, proprietary, user-created models
  - Worse yet, modeling short cuts (e.g., load netting) are used without adequate technical basis

Utility Industry Modeling Needs

- NERC Intermittent and Variable Generation Task Force has identified the lack of industry-standard validated models as major barrier to renewable energy development

"Validated, generic, non-confidential, and public standard power flow and stability (positive-sequence) models for variable generation technologies are needed. Such models should be readily validated and publicly available to power utilities and all other industry stakeholders. Model parameters should be provided by variable generation manufacturers and a common model validation standard across all technologies should be adopted. The NERC Planning Committee should undertake a review of the appropriate Modeling, Data and Analysis (MOD) Standards to ensure high levels of variable generation can be simulated."

Source: NERC Special Report, Accommodating High Levels of Variable Generation, http://www.nerc.com/files/IVGTF_Report_041609.pdf

Type of Planning Models

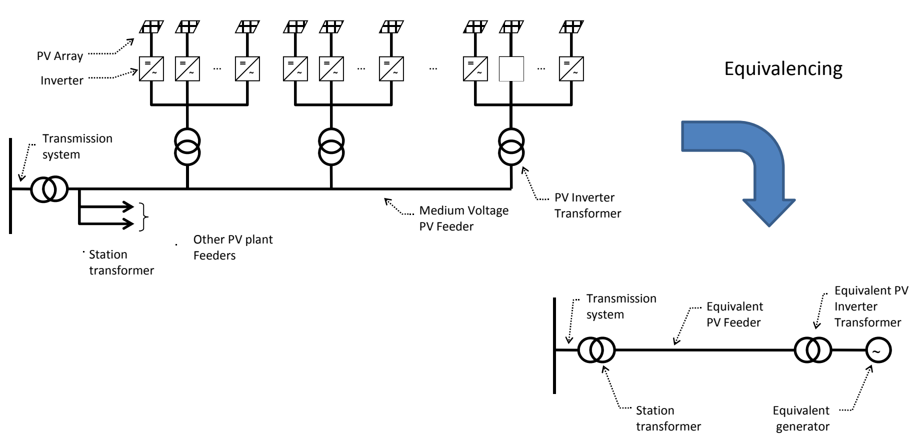
Type	Main Application	Example of Commercial Platforms
Power flow, unbalanced	Power flow (static) simulation of distribution networks. Software also does motor start, protection coord., etc.	FeederALL, SynerGEE, EasyPower
Power flow, positive sequence	Large-scale power flow simulations of bulk transmission systems	PSS/E, PSLF, ETAP, Power World
Dynamic, positive sequence	Large-scale dynamic simulations of bulk transmission systems	PSS/E, PSLF, ETAP
Transient, three phase	Detailed analysis of power system electromagnetic/mechanical and control interaction and performance	PSCAD, Matlab, EMTP-RV
Short Circuit	Fault analysis protection coordination	Aspen, SynerGEE,

PV System Power Flow Models

- PV inverters may be modeled as conventional generators in the steady state
- Over and under excitation limits must be set with cognizance of inverter reactive capabilities and modes:
  - Constant power factor
  - Constant reactive power
  - Voltage regulation
- For large-scale simulations, power flow modeling data requirements must be reduced through "equivalencing", similar to wind plants
  - Refer to existing WECC Wind Power Plant Power Flow Modeling Guide (*www.wecc.biz)*

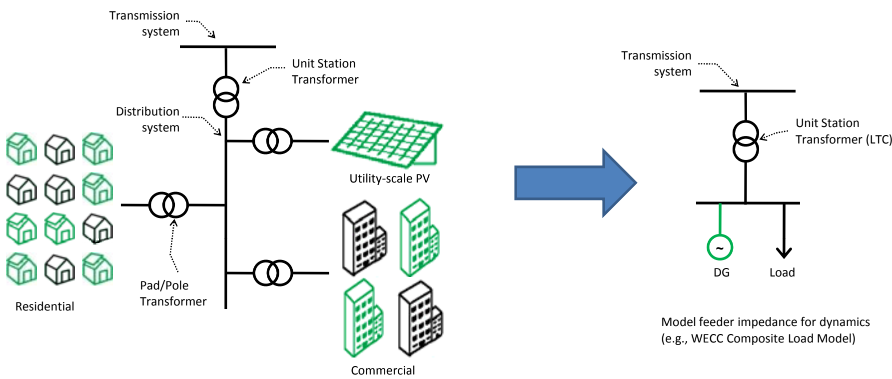
PV System Power Flow Models

- For utility-scale PV



PV System Power Flow Models

- For distributed PV



PV System Dynamic Models

- Vendor-specific, user-written models have a role, but don't meet critical needs
- Generic models have multiple advantages
  - Provide viable alternative to meet utility requirements
  - Allow interconnection studies to proceed before inverter and PV module manufacturers are selected
  - Reduce manufacturer confidentiality concerns with respect to proprietary aspects of user-created models
  - Provide improvements in:
    - Quality (thoroughly tested for compatibility with core software)
    - Portability (across different simulation platforms)
    - Usability (similar to familiar look and feel of conventional generator/turbine/exciter standard library models)

PV System Dynamic Models

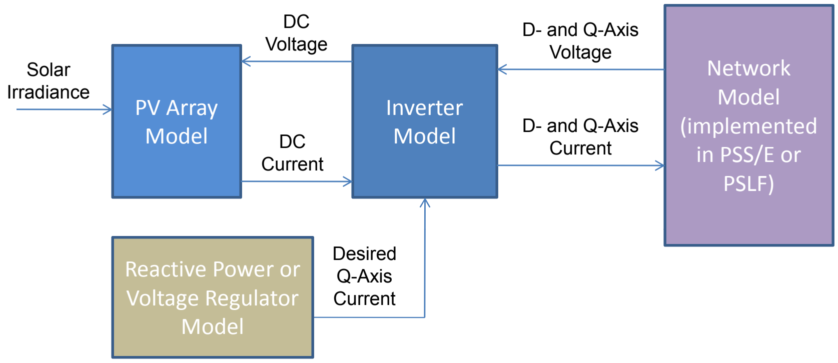
- A user-friendly generic PV system dynamic model would:
  - Approximate the aggregate dynamic response of a large number of inverters at a common point of interconnection
  - Be suitable for simulating plant response of the plant to grid disturbances, typically 3-phase faults up to 200 ms in duration and ground faults up to one second in duration
  - Allow for simulation of the post transient response of the plant for periods of 20 to 30 seconds
  - Allow for simulation of the response of the plant to cloud-induced irradiance transients
  - Allow for simulation time steps as high as ½ cycle (8.3 ms)
  - Provide for user-settable gains, time constants, and feature on/off switches (e.g., for voltage control, droop response, etc.) that would be specified by the manufacturers for their specific hardware
  - Validated against field data, higher order (EMTP-type) models, or both

PV System Dynamic Models

- Generic models pose challenges that can be overcome
  - Evolving technology and performance standards
    - Models need to include existing as well as future capabilities
    - Grid codes activities can guide model development
  - Access to detailed technical information from manufacturers for model development and validation
- Timing is right
  - Numerous user-written models have been developed
  - Industry interest is very high
  - Have opportunity to build on technical work and industry connections laid out by WECC/IEEE generic wind generator modeling effort

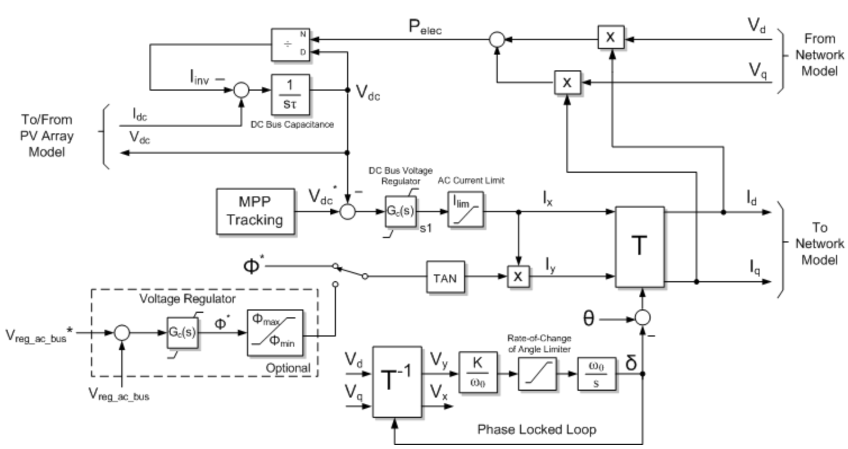
A Potential Implementation

- Model connectivity



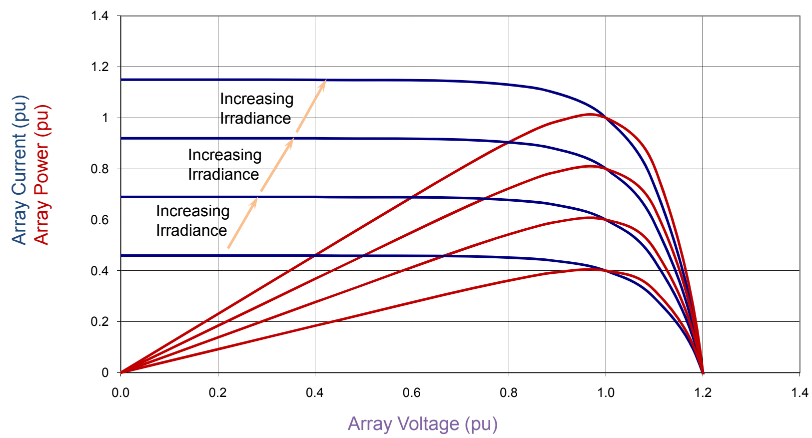
A Potential Implementation

- Inverter model



A Potential Implementation

- PV array model



A Potential Implementation

- Basic Assumptions
  - PV array is voltage- and irradiance-dependent current source
    - Temperature impacts can be neglected in simulation frames of interest for transient stability
    - Current response to voltage or irradiance transient is instantaneous (algebraic)
  - Inverters are high-frequency, pulse-width-modulated, ac current-regulated, voltage-source type
    - With ½ cycle time step, current regulator and modulator dynamics may be neglected… perhaps
    - Primary dynamics are due to inverter dc capacitor bank, dc voltage regulator and ac phase lock algorithms
    - Additional dynamics may be introduced to influence real and reactive power ramp rates

Activities Already Underway

- PV modeling initiative already started under the auspices of the WECC Modeling and Validation Work Group (MVWG)
  - Development, implementation & dissemination to be conducted openly
  - Similar in character to the generic wind modeling, also championed by WECC
- WECC group has broad industry representation
  - National Laboratories (Sandia coordinating effort)
  - Utilities
  - Equipment manufacturers
  - Project developers and systems integrators
  - Software developers
  - Consultants
- Initial focus is on positive-sequence power flow and dynamic models
- Models to be introduced to broader audience via technical coordination and outreach (WECC, NERC, IEEE)

Conclusions

- PV generation proposed and under development is becoming too large to ignore in the planning process
- The lack of access to user-friendly, validated models is a barrier to rapid deployment of PV
  - User written models have a role, but don't meet critical utility requirements
  - Need to make progress on standardized, validated PV system models for use in traditional transmission planning
- Generic models pose technical and institutional challenges that can be overcome
- Industry efforts already underway… Stay Tuned!

Questions and Discussion

National Renewable Energy Laboratory
Innovation for Our Energy Future

Utility operations and variable generation

Utility-scale PV Variability Workshop

Michael Milligan

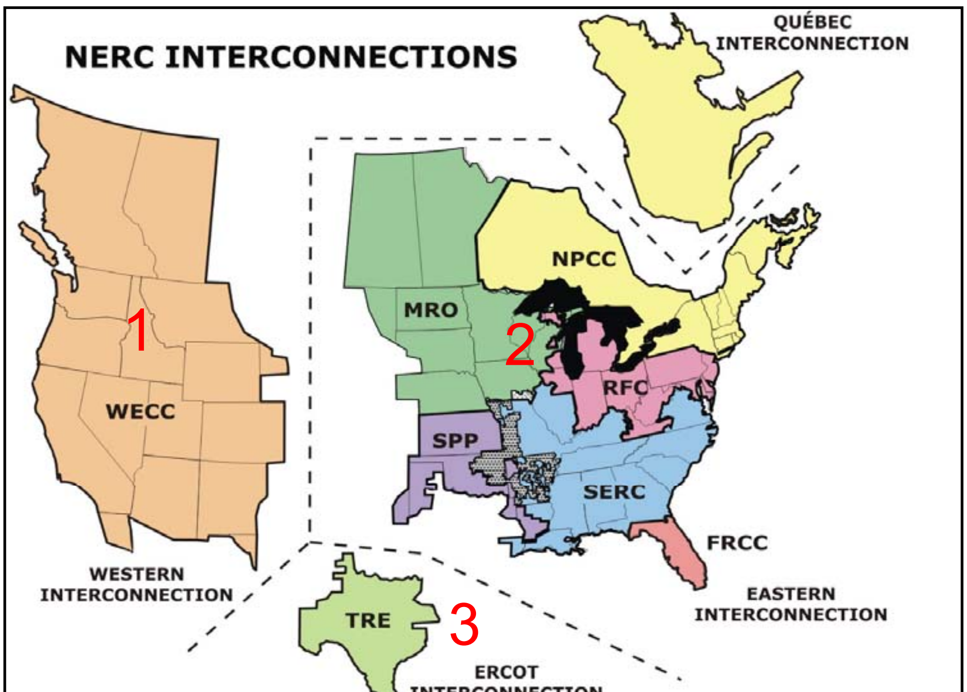
Oct 7, 2009

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Outline

- Overview of utility operations
  - Interconnections
  - Balancing
  - Time frames for operations
- Possible impacts of PV variability and uncertainty
- Mitigation alternatives

OVERVIEW OF UTILITY OPERATIONS: VG INTEGRATION



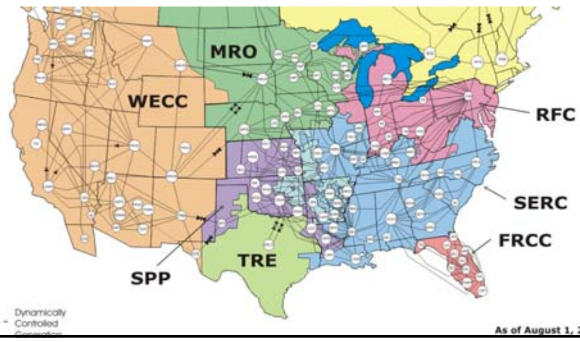
General Operating Requirements

- The interconnection must be balanced

  ∑ loads = ∑ generation *

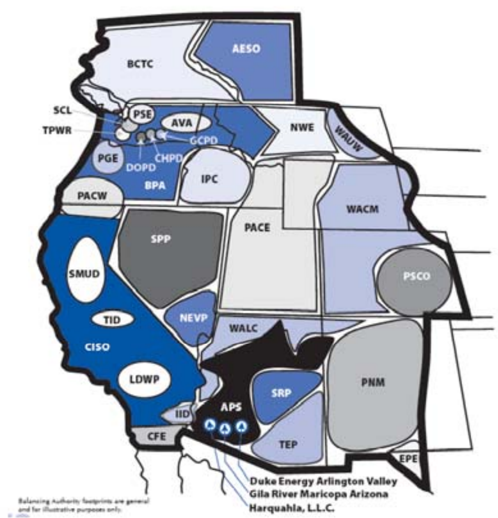
- Implication for individual balancing areas (BAs)

  ∑ loads = ∑ generation + Imports – Exports

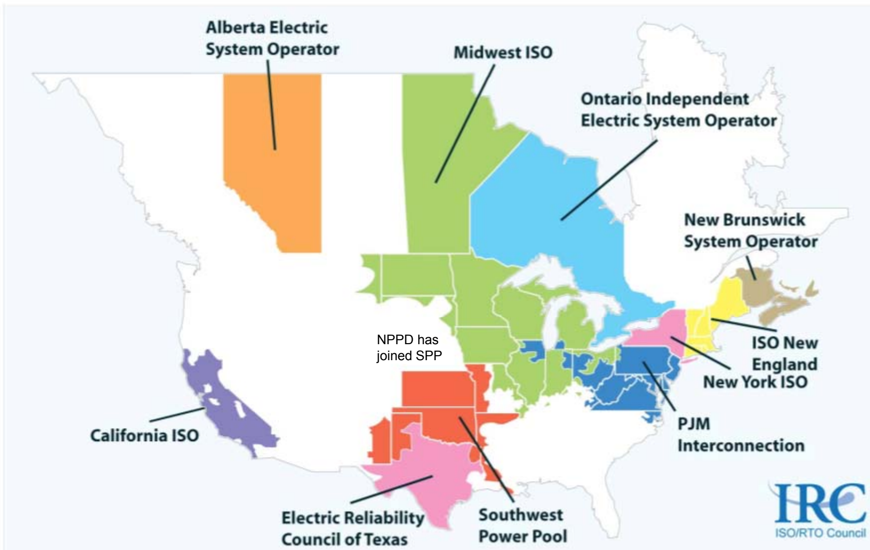


* DC ties can span two interconnections, but these are limited

Balancing Areas in the West



Markets cover part of the U.S.

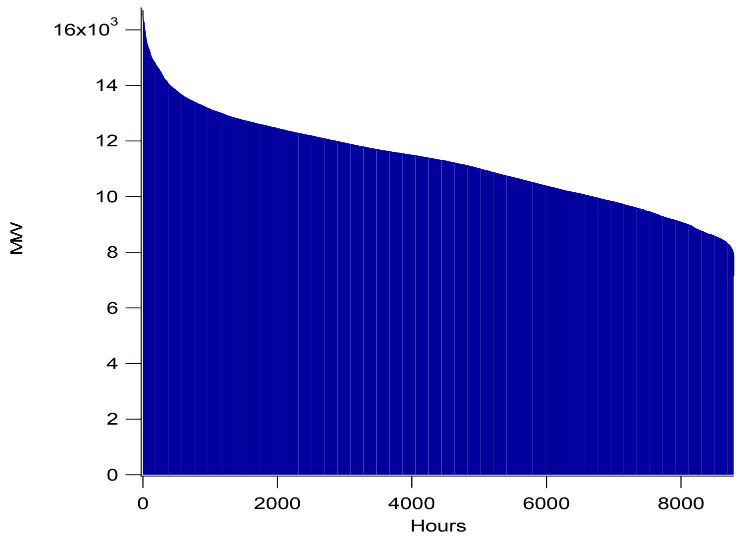


How does the utility schedule resources?

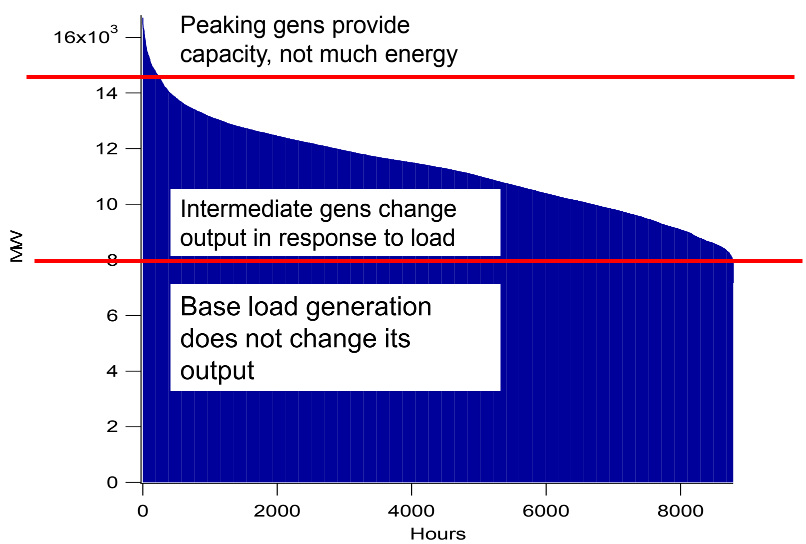
- Non-market areas (regulated by state PUCs)
  - Balancing Authority is responsible for scheduling generation to meet expected loads
  - Individual utilities will often provide schedules to BA, based on economics
- Market areas
  - Similar, except the schedules are induced by the energy market, not single entity

Economic Dispatch

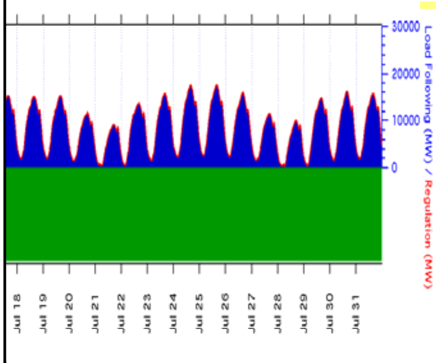
Load Duration Curve

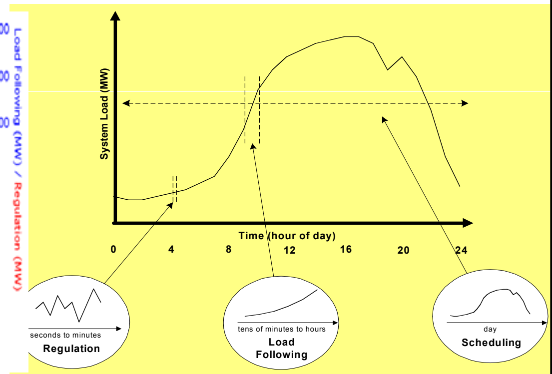


Economic Dispatch



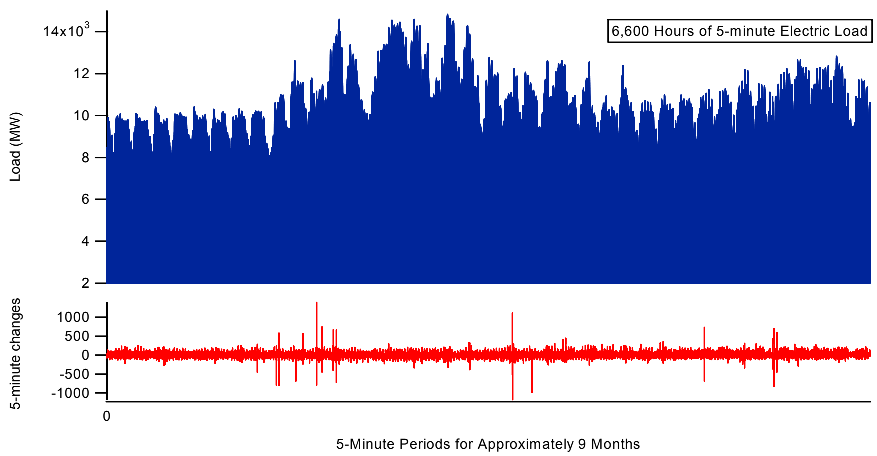
A Chronological View



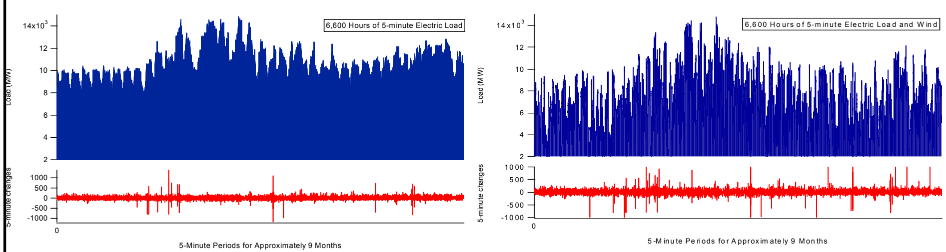


Hours to Day ahead: use load forecast to commit units
10 minutes to few hours: manually adjust generator set points
Seconds to minutes: AGC automatically adjusts generator output

Load is inherently variable



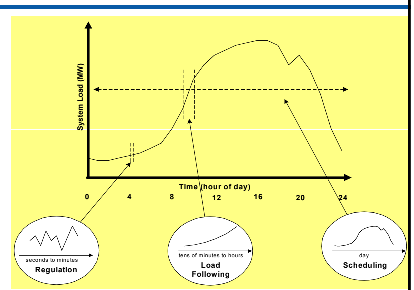
Impact of 25% Wind Energy Penetration: 5-minute data



- Wind: Ramp requirements increase with 25% wind energy penetration. The upper panel also shows the importance of being able to achieve lower minimum loads by the conventional generation fleet.
- Solar: Increase in ramping requirements; min-gen not an issue

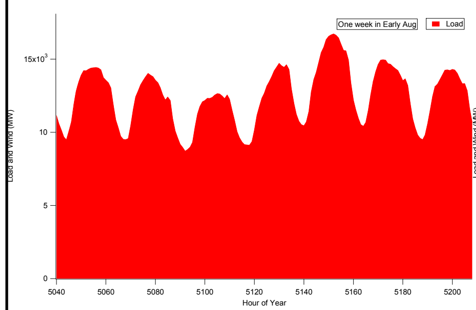
Variable generation increases the variability that must be managed on the grid

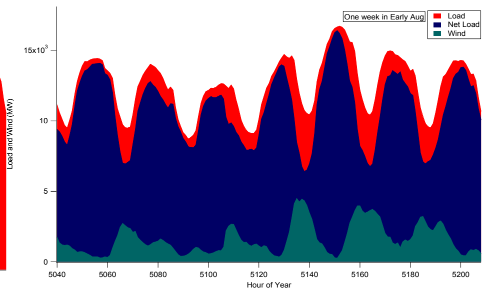
- Wind
  - Some impact on regulation
  - More significant impact on load-following and unit commitment
- PV
  - Potentially large impact on regulation
  - Some impact on load following, likely less significant than on regulation and wind



Unit commitment and uncertainty

- Is there sufficient committed capacity to cover uncertainty of load forecast error, VG forecast error? (spin)
- How much non-spin is available?
- Can I transact with the neighbors on fast time scales?





Advanced unit commitment

- Rolling commitment as new information becomes available ~6-hour time steps
- Stochastic unit commitment can help hedge your bets
- Does unit commitment handle the “sharp edges” or box you in?

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Data Requirements for Integration Analysis: VG and Load

- Weather is common driver
- Hourly VG and load data must be from same year for consistent analysis and plausible results
- Use of meso-scale weather models or actual VG production is state of the art
- Utility Wind Integration and Operating Impact State of the Art, IEEE Transactions, Aug 2007.

CAPACITY VALUE

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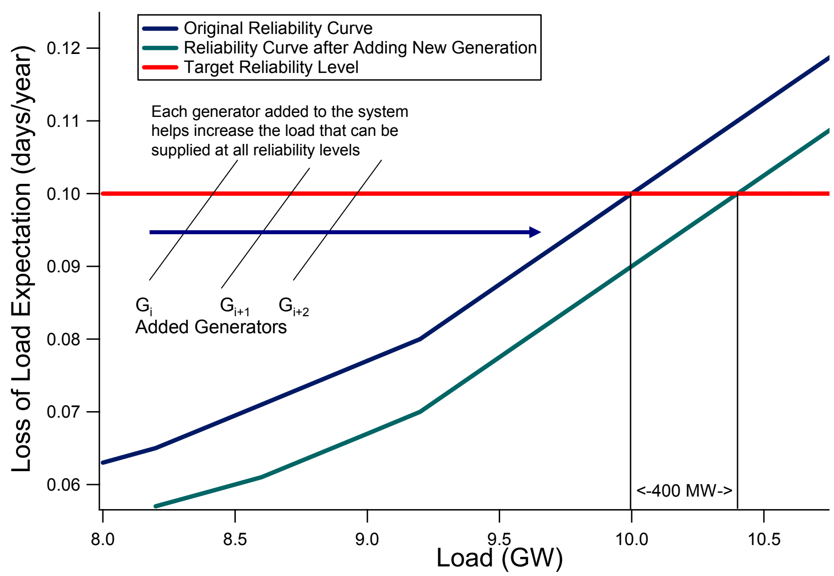
System Adequacy

- Often measured based on installed capacity, peak load, and a planning reserve
- A fixed planning reserve margin (15%) does not in itself provide a measure of adequacy
- No system can be perfectly adequate
- How adequate is adequate enough?
- Quantify the number of times system will be inadequate – often measured as hours/year; days/year (1d/10y ≈ 99.97%)

Effective Load Carrying Capability (ELCC)



Pitfalls (things to avoid)

- Using load and VG data from different years
- Applying load forecasts to load shape that changes underlying "weather" assumption
- Sampling VG/resource data from different years (i.e. long term database)
- Assume that one year is enough

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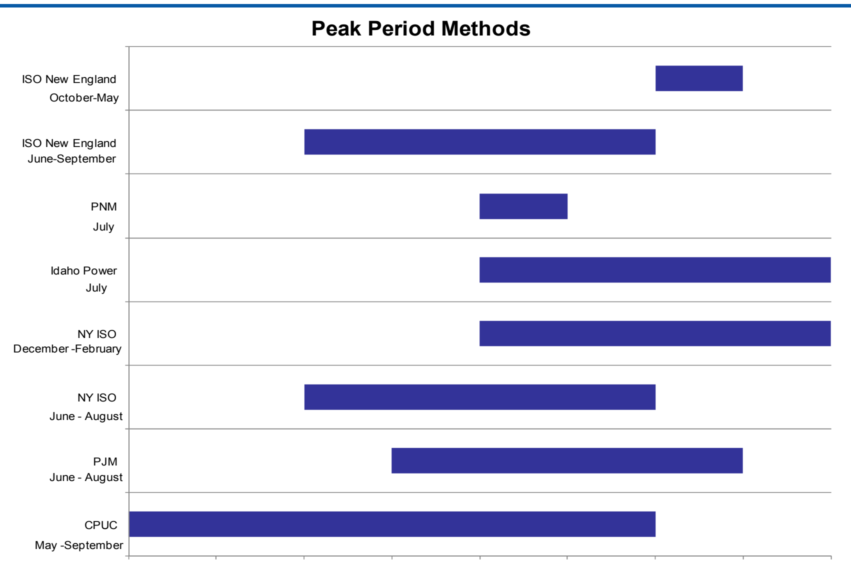
Simplified approaches are sometimes applied (full ELCC computation can be expensive)



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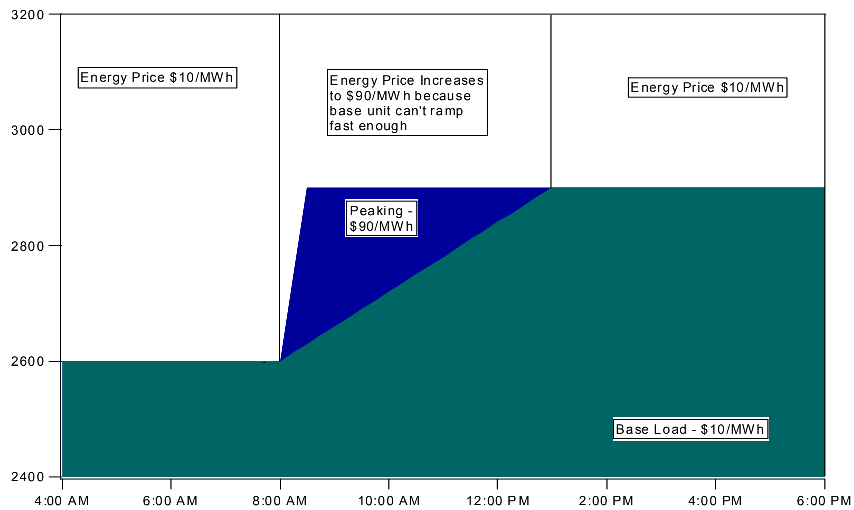
Issues for high VG penetration: what is needed for successful integration?

Key Challenges for VG Integration at High Penetration

- Can the increased variability be accommodated?
- Can the increased uncertainty be accommodated?
- Is there sufficient turn-down capacity?
- Is there sufficient transmission to ensure deliverability?

Can the non-wind fleet ramp quickly enough?



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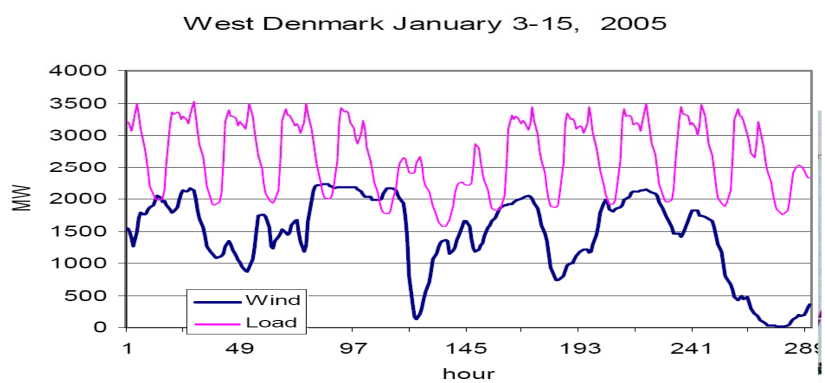
Integrating "large" VG penetrations: what does it take?

- Better use of existing flexibility
- Acquire additional flexibility across BAs
- Acquire additional physical flexibility



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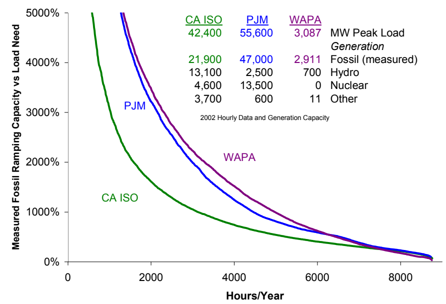
Better use of existing flexibility

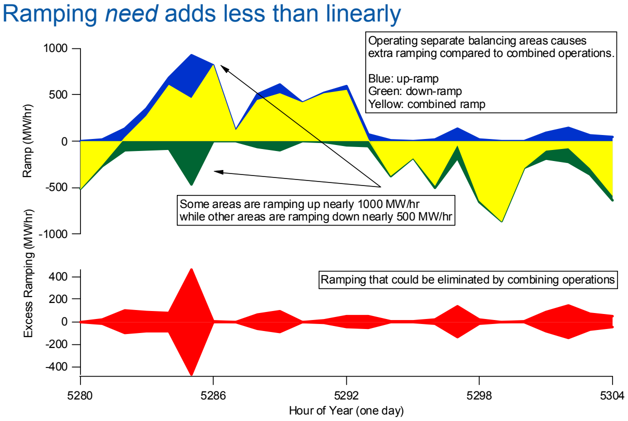
- Tap into maneuverable generation that may be "behind the wall"[1]
- Provide a mechanism (market, contract, other) that benefits system operator and generator
- Fast energy markets help provide needed flexibility[2] and can often supply load following flexibility at no cost[3]



[1]Kirby & Milligan, 2005 Methodology for Examining Control Area Ramping Capabilities with Implications for Wind http://www.nrel.gov/docs/fy05osti/38153.pdf
[2]Kirby & Milligan, 2008 Facilitating Wind Development: The Importance of Electric Industry Structure. http://www.nrel.gov/docs/fy08osti/43251.pdf
[3]Milligan & Kirby 2007, Impact of Balancing Areas Size, Obligation Sharing, and Ramping Capability on Wind Integration . http://www.nrel.gov/docs/fy07osti/41809.pdf

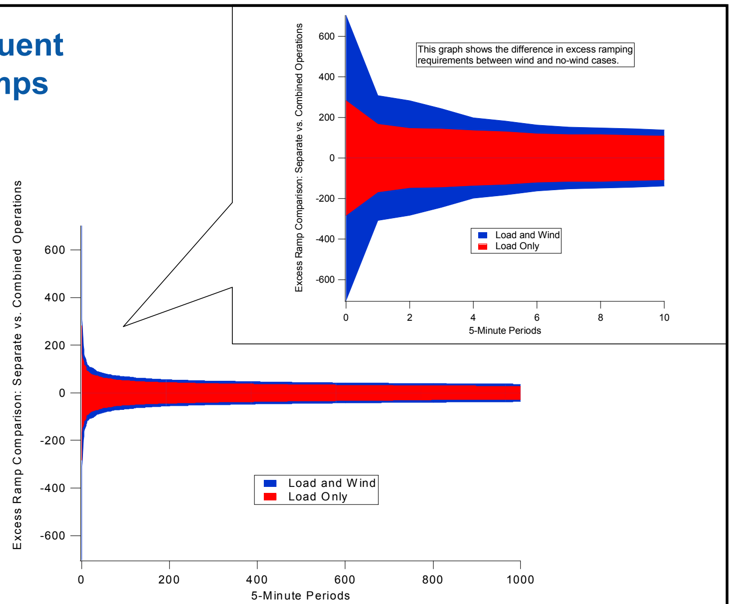
Acquire additional flexibility across BAs

- Reduce the need for ramping by combined BAs (real or virtual)
  - Inter-BA scheduling rules/practices
  - Ramping *capability* adds linearly
  - Ramping *need* adds less than linearly



Milligan & Kirby 2007, Impact of Balancing Areas Size, Obligation Sharing, and Ramping Capability on Wind Integration . http://www.nrel.gov/docs/fy07osti/41809.pdf

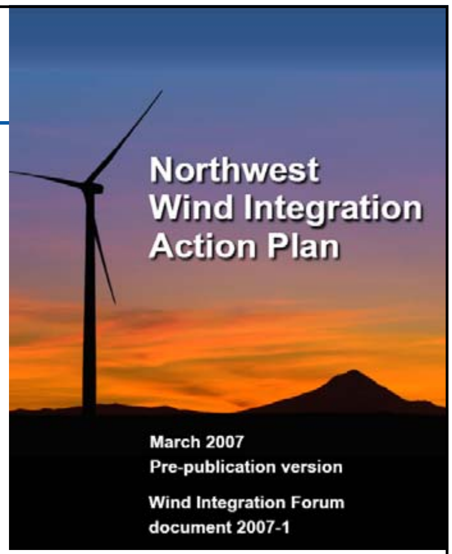
Large, infrequent 5-Minute Ramps can be significantly reduced



Milligan & Kirby 2008, An Analysis of Sub-Hourly Ramping Impacts of Wind Energy and Balancing Area Size: http://www.nrel.gov/docs/fy08osti/43434.pdf

Recognized Importance of Fast Energy Markets

- Fast markets
  - Will improve overall system performance and economics
  - Will correctly separate load following from regulation, increasing flexibility and reducing costs



Milligan & Kirby 2007, Impact of Balancing Areas Size, Obligation Sharing, and Ramping Capability on Wind Integration . http://www.nrel.gov/docs/fy07osti/41809.pdf found that fast energy markets can often supply the required load following capacity as a by-product of the energy market.

Balancing Area Consolidation: What Other Analyses/Experiments are Underway?

- Virtual consolidation
  - NTTG's ADI
  - Possible expansion to load-following time scale
  - Joint Initiative DSS, ITAP
- NREL's Large-scale studies
  - Western Wind and Solar Integration Study (WWSIS)
  - Eastern Wind and Transmission Study (EWITS) with JCSP
  - Nebraska Power Association

Balancing Area Consolidation: What Other Analyses/Experiments are Underway?

- Activity in the NW includes BPA's 'feed-forward' AGC concept
- Joint NREL-PNNL work
  - Interest in WECC-wide analysis collaboratively with WECC and Variable Generation Subcommittee
  - Northwest analysis

Other Flexibility Options

- Fast-ramping generation with good heat rates, low turn-down, low start-up cost
- Bi-lateral pooling agreements (similar to ADI but longer time frames)
- Innovation in hydro scheduling
- Economic VG curtailment, ramp limitations during critical periods
  - Morning load pickup or evening load drop off
  - Other
- Storage has value, but may not be currently cost-effective

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Summary

- Aggregation damps variability (solar, wind, load, and solar+wind+load together)
- Variability can be measured statistically and mapped to current operational practice
  - Load following
  - Regulation
- We care about tail events, and these often have important VG and load influences →time-synchronized data
  - Potential to reduce tail events thru aggregation
- Forecasts help, but must be brought into standard operating practice/tools

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WindLogics®

Solar Power Forecasting

Perspective and Understanding on Solar Power Forecasting

Utility-Scale PV Variability Workshop

October 7, 2009
Cedar Rapids, Iowa

Mark Ahlstrom and J. Adam Kankiewicz
mark@windlogics.com

WindLogics

WindLogics, NextEra Energy Resources & FPL

- WindLogics founded in 1989 by supercomputer architects
- Assessment, forecasting, operations and integration of renewable energy
- Staff of 80, including a Ph.D.-level research center
- Became FPL Energy subsidiary (now NextEra) in 2006
- NextEra is largest wind and solar developer/owner in North America

NEXTera ENERGY RESOURCES

The General Situation

- Clouds are the number one influence on a solar forecast
  - You can see coherent patterns of motion for "stable" clouds
  - Convective events ("unstable" clouds) will always be a challenge to predict, though like for wind, we can roughly predict the risk
  - Weather models have challenges with cloud forecasting
- There are excellent satellite-based cloud resources available to guide short term solar forecasts (no analogy for wind)
- Aerosols and haze also have a significant impact on energy production (but less so on ramps)

3

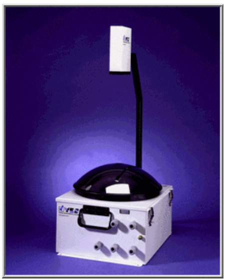
So what's the problem here…

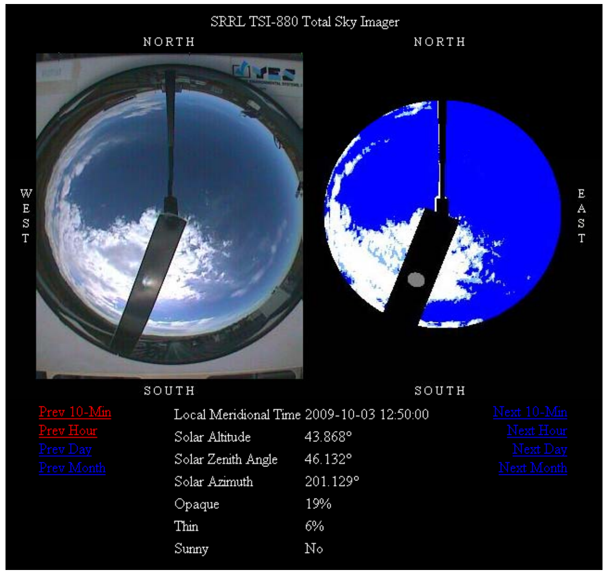
- Very short term ramp & variability forecasting
  - Next thirty minutes
- Load following forecasting
  - Next five hours
- Day-ahead unit commitment forecasting
  - Next six hours to two days

4

Visual Solar Forecasting (next minutes)

Yankee Environmental Systems Total Sky Imager (TSI-880)





http://www.nrel.gov/midc/srrl_bms

NREL

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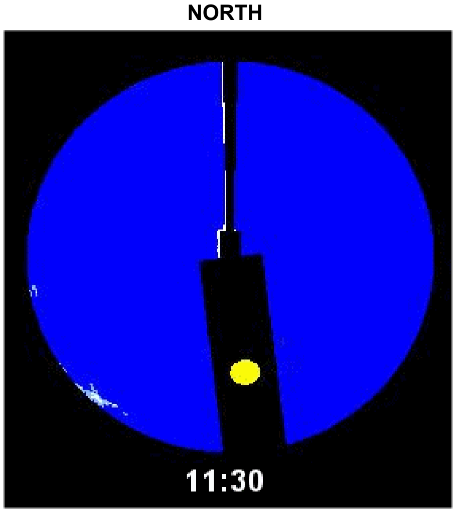
Sub-Hourly Solar Forecasting (next minutes)

NORTH

W E S T



E A S T

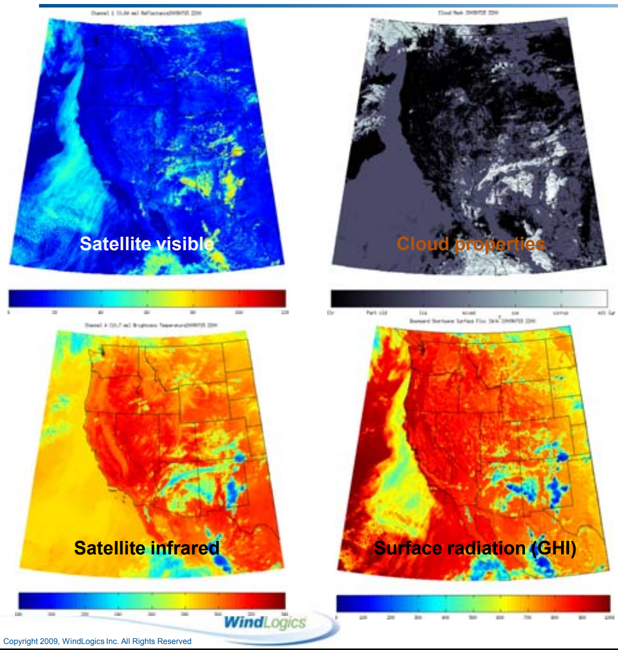
SOUTH

- Digitized cloud mask
- Short term forecasting
- Cloud tracking capable
- Operational assessment

Courtesy of NREL

6

Satellite-based Solar Forecasting (next hours)



July 15, 2009

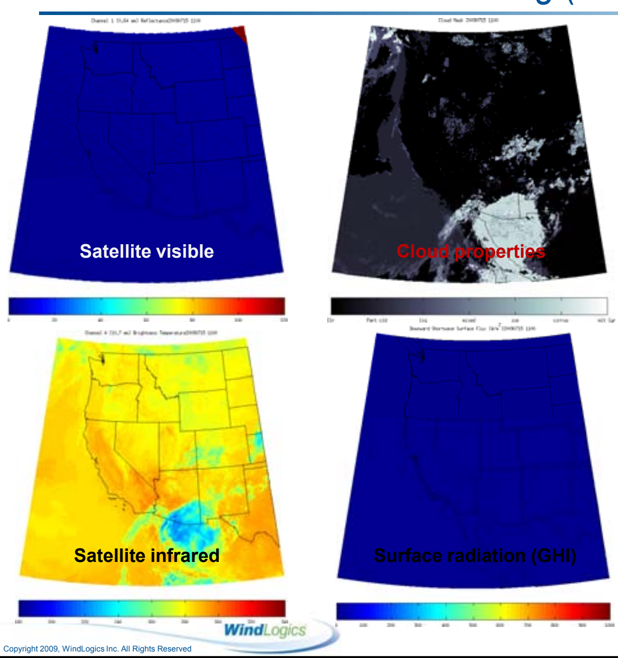
Satellite imagery, retrieved clouds and surface radiation from GOES West from NOAA's GOES Surface and Insolation Products (GSIP) Algorithm

Dr. Istvan Laszlo
NOAA/NESDIS/STAR
Dr. Andrew Heidinger
UW/CIMSS/NOAA

Courtesy of
Dr. Manajit Sengupta

7

Satellite-based Solar Forecasting (next hours)



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Courtesy of
Dr. Manajit Sengupta

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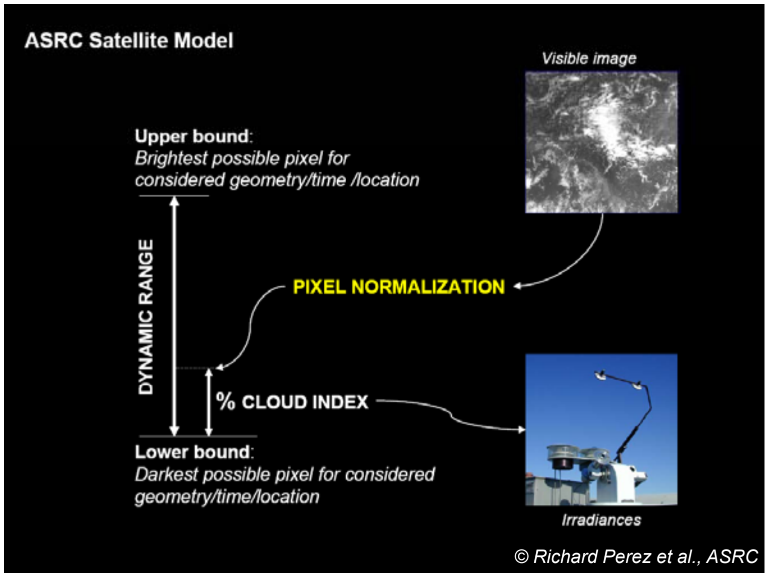
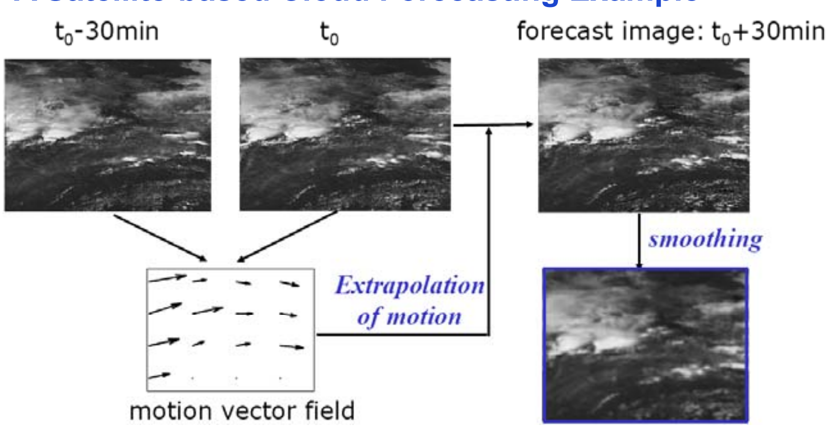
Satellite-based Solar Forecasting (next hours)



Motion Vector Analysis of Cloud Fields

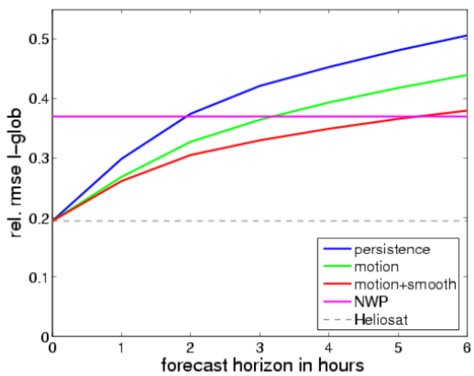
A Satellite-based Cloud Forecasting Example



Assumes Steady-State Cloud Field

Satellite-based Solar Forecasting

Comparison of satellite-based forecasts and forecasts based on Numerical Weather Prediction (NWP) models



- Up to 5 hours: forecast based on satellite images
- more than 5 hours: NWP based forecast

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CARL VON OSSIETZKY universität OLDENBURG

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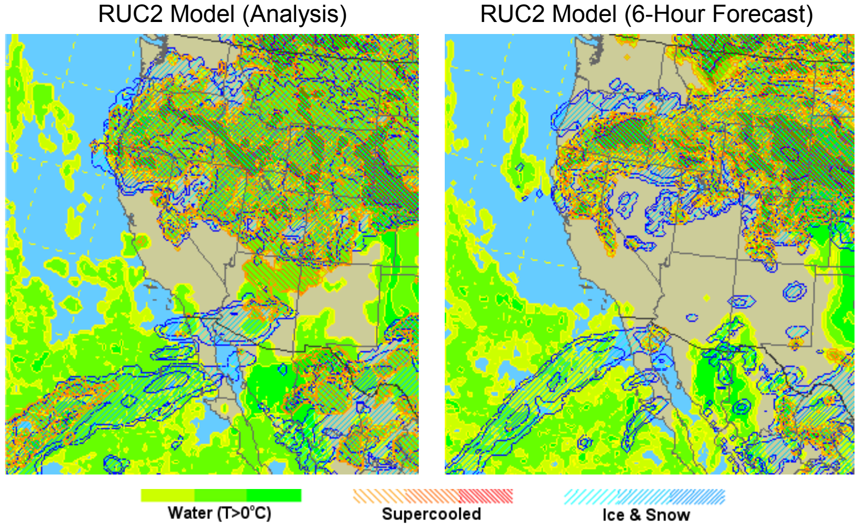
NWP Solar Forecasting

RUC2 Model (Analysis) RUC2 Model (6-Hour Forecast)



Integrated Liquid and Frozen Hydrometeors (all levels)

Courtesy of NCAR RAL

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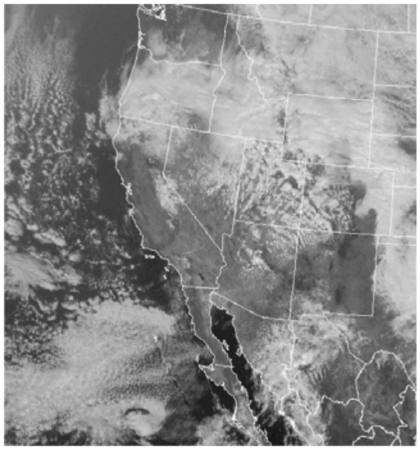
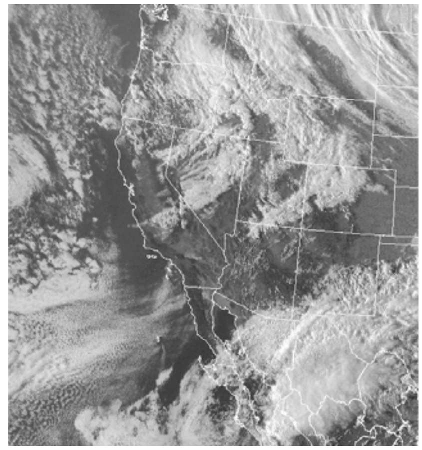
NWP Solar Forecasting

Visible Satellite (Analysis)



Visible Satellite (6-Hour Forecast)



Courtesy of NCAR RAL

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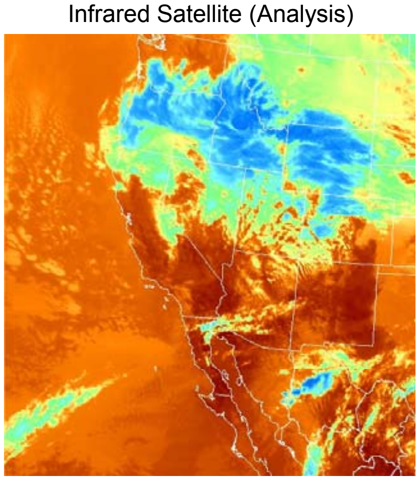
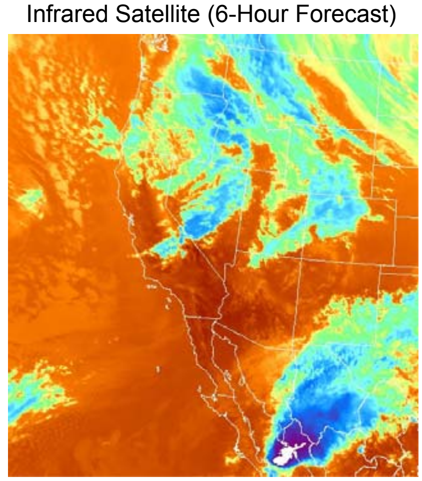
NWP Solar Forecasting

Infrared Satellite (Analysis)



Infrared Satellite (6-Hour Forecast)



Courtesy of NCAR RAL

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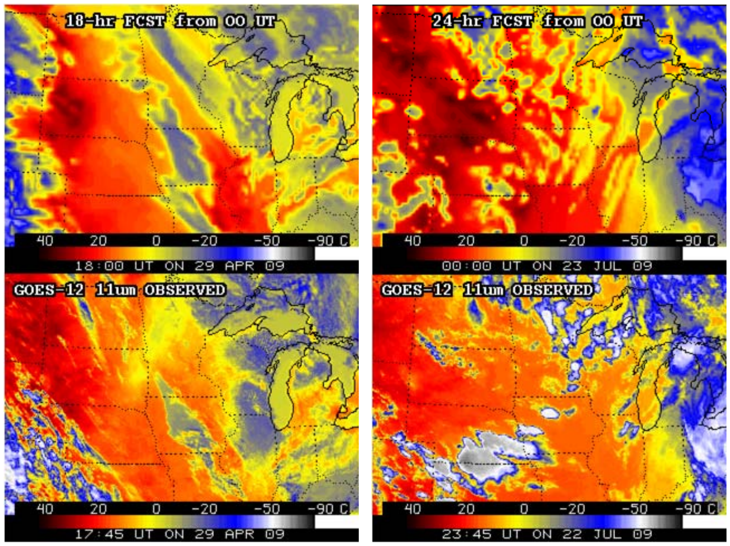
NWP Solar Forecasting – Convective Challenges

NCEP Model (GFS) Forecast Examples (a convective example on left)



Predicted Satellite Irradiance (11µm)

Observed Satellite Irradiance (11µm)

Courtesy of CIMSS

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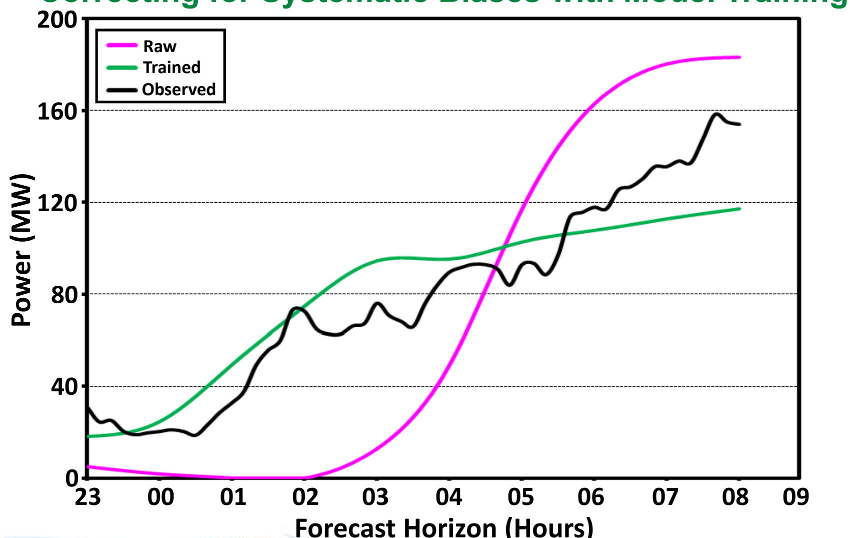
Motivation for Forecast Training

Correcting for Systematic Biases with Model Training



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Conclusions

- Solar forecasting & integration build on the industry's wind integration experience
- While accurate forecasting is challenging, solar has some characteristics that make it easier than wind forecasting
- Although still in development, we can expect to see a variety of good solar forecasting models and services
- In the control room, we should look work toward a unified view of both wind and solar integration
- Because NERC and others have already started work on variable generation issues, and because solar is already being included in this work, solar is on a fast path

Near Future

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Solar Technical Product Manager
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Florida Power & Light DeSoto Project (25 MW PV) in Central Florida - Commissioning Fall 2009

GE Energy Infrastructure

Wind and Solar Integration Studies

October 7, 2009
Utility Scale PV Variability Workshop

Cedar Rapids

Nicholas W. Miller

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Large Scale Solar Integration Studies

Overview

- Experience
- Objectives
- Data (as available)
- Methods and results
- Data (what we want in the future)

"oh yeah, and we do Wind, too."

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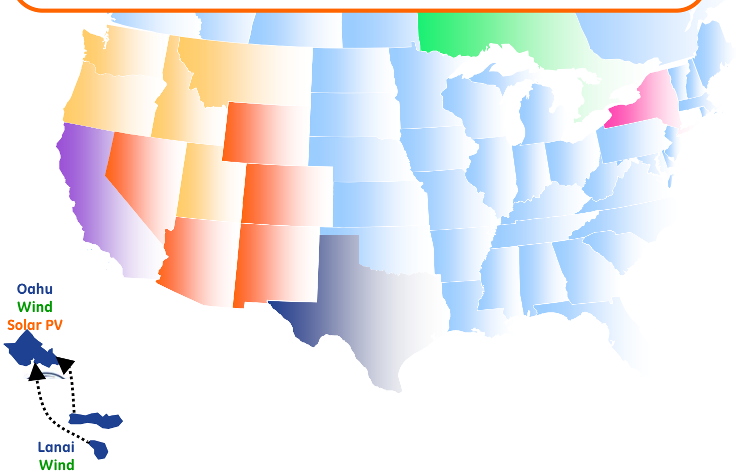
Large scale renewable studies by GE

These studies were commissioned by the Energy Commissions and ISOs of each region… . .

- **Examining the Feasibility of 100+ GW of new wind and other renewable resource additions**
- Considering Operability, Costs, Emissions, Transmission Constraints, Forecasting



2004 New York:
3 GW Wind
10% of Peak Load
4% of Energy

2005 Ontario:
15 GW Wind
50% Peak Load
~30% Energy

2006 California:
13 GW Wind
3 GW Solar
5 GW Bio & Geo
26% Peak Load
15% Energy (33% Total)

2007 Texas:
15 GW Wind
25 % Peak Load
17% Energy

2008-9 Western Wind & Solar:
(all of Western US)
72 GW Wind
15 GW Solar
50% Peak Load
27% Energy

3

Variable Generation

Wind
- Variations cover many timescales
- Season, day, hour, minute

Solar
- Variations are dominated by day/night cycle and sky conditions (clouds)

Biomass and geothermal generation are not intermittent

Objectives (typical large scale study)

Evaluate grid operation with increasing levels of variable generation

- Target levels of wind and solar penetration

Identify and quantify system performance and operation problems

- Load following, regulation, minimum load, etc.

Identify and evaluate possible mitigation methods

A mix of examples from the California and Western Wind and Solar Integration studies follows…

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California Study: 4 Scenarios Analyzed

2006 Base Case – Existing transmission system with existing mix of generation resources

- Includes 2,100 MW wind and 330 MW solar

2010T Tehachapi Case – 20% Renewable Energy

- 7,500 MW wind and 1,900 MW solar in California
- Includes 4,200 MW of wind in Tehachapi region and new 500 kV transmission to support it

2010X Accelerated Case – 33% Renewable Energy

- 12,500 MW wind and 2,600 MW solar in California

2020 Case – 33% Renewable Energy

- 12,700 MW wind and 6,000 MW solar in California

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Wind and Solar Generation in California

	2006	2010T	2010X	2020
Concentrating Solar (CS)				
Number of Sites	7	12	42	43
Total CS MW	330	1200	2100	3100
Photovoltaic (PV)				
Number of Sites	0 *	136	128	228
Total PV MW	0 *	630	530	2900
Wind Plants				
Total Sites in CA	57	98	142	147
Sites in Tehachapi	16	40	54	54
Total Wind MW	2100	7500	12500	12700

** Existing PV aggregated with load*

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Types of Analysis

Statistical Analysis

- Multiple time periods (Hourly, 5-minute, 1-minute)

Production Cost Simulation with MAPS

- Hour-by-hour simulation of grid operations for an entire year (3 years of different wind, solar and load profiles)

Quasi-Steady-State Simulation with PSLF

- Minute-by-minute time-sequenced power flows for entire WECC grid for several hours

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Data

Power flow data from Davis Power Consultants

- Scenarios 2006, 2010T, 2010X, 2020

Load data from CAISO, 2002-2004

- Hourly load MW, forecast and actual
- 4-sec load MW for about 400 days
- Load data scaled up to peak for 2006, 2010, 2020

Wind data from AWS Truewind, 2002-2004

- Hourly wind MW, forecast and actual
- 1-minute wind MW for 51 selected periods
- Separate wind profile data for each wind farm

Production simulation data for California and WECC from Rumla, Inc.

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Data

Solar data from multiple sources

- Hourly and 1-min MW for Sungen and Luz for 2002-2004 (CAISO and UC-Davis)
- Hourly Stirling solar MW for Mojave and Imperial for 2002-2004 (NREL and SES)
- Hourly and 15-min Photovoltaic MW for one year, aggregated by zip code (CPUC - SGIP)
- 1-min or 3-min solar insolation data at two sites, for January and July 2002 (NREL, ARSC SUNY Albany)

Based on this data, GE compiled solar profiles for multiple sites across California

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Compiling and Extrapolating

Tricks we used to extend the data

- Extraction of 1-min or 3-min variability – essentially high pass filter
- Retain temporal and spatial diversity for slower variations (1 hour and 15 minute samples)
- Overlay 'fast variability'
- Random draw of variability from a limited sample
- Assumes NO correlation for high frequency variability

Best available…but is it good enough?

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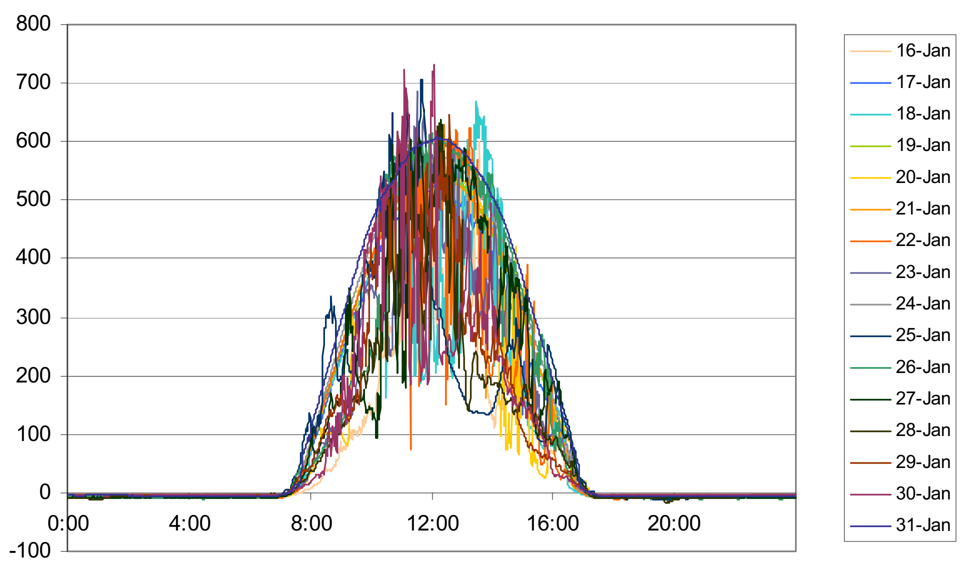

1 minute resolution; single site insolation (w/m^2) in CO. Jan 2002

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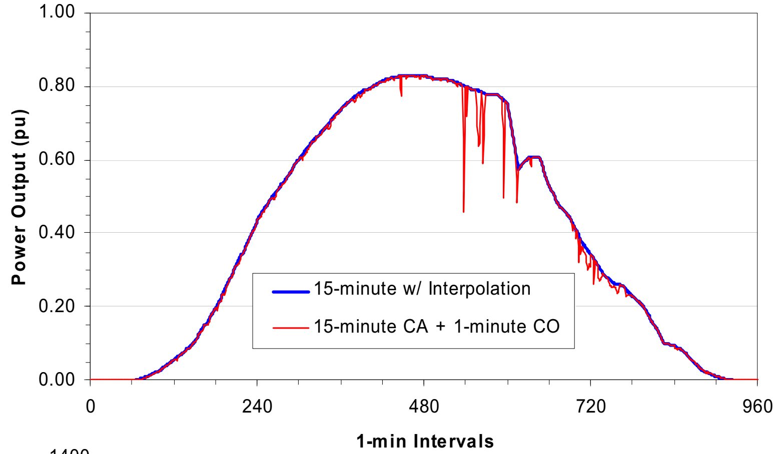
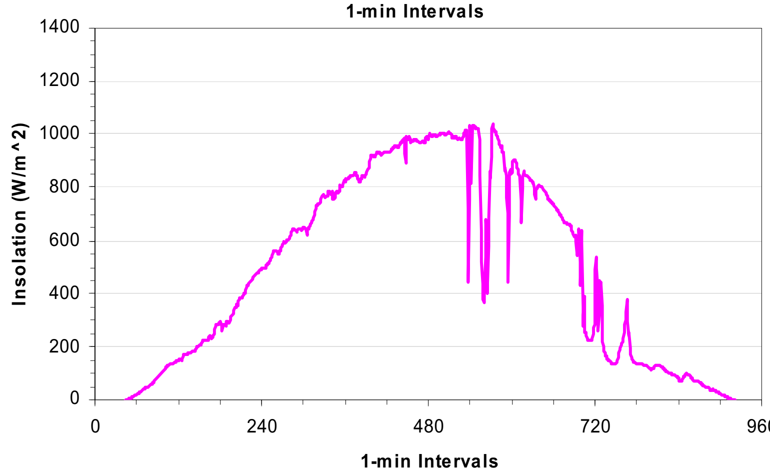
PV fast variability overlay

Comparison of Original 15-minute Data and Final Profile with 1-minute Variability.



Irradiation Data used as Source of 1-minute Variability in Example.



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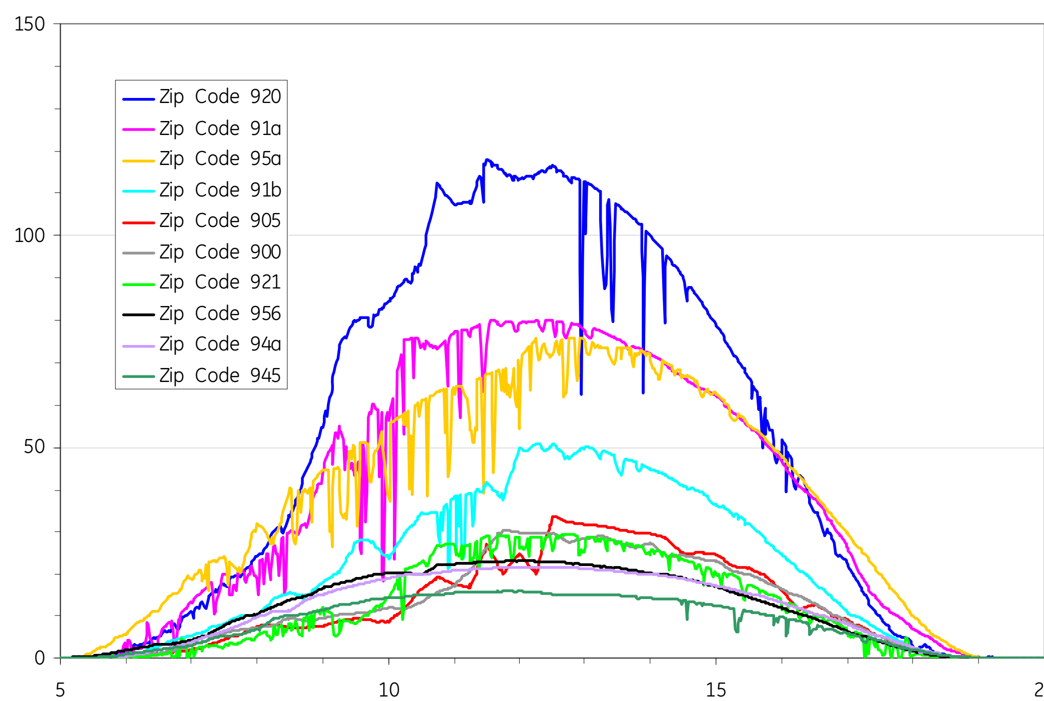
Example PV Solar Zip Code Profile for a July Morning



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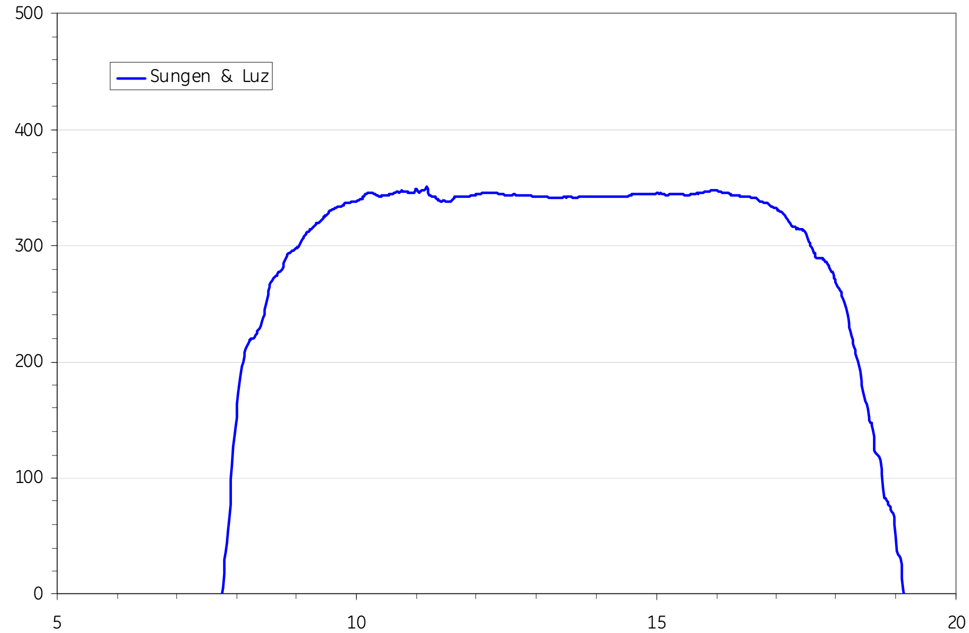
Example Concentrating Solar Project Profile for a May Day



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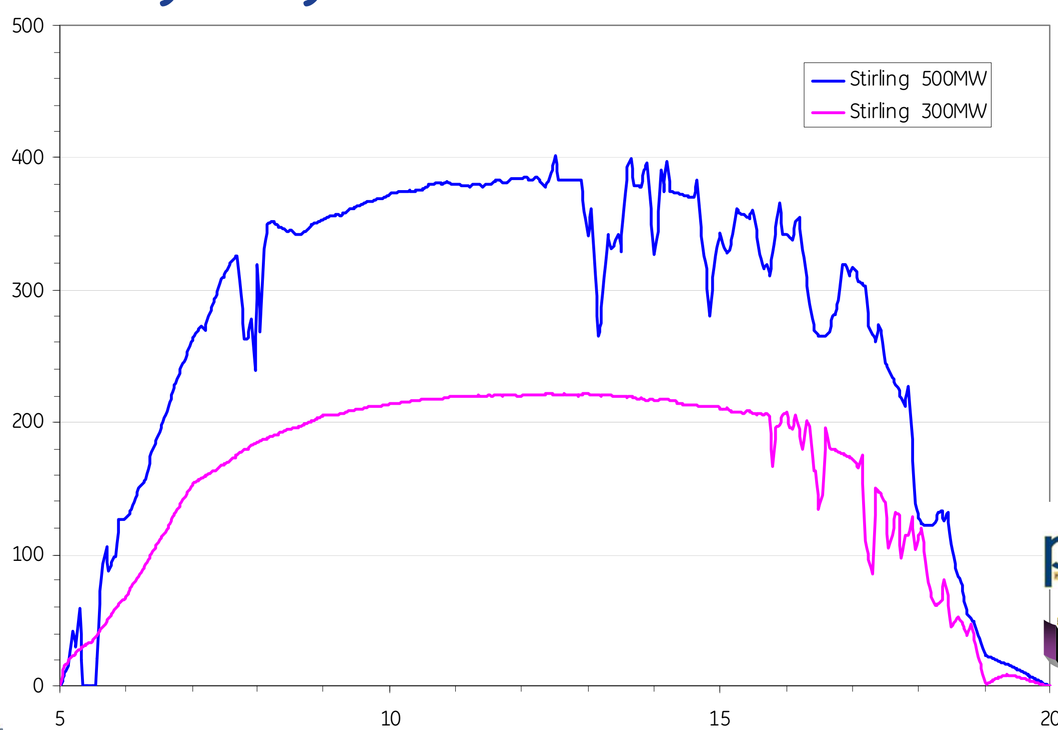
Example Stirling Solar Project Profile for a May Day



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Some of the things we observed and learned

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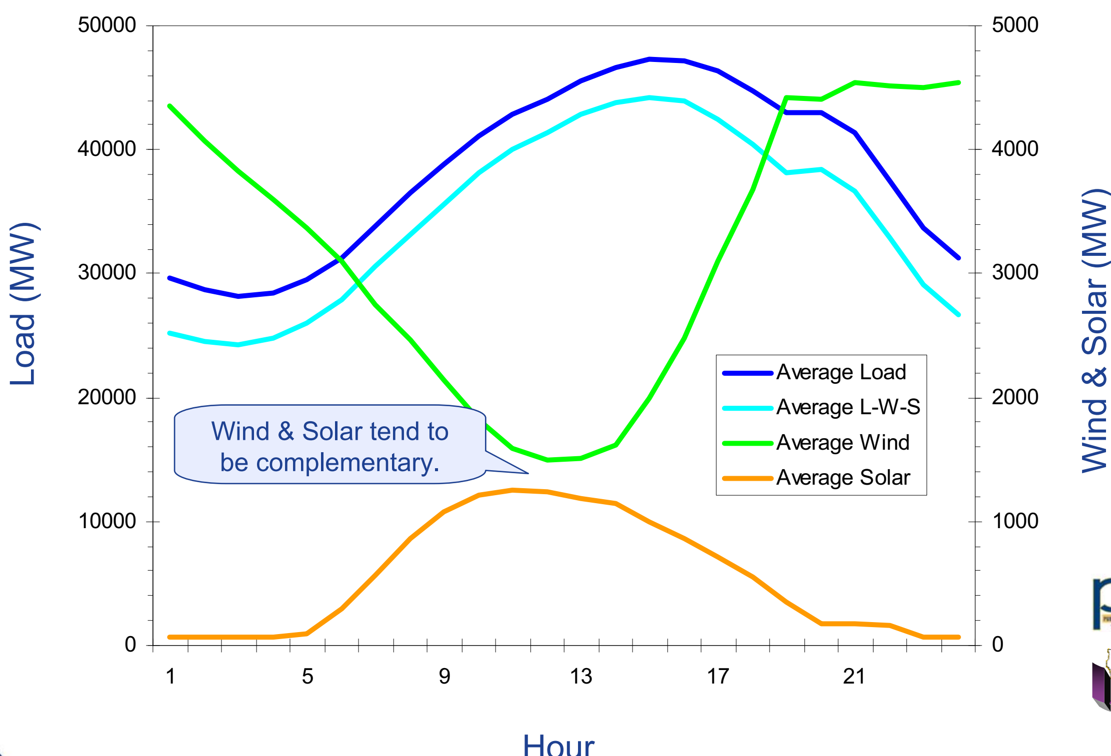
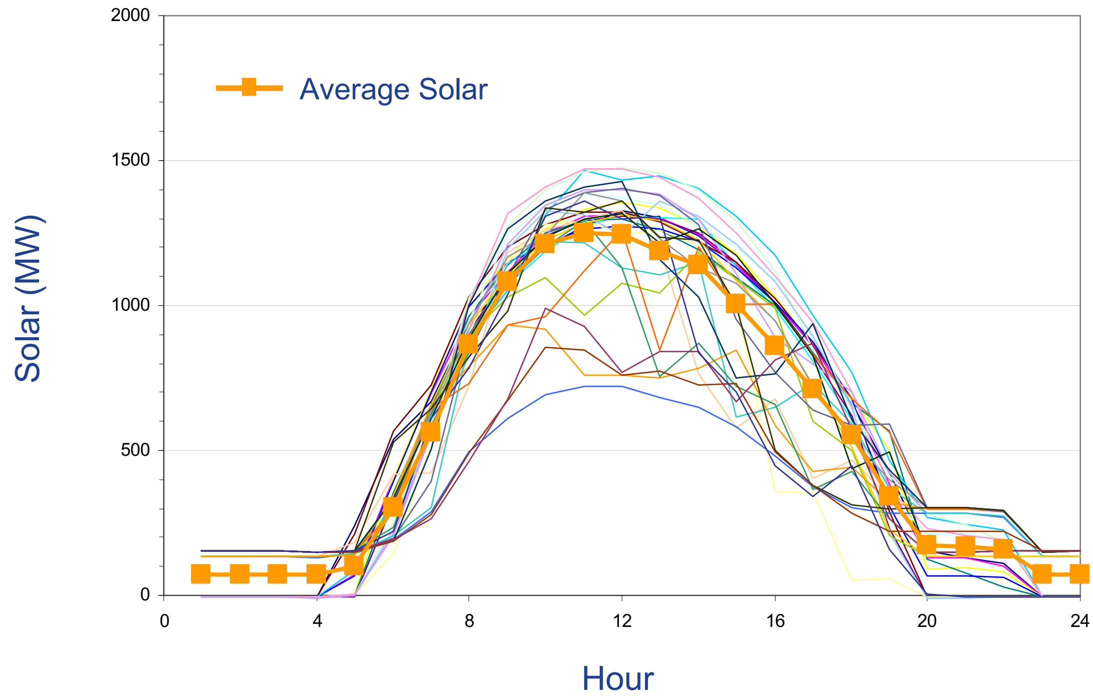
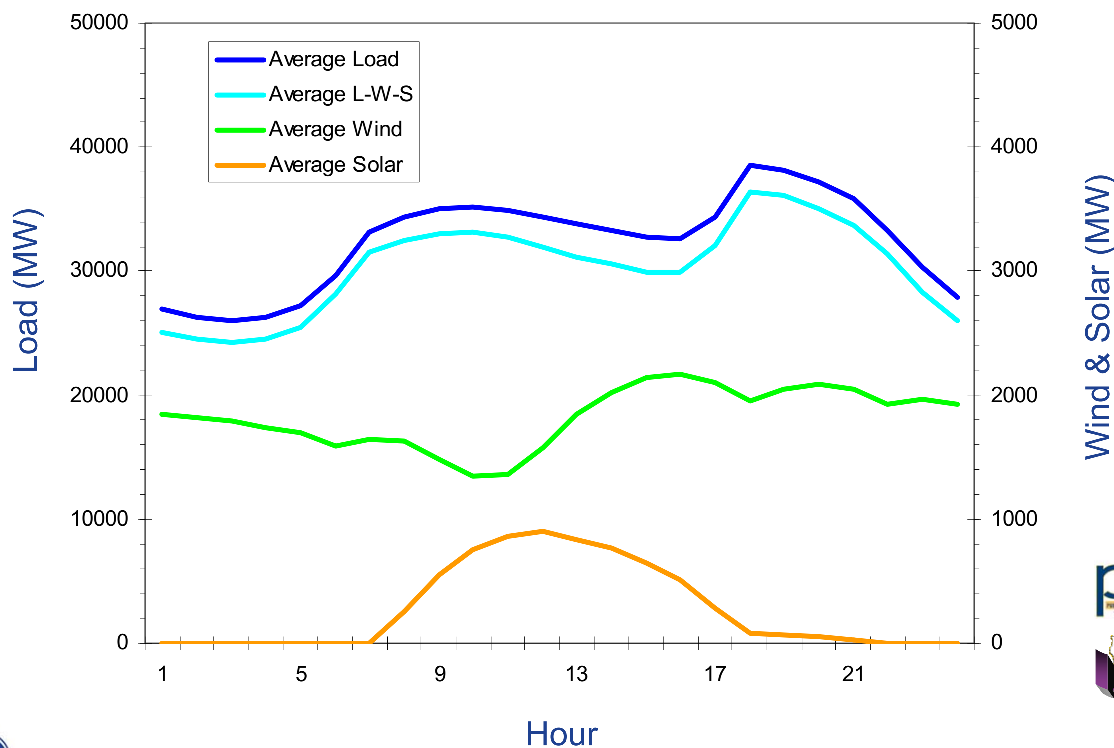
Temporal Pattern: July 2003 Average Day



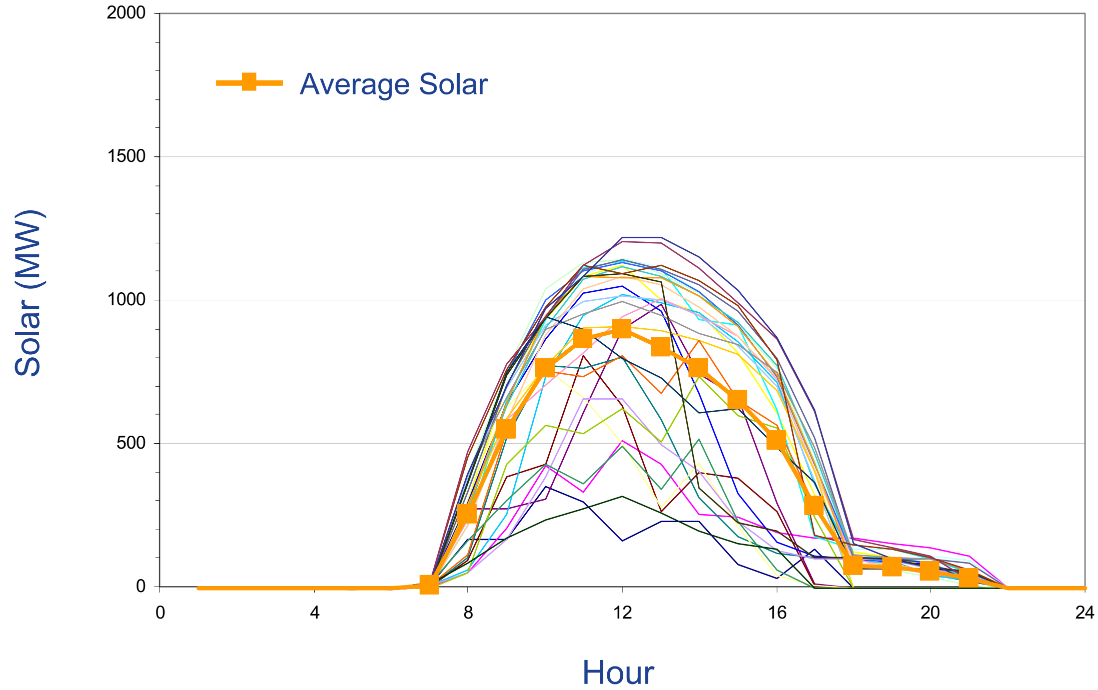
Temporal Pattern: All Days of July 2003



Temporal Pattern: January 2002 Average Day

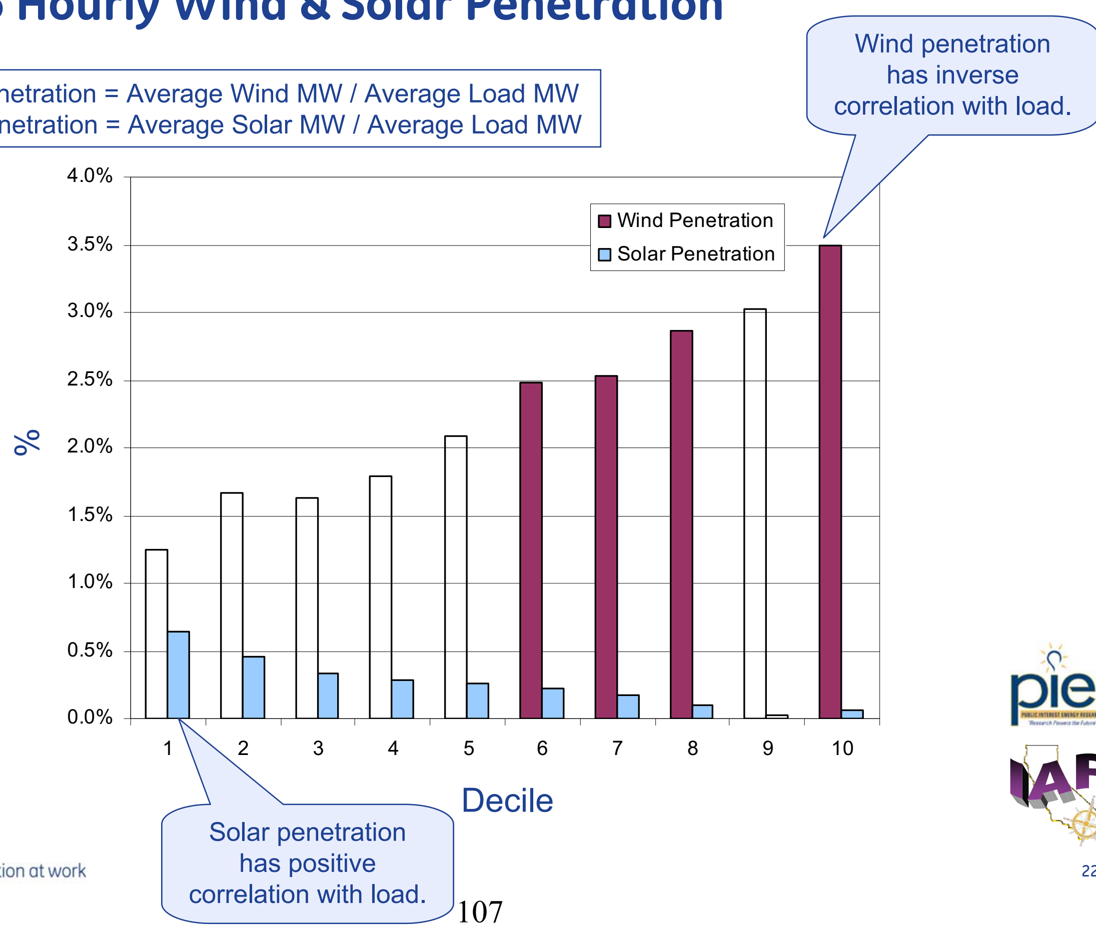


Temporal Pattern: All Days of January 2003

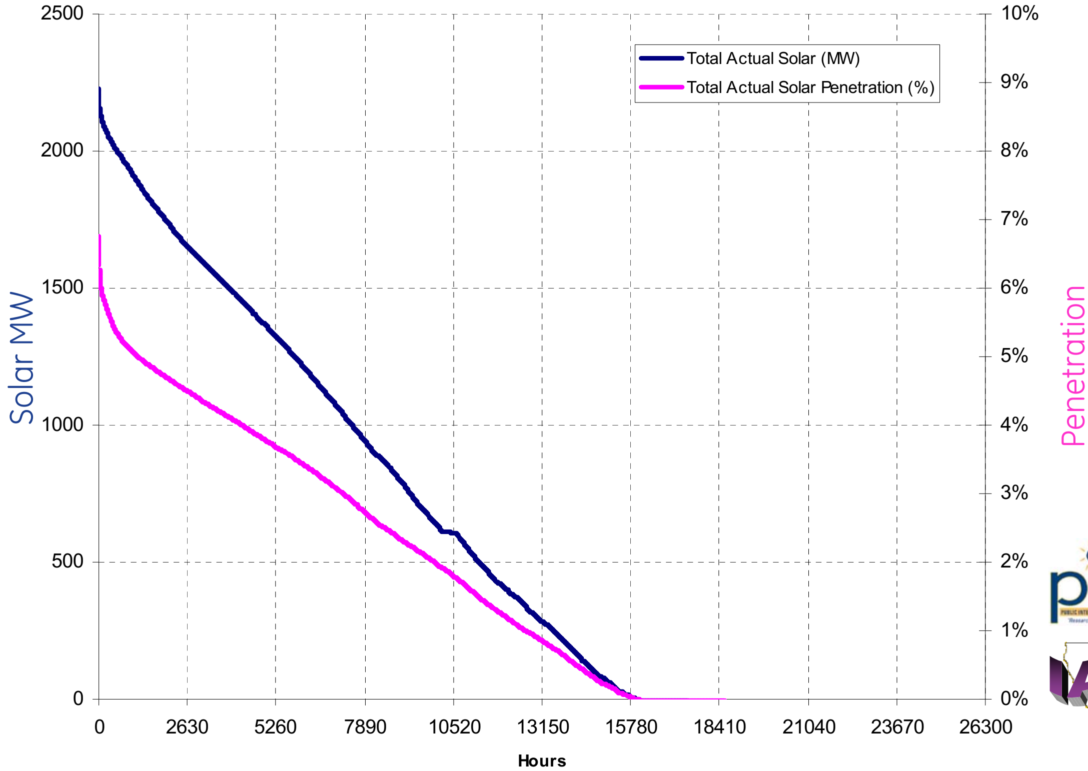


2006 Hourly Wind & Solar Penetration

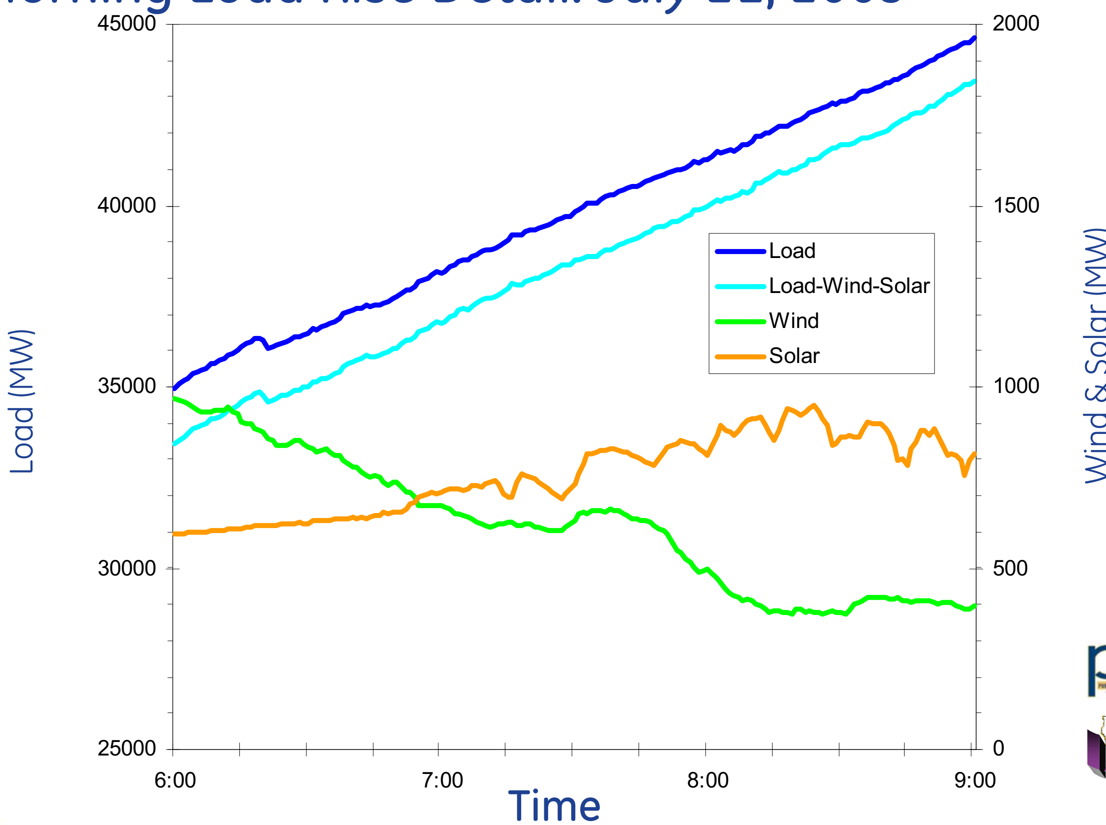
Wind Penetration = Average Wind MW / Average Load MW
Solar Penetration = Average Solar MW / Average Load MW



Solar Generation and Penetration Duration Curves – 2010X



Morning Load Rise Detail: July 21, 2003



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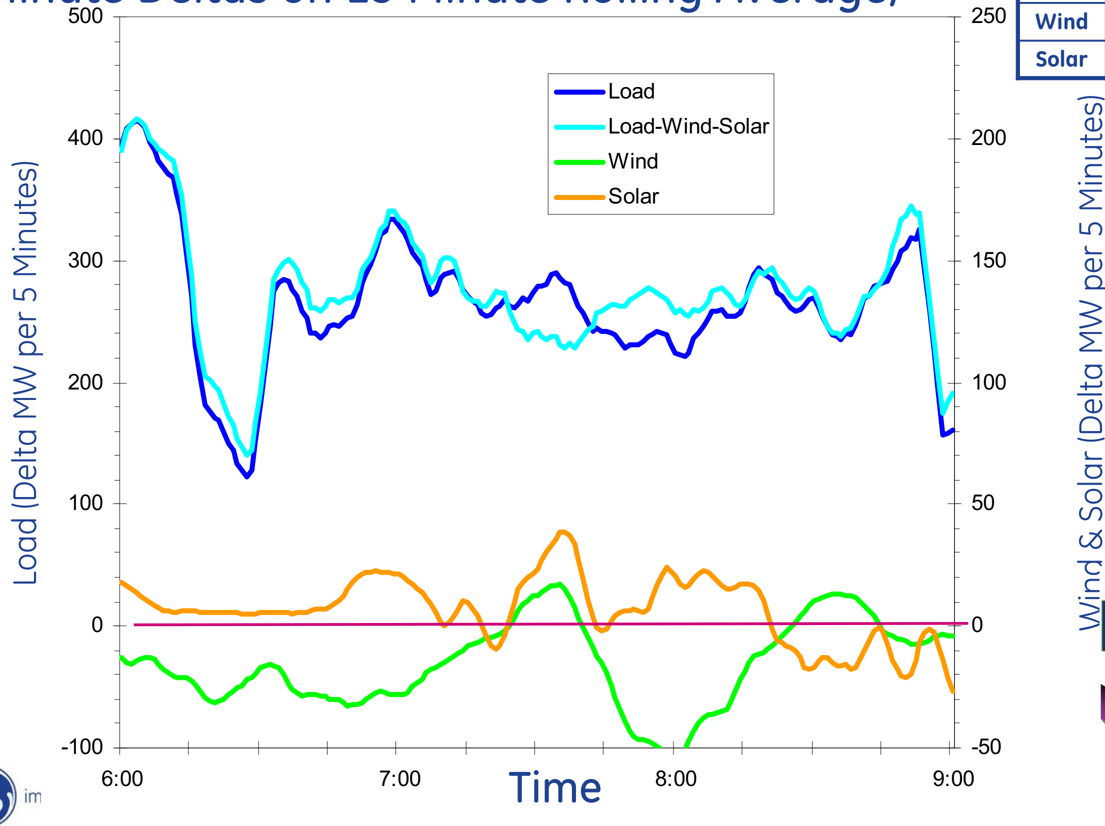
Load Following Requirement: July 21, 2003
(5 Minute Deltas on 15 Minute Rolling Average)

	Mean	σ
Load	265	54
L-W-S	275	52
Wind	-16	18
Solar	7	13



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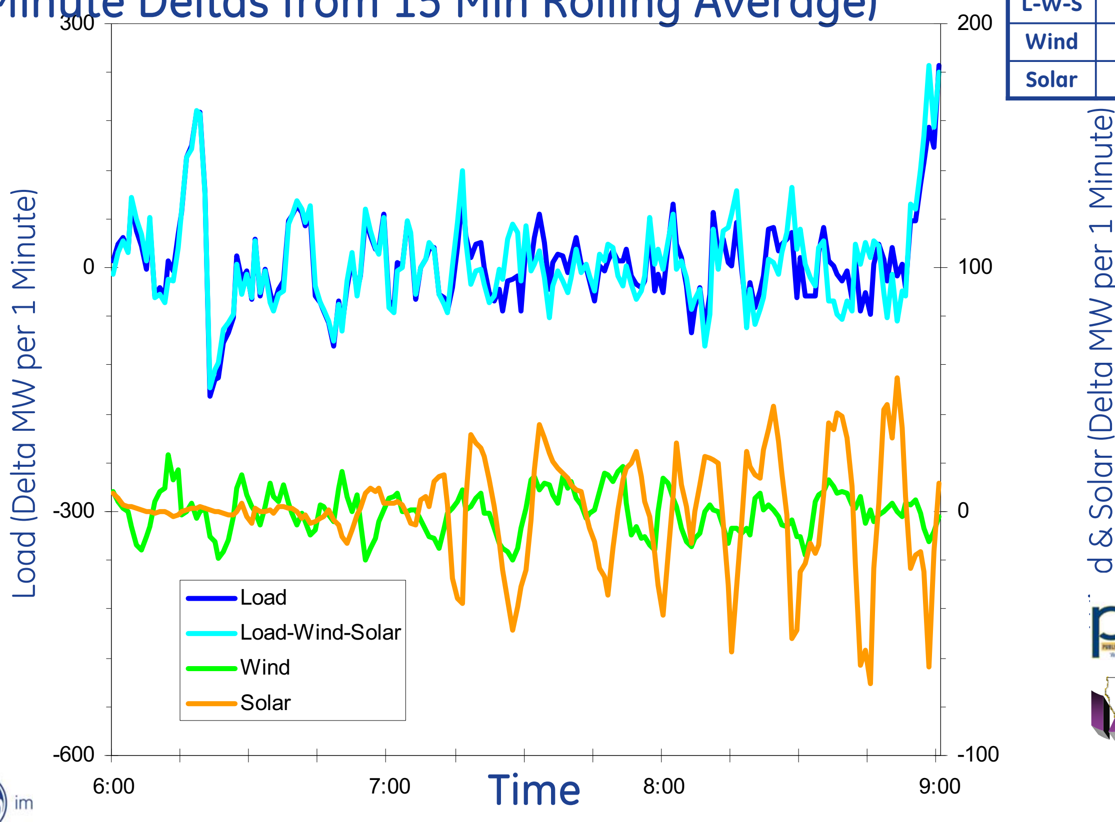
Regulation Requirement : July 21, 2003
(1 Minute Deltas from 15 Min Rolling Average)

	Mean	σ
Load	6.5	56
L-W-S	6.8	61
Wind	-0.3	9
Solar	0.0	22



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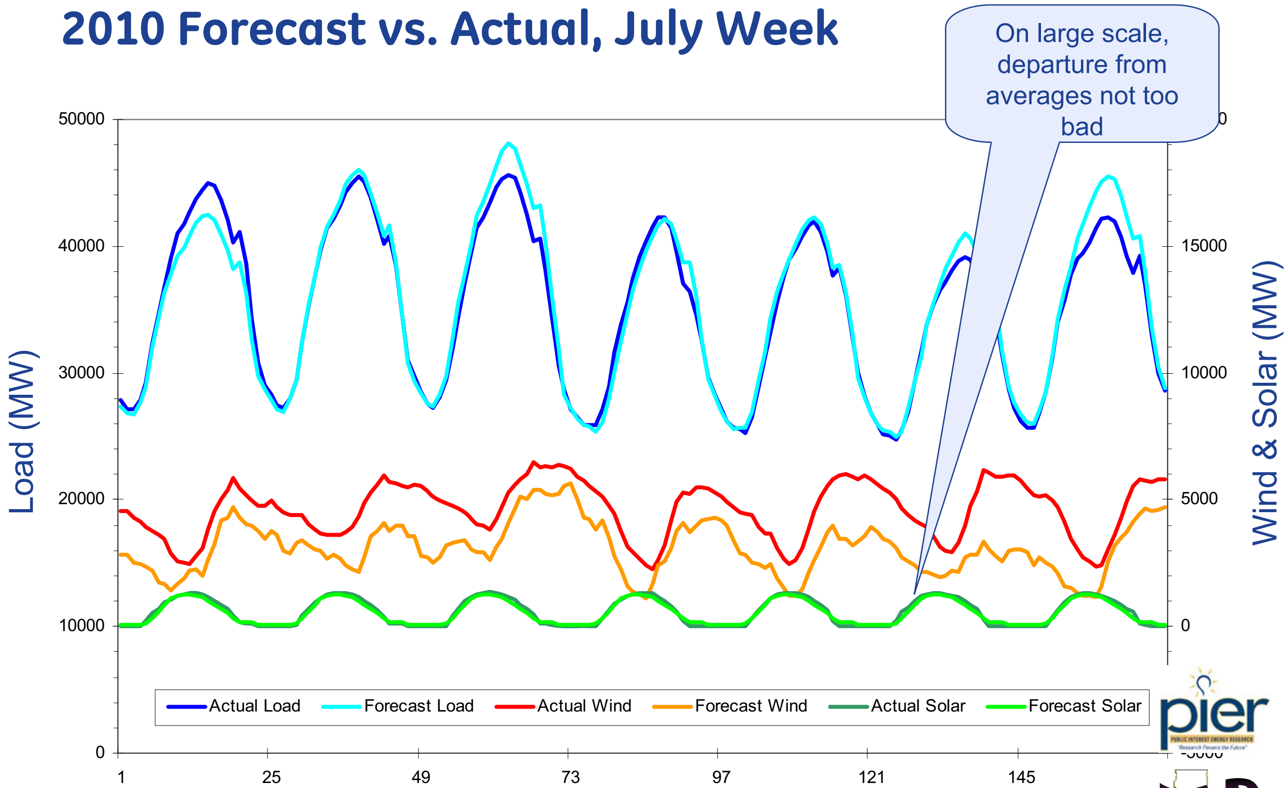
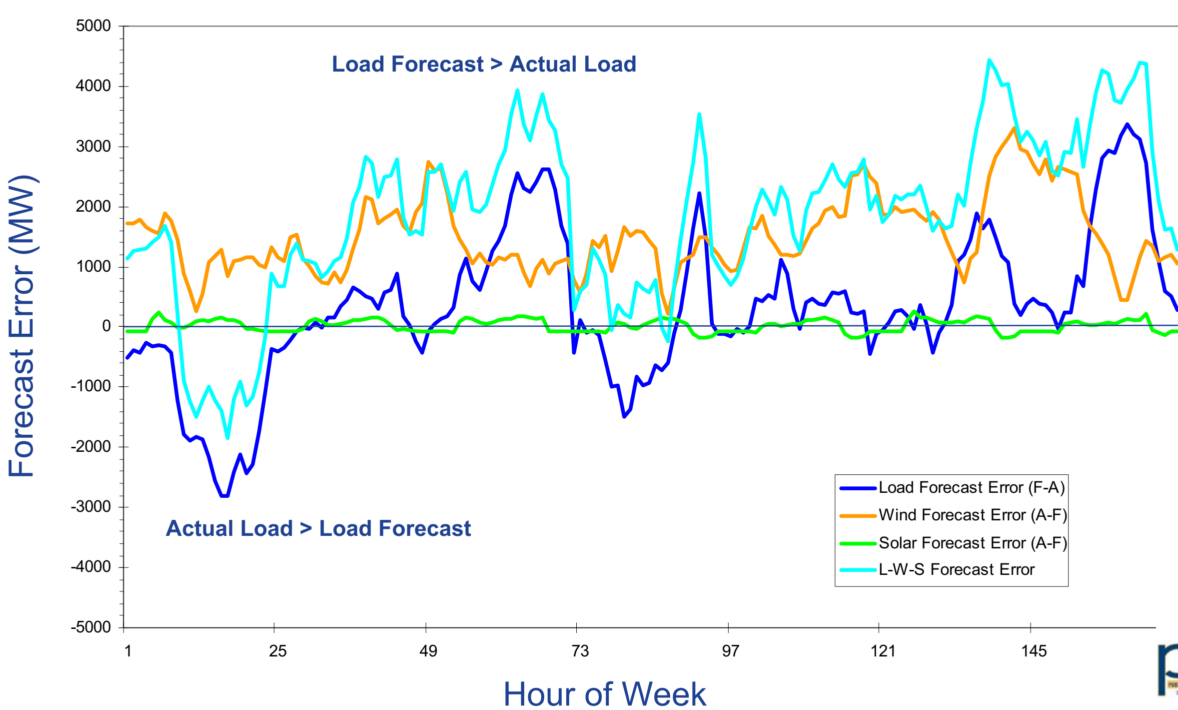
2010 Forecast vs. Actual, July Week



daily average by month forecast seems OK for low penetrations, but won't work forever…

imagination

2010 Forecast Errors, July Week



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2006 Hourly Statistics: Example from One Decile

Each Bin (Load)	1
P_Load (Max)	48113.5
P_Load (Min)	36778.9
Sigma (Delta L)	
Delta L (Max)	4529.3
Delta L (Min)	-4334.4
Delta L (Avg)	225.2
Load (Avg.)	40162.9
Load F-A (Avg)	156.9
Load F-A (Sigma)	1317.8
Load F-A (Max)	5824.7
Load F-A (Min)	-6281.2

Standard Deviation, σ :
68.3% of Values within 1σ of Mean
99.7% of Values within 3σ of Mean

Forecast Error is F-A = Forecast minus Actual

Each Bin (L-W-S)	1
P_L-W-S (Max)	47736.2
P_L-W-S (Min)	35988.1
Sigma (Delta L-W-S)	1294.4
Delta L-W-S (Max)	4924.3
Delta L-W-S (Min)	-4294.7
Delta L-W-S (Avg)	241.6
Load_L-W-S (Avg.)	39397.6
Wind (Avg.)	492.0
Solar (Avg.)	252.9
Wind Penetration	0.012
Solar Penetration	0.006
L-W-S F-A (Avg)	231.5
L-W-S F-A (Sigma)	1339.4
L-W-S F-A (Max)	6402.1
L-W-S F-A (Min)	-6442.8
Wind F-A (Avg)	-78.7
Wind F-A (Sigma)	196.5
Wind F-A (Max)	536.5
Wind F-A (Min)	-1104.4
Solar F-A (Avg)	-14.1
Solar F-A (Sigma)	60.0
Solar F-A (Max)	305.8
Solar F-A (Min)	-174.8

Wind Penetration = Average Wind/ Average Load
(The average is over all hours in a decile)

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2006 Hourly Statistics

Each Bin (Load)	1	2	3	4	5	6	7	8	9	10	All year
P_Load (Max)	48113.5	36776.3	33502.6	31858.7	30654.6	29429.7	27776.0	26093.2	24615.4	23073.6	48113.5
P_Load (Min)	36778.9	33504.8	31859.9	30655.7	29429.8	27776.7	26093.2	24616.4	23073.8	19443.1	19443.1
Sigma (Delta L)	1253.5	1555.3	1470.9	1363.1	1555.2	1816.4	1663.3	1435.9	1075.3	668.9	1436.3
Delta L (Max)	4529.3	4854.2	4775.9	4374.8	6123.0	6070.9	3823.8	3245.1	2862.1	1706.5	6123.0
Delta L (Min)	-4334.4	-4445.8	-4382.4	-4371.6	-5122.3	-4017.0	-3535.5	-3199.9	-2868.1	-2567.1	-5122.3
Delta L (Avg)	225.2	317.3	209.3	129.9	116.6	-19.4	-178.1	-261.5	-309.3	-228.6	0.2
Load (Avg.)	40162.9	34994.6	32598.0	31240.2	30062.7	28656.8	26910.6	25352.7	23839.9	22058.5	29587.2
Load F-A (Avg)	156.9	313.4	140.8	178.4	147.4	93.5	35.6	-1.9	-24.1	59.2	109.9
Load F-A (Sigma)	1317.8	1023.1	745.7	704.3	639.7	672.0	622.7	557.9	589.4	520.2	781.1
Load F-A (Max)	5824.7	6533.2	4761.5	4813.4	3790.9	3585.2	4172.8	2531.2	3840.6	2208.4	6533.2
Load F-A (Min)	-6281.2	-3896.0	-3063.2	-3400.1	-3422.8	-3588.7	-2759.4	-2777.6	-1940.3	-1674.5	-6281.2

Each Bin (L-W-S)	1	2	3	4	5	6	7	8	9	10	All year
P_L-W-S (Max)	47736.2	35985.0	32800.0	31197.2	29993.8	28722.4	27068.3	25376.5	23849.1	22406.8	47736.2
P_L-W-S (Min)	35988.1	32800.7	31197.3	29994.3	28722.4	27068.7	25376.6	23850.7	22407.2	18567.2	18567.2
Sigma (Delta L-W-S)	1294.4	1546.6	1456.4	1398.8	1587.0	1828.5	1699.9	1446.4	1048.9	698.9	1451.0
Delta L-W-S (Max)	4924.3	4728.7	4857.2	4580.7	6090.8	5981.0	3946.6	3240.9	2914.2	2447.8	6090.8
Delta L-W-S (Min)	-4294.7	-4533.4	-4450.4	-4592.1	-5155.4	-4173.7	-3956.1	-3451.9	-2814.0	-2613.0	-5155.4
Delta L-W-S (Avg)	241.6	320.0	183.1	149.5	128.5	-52.7	-146.0	-265.4	-307.1	-250.3	0.1
Load_L-W-S (Avg.)	39397.6	34243.5	31937.5	30590.7	29386.4	27927.0	26188.3	24619.5	23135.7	21373.8	28879.5
Wind (Avg.)	492.0	571.3	520.8	549.3	611.3	692.6	662.6	704.5	698.6	745.7	624.9
Solar (Avg.)	252.9	156.4	104.8	88.2	77.1	61.1	44.2	24.5	5.6	13.3	82.8
Wind Penetration	0.012	0.017	0.016	0.018	0.021	0.025	0.025	0.029	0.030	0.035	0.022
Solar Penetration	0.006	0.005	0.003	0.003	0.003	0.002	0.002	0.001	0.000	0.001	0.003
L-W-S F-A (Avg)	231.5	447.6	247.0	300.8	275.9	261.4	201.6	184.5	141.6	269.0	256.1
L-W-S F-A (Sigma)	1339.4	1059.7	803.2	749.1	713.8	738.8	684.4	660.6	635.9	570.5	829.0
L-W-S F-A (Max)	6402.1	6554.7	4462.6	4518.7	3958.8	3396.6	4686.7	4973.7	3978.8	2321.2	6554.7
L-W-S F-A (Min)	-6442.8	-3954.0	-3035.8	-3205.0	-3343.1	-3555.5	-2667.8	-1773.2	-1742.9	-1700.6	-6442.8
Wind F-A (Avg)	-78.7	-127.9	-111.5	-125.8	-133.9	-169.9	-159.1	-176.8	-171.1	-202.7	-145.7
Wind F-A (Sigma)	196.5	227.3	229.6	240.0	246.1	254.3	260.0	261.4	273.4	284.7	250.9
Wind F-A (Max)	536.5	629.8	645.6	706.9	617.9	697.9	719.9	701.2	611.9	712.5	719.9
Wind F-A (Min)	-1104.4	-1134.2	-992.4	-1083.1	-1058.8	-1078.5	-1072.7	-1079.3	-1135.5	-1136.6	-1136.6
Solar F-A (Avg)	-14.1	-4.1	-1.1	2.6	5.5	4.6	4.1	0.8	0.4	-3.0	-0.4
Solar F-A (Sigma)	60.0	60.5	52.9	55.0	53.9	51.4	48.6	39.2	25.0	37.5	49.8
Solar F-A (Max)	305.8	285.6	205.1	237.1	278.2	225.2	210.1	222.9	174.9	130.9	305.8
Solar F-A (Min)	-174.8	-245.8	-240.7	-658.7	-717.0	-724.4	-656.1	-670.8	-342.7	-547.9	-724.4

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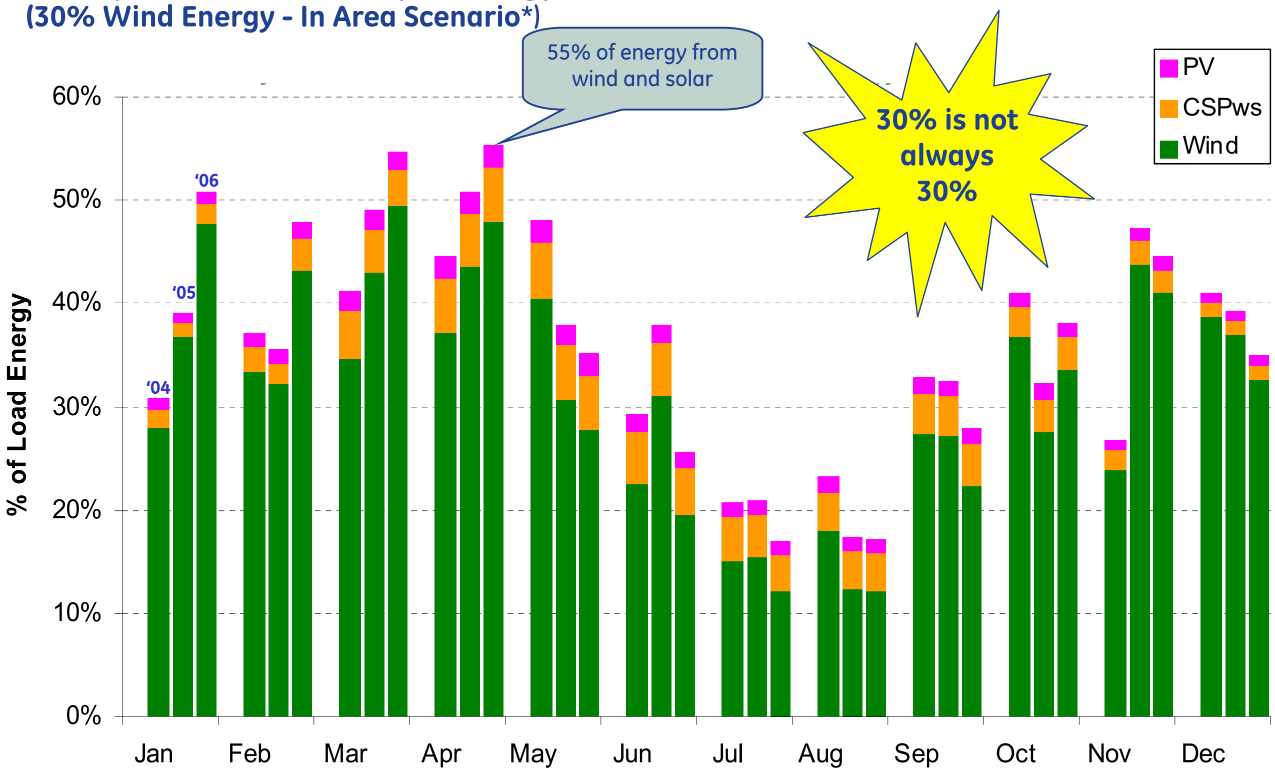
30

Footprint % Monthly Energy from Wind and Solar for 2004 – 2006

(30% Wind Energy - In Area Scenario*)



2006 % monthly energy ranges from 18% (Jul) to 55% (Apr) in study footprint

Source: NREL Western Wind & Solar Integration Study

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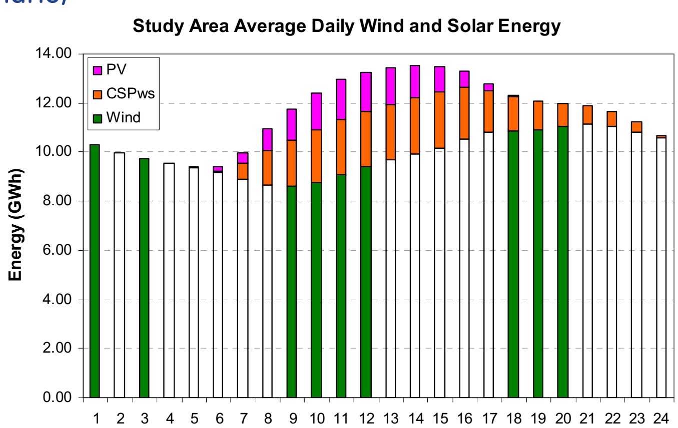
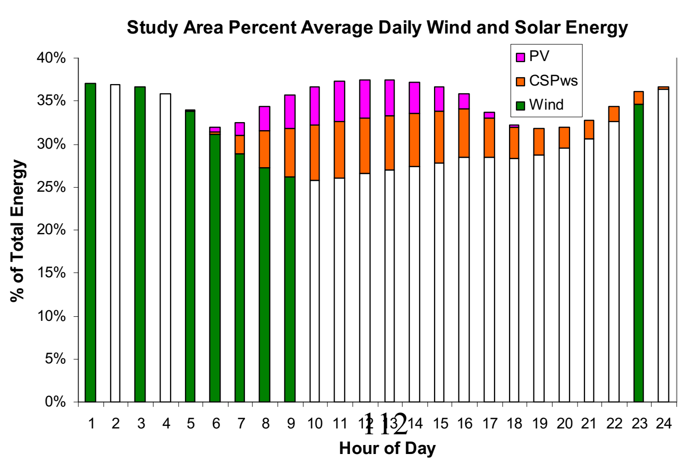
Average Hourly Energy from Wind and Solar Over Entire Year

(30% In Area Scenario)





Solar tends to complement wind variation over the day

Source: NREL Western Wind & Solar Integration Study

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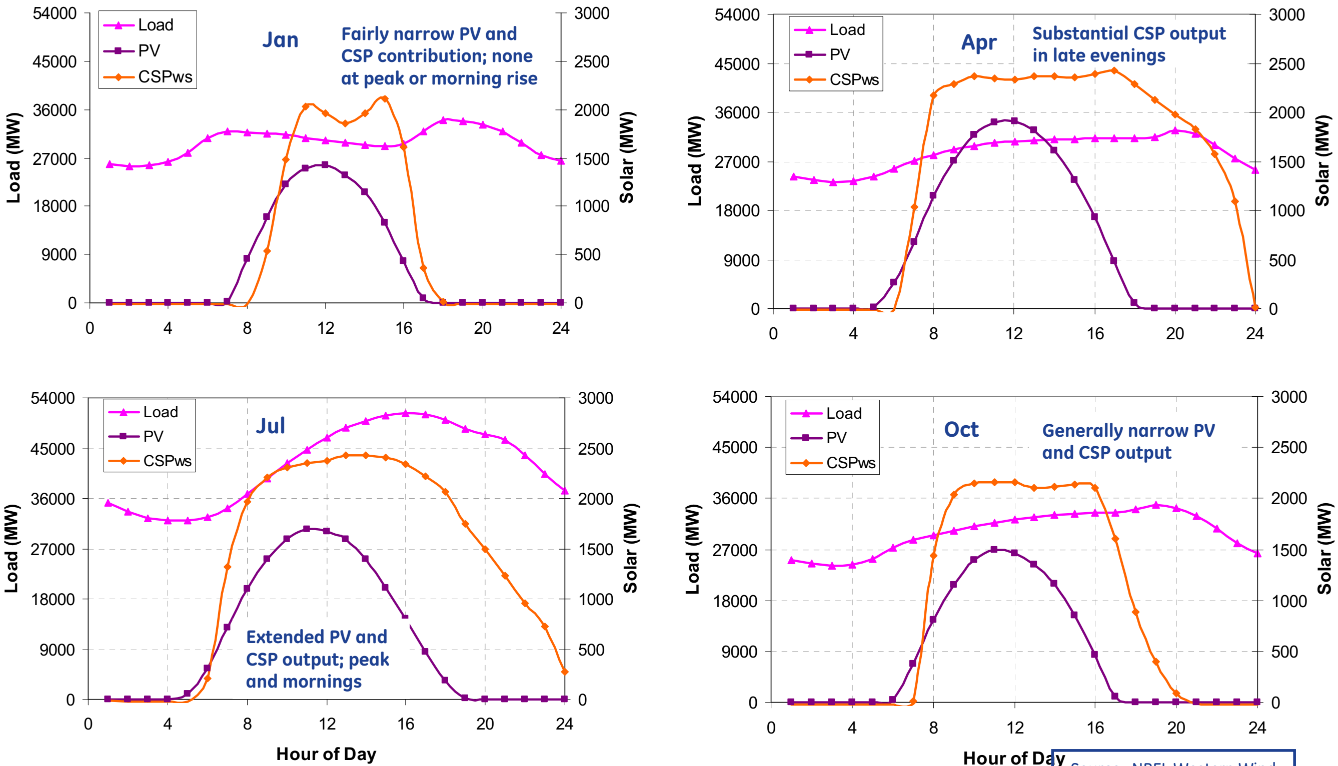
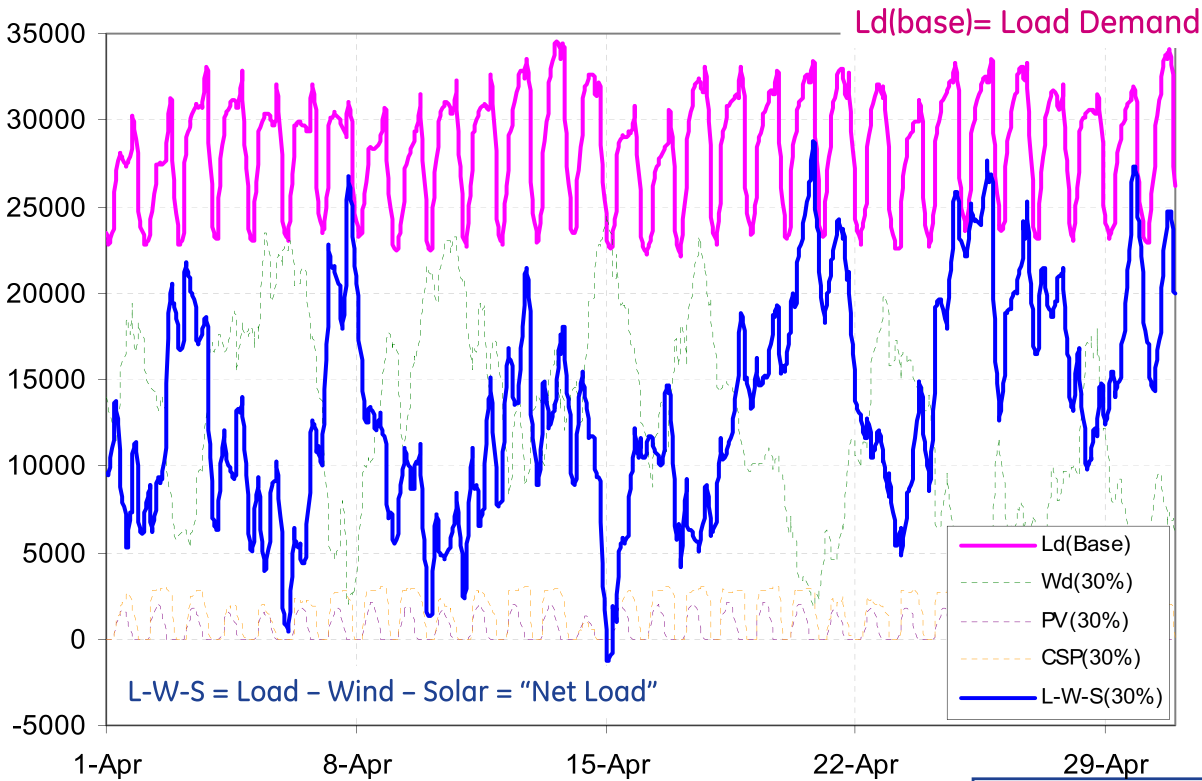
Study Area CSPws and PV Average Daily Profiles By Seasonal Month (30% In Area Scenario)



Source: NREL Western Wind & Solar Integration Study

Operations…

Study Footprint Total Load, Wind and Solar Variation Over Month of April
(30% Wind Energy in Footprint)



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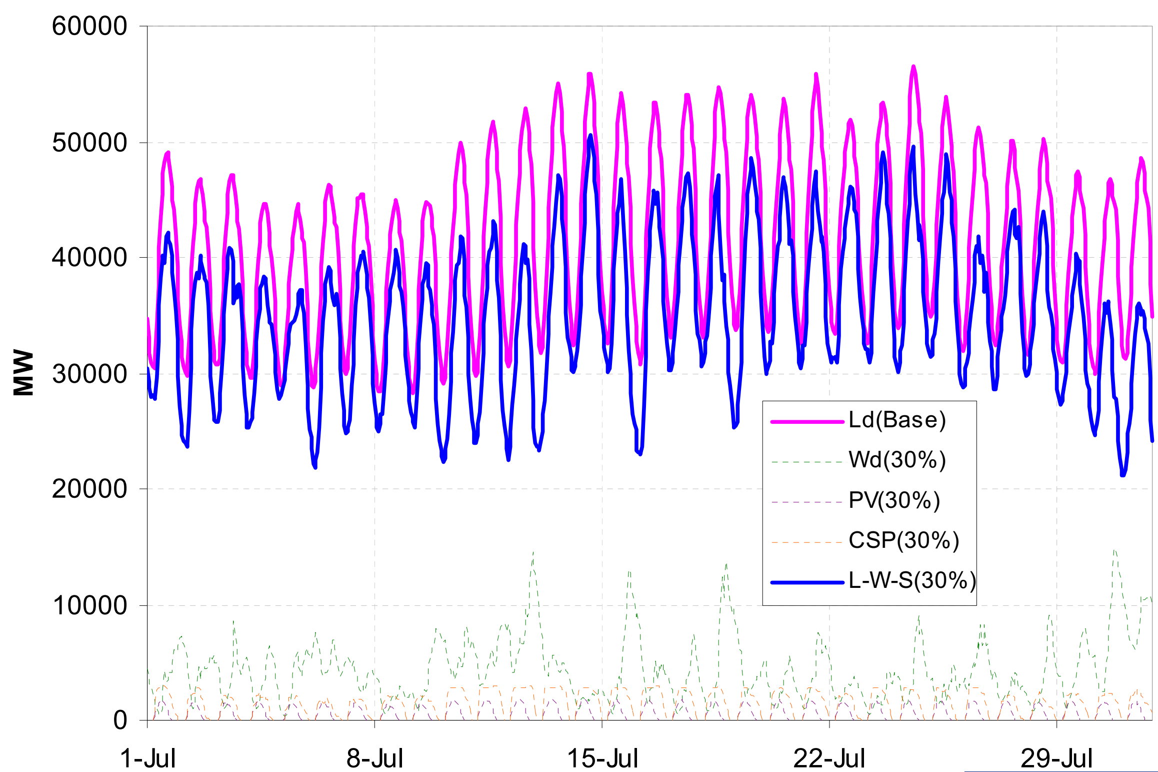
Source: NREL Western Wind & Solar Integration Study

35
1

Study Footprint Total Load, Wind and Solar Variation Over Month of July
(30% Wind Energy in Footprint)



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Source: NREL Western Wind & Solar Integration Study

36
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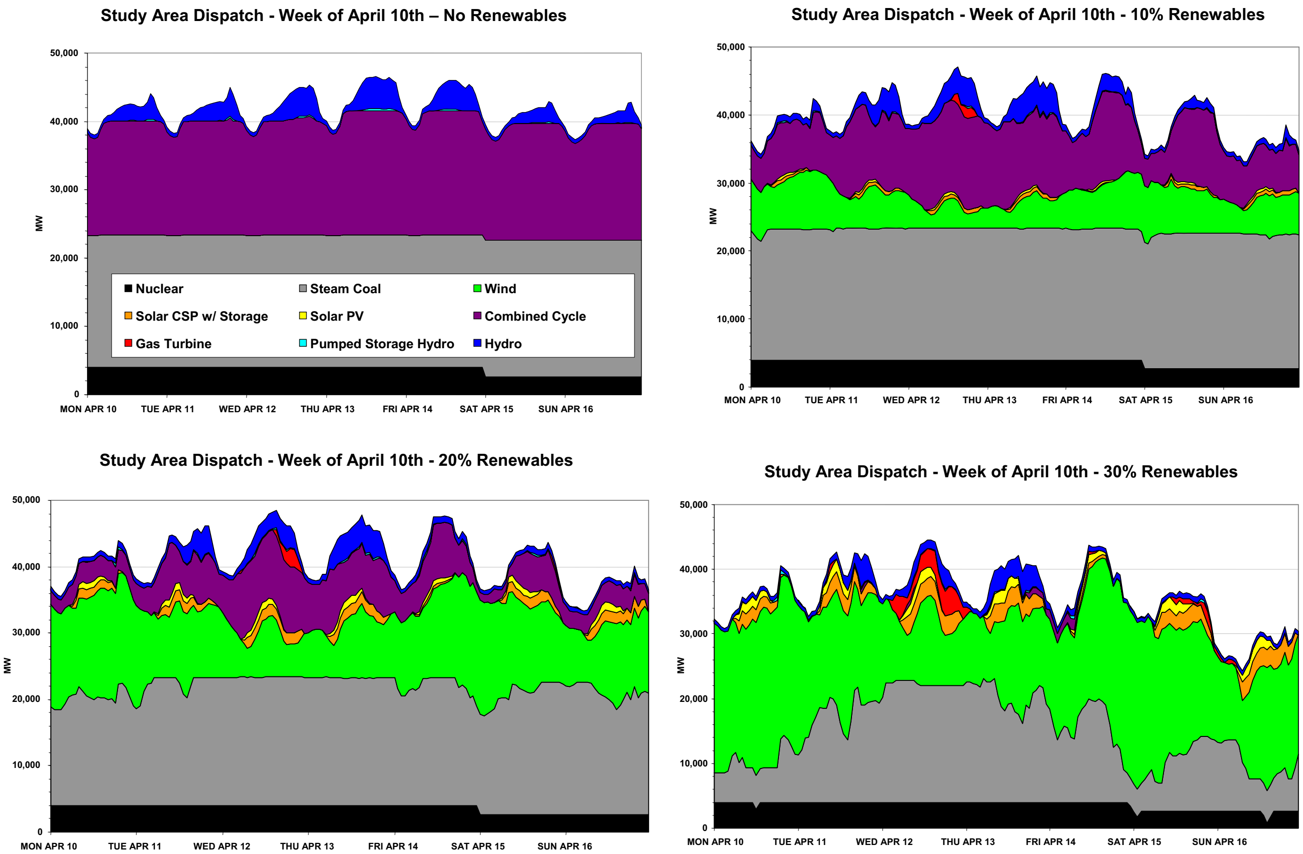

April 10, 2006

Source: NREL Western Wind & Solar Integration Study

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Data Requirements (what we might need in future)

One year (or more, depending on study) of 10-minute time synchronized wind and solar power data for each of the sites. 10-minute resolution:

- has been used effectively in recent studies
- (roughly) the lower limit for resolution using meso-scale analytical techniques

One year (or more) of hourly, day-ahead solar power forecast data

Higher resolution time synchronized wind and solar power data for selected windows (e.g. 1-3 hours) of interest

- Selected windows typically screened from longer-term data and system considerations
- Resolution of 1-2 second sampling needed for small or granular systems [experience jury is out on what "small or granular means" – needs thought and depends on the focus of the study]
- Resolution of 1-2 minute needed for larger system analysis

Solar plant size, type, substation location for each site

Each data must be time synchronized for the future study year(s)

- Maintain solar/wind/load time and space relationship.

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NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Development of Data Sets for PV Integration Studies

Utility scale PV
Variability Workshop

Ray George

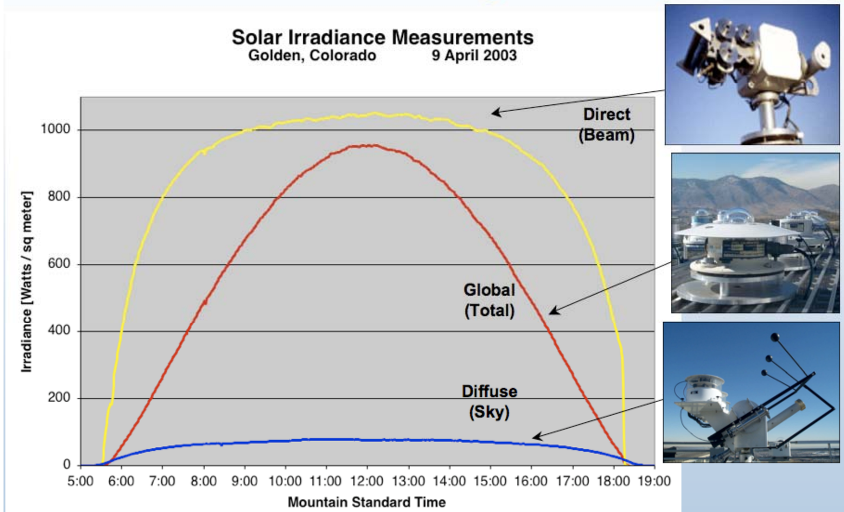
7 October 2009

Problem Identification

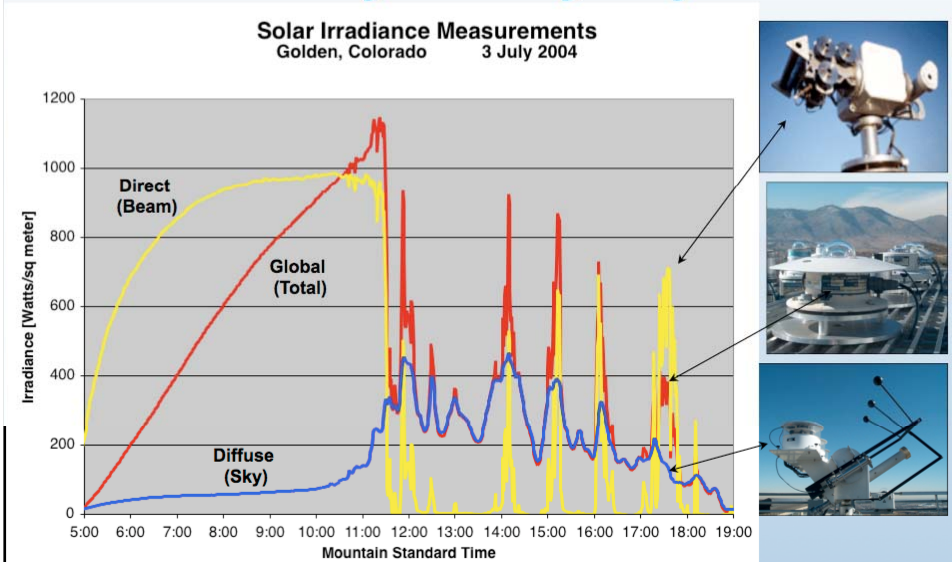
- Analytical studies need consistent data for any location, with greater resolution (temporal and spatial) than the current data sets provide.
- Solar or PV Measured (Real) data – Spatially sparse but temporally dense – applies only to a single point or a small area
- Satellite (Modeled) data – Spatially denser but temporally sparse. Fundamental limitations preclude their direct use for dispatch and grid stability.
- Existing modeled and measured data must be combined, using a detailed spatial and temporal analysis, to match the desired analysis.
- Unrealistic outcomes must be avoided!

Solar Radiation and PV

Clear Sky



Partly Cloudy Sky

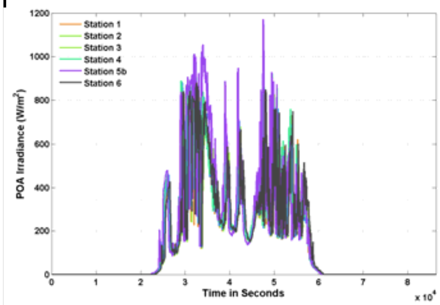


http://www.nrel.gov/midc/srrl_bms

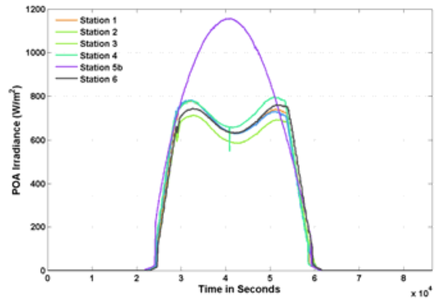
NREL National Renewable Energy Laboratory

Example of 60 second "averaging" and "sampling" – POA Irradiance

Partly Cloudy Day



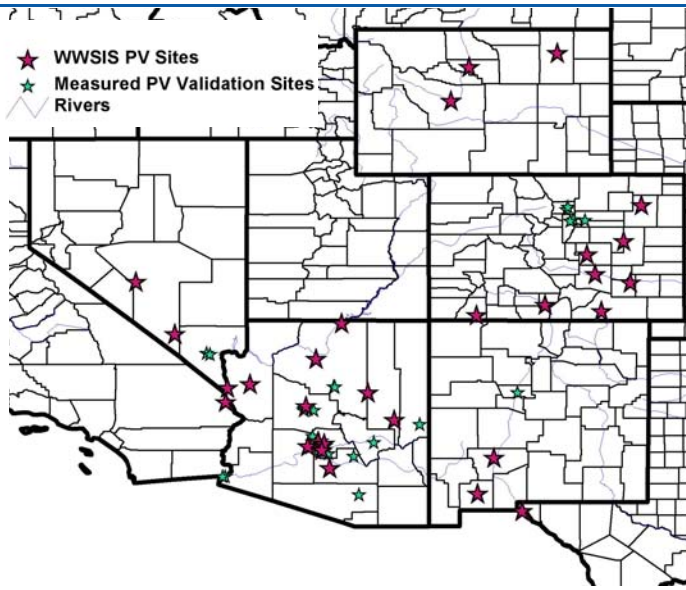
Clear Day



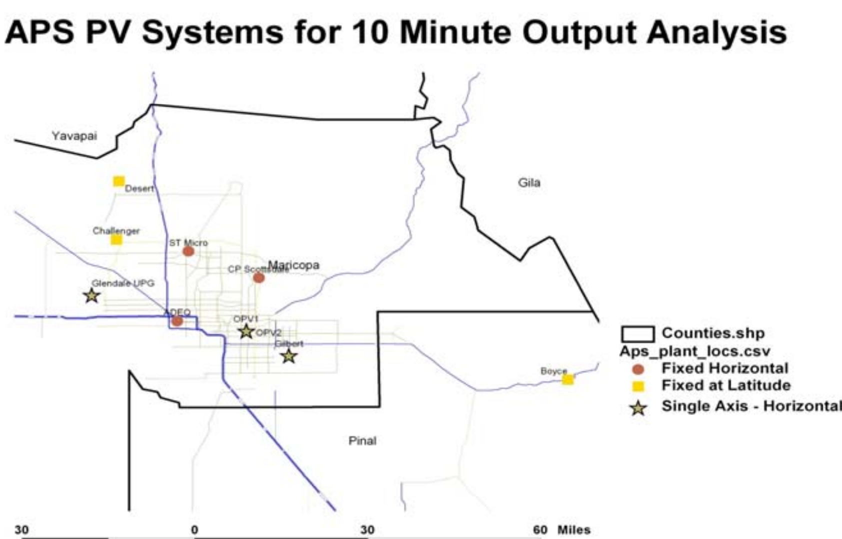
WWSIS PV Modeling Approach

- Western Wind and Solar Integration Study
- Goal: Assess the grid environment under high penetrations of wind, CSP, PV.
- Required: PV output data for any location in SW US, 10 minute time step.
- Analysis focused on 10 minute ramp rates of load and renewables.
- Input Data – Hourly satellite estimated solar resource, and surface measured weather data.
- Output – Estimated 10 minute power production from a mixture of PV systems totaling 100 MW

WWSIS PV Modeling at 29 Sites



PV Output Data for Model Validation



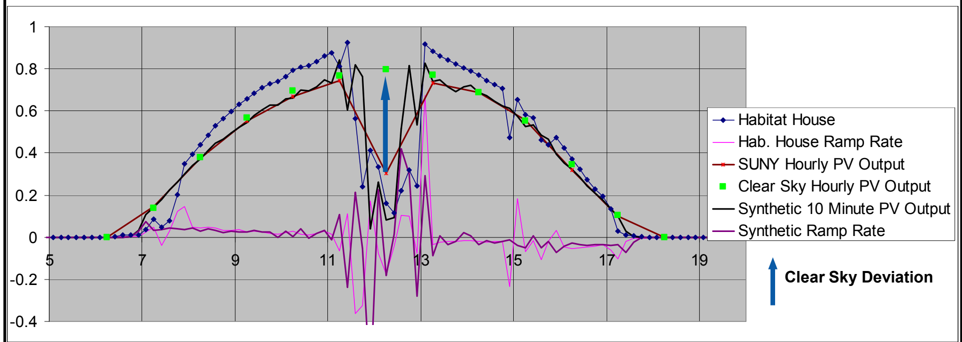
Providing PV data for Analytical Studies

1. Produce a time series of solar measured data, or PV output, which replicates the ramp distribution of a small system or solar radiation measurement, for each desired location.
2. If available, use **surface measured data**. Select the best data for each location in your scenario, using GIS techniques
3. If not enough measured data is available, **create a model** to synthesize the time series you need.
4. Use a **lowpass filter** to modify the ramp rates of each time series to match the PV deployment scenario.
5. Assess the **spatial correlation** between the sites you have chosen in your scenario. Assure that there is not too much or too little correlation between and among the sites.

WWSIS Solar Data Requirements

- Outputs should be consistent, even from locations far from any measured data.
- Initial requirement is for 10 minute average outputs, for three years (2004 - 2006).
- We assume random subhourly fluctuations are **UNCORRELATED** across all sites.
- Later requirement is output from the same systems, except at **one minute resolution**, for selected days in the two year period.
- **Ramp rates** of PV output are the most important test of **realism**.

WWSIS 10-Minute PV Model



Model **Inputs**: AC power from **PVWatts**, for…
1.) Hourly satellite modeled, 2.) 10-minute clear sky.

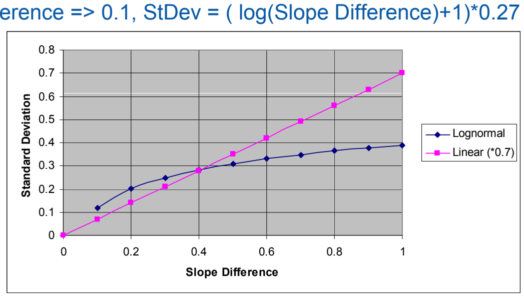
Model **Outputs**: Synthetic AC power on 10 minutes, interpolated to match satellite, random fluctuations to match annual ramp distribution

WWSIS Model Approach

1. **Normalize** all data to percent of **DC power rating**.
2. Find hourly (absolute) deviation between clear sky and modeled.
3. Use transformation function to match slope difference of deviations to Standard Deviation of random fluctuations

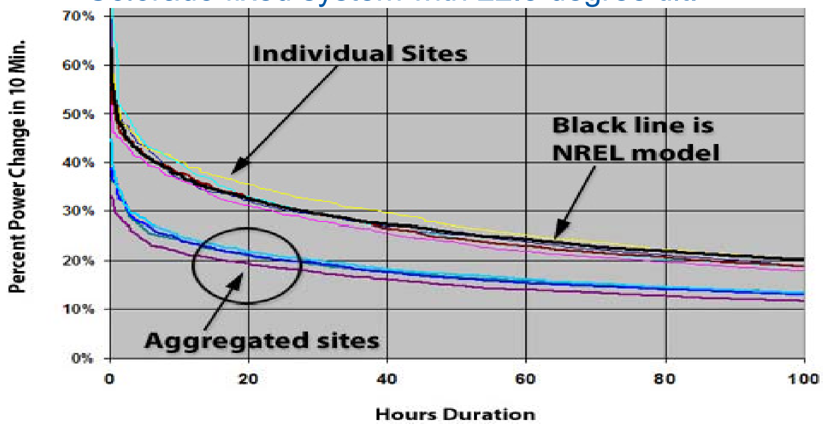
If Slope Difference < 0.1, StDev = 0 (clear sky or close to it.)

If Slope Difference => 0.1, StDev = (log(Slope Difference)+1)*0.27 + 0.11

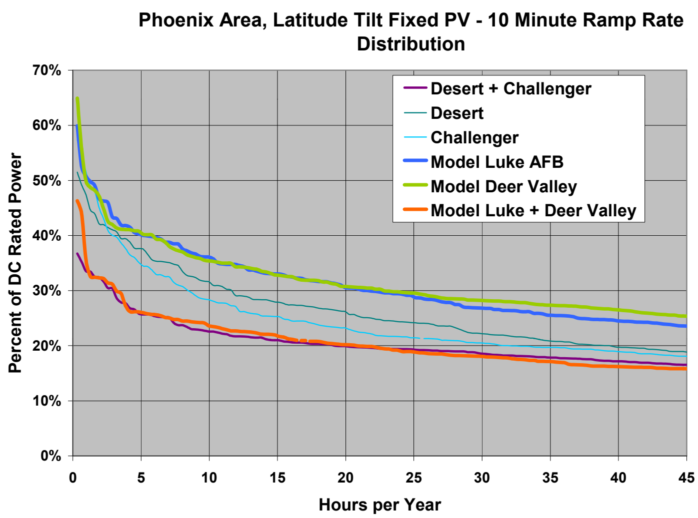


WWSIS PV Data Ramp Rate Validation

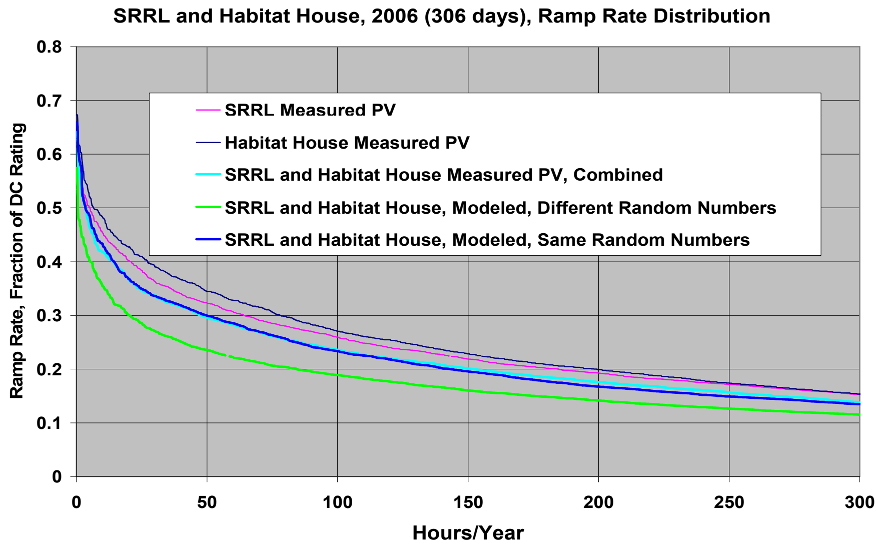
- **PV output ramp rates** are primary validation data.
- Same model used for all collector types.
- Validation using Arizona **1-axis tracking PV**, and Colorado fixed system with 22.5 degree tilt.



Phoenix Latitude Tilt

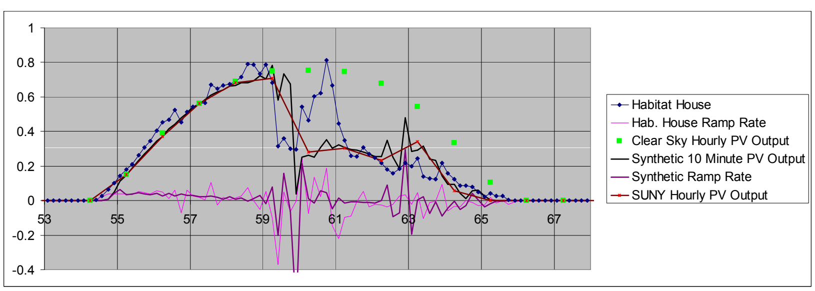


10 Min PV From Habitat House (4 MW Fixed PV), and from Measured Solar at NREL SRRL Distance Between Sites = 8.8 km.



WWSIS Model - Problems

1. All model data from 1 location.
2. No use of measured data.
3. Results not very deterministic. Correlations with wind could be missed.
4. PVWatts does not match observed PV output



Summary of WWSIS 10 Minute Model

1. Model applied for each of 12 different PV collectors using the same parameters over a wide range of conditions, locations, times of year. For each location, the model runs are applied using the SAME random numbers.
2. Model outputs are weighted according to a distributed PV scenario, fixed orientations are preferred, only 15% tracking PV
3. Phoenix – Low correlation between sites as close as 12.5 km. apart.
4. Golden, CO – Fairly high spatial correlation between sites 8.8 km. apart
5. In general, data from a single point, when averaged over 10 minutes, give the correct ramps for any compact plant.
6. NO lowpass filter applied to model time series.

The Problem…

Multi-MW PV plants plus DG PV planned in the Big Wind timeframe

Very little is known about multi-MW PV variability on a fast (subhourly) timescale

- High wind, partly cloudy days can lead to extremely fast ramps (faster fluctuations than wind plants)

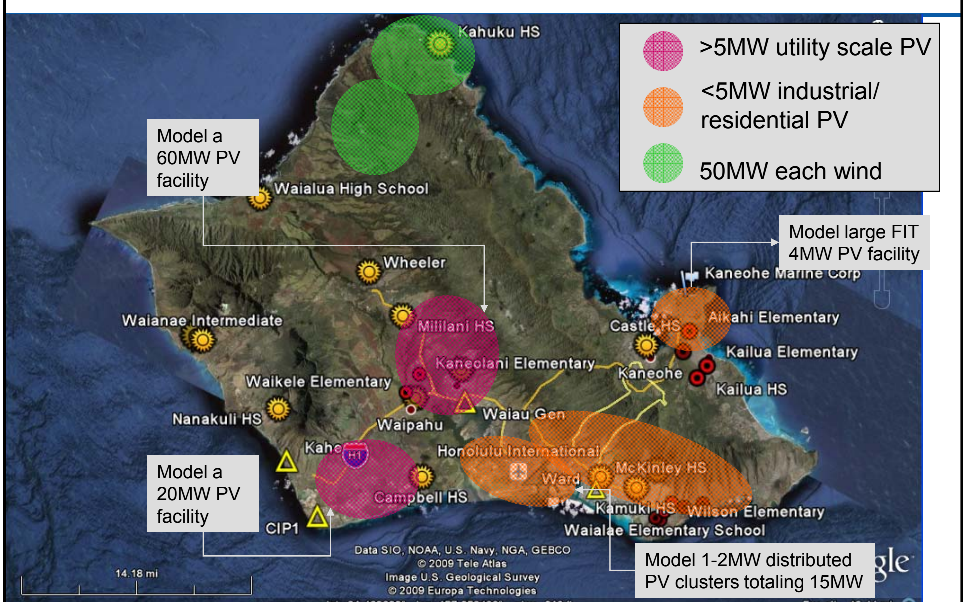
PV Variability Working Group (labs, utilities, developers) established to work on this issue

There is little sub-minute data for large-scale PV systems and not much sub-hourly data

State-of-the-art solar resource modeling is hourly, 10 km resolution

OWITS PV Deployment Scenario

15 MW Residential PV (Distributed Generation)
5 MW PV Plant, Kaneohe area.
20 MW Utility PV plant, Campbell Industrial Park area.
60 MW Utility PV plant, centrally located North of Pearl Harbor
Residential PV spread over Honolulu urban corridor



Data Available for Oahu PV Modeling

Measured GHI and PV output from schools – 15 minutes – for 2 years or more.

Measured Solar radiation – from 4 sites – 1 second – starting in June 2009

Solar radiation – clear sky – 10 minute averages – model and input data are matched to satellite model.

Modeled PV output – uses PVWatts for any collector orientation

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Weather service – observed ceiling, clouds, winds. Also numerical modeled/interpolated winds, etc.

RAWS – hourly global radiation

OWITS Solar Data Requirements

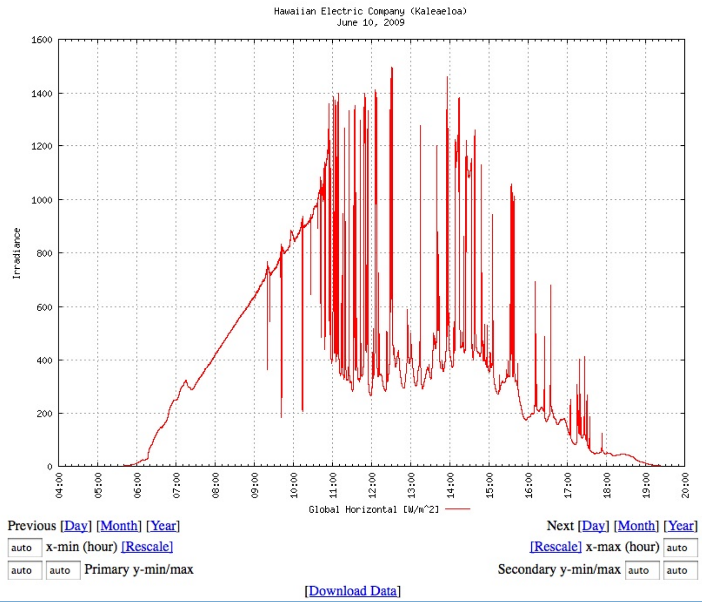
- PV system output in MW for 4 different "systems"
- Initial requirement is for 10 minute average outputs, for two years (2007 and 2008).
- Later requirement is output from the same systems, except at two second resolution, for selected days in the two year period.
- Data should be as realistic as possible, given the state of our knowledge
- Ramp rates of PV output are the most important test of realism.

NREL/HECO 1 Second Solar Data Stations

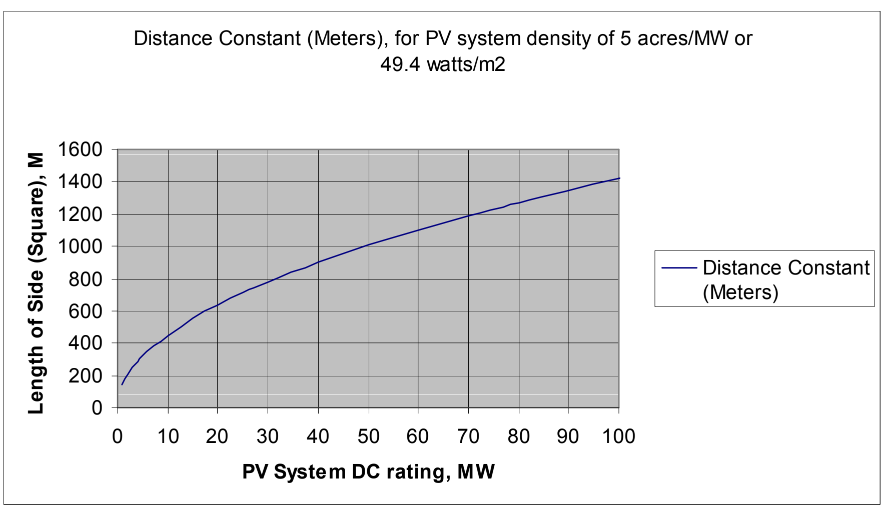
- Data from 4 locations, starting June 4, 2009
- One second data rate, for Global Horizontal only.
- Two sites are 1060 meters apart, providing data on correlations within a large PV plant.
- Analysis of these data used to guide the synthesis of 10 minute (and later 2 second) data.

Map of NREL/HECO 1-second Solar Stations

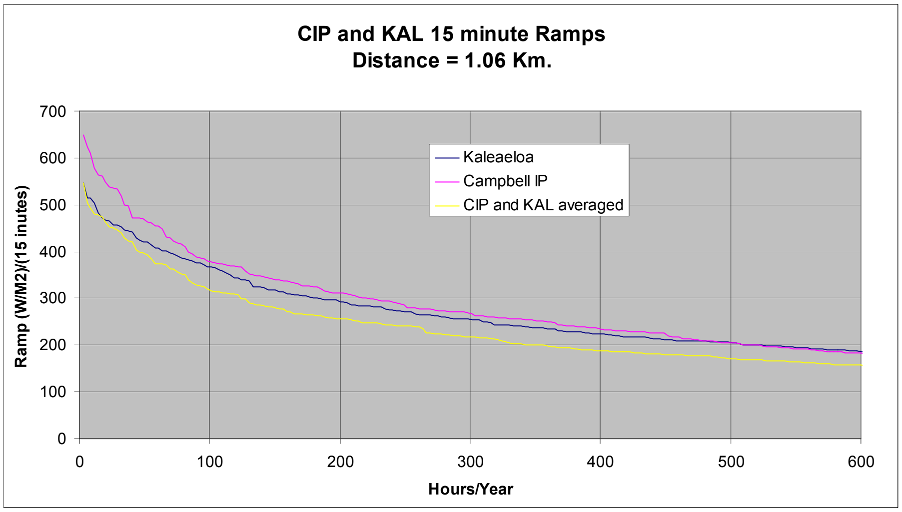
One Second Data Shows High Variability



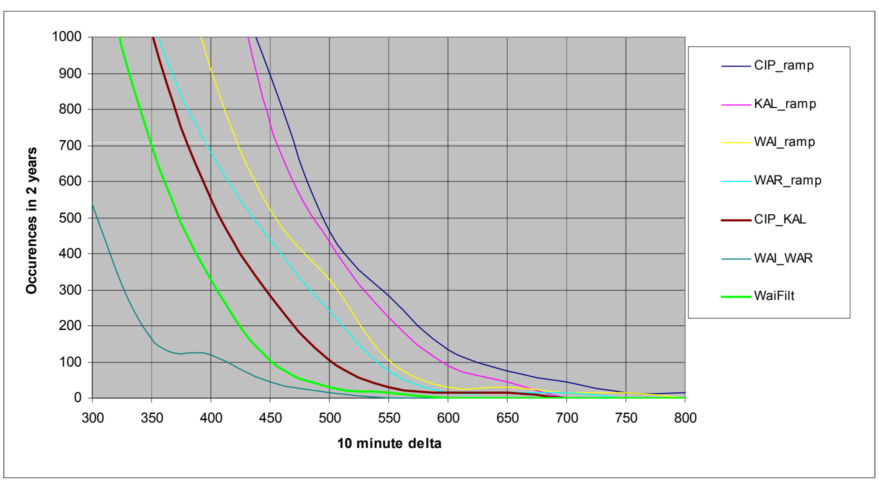
Size of PV Array = Distance Constant



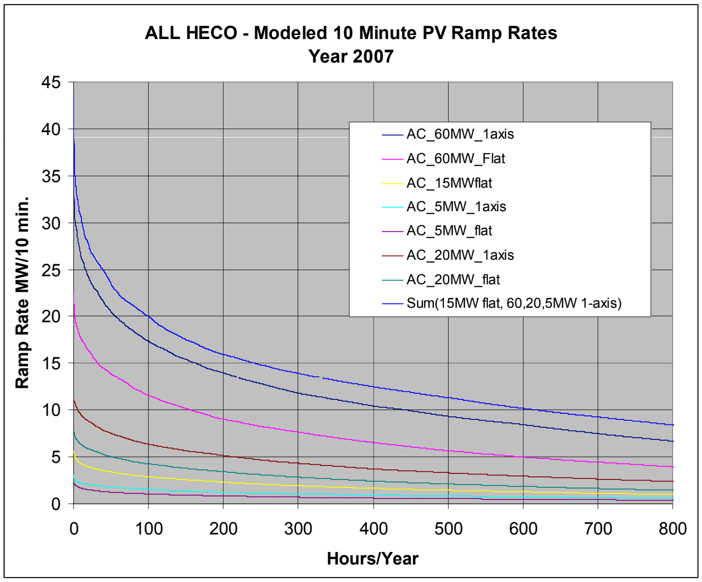
Spatial Smoothing for 1 KM (60 MW)



Filter Single Point GHI to Match Area Distribution



10 Minute Ramp Rates in MW

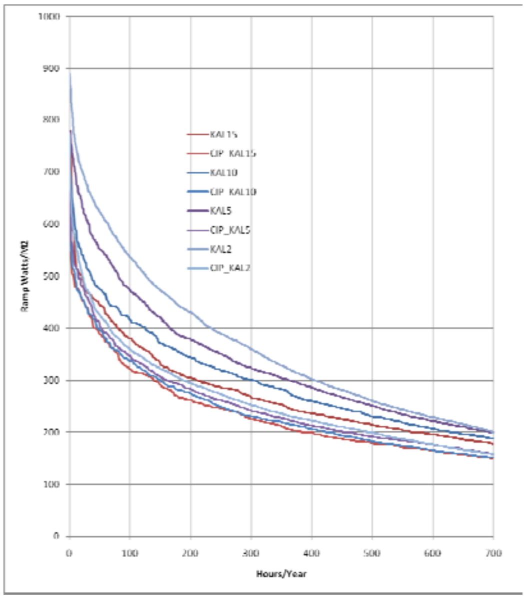


OWITS PV Technology Assumptions

(All assumptions open to modification)

- Data processing and validation for Global Horizontal (GHI) radiation
- PV system output will be modeled for crystalline silicon PV technology.
- PV system size is the rated DC output of the PV panels for GHI = 1000 watts/m2 (industry standard)
- Grid connected PV systems will have maximum inverter output equal to PV system size (DC rated capacity)
- PV output data streams will be available for fixed horizontal PV collectors and 1-axis tracking collectors. (Other collector types could be added if needed.)
- Residential PV will be assumed all fixed horizontal
- Utility PV plants will be 1-axis tracking.

Two GHI Stations, 1060 Meters Apart



KAL = 1 station –

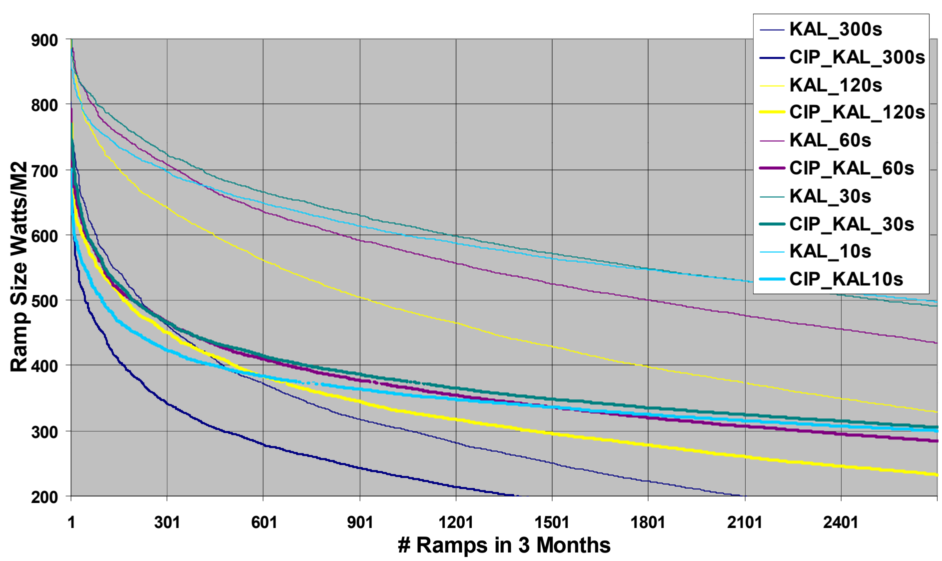
2 min averaging – more and larger ramps than 15 minutes.

CIP_KAL =

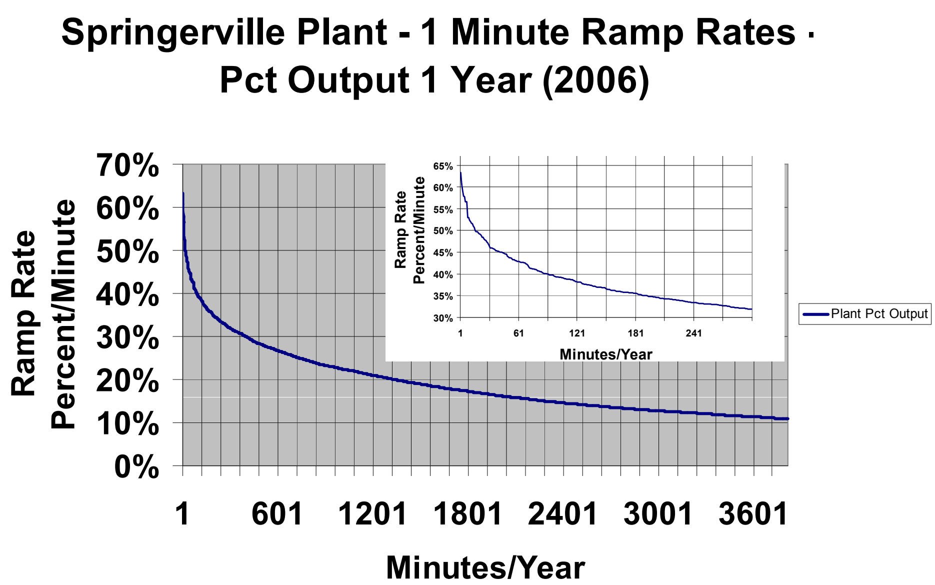
2 station average –

2 minute and 15 minute ramps almost the same.

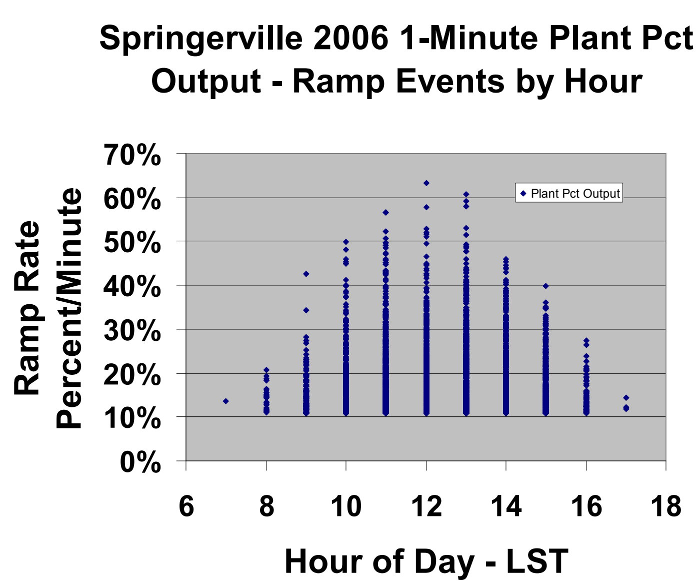
Ramps for KAL and CIP_KAL sites



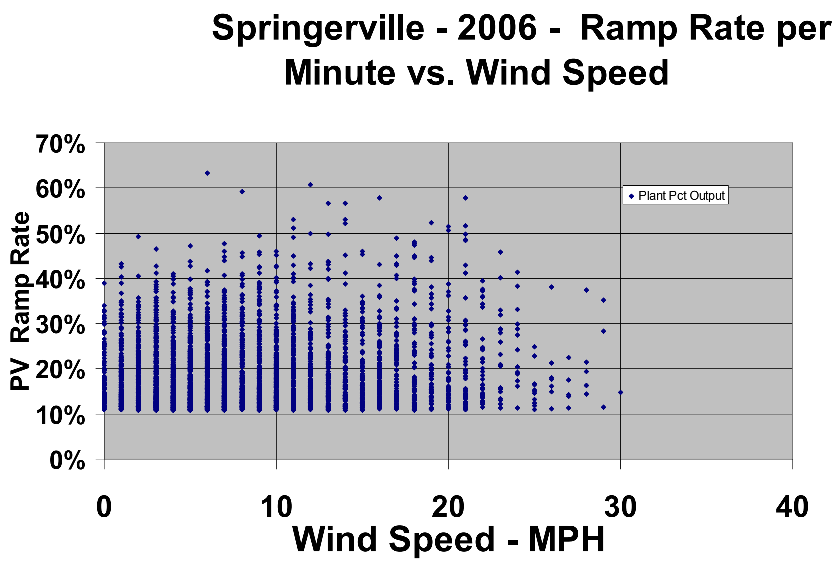
4.6 MW Plant – Distance Const ~450 m.



Large Ramps at All Daylight Hours

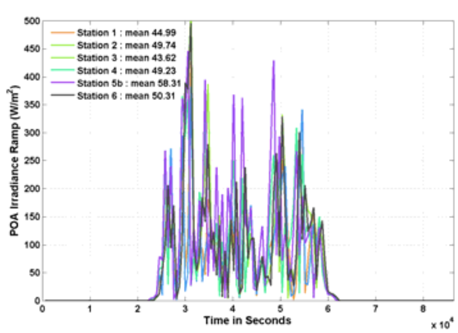


PV Ramp Rate vs. Wind Speed

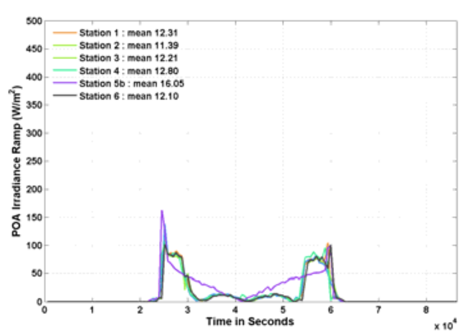


Example of 600 second "averaging" and "sampling" – <u>POA Irradiance Ramps</u>

Partly Cloudy Day

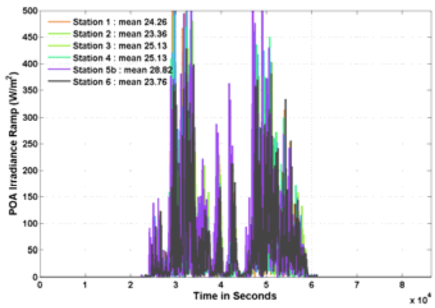


Clear Day

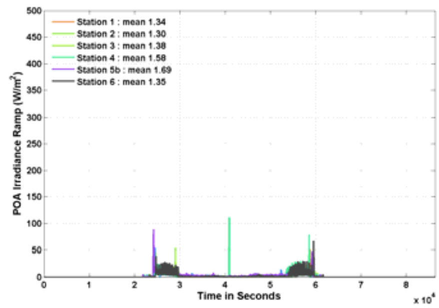


Example of 60 second "averaging" and "sampling" – POA Irradiance Ramps

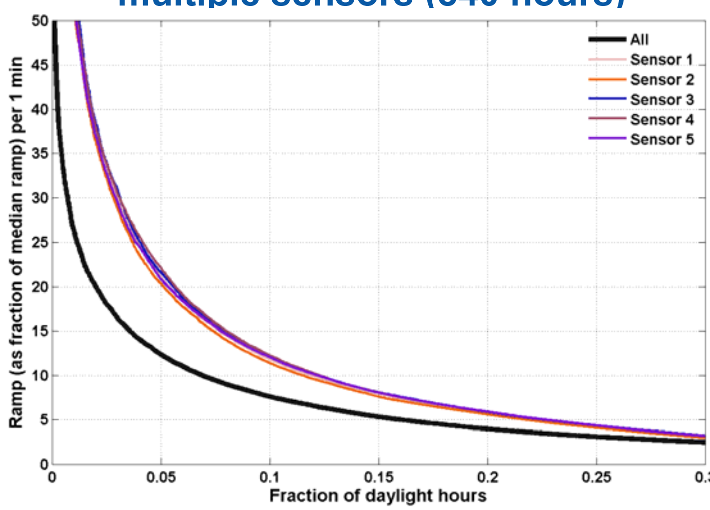
Partly Cloudy Day



Clear Day

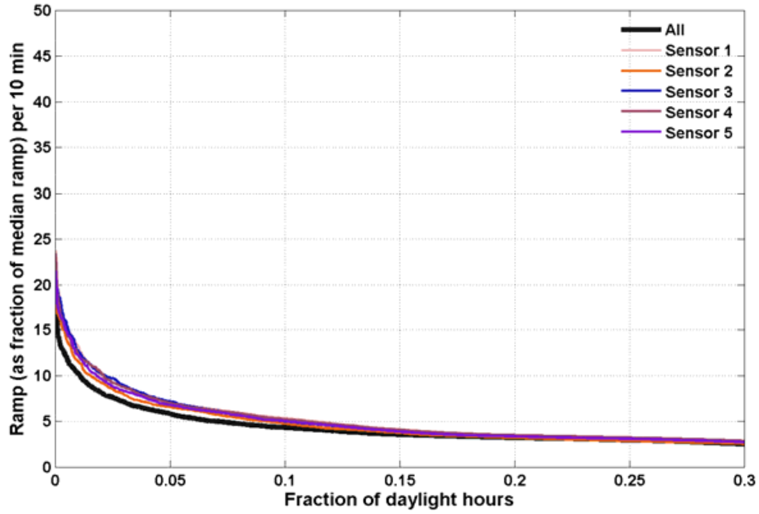


Power Output Ramp (as fraction of median ramp) Distribution for 1 minute data using single and multiple sensors (840 hours)



Power Output Ramp (as fraction of median ramp)

Distribution for 10 minute data using single and multiple sensors (840 hours)



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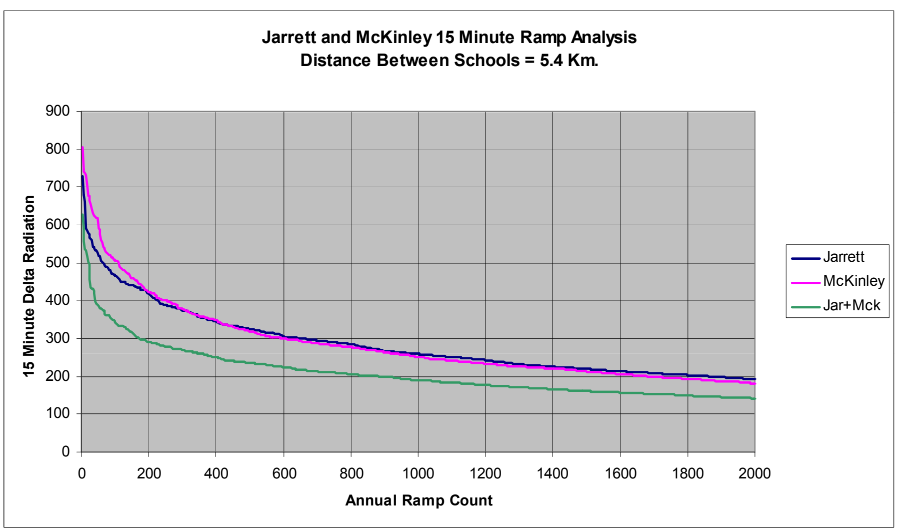
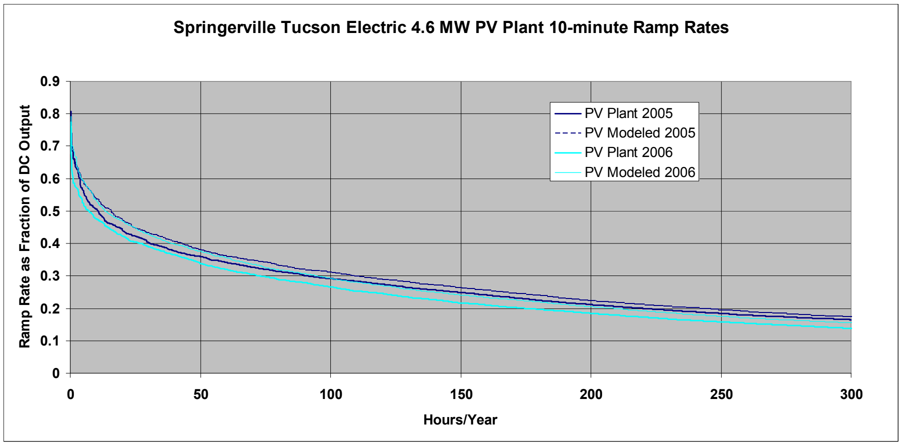
OWITS PV Data Ramp Rate Validation



Springerville 10 Minute Ramps Match



On Using Mesoscale Models for Solar Resource Modeling

Michael Brower, CTO
AWS Truewind, LLC
October, 2009
mbrower@awstruewind.com

Outline

- Background and motivation
- Mesoscale modeling status and challenges
- Mean solar patterns
- High-frequency fluctuations
- Next steps

Background

AWS Truewind

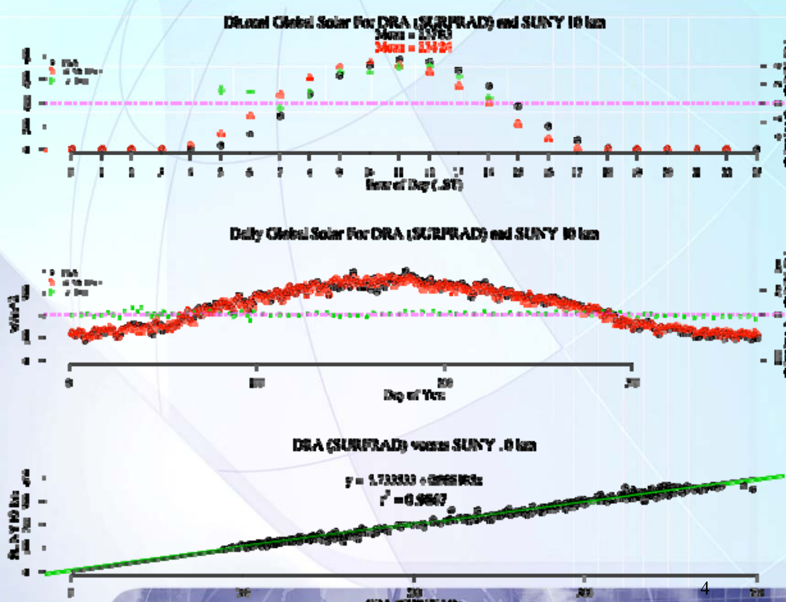
- NSRDB is currently the main nation-wide data set for solar resource assessment
- Based on a combination of
  - direct radiation measurements (1% of data)
  - cloud observations/METSTAT model
  - GOES satellite imagery/SUNY model
- Gridded data have 10 km resolution
- Time series in hourly intervals from 1991-1997 (METSTAT) and 1998-present (SUNY)
- Results compare well with direct observations

Desert Rock NV

AWS Truewind

W m^{-2}

W m^{-2}



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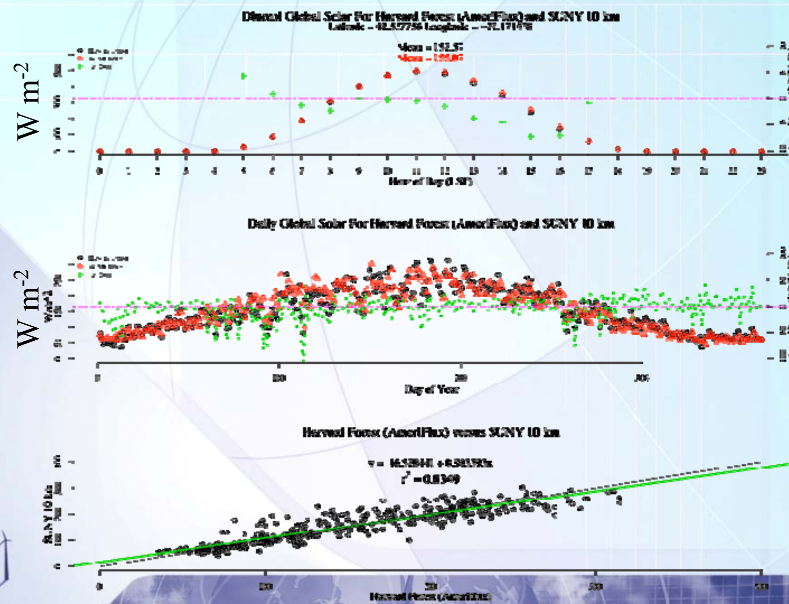
Harvard Forest, MA



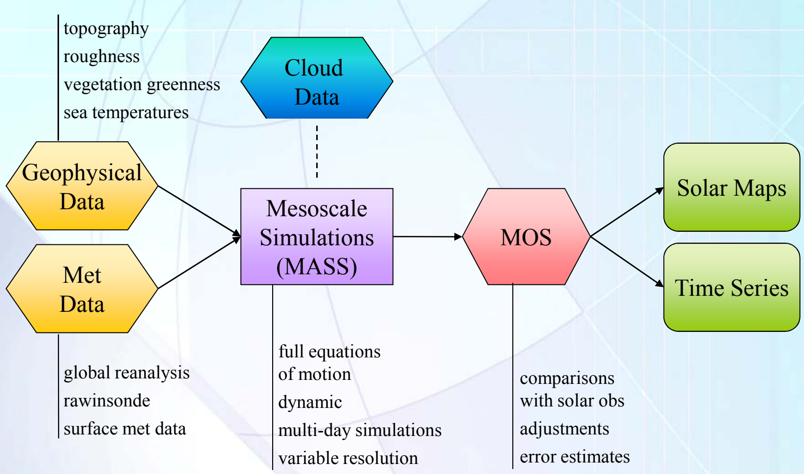
Why Consider Mesoscale Modeling?

- May be difficult to improve on SUNY model accuracy, but
- Would provide additional flexibility with respect to
  - Period of record (pre-1991)
  - Spatial resolution (down to hundreds of meters)
  - Temporal resolution (minutes)
  - Geographic regions (any area of globe may be modeled)
- Easily integrated with mesoscale-model-based wind resource mapping
- Essential for real-time solar forecasting
  - May employ satellite data to improve initial conditions

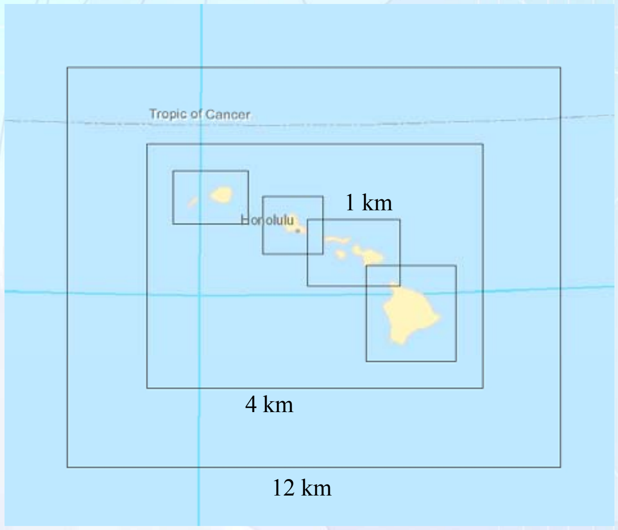
Status and Challenges

- Mesoscale modeling not commonly used for solar resource assessment
  - But there is a precedent for wind (e.g., EWITS, WWSIS)
- Accuracy of technique for solar not yet proven
  - Critical challenge: clouds
- High temporal resolution requires high spatial resolution = large CPU time

Mesoscale Modeling Process

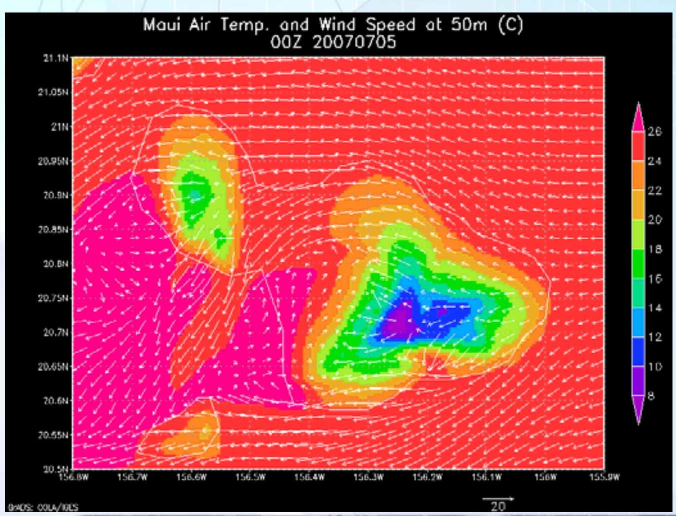


Nested Grids



Simulaton Snapshot

Wind Vectors and Temperatures



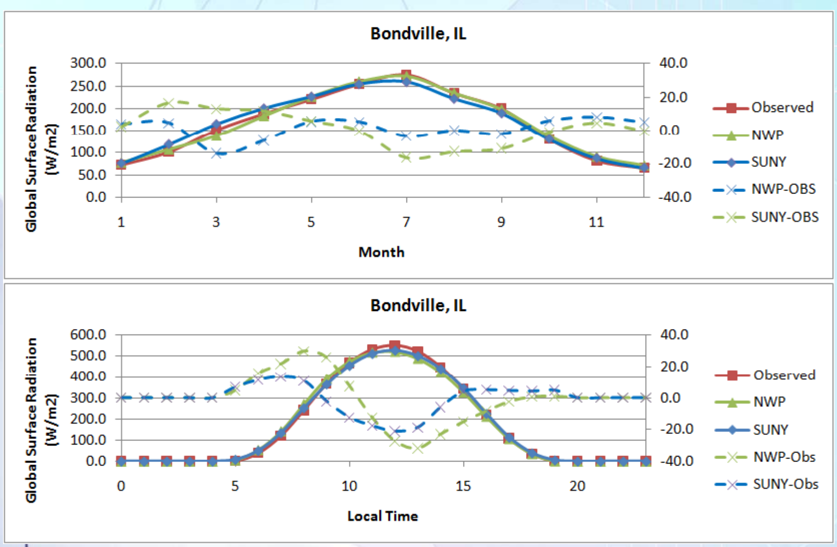
Preliminary Tests Using AWST windTrends Dataset

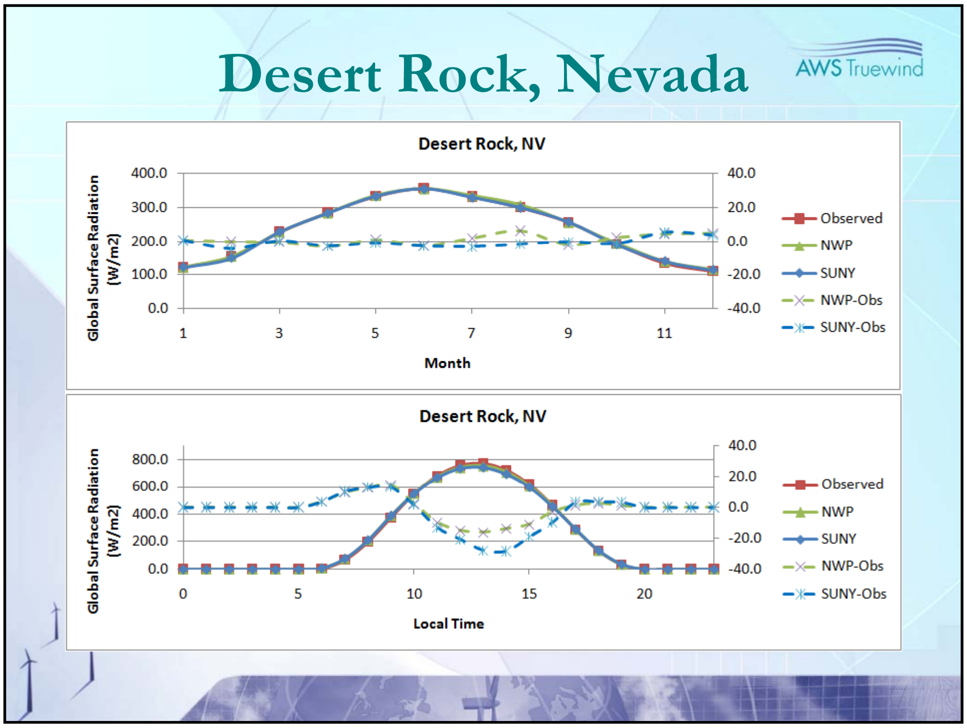
AWS Truewind

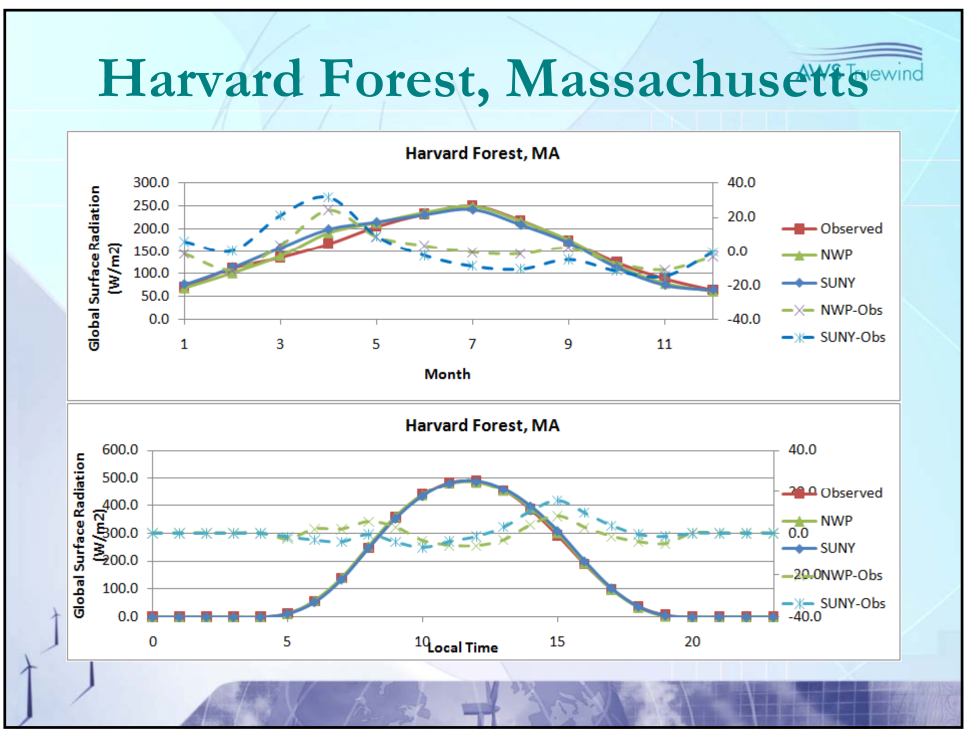
- Mesoscale simulations covering North America
- "Controlled reanalysis"
  - Assimilates only rawinsonde data at fixed heights
- 1997-present
- 20-km spatial, 1-hour temporal resolution
- Performed MOS to solar observations (validation data not included in training data)

Bondville, Illinois

AWS Truewind




Desert Rock, Nevada
AWS Truewind
Desert Rock, NV
Global Surface Radiation (W/m2)
Month
Observed
NWP
SUNY
NWP-Obs
SUNY-Obs
Desert Rock, NV
Global Surface Radiation (W/m2)
Local Time
Observed
NWP
SUNY
NWP-Obs
SUNY-Obs


Harvard Forest, Massachusetts
AWS Truewind
Harvard Forest, MA
Global Surface Radiation (W/m2)
Month
Observed
NWP
SUNY
NWP-Obs
SUNY-Obs
Harvard Forest, MA
Global Surface Radiation (W/m2)
Local Time
Observed
NWP
SUNY
NWP-Obs
SUNY-Obs

Error Statistics

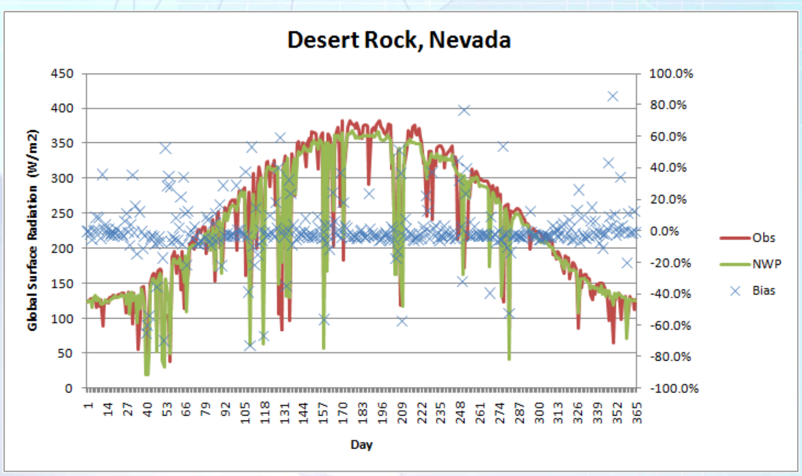
AWS Truewind

Six Stations

	Monthly Means		Diurnal Means	
	NWP	SUNY	NWP	SUNY
Mean Bias (W/m^2)	1.1	0.3	0.1	0.3
Standard Error (W/m^2)	12.8	14.3	12.0	9.1

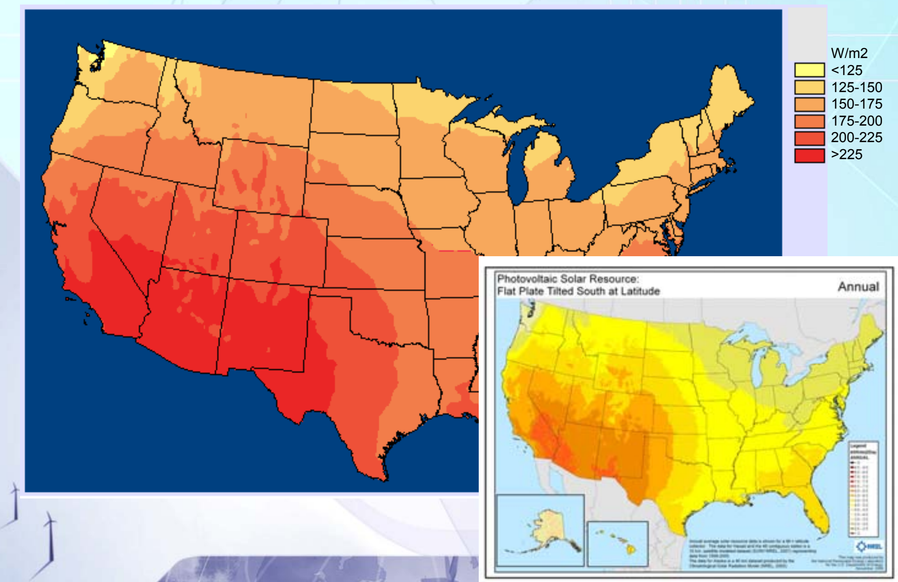
Daily Fluctuations

AWS Truewind



Preliminary Solar Map

AWS Truewind



High-Frequency Fluctuations

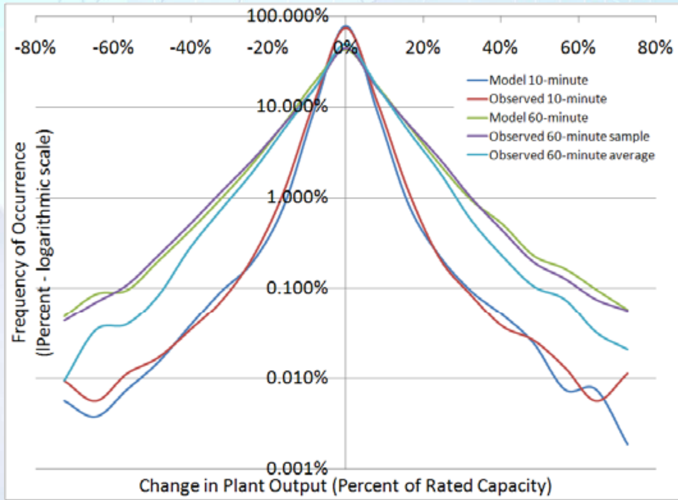
AWS Truewind

- Cloud passage time depends on cloud height, wind speed, size of PV array. Typical ramp times:*
  - For a point measurement: 1-5 s
  - For a 50 MW PV project: 60-120 s
- Wind projects cover a larger area, and wind speeds are lower at hub height, therefore wind variability tends to be less.
  - For a 50 MW wind project: 180-320 s
- Direct mesoscale modeling for wind is practical down to 10 minute time resolution

*Assumes clouds at 1000-5000 m height, 7-15 m/s speed, 10% efficient array, 1000 W/m^2 maximum irradiance

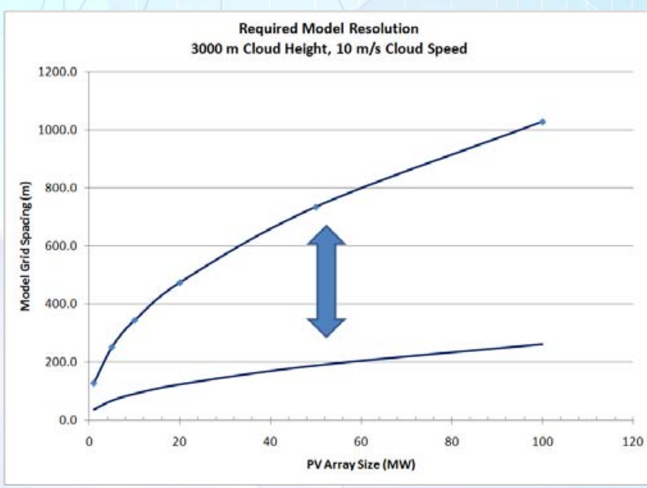
Wind Ramp Spectrum

10-Minute & 60-Minute Ramps



Required Solar Model Resolution

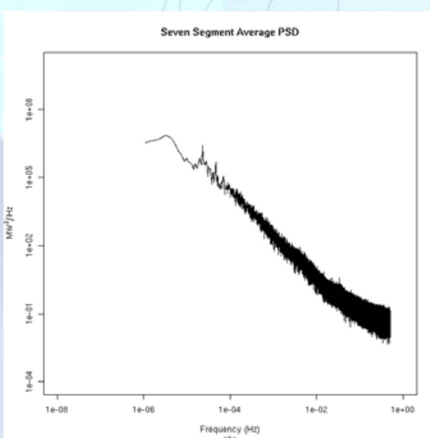
To Simulate Cloud Passage Directly



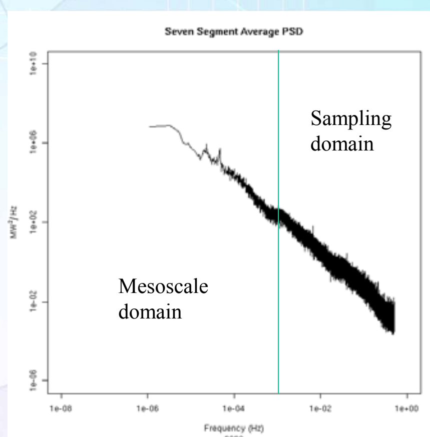
Alternative High-Frequency Variability Techniques

- Direct cloud observations (i.e., ceilometer, satellite)
  - Ground measurements have a limited range of view
  - Satellites have limited spatial, temporal resolution
- Statistical sampling of irradiance or PV data
  - Successfully applied to wind energy
  - Requires representative data from actual plants or measurements
  - Scale-up issues
  - Generally assume no correlation between projects – may need refinement to capture time lags

Wind Sampling Technique



Observed



Synthesized

Conclusions

AWS Truewind

- Mesoscale modeling can produce mean solar resource estimates of similar accuracy to SUNY model
- As a complementary tool, mesoscale modeling could provide additional spatial, temporal, and geographic flexibility
- High-frequency fluctuations for <100 MW PV arrays could potentially be modeled, but this would be costly in CPU; >100 MW needs to be demonstrated
- Methods combining mesoscale modeling with statistical sampling and/or direct or inferred cloud observations are likely necessary

Spatial and Temporal Scales of Solar Variability: Implications for Grid Integration of Utility-Scale Photovoltaic Plants

Andrew Mills and Ryan Wiser

Lawrence Berkeley National Laboratory
Electricity Markets and Policy

Utility-scale PV Variability Workshop

October 7, 2009

Presentation Overview

- Motivation
- Data and Approach
- Characterizing Variability at a Single Site
- Characterizing Temporal and Spatial Scales of Diversity
- Variability at the System Level
- Estimating the Costs of Managing Short-term Variability
- Impact of Geographic Diversity on the Costs of Managing Short-time scale PV Variability

Concern that Rapid Fluctuations in PV Output Are a Potential Roadblock to PV Integration

- NERC Integrating Variable Generation Task Force: "*…PV installations can change output by +/- 70% in a time frame of two to ten minutes, many times per day. Therefore, these plants should consider incorporating the ability to manage ramp rates and/or curtail power output.*"
- Numerous academic studies between 1980 – 1996 suggested potential limits to increasing PV penetration due to inability or high cost of operating conventional generation to respond to rapid fluctuations in PV
- Many of these concerns/studies lack detailed consideration of the effect of geographic diversity in smoothing aggregate output of several PV plants
  - Cloud models, anecdotal evidence, and increasingly available actual plant output suggests geographic diversity will play an important role in mitigating rapid fluctuations at the system level, as is already well known for wind energy

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Data and Approach

- Use time-synchronized data from multiple sensors to develop relationships between:
  - Time-scale of variability
  - Variability at one site; variability of aggregate of multiple sites
  - Number of sites and geographic orientation of sites
- Apply similar approach to solar and wind data in the same region
- Estimate the potential implications of geographic diversity on the cost of managing variability
  - Use 'back-of-the-envelope' estimation applied similarly to wind and solar
- Data source: Southern Great Plains in ARM – 1-min data from 2004
  - 23 time-synchronized solar insolation sites (20-450 km spacing)
  - 14 time-synchronized 10-m wind anemometers (40-450 km)

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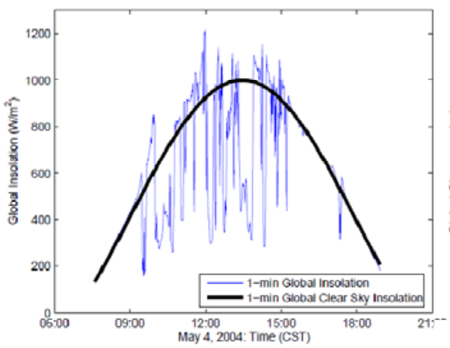
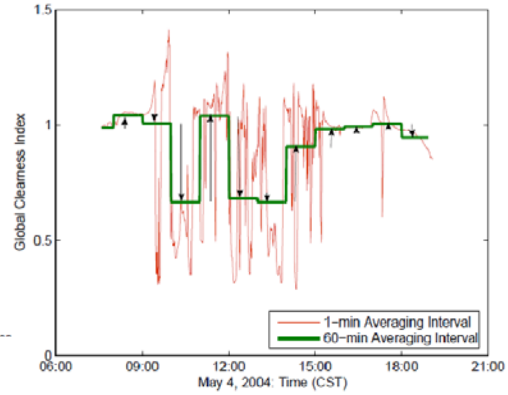
Clouds Can Produce Rapid Ramps in Solar Insolation at a Single Point





Deltas: Step change from one averaging interval to the next

Clearness Index: Ratio of clear-sky solar insolation to measured insolation

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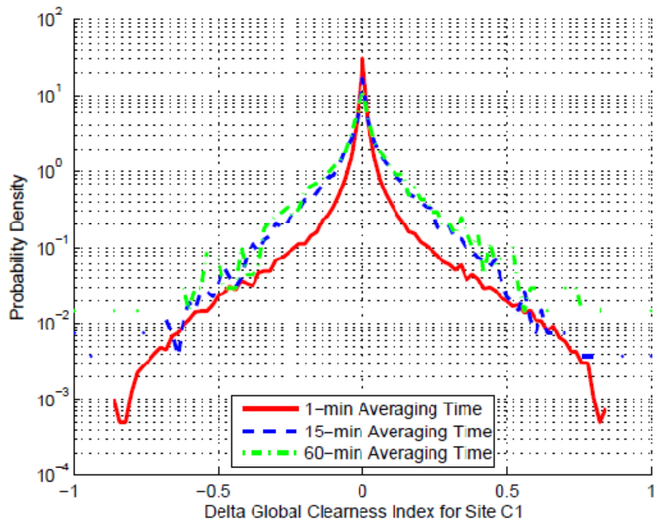
Clouds Can Produce Rapid Ramps in Solar Insolation at a Single Point



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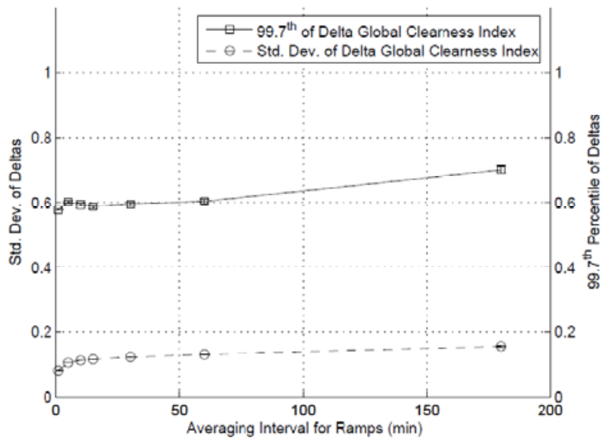
Variability Metric is Standard Deviation and 99.7th Percentile of Deltas



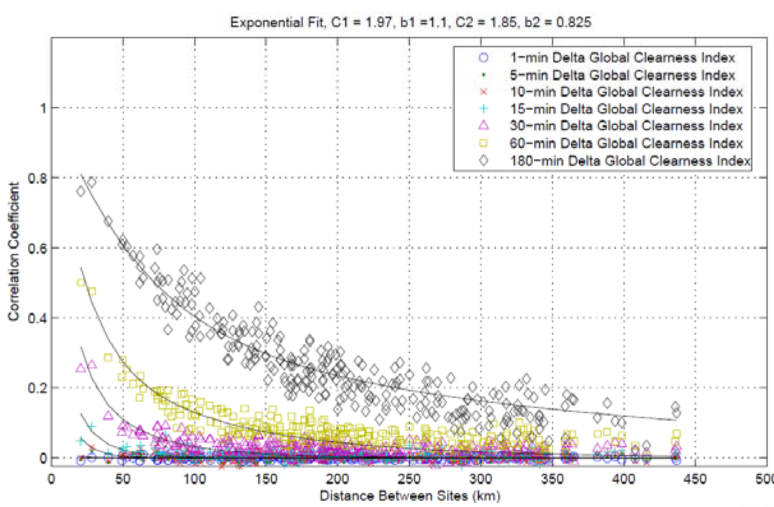
Characterize variability over different time-scales as:

(1) The standard deviation of the deltas

(2) The 99.7th percentile of the deltas

Extreme changes are observed from one hour to the next (60-min deltas) and even one minute to the next (1-min deltas)

Short Time-Scale *Changes* in Insolation are Uncorrelated Between Sites



Temporal and Spatial Scales of Diversity Can be Used to Predict Variability at System Level

$$\frac{\left(\Delta\sigma_k^{\bar{t}}/N\right)}{\Delta\sigma_{k_1}^{\bar{t}}} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\rho^{\bar{t}}\left(\Delta k_i^{\bar{t}}, \Delta k_j^{\bar{t}}\right)}$$

- ($\Delta\sigma^t_k$/N): Average variability for a time-scale *t* at system level for *N* sites
- $\Delta\sigma^t_1$: Variability at a single site
- ρ^t: Correlation coefficient of step-changes in clearness index between two sites
- If all sites are uncorrelated ($\rho^t = 0$), average variability is ***1/sqrt(N)*** times the variability at a single site
- If all sites are perfectly correlated ($\rho^t = 1$), average variability is ***equal*** to the variability at a single site

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Diversity Within a Control Area Will Significantly Smooth Rapid Ramps

Ramps at a single site can be severe, but diversity between sites can mitigate ramps.

Similarly sited wind and solar appear to have similar variability

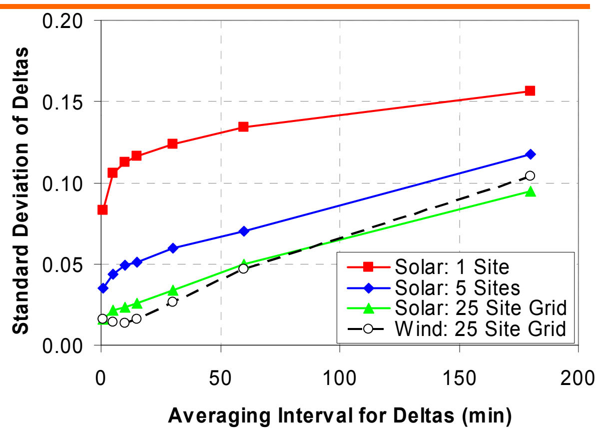
5 close sites

~ 7,000 sq. km

25 site grid

5 X 5 Site array with 40 km spacing between sites

~ 40,000 sq. km



Caveat: Each site is based on a single point measurement, additional smoothing will occur for both wind and solar over short-time scales within individual sites. These results overstate variability of plants below ~10-min time scale

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Costs to Manage Short-term Variability: Assumptions

- Short-term variability is managed by increasing reserves at the power system level (as opposed to plant level)
- Reserves are increased to manage variability over three time scales:
  - Regulation (1-min deltas)
  - Load Following (5-min deltas)
  - Operating Reserve Margin (60-min deltas)
- Grubb (1991): Cost of reserves is due to:
  - Part-load efficiency penalty for spinning plants (assumed to be 15%)
  - Use-of high cost energy from quick-start standing plant when standing reserves are deployed (applicable to 60-min deltas only)
- Used characteristics of MISO load and assumptions made in 2006 MISO Wind Integration Study to estimate increase in reserve costs due to increased variability from solar and wind

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Integration Costs of Solar Dramatically Impacted By Geographic Diversity, and May Be Less than for Comparably Sited Wind

Time Scale	Increased Reserve Costs ($/MWh)				
	Reserves Constant Throughout Year				Reserves Change with Position of Sun
	Solar			Wind	Solar
	1 Site	5 Sites	25 Site Grid		
1-min Deltas (Regulation)	$14.7	$5.0	$1.6	$1.1	$0.2
5-min Deltas (Load Following)	$7.0	$2.1	$0.7	$0.2	$0.1
60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)	$5.2	$2.2	$1.3	$0.8	$0.2
Total Cost	**$26.9**	**$9.3**	**$3.5**	**$2.1**	**$0.5**

Example costs based on 10% penetration of solar or wind on capacity basis

Why are solar costs lower?

Reserves can be held in proportion to clear-sky insolation for solar

Reserves are held at the same level all year for wind

Integration costs include unit-commitment costs which are not considered here

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Preliminary Conclusions

- Variability in solar insolation at a single site can be severe. Scaling a single point measurement of insolation leads to projections of high costs to manage PV variability
- 1-min to 10-min step changes in solar insolation for sites as close as 20 km apart, however, are uncorrelated
- Aggregation of multiple sites at the system level leads to significant smoothing of ramps, particularly over short time-scales
- Costs to manage short-term PV variability from multiple sites aggregated to the system level may be similar to the modest costs to mange short-term variability of wind

Acknowledgements

- Project funded by the Office of Electricity and the Solar Technologies Program at DOE
- Special thanks to:

  Michael Milligan, Yih-huei Wan, Debbie Lew, Ben Kroposki, Dave Renne, Mark O'Malley, Abe Ellis and Brian Parsons

Backup Slides

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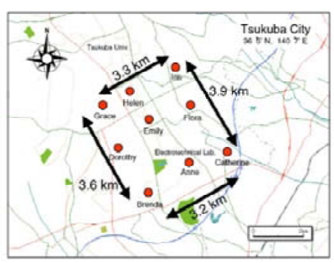
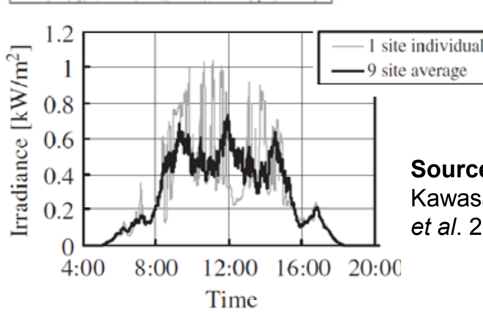
Next Steps

- Characterize temporal and spatial scales of geographic diversity in high-solar regions
- Estimate the degree to which smoothing occurs at the plant level; compare within-plant smoothing to wind
- Perform more detailed studies of reserve costs using production cost models and time-synchronized PV and load data



12.25 sq. km = 3025 acres ~ 350 MW PV plant



Source: Kawasaki *et al*. 2006.

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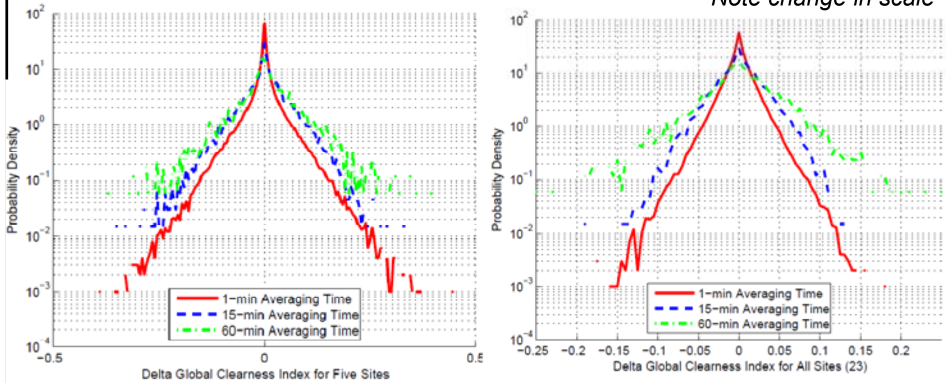
Variations are Smoother for Aggregate of Multiple Sites Compared to a Single Site

Note change in scale



• Deltas are relatively smaller with more sites; aggregation is particularly effective for shorter time-scales

• Shape of distribution of deltas becomes less “fat-tailed”

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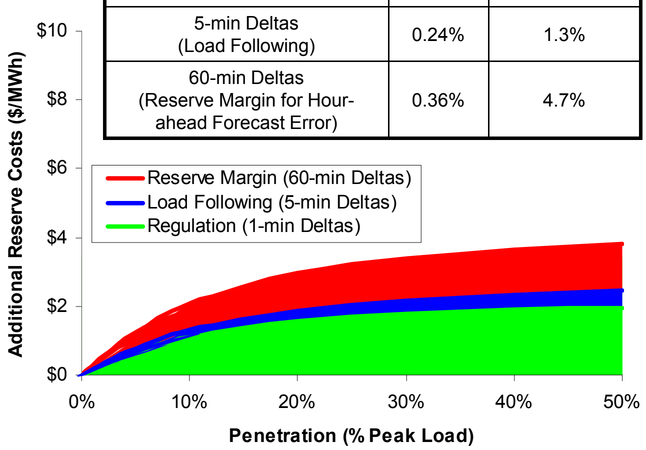
BERKELEY LAB

Costs to Manage Short-term Variability: Simple Example for Wind

Time-Scale	Load (% Peak)	Wind (% Nameplate)
1-min Deltas (Regulation)	0.13%	1.7%
5-min Deltas (Load Following)	0.24%	1.3%
60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)	0.36%	4.7%



Analysis Relies on Many Simplifying Assumptions:

Reserves are constant throughout year for both load and net-load

One type of plant provides spinning reserve throughout year (marginal cost at full load = $55/MWh)

One type of plant provides standing reserve (marginal cost = $85/MWh, no start-up cost)

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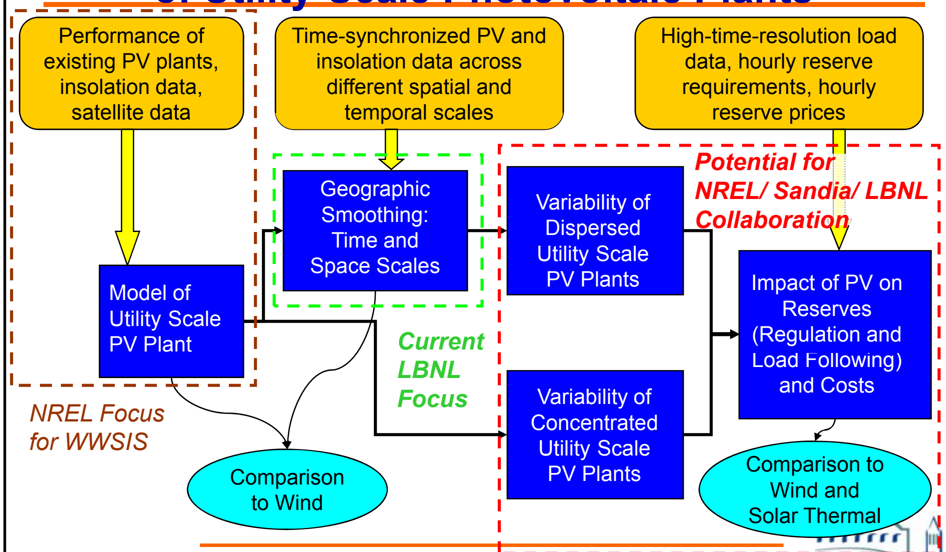
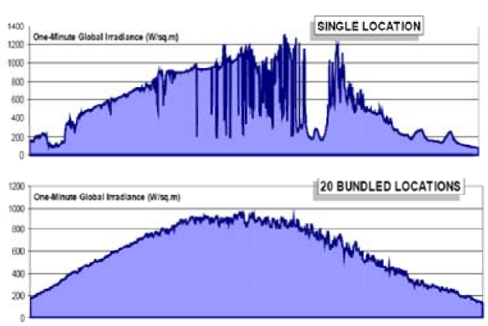
Energy Analysis Department

Broad Sketch of Research Required to Assess the Operational Integration Impacts of Utility-Scale Photovoltaic Plants



Geographic Diversity Smoothes Rapid Variations in Output

Information about the benefits of geographic diversity need to be incorporated into the analysis of utility-scale PV grid integration impacts



Source: Hoff et al. 2008

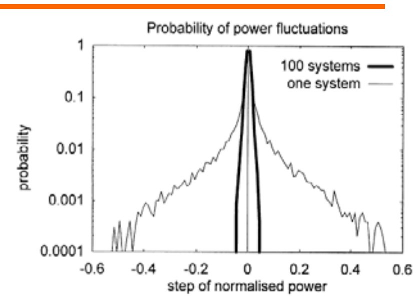


Fig. 5. The time series of both the power generation of an individual PV system and of the combined systems are scanned for differential power steps. For instance, a probability at the normalised power of delta $P/P_{inst.}=0.2$ means that in the investigated period ($P/P_{inst.}>0$) power differences of 20% of the installed power have occurred between two time steps with this probability. Positive values indicate an increase in power, negative values a decrease. The time resolution is 5 min, the class width of the normalised power levels is 0.01.

Source: Weimken et al. 2001

Temporal and Spatial Scales for Correlation of Changes in Wind Power are Well Understood

*Correlation of changes in **wind power** output is a function of distance and time-scale. 5-min variations in wind plants over 20 km apart are statistically uncorrelated.*

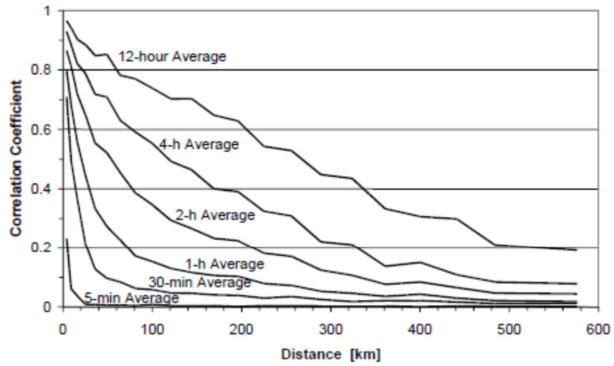
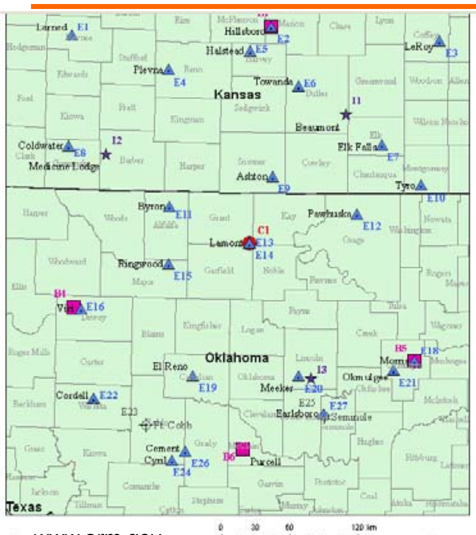


Figure 7. Correlation coefficient of Δp for different average times over the distance

Source: Ernst, Wan, and Kirby 1999

Analysis of Temporal and Spatial Scales of Geographic Diversity: ARM Program



- *www.arm.gov*

- Use 1-min data from 2004 to estimate correlation coefficient for changes in:
  - global insolation,
  - direct insolation, and
  - clearness index*

  between pairs of stations in the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurement (ARM) Program.
- Calculate histograms of changes in solar insolation over different time-steps for a single site (C1) and all 23 available sites (C1 & E1-27 excl. E-14 & E-26)

**Clearness Index:* Ratio of measured insolation to "clear sky" insolation (i.e. insolatior clouds). SGP data includes clear sky insolation

Diversity Decreases Probability of Large Swings in Solar Insolation for Multiple Sites

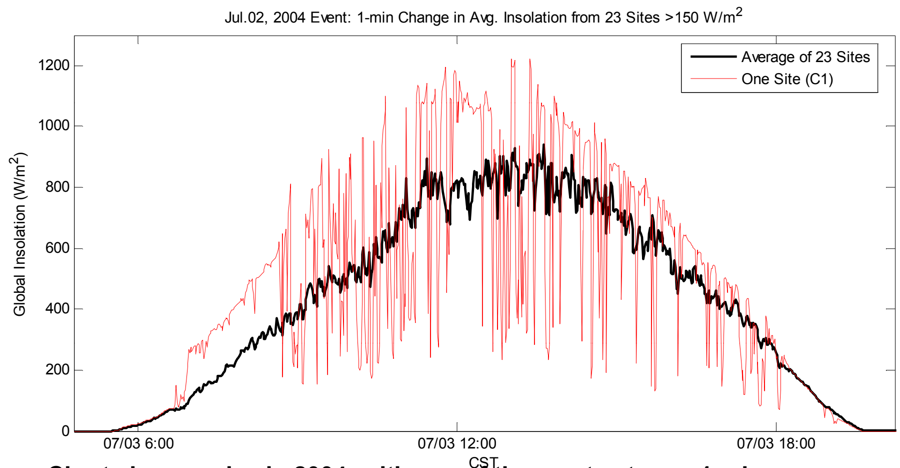


Chart shows a day in 2004 with one of the most extreme 1-min changes in global solar insolation simultaneously measured at all 23 sites

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Diversity Decreases Probability of Large Swings in Solar Insolation for Multiple Sites

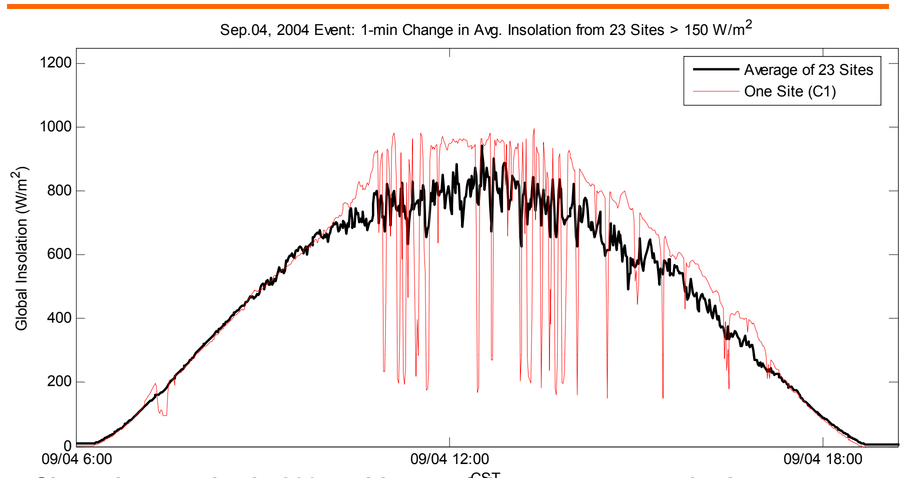

Chart shows a day in 2004 with one of the most extreme 1-min changes in global solar insolation simultaneously measured at all 23 sites

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Energy Analysis Department

National Renewable Energy Laboratory
Innovation for Our Energy Future

Comparison of PV and Wind Variability

Utility Scale PV Variability Shop

Cedar Rapids, Iowa

Yih-huei Wan

October 7, 2009

Presentation Outline

- Introduction
- Data Sources
- Average Profiles of PV and Wind Power
- Ramping Statistics on Different Time Scales
- Comparison of PV and Wind Ramp Distribution
- Correlation among Plants
- Summary

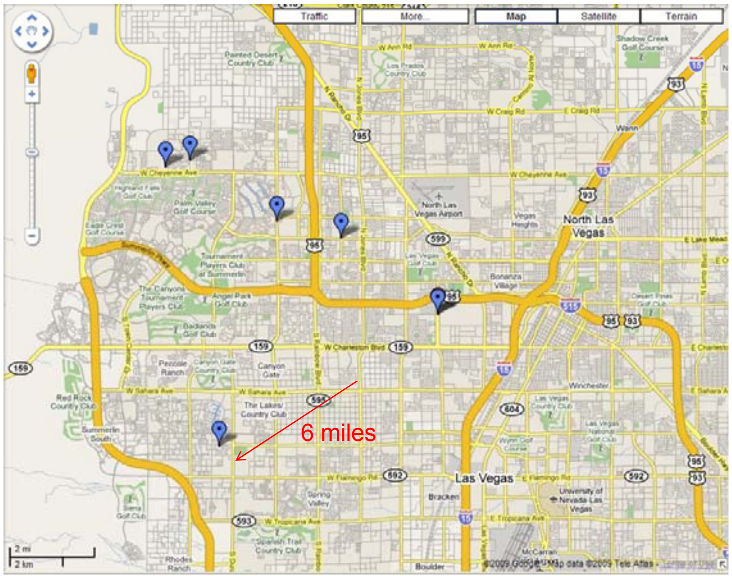
Introduction

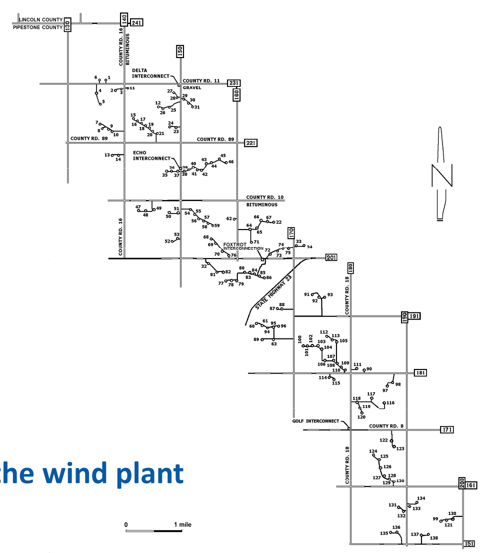
- Both PV and wind power are variable in nature
- The outline of PV production is well-known because the position of sun is fixed at any given time
- Outputs from PV facilities within the same time zone could be highly correlated
- Although wind can change quickly, its short-time frame (1-second and 1-minute) changes are limited. Coupled with turbine inertial, the short-time frame wind power changes are small and not totally random.
- There is no inertial in PV panel and the associated inverter.

Data Sources

- PV Data – 1-minute PV output data from 6 LVWD facilities (2007 through April 2009)
  1. Ronzone (675 kW, single-axis tracking)
  2. Ft Apache (325 kW, single-axis tracking)
  3. Gd Canyon (325 kW, single-axis tracking)
  4. Spg Mtn (450 kW, single-axis tracking)
  5. Luce (450 kW, single-axis tracking)
  6. LVSP (450 kW, fixed-tilt)
- Wind Data – 1-minute plant output data from plants in Buffalo Ridge area (Minnesota) during the same period; mostly 750-kW turbines

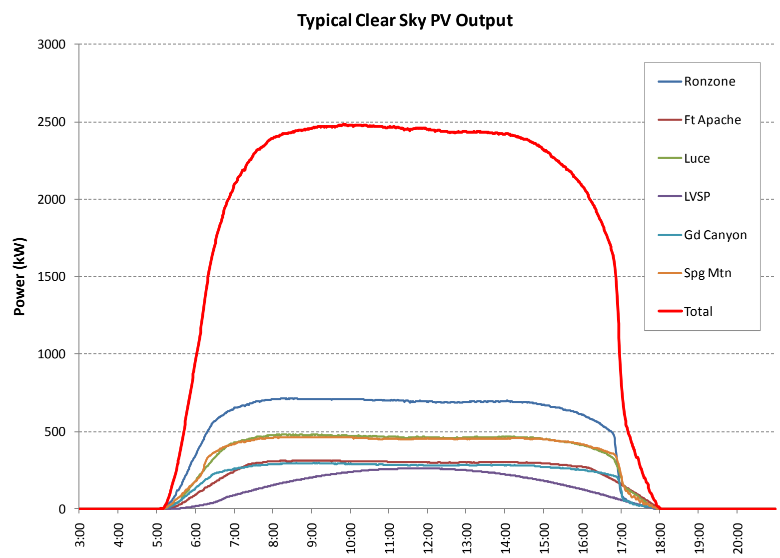
Locations of PV Facilities



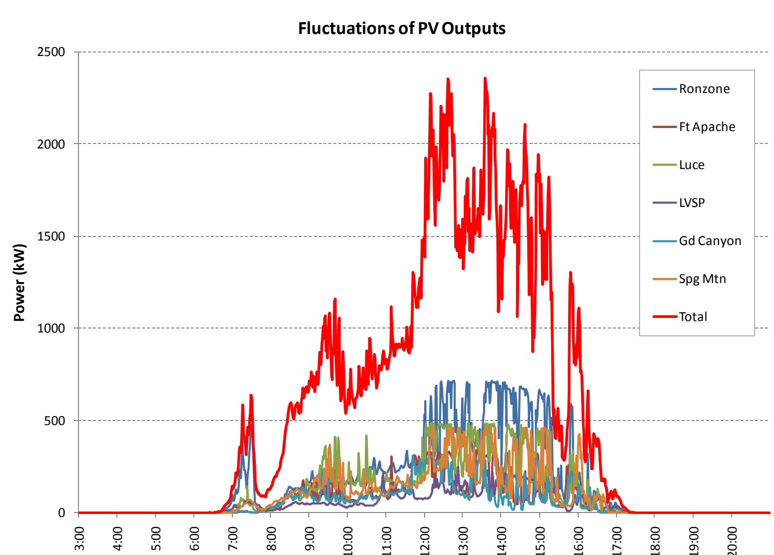


Locations of turbines at the wind plant

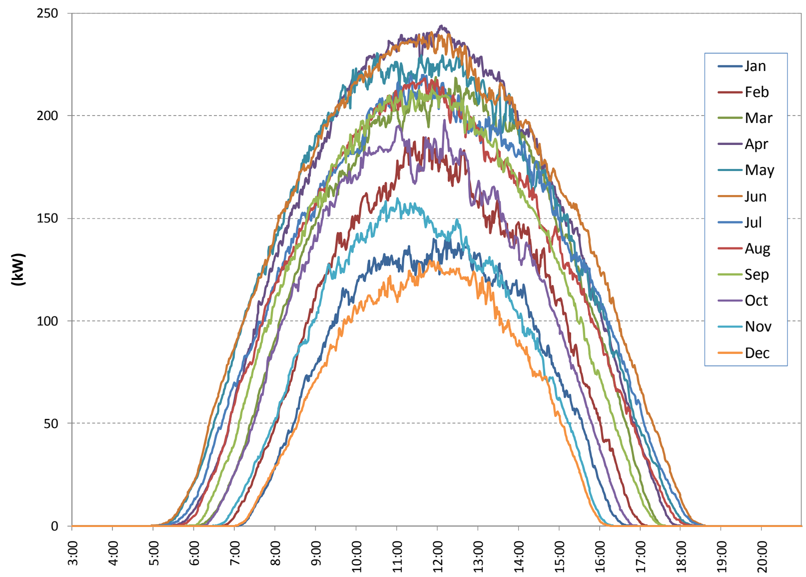
PV Profiles (clear sky)



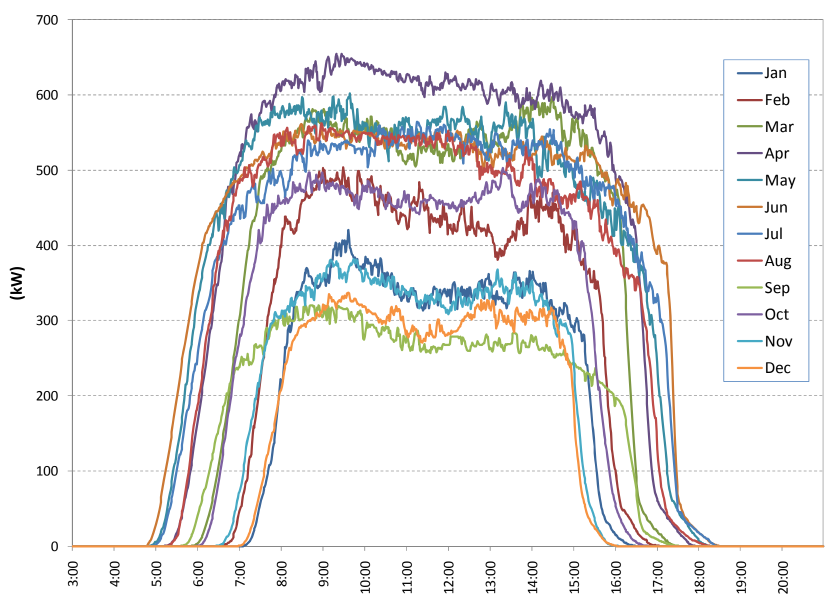
PV Profiles (cloudy day example)



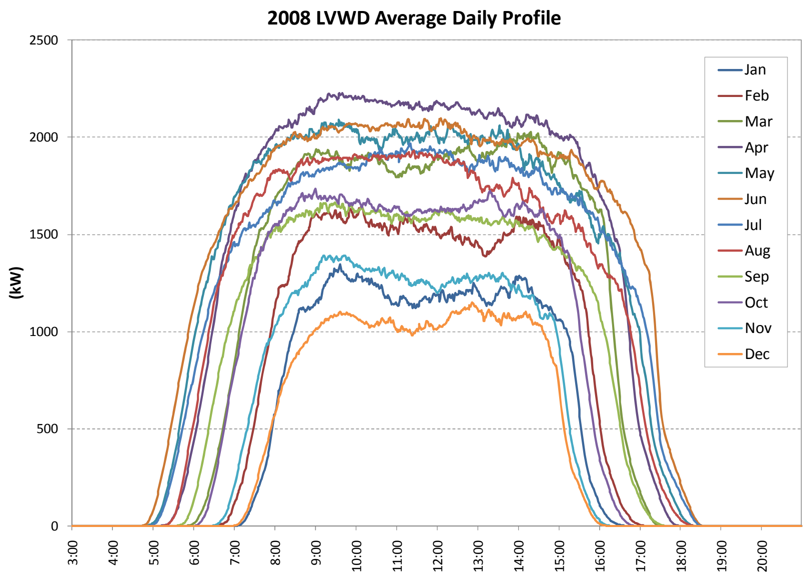
Fixed-tilt PV Monthly Average Profiles



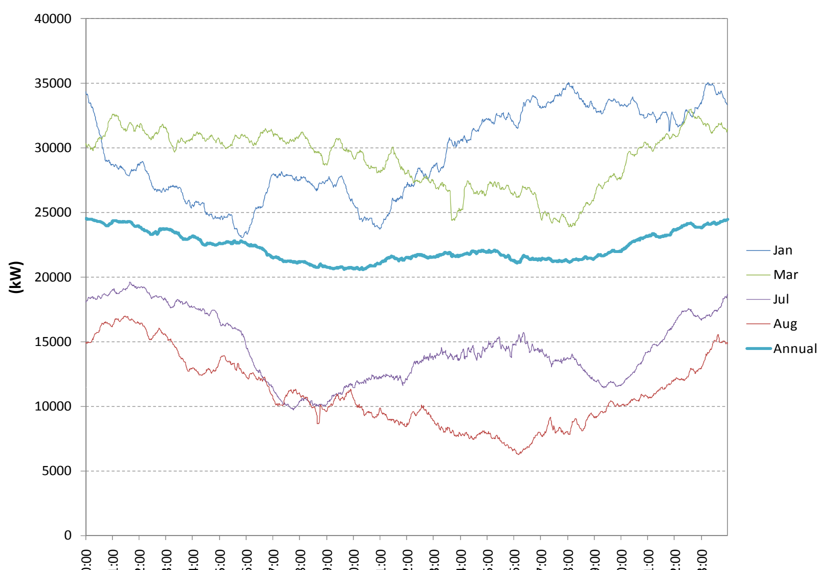
Single-axis Tracking PV Monthly Average Profiles



PV Monthly Average Profiles



Wind Power Monthly Average Profiles



Wind Ramp Statistics

	Delta (22.5 MW)			Golf (41.3 MW)			LB (63.8 MW)			BR (240 MW)		
1-minute												
	Stdev	Max (+)	Max (−)	Stdev	Max (+)	Max (−)	Stdev	Max (+)	Max (−)	Stdev	Max (+)	Max (−)
2007	1.6%	71%	94%	1.2%	75%	92%	1.0%	50%	53%	0.5%	30%	57%
2008	1.5%	73%	86%	1.2%	68%	93%	0.9%	58%	53%	0.5%	20%	79%
2009	1.6%	71%	82%	1.2%	67%	60%	1.0%	54%	81%	0.5%	12%	28%
10-minute												
2007	5.0%	78%	85%	4.3%	88%	90%	3.7%	79%	86%	2.5%	44%	92%
2008	4.5%	87%	90%	4.2%	66%	86%	3.5%	56%	57%	2.4%	39%	82%
2009	4.5%	68%	77%	4.1%	73%	73%	3.4%	63%	63%	2.6%	23%	36%
1-hour												
2007	10.7%	74%	84%	10.1%	85%	68%	9.6%	76%	65%	8.1%	57%	48%
2008	9.8%	76%	65%	9.9%	75%	79%	9.4%	74%	55%	8.0%	51%	56%
2009	9.7%	83%	75%	9.6%	77%	65%	9.3%	75%	69%	8.6%	49%	38%

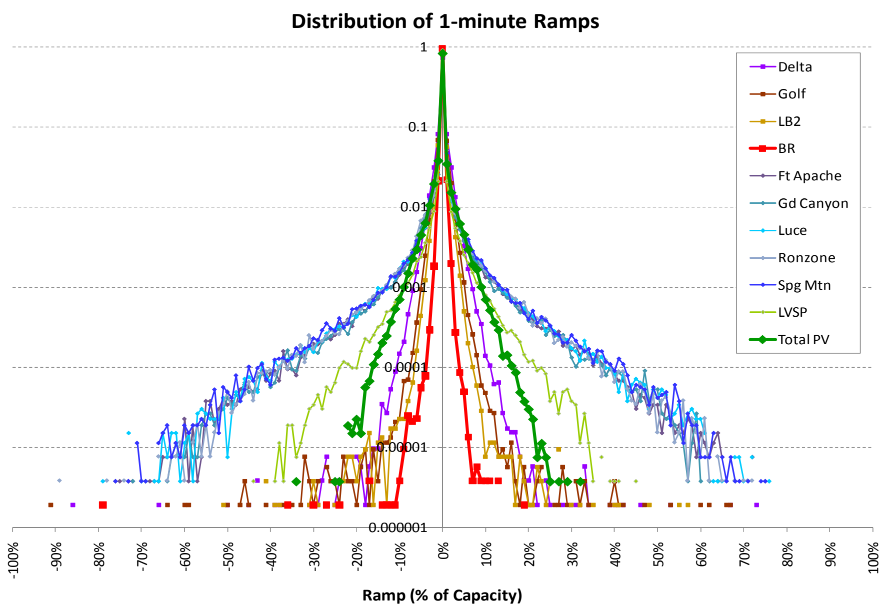
- Outputs from bigger the wind plants (or more turbines) are less variable than smaller plants
- Detailed analysis shows that the severe down ramps in shorter time frame are invariably caused by outages or curtailment; severe up ramps are the results of starting under high wind

PV Ramp Statistics

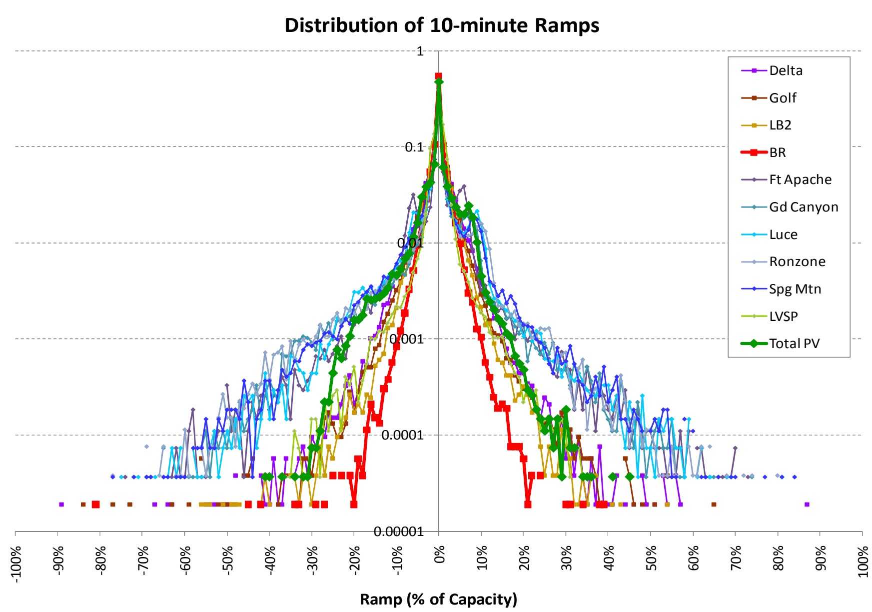
	LVSP (450 kW)			Spring Mtn (450 kW)			Ronzone (675 kW)			Total (2675 kW)		
1-minute												
	Stdev	Max (+)	Max (−)	Stdev	Max (+)	Max (−)	Stdev	Max (+)	Max (−)	Stdev	Max (+)	Max (−)
2007	1.8%	42%	38%	4.3%	76%	83%	4.0%	72%	87%	1.7%	27%	24%
2008	2.0%	46%	45%	4.4%	75%	77%	4.2%	73%	89%	1.7%	32%	35%
2009	2.1%	47%	40%	4.7%	79%	72%	4.5%	77%	78%	1.9%	32%	28%
10-minute												
2007	3.2%	29%	33%	8.7%	79%	84%	8.3%	77%	70%	4.9%	31%	38%
2008	3.6%	35%	36%	8.2%	85%	77%	8.3%	81%	78%	5.0%	46%	42%
2009	3.5%	35%	39%	8.3%	76%	73%	8.5%	71%	69%	5.4%	41%	37%
1-hour												
2007	8.4%	34%	30%	20.0%	75%	76%	21.2%	76%	79%	16.8%	46%	54%
2008	8.7%	35%	35%	20.6%	89%	70%	20.8%	71%	74%	16.9%	50%	62%
2009	8.9%	34%	38%	21.4%	64%	82%	22.3%	62%	74%	17.9%	54%	51%

- Outputs from single-axis PV appears to be more variable than fixed-tilt PV. It’s not clear this is true in other areas.
- No clear conclusion about PV and wind variability can be drawn because the size differences between PV and wind (more PV data needed)

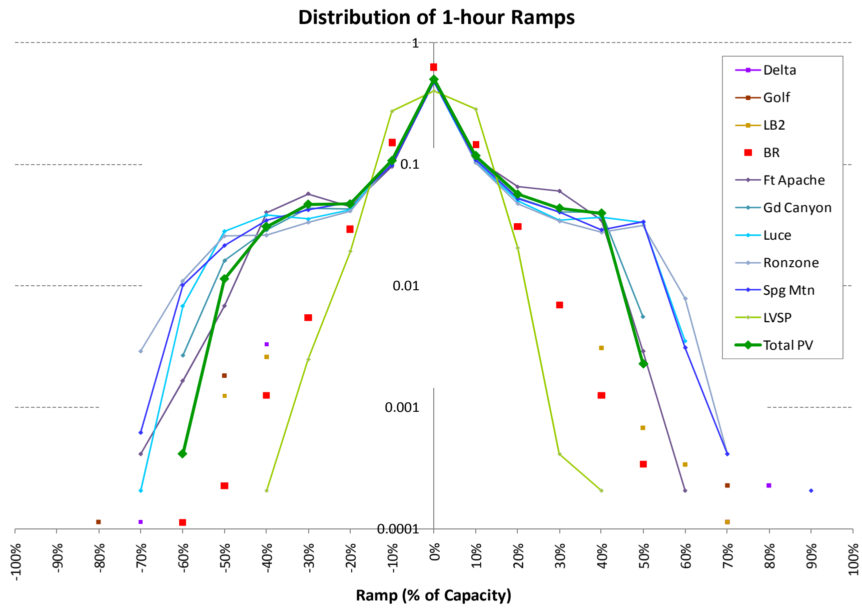
1-minute Ramp Distribution of PV and Wind



10-minute Ramp Distribution of PV and Wind



1-hour Ramp Distribution of PV and Wind



Correlation among Plants

- Correlation between adjacent PV facilities is higher than further away PV facilities (avg. 0.93 vs 0.78)
- PV facilities have slightly higher correlation coefficients than adjacent wind plants (avg. 0.84)
- Further analysis will look into 1-second PV time series

Summary

- PV have relatively large up ramp in the morning and down ramps in the afternoon, but their magnitudes is bounded by clear sky values.
- Even for relatively short distance and small installations, PV facilities still benefit from spatial diversity.
- More high resolution data from larger PV installations are needed to have a better understanding of the variability issue.

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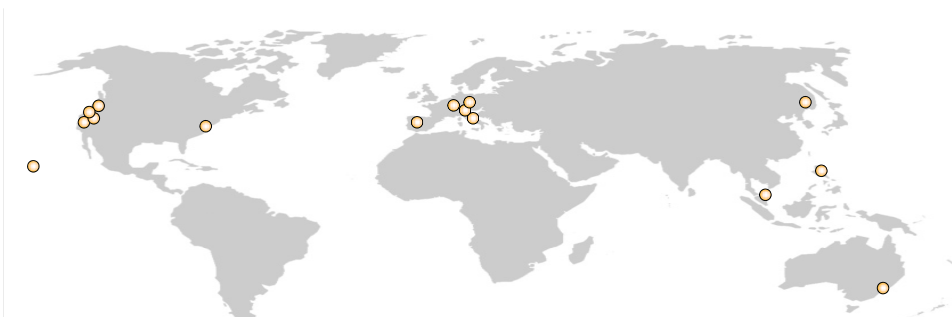
Variability In A Large-Scale PV Installation

Carl Lenox

Principal Engineer, Technology Development

October 7, 2009



Established and Proven Technology Innovator

- Incorporated in 1985
- Publicly traded company: NASDAQ
- 4,000 employees, 100 % solar
- 25 years of R&D, 85 patents
- Manufacturing U.S., Philippines, Malaysia
- Diversified portfolio: residential, commercial, power plant & utility
- World record cell efficiency: 23.4%
- 500 systems over 4 continents
- Over 400 MW installed worldwide

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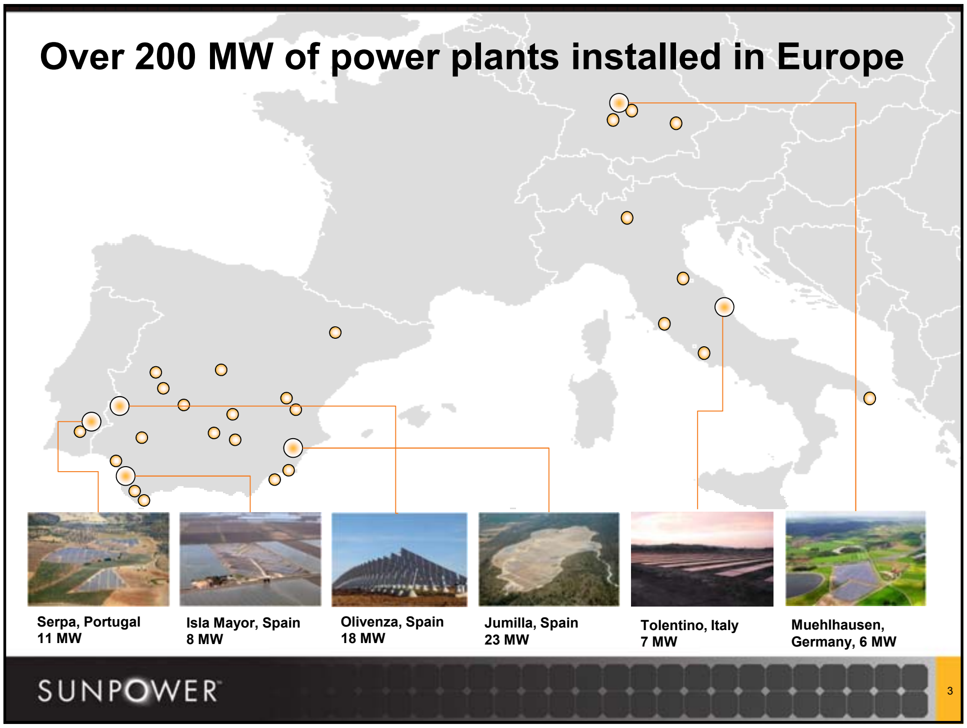
Over 200 MW of power plants installed in Europe
Serpa, Portugal
11 MW
Isla Mayor, Spain
8 MW
Olivenza, Spain
18 MW
Jumilla, Spain
23 MW
Tolentino, Italy
7 MW
Muehlhausen,
Germany, 6 MW
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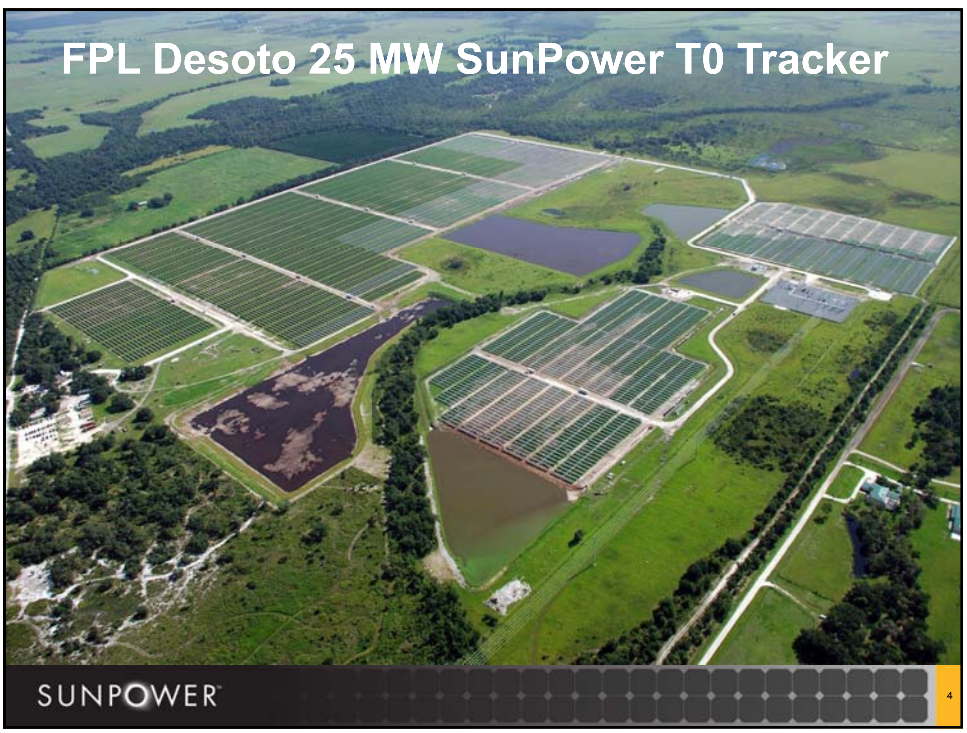
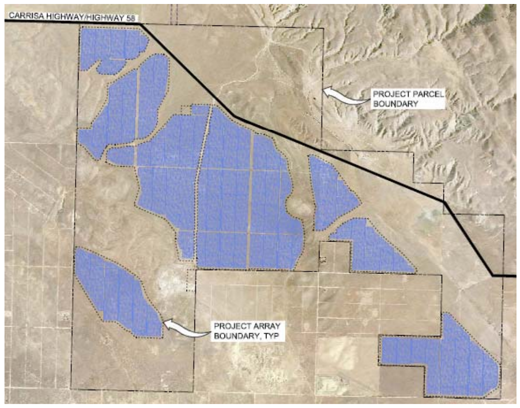
3


FPL Desoto 25 MW SunPower T0 Tracker
SUNPOWER
4

SPWR's California Valley Solar Ranch – 210 MW

≈ 5 km



Preliminary Plant Layout *

* 2010 Projected Construction Start

Today's Presentation

- Based on 1-second resolution data from ~13 MW (AC) site in Nevada
- Data is at the inverter level (typically 250 kW), time synchronized
- Dates from 5/11 – 9/7/2009 – 120 days
- We consider these results to be preliminary – more to be done!

Questions For Today

- **What are useful interval(s) for data collection?**
- **How frequently do large changes in output occur?**
- **How does variability change with scale, and over different intervals?**

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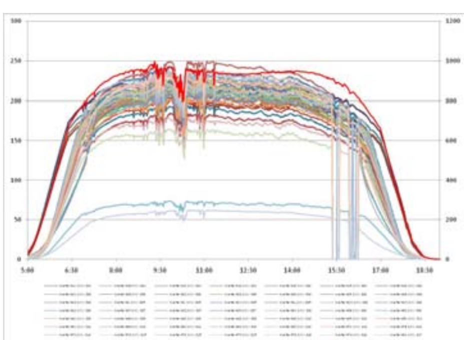
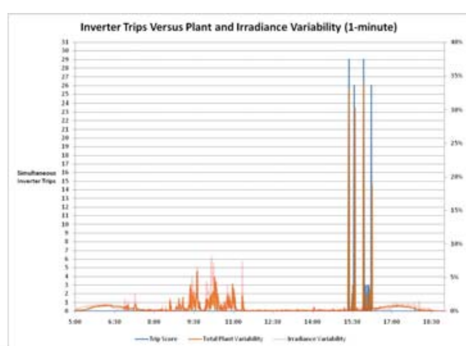
An Important Note

- This site uses typical UL Listed commercial inverters, IEEE 1547 compliant
- Multiple, simultaneous inverter trips cause the largest short-duration changes in output (1-sec and 10-sec).
- The signature of these trips indicate they are most likely due to anti-islanding – operating as designed.
- Consistent LVRT requirements and implementation should significantly mitigate this issue.
- This cause of variability is excluded from most of the analysis – noted where included.





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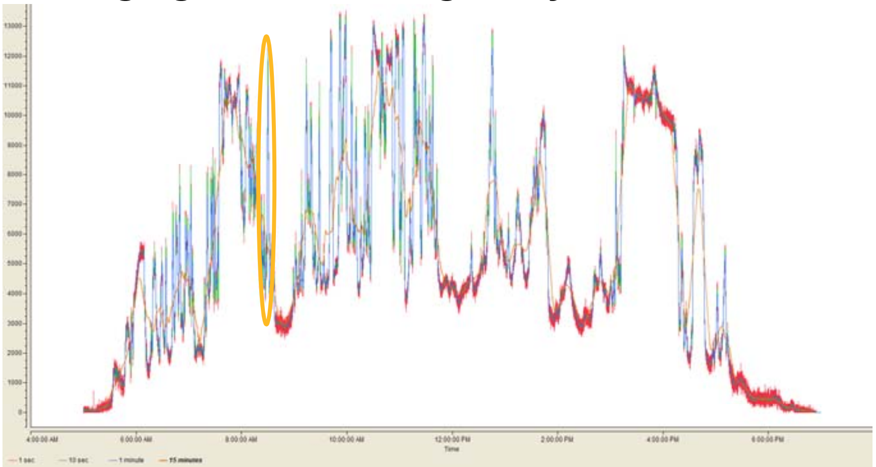
Averaging Interval – Single Day



Day with highest 10-sec maximum variability

Red = 1 sec, Green = 10 sec, Blue = 1 minute, Orange = 15 min

Except for 1 sec data, all are centered moving averages.

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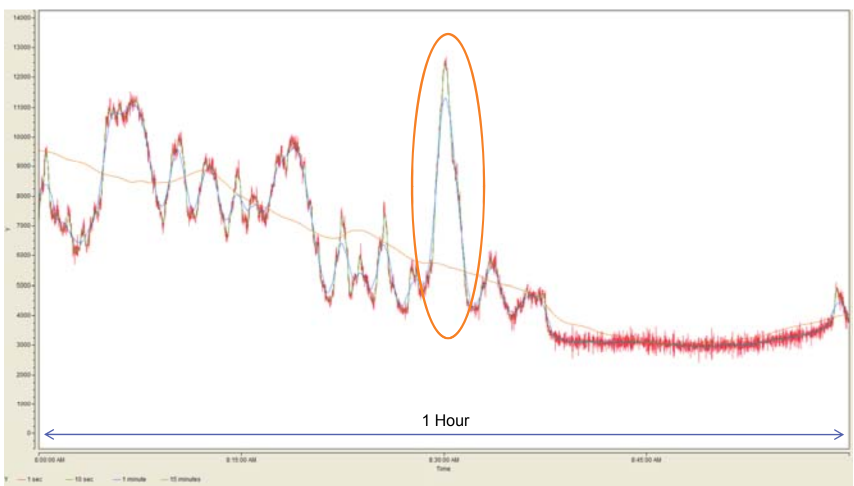
Averaging Interval – Single Day



Noise in 1-second data is a data acquisition artifact (pulse meter)

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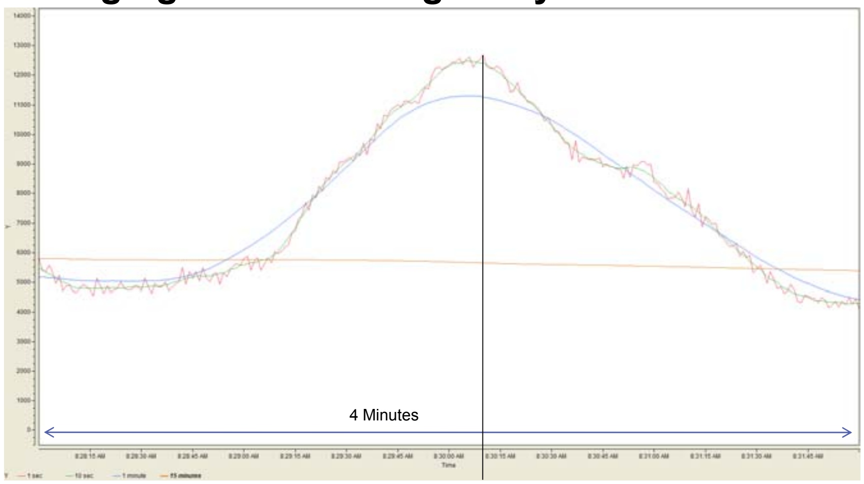
Averaging Interval – Single Day



- 1 minute data captures 80% of deviation from the long term trend even in this very extreme event.
- 10 second data captures 97% of deviation.
- 1 second data deviation from 10-second trend is at least partially pulse count noise.

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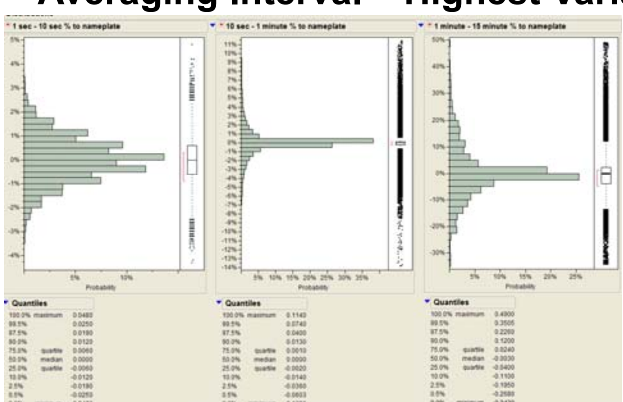
Averaging Interval – Highest Variability Day



Distributions show the difference between the shorter interval data, and the longer interval trend.

Interval to Trend	95% within	All
1 sec to 10 sec	+/- 2%	+/- 5%
10 sec to 1 min	+/- 4%	+11% / -14%
1 min to 15 min	+/- 20%	+ 50% / -34%

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Data Intervals - Conclusion

- One second resolution data may not be required to characterize variability of 10 MW+ plants.
- One minute data is very useful for some purposes since it is much easier to handle and analyze, but it seems to underestimate variability in extreme events.
- Use of ten-second data is recommended where it is important that short-term transients are captured completely.
- Ten second data does not adequately characterize rapid changes in irradiance measured at a single point. This also likely holds for smaller PV arrays which can be approximated as a point.
- 15 minute data misses large, short interval transients.

Future Work:

- Verify relationship between 1 sec and 10 sec data at large PV site with better data acquisition.
- Extend this type of analysis to more days – not just one, extreme day.
- Data interval selection should comprehend what is relevant to system operations. In other words, do transients that last 1 second matter? 10 seconds? 1 minute?

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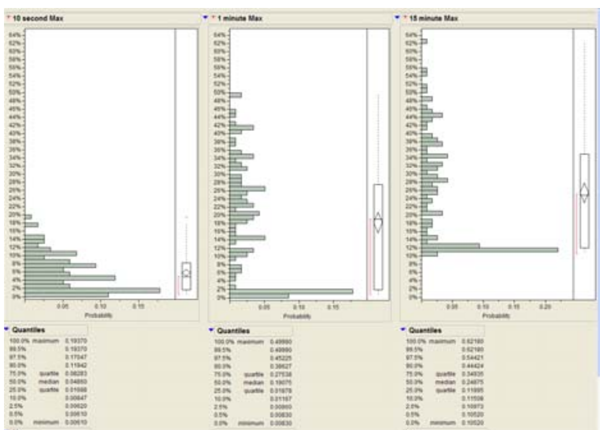
Distribution of Maximum Variability



This shows the distribution of the **largest** absolute change between periods as % of AC nameplate, on a given day, for all days analyzed.

For 10-second data, the data point for a day is the single largest change between the 4320 intervals in that day.

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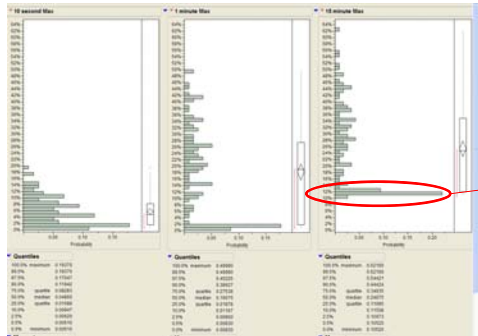
Distribution of Maximum Variability – All Days



Note floor on 15 minute data.10-13% in 15 minutes is max change on a clear day – driven by sunrise or sunset.

Averaging Interval	90% of days (108 days)	10% of days (12 days)
10 second max	<12% (1.2% / sec, sustained)	12% - 19%
1 minute max	< 39% (0.65% / sec, sustained)	39% - 50%
15 minute max	< 44% (2.9% / min, sustained)	44% - 62%

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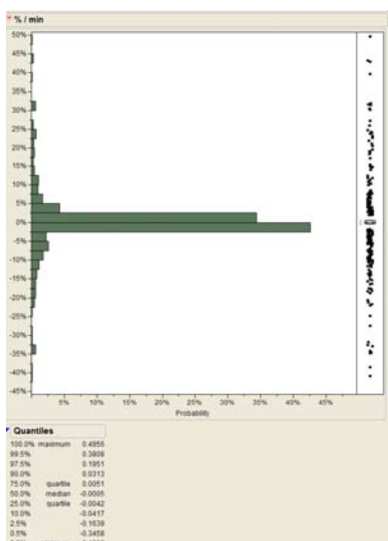
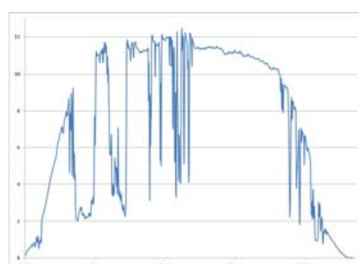
Distribution Within A Highly Variable Day





Day with largest 1-minute interval change

Prob. of change between 1-min intervals	
80% of all intervals between	-4% & +3%
95% of all intervals between	-16% & +20%
99% of all intervals between	-35% & +38%

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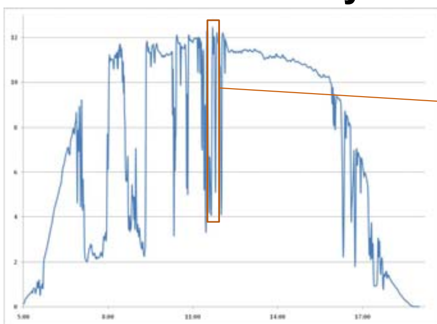
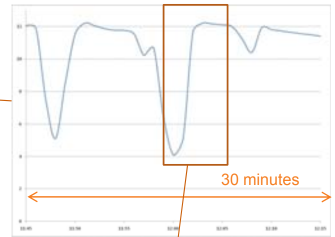
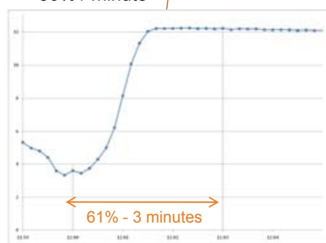
Maximum Variability Snapshot





50% / minute



Peak 1-minute change (12:01 – 12:02) of all days
(1 of 100,800 intervals)

A Few Points:

- **A "spiky looking" graph can be misleading.**

Even large, rapid changes occur over a minute or two, not in "a second" as has been stated.

Not readily apparent from visual inspection of a plot spanning 12 hours!

- **No operational issues**: the utility has investigated, and has not found, any operational issues related to this site.

- **This system is "high penetration"** relative to the distribution system capacity (as defined by DOE, "high penetration" PV is >30% peak on peak).

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Variability Occurrence - Conclusions

- Approximately 1/3 of days are clear and cloudless during these 4 months.

- Remaining 2/3 have a wide spread of variability – long, flat tails in distribution.

- These observations may not be generalizable - obviously, results will vary for different seasons and locations.

- Reporting the maximum change between intervals can be misleading, because this is an by definition a statistical outlier – especially an issue as intervals become shorter.

- It is also misleading to report variability over one interval in the same units as another interval.

For instance, while it may be tempting to report a measured change of 10% in 10 seconds as 60% / minute, this is incorrect, because the former value is a nearly instantaneous maximum and not sustained.

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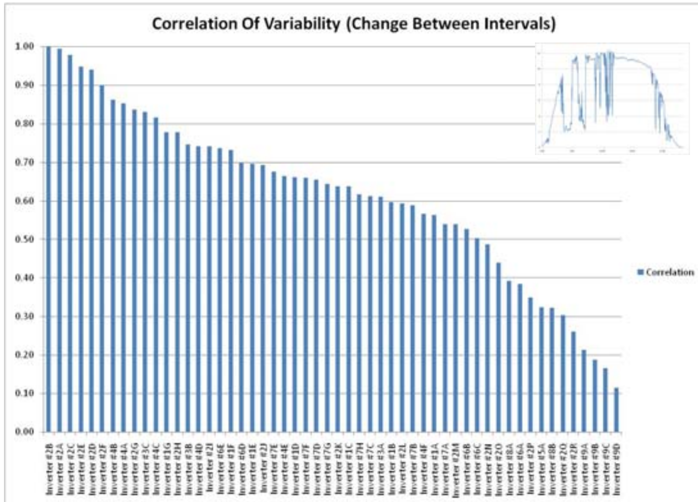
How Does Variability Scale?



Ordered Correlation of **changes** in 1-minute output across inverters
Reference is median peak variability inverter for this day

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How Does Variability Scale?

Maximum 1-minute change, on the highest 1-minute variability day

Single-Point Irradiance Sensors

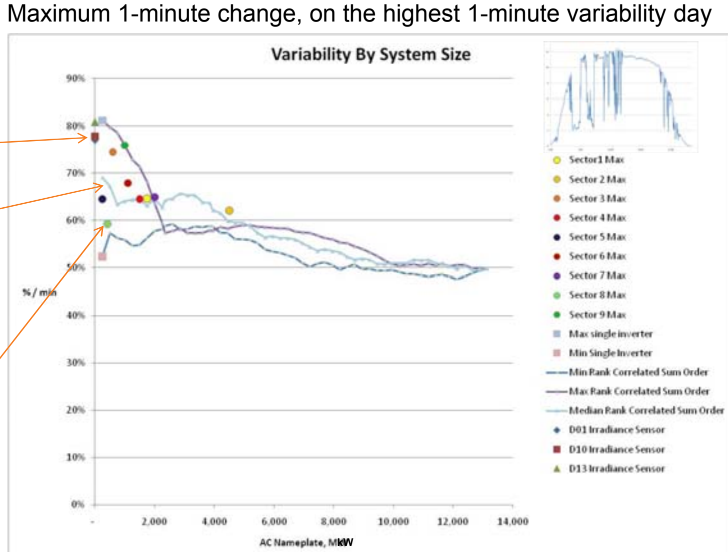
Lines:

Several alternate sum orders, where order is determined by ranked correlation starting with the highest, median, and lowest peak variability single inverter respectively.

Large Data Points:

Contiguous plant sectors or single inverters of note.

Sector 1 is single-axis tracking. All others are tilted single axis.



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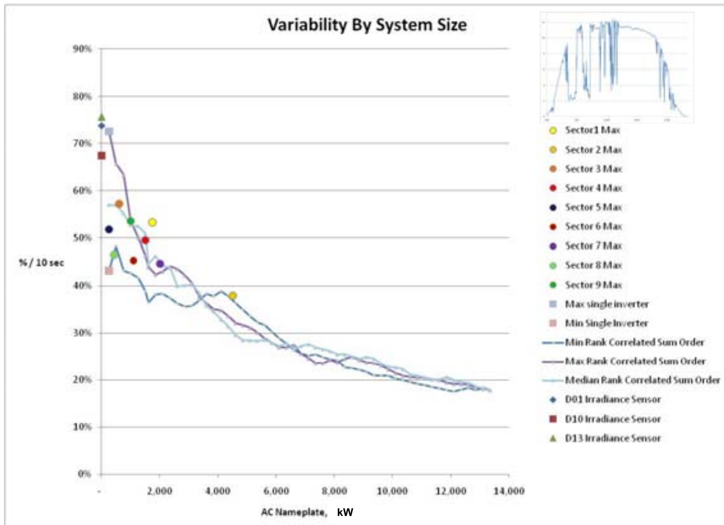
How Does Variability Scale?

Maximum 10 second change, on the highest 1-minute variability day



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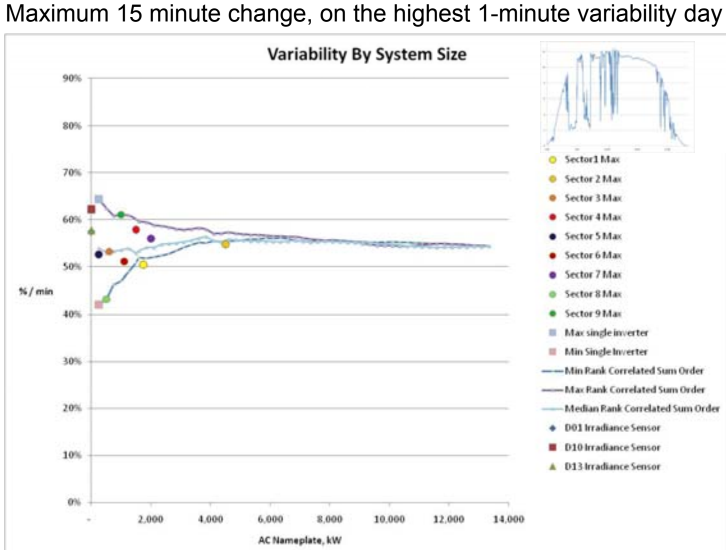
How Does Variability Scale?

Maximum 15 minute change, on the highest 1-minute variability day



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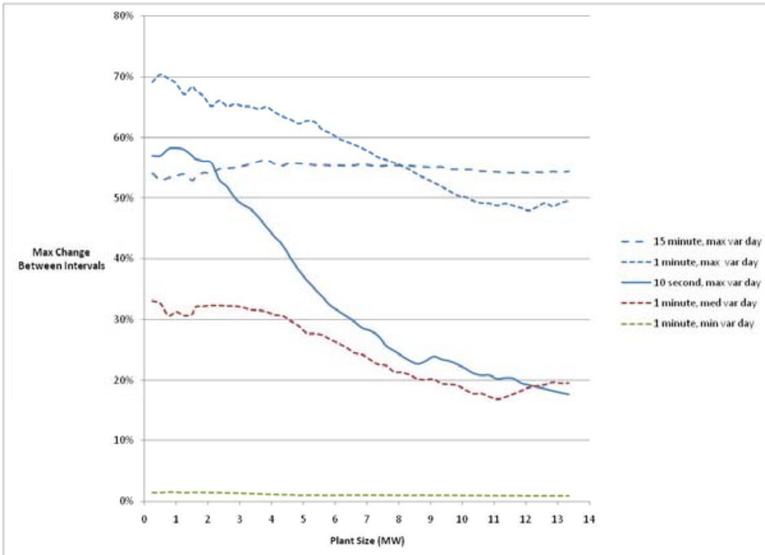
22

How Does Variability Scale?



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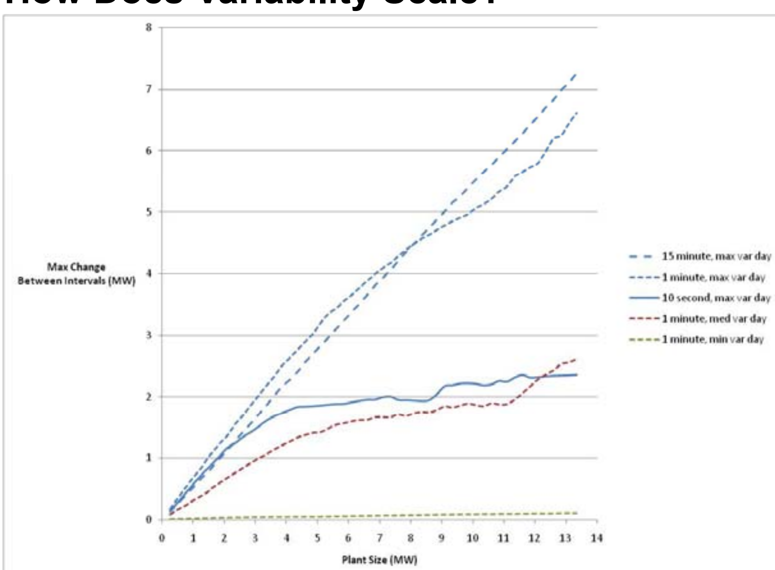
23

How Does Variability Scale?



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Variability Comparisons – Scale Matters!

Is CSP really smoother?

A few factors:

- **Thermal mass -** commonly cited
- **Scale** - CSP plant shown is *6X* size of PV plant
- **Plant Operations** - CSP operators often actively control plant output to avoid transients which can damage the equipment

What is the relative contribution of these factors?

Similar questions pertain to comparisons with wind generation.

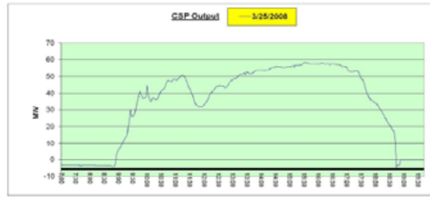

Figure 2.10: Parabolic trough CSP plant on a partly-cloudy day (Sampling time of 10 sec.)

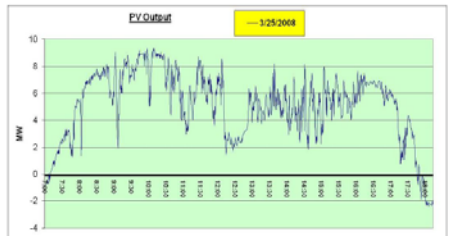

Figure 2.12: PV Plant output on a partly-cloudy day (Sampling time 10 seconds)

Figures from NERC Special Report: Accommodating High Levels of Variable Generation

Variability Scale – Conclusions*

- **Mitigation of variability with geographical diversity depends strongly on the time interval considered and is significant. At this scale (teens of MW), maximum daily variability (%):**
  - Is constant with size on a 15 min basis
  - Modestly decreases with size on a 1 min basis ~35% reduction versus point measurement.
  - Strongly decreases with size on a 10 sec basis – ~70% reduction versus point measurement.
- **For a given day and location, the maximum variability of a "system" of a given nameplate rating can vary widely on a percentage basis, especially for small systems. Contributing factors include:**
- Sum order – Whether it is physically contiguous; aspect ratio; orientation relative to cloud movement.
- Specific variations in cloud patterns relative to location non-uniform, 2D effects of small clouds.
- Varying DC ratings of inverter blocks, all of which have the same nominal AC nameplate.
- **Relatively minor sources of variance may appear as large differences on a % per interval basis** which will make it difficult to draw meaningful conclusions about larger systems. The differences are small on a kW / interval basis for small systems.

* For the analyzed data set

Variability Scale - Conclusions

• **Variability of even a relatively small PV block (250 kW) is, in general, significantly lower than single-point irradiance measurements at 1 minute intervals and below.**

Use of a single point irradiance measurement to estimate the short-interval variability of commercial and utility scale PV systems will likely significantly over predict actual variability.

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What's Next?

• Continue to develop understanding of how variability scales with system size, and geographical dispersion, for different locations and system types.

• Determine what data intervals are most critical and work to standardize.

• Develop modeling tools to study the impact of PV system dynamics on the utility system – both distribution and transmission.

• Develop appropriate, consistent interconnection requirements to ensure that PV systems do not needlessly contribute instability in the event of a fault.

• Develop forecasting methods

SunPower is committed to participating in collaborative activities to get this done!

• NERC IVGTF participant
• WECC PV Integration Task Force member
• DOE Solar Vision 2030 Study participant

• **And of course, honored to be with you here today!**

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www.sunpowercorp.com

Quantifying PV Output Variability

Thomas E. Hoff and Richard Perez
Clean Power Research
www.cleanpower.com

Utility-scale PV Variability Workshop
October 7, 2009

CLEAN POWER® RESEARCH

NYSERDA
New York State Energy Research and Development Authority

Why This Topic is Important to Utilities

System Planning

Maximizing the benefits while minimizing grid impacts of PV requires utilities to influence where PV systems are installed

System Operation

Optimize utility system operation once systems are installed requires the ability to forecast PV variability

Intermittency Questions

1. What is the effect of short-term output variability?

2. What needs to be done to forecast short-term output variability?

Question #1

What is the effect of short-term output variability?

Objective

Quantify relative power output variability for a fleet of identical PV systems

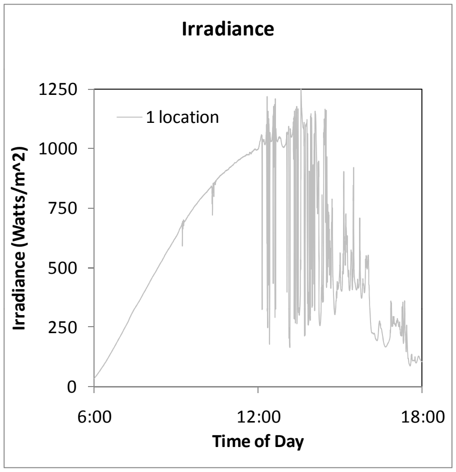
Key Findings

Relative Output Variability is based on:

1. Number of PV systems
2. Dispersion Factor

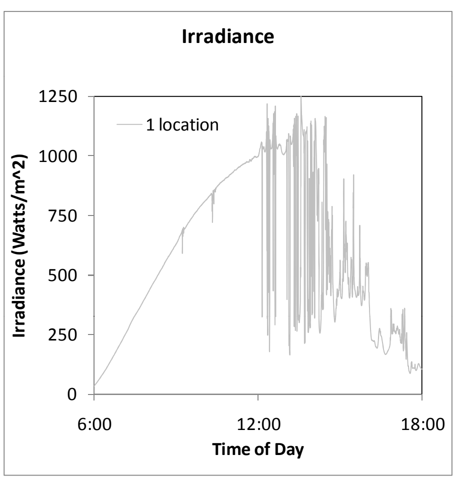
Relative Output Variability
Output variability for fleet / Output variability at single location

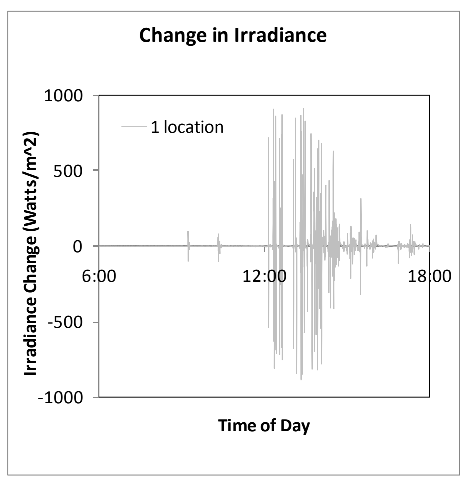
What is Meant by Variability?



Relative Output Variability
Output variability for fleet / Output variability at single location

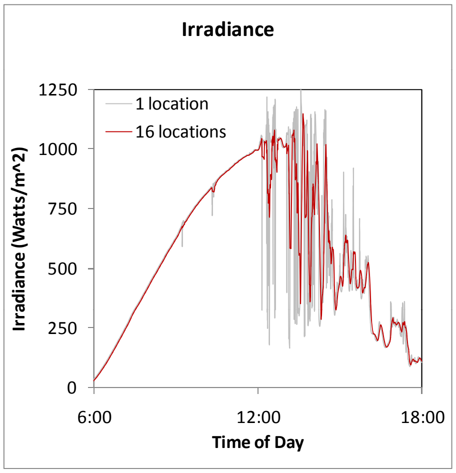
What is Meant by Variability?

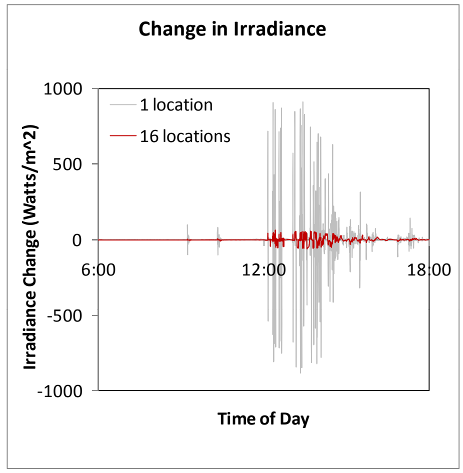




Relative Output Variability
Output variability for fleet / Output variability at single location

How Number of Systems Affects Variability





Relative Output Variability
Output variability for fleet / Output variability at single location

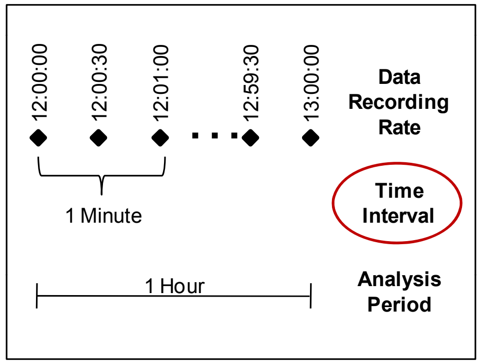
What is Dispersion Factor

- Dispersion Factor is the number of Time Intervals for a cloud to pass across the distance of the entire PV Fleet

Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

What is Time Interval?

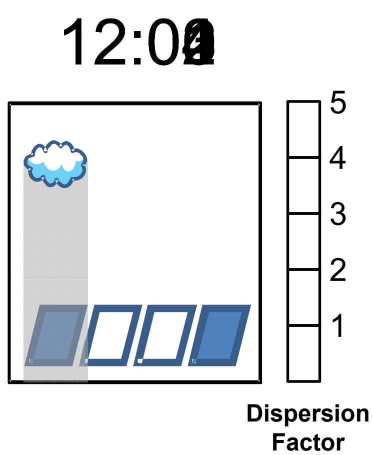


Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

Dispersion Factor For Moderate Cloud Transit Speed

Moderate Cloud Transit Speed
(Dispersion Factor = 4)

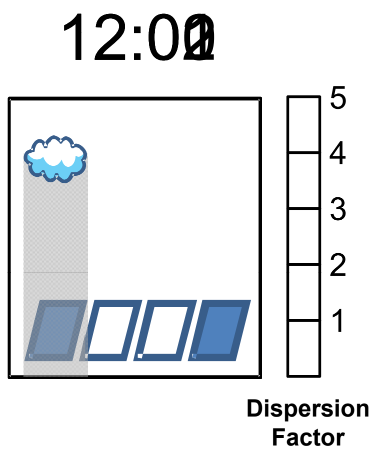


Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

Dispersion Factor

Fast Cloud Transit Speed
(Dispersion Factor = 2)



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

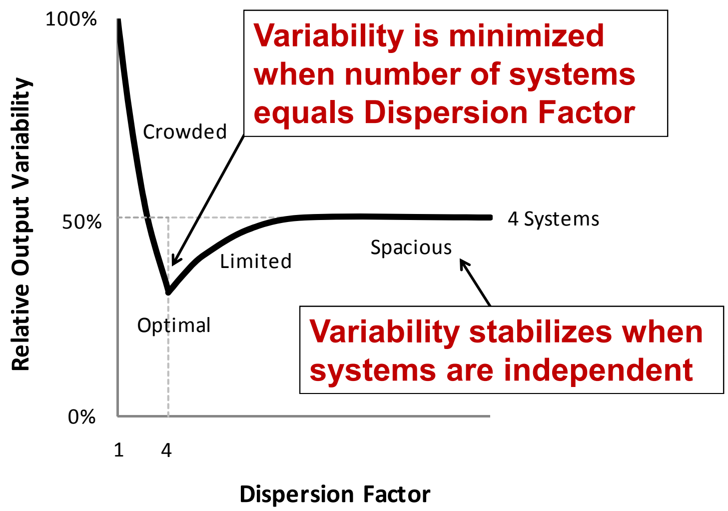
Model Results Categorized in 4 Regions

Crowded	Number of Systems > *Dispersion Factor*
Optimal (Point)	Number of Systems = *Dispersion Factor*
Limited	Number of Systems < *Dispersion Factor*
Spacious	Number of Systems << *Dispersion Factor*

Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

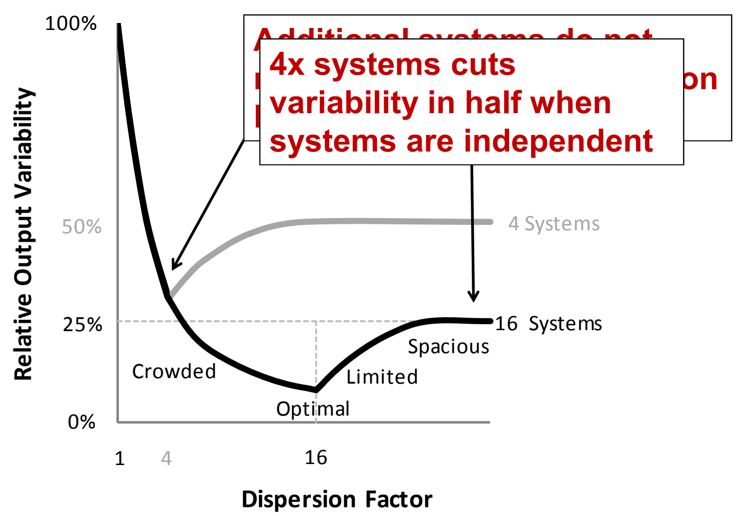
Relative Output Variability: 4 Systems



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

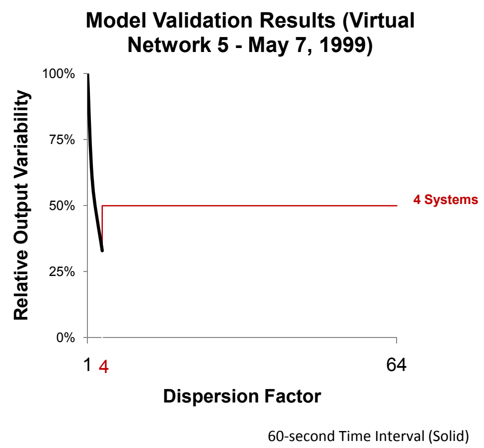
Relative Output Variability: 16 Systems



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

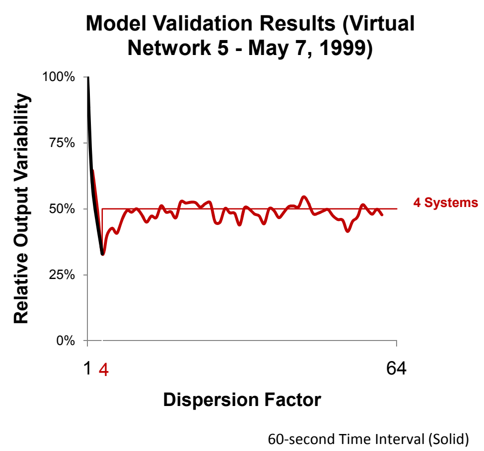
Validation: Construct Model for 4 Systems



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

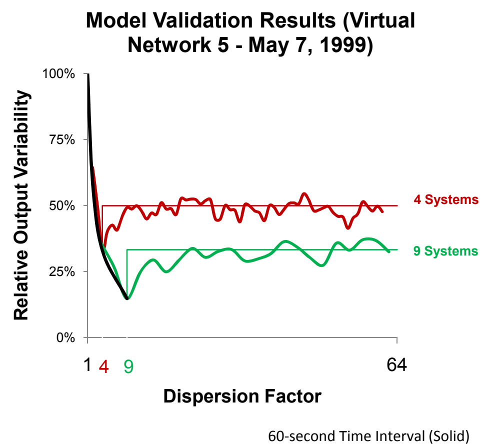
Add Measured Data



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

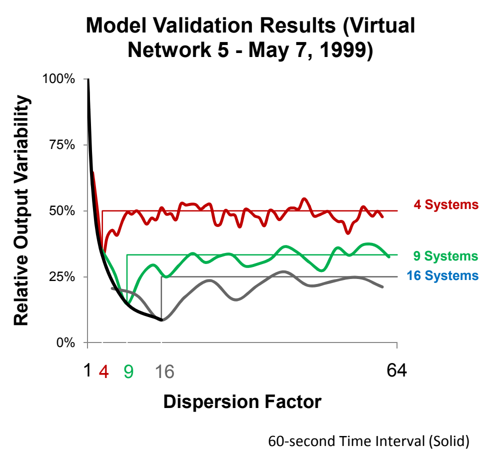
Repeat for 9 Systems



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

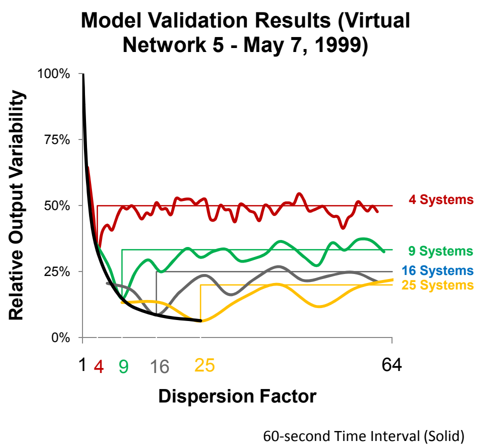
Repeat 16 Systems



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

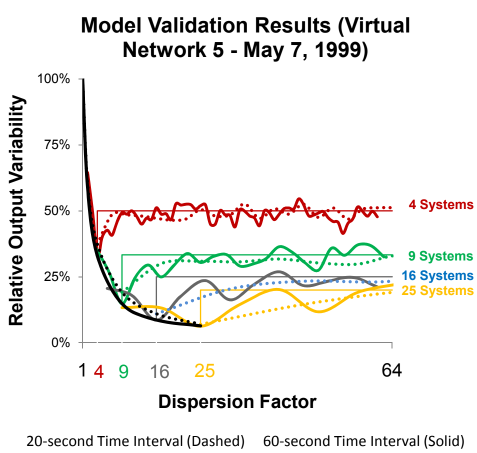
Repeat for 25 Systems



Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

Repeat w/ 20 Second Time Interval

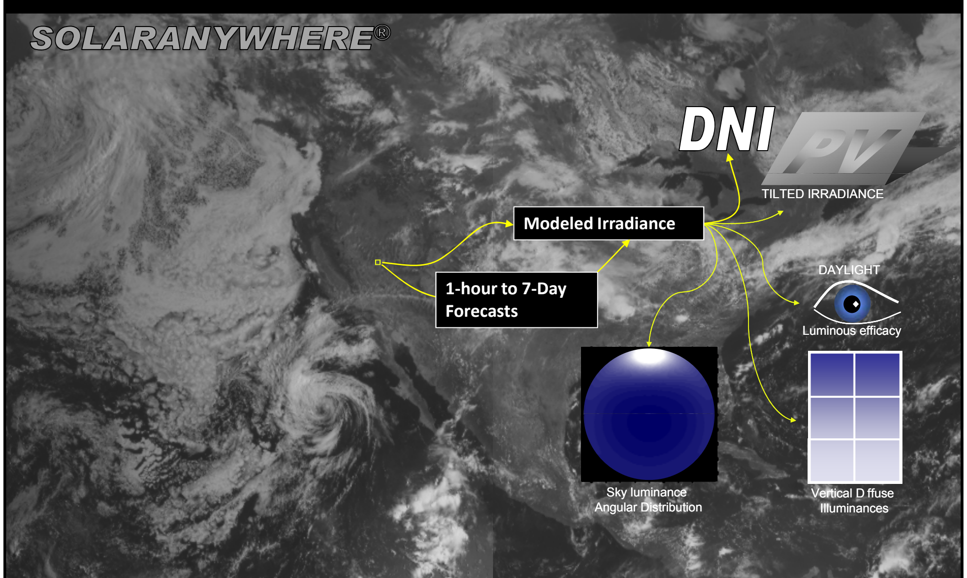


Relative Output Variability
Output variability for fleet / Output variability at single location

Dispersion Factor
Number of Time Intervals for cloud to pass across the PV Fleet

Question #2

What needs to be done to forecast short-term output variability?



Current-to-5 hours
CLOUD MOTION

Patterned after Lorenz et al.

© Richard Perez et al.

How This Relates To Output Variability

Relative Output Variability is based on:

1. Number of PV systems

2. Dispersion Factor

   Dispersion Factor is the number of Time Intervals for a cloud to pass across the distance of the entire PV Fleet

Conclusions: Relative Output Variability

- Can be quantified based on the number of PV systems and the Dispersion Factor
- Equals inverse of the square root of the number of systems for dispersed PV systems
- Can be minimized for optimally-spaced PV systems for a given Cloud Transit Speed

Next Steps

- Further model validation
- Extend model to arbitrary fleet configuration
- Integrate with SolarAnywhere® (www.solaranywhere.com) forecasting

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RESEARCH

Characterization of short-term PV variability for large PV systems

October 7, 2009

Joshua Stein Ph.D.
Principal Member of Technical Staff
Sandia National Laboratories

Utility Wind Integration Group: Utility-Scale PV Integration Workshop
Cedar Rapids, IA

How Important is Variability?

- Utilities are in the business of servicing a variable load.
- Ancillary services provide variability control
  - Voltage Control (seconds) [VAR support]
  - Regulation (~ 1 min) [online AGC*]
  - Spinning Reserve (seconds to <10 min) [online]
  - Supplemental Reserve (<10 min) [offline but staffed]
  - Replacement Reserve (<30 min) [offline but staffed]
  - Planning and forecasting (hours – days)

* Automatic generation control

When is Variability Important?

- Variability is only important if it significantly adds to the net load variability.
  net load = load – non-dispatchable generation
- Impact of variability depends on where the PV system is connected to the grid, penetration level, types of load serviced, and available generation options.
- On clear days, solar (diurnal) variability can help utilities serve peak loads.

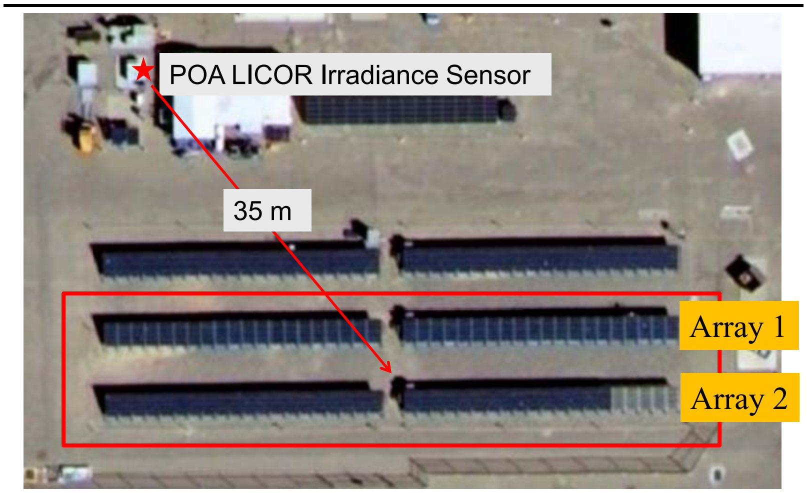
Presentation Outline

- Part 1: Discuss differences between irradiance and PV power.
  - Identify factors affecting power variability for clear and partly cloudy days
- Part 2: Explore measures of variability
- Part 3: Present variability analysis results for existing PV systems.
  - Small (30kW)
  - Large (many MWs)

Part 1

- The difference between irradiance and PV output power…

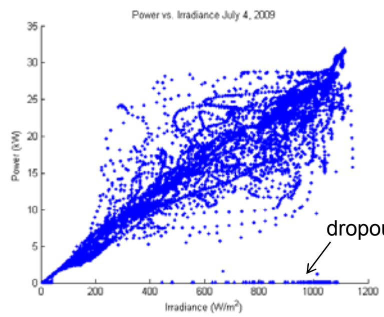
Sandia 30 kW Array (1-Sec Data)

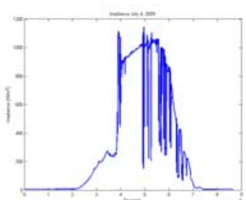


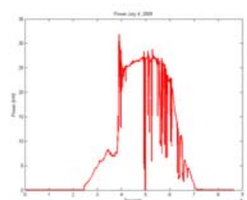
30 kW latitude tilt array

Difference Between Irradiance and PV Power

- PV power output is not a simple linear function of irradiance, especially on partly cloudy days.
  - Spatial-temporal effects
  - Inverter effects
  - Incident angle effects
  - Temperature effects

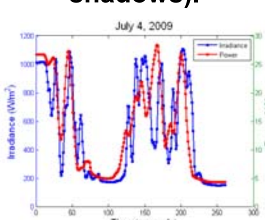


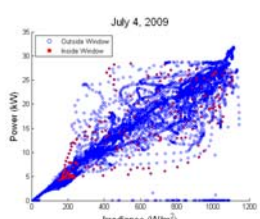


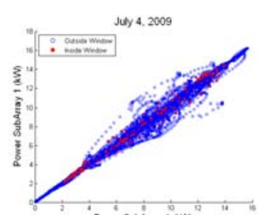


Spatial-Temporal Effects

- Short periods (5-20 seconds) of non-linear excursion are likely due to spatially- heterogeneous irradiance over distances as small as 30-50 m (slow moving, sharp shadows).



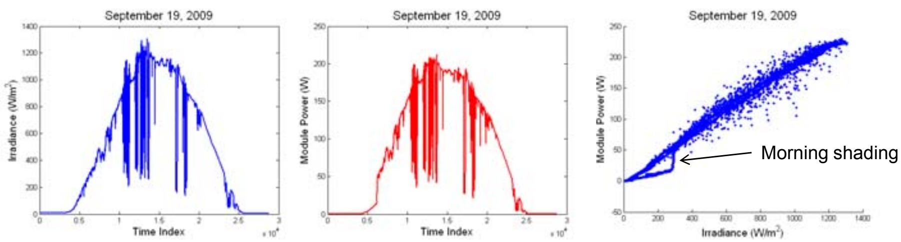




- Sandia is developing a wireless 1-sec irradiance sensor network
  - Deployments in: Albuquerque, NM, Lanai, HI, and other sites in the near future

Inverter Effects

- Array + Inverters may not convert 100% of available irradiance.
  - MPPT issues, IEEE 1547 dropouts, inverter “clipping”, partial shading, … etc.
- Single 200 W module with micro-inverter

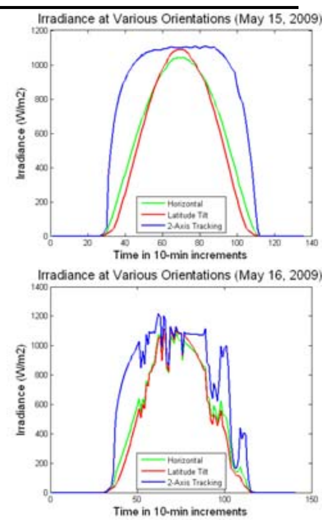


- Scatter indicates that inverter causes some of the variation between irradiance and A/C power.

Module located 5 m from irradiance sensor (2-sec data frequency).

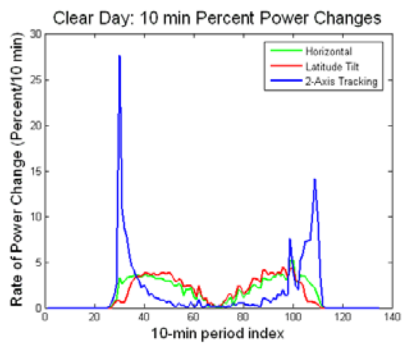
Incident Angle Effects (1)

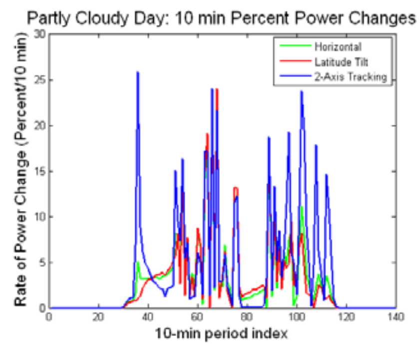
- Global irradiance is measured on a horizontal plane
- PV arrays are either fixed or tracked.
- PV output is proportional to irradiance on the plane of array
- Tracked systems can harvest more energy than fixed tilt systems and therefore have greater potential for larger power changes from passing clouds.



Incident Angle Effects (2)

- Power changes will be greater with tracked PV systems than for fixed tilt systems at the beginning and end of the day.





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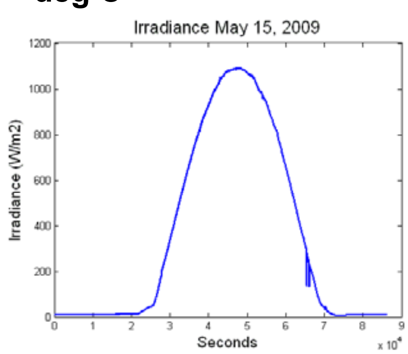
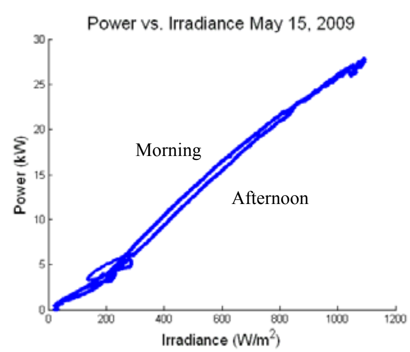
Temperature Effects

- PV efficiency decreases as temperature increases.
- May 15, 2009, air temp increased all day from 16 to 30 deg C





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Part 2

- **Measures of variability…**

How to Characterize PV Output Variability?

- **Examine the distribution of irradiance and power changes ('ramps') over a fixed time interval (e.g., 1-sec, 1-min, 10-min, etc.) (e.g., Wan and Bucaneg, 2002)**
- **Step Changes: $P_t - P_{t+k}$, where t is time (1 to nt) and k is fixed time interval**
- **Ramping Rates:**
  1) **rate of change of moving average**
  2) **least squares linear regression slope of $P_{t \rightarrow t+k}$**

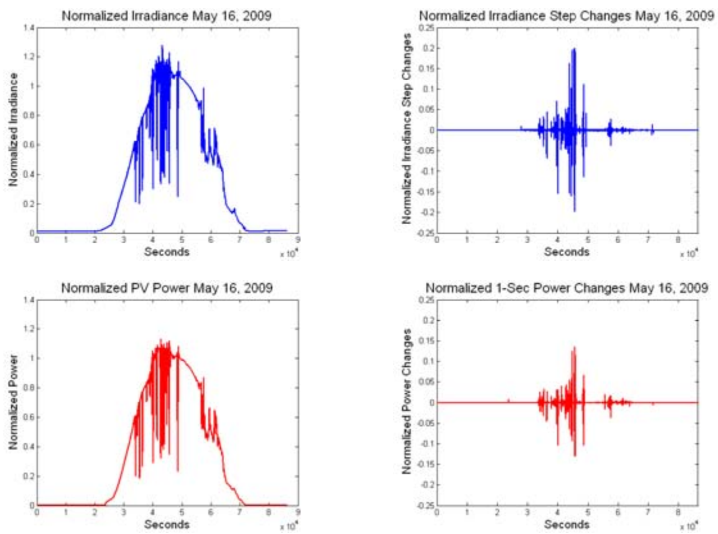
Steps for Characterizing Variability

- Normalize irradiance and power
- Calculate ramp rates for fixed time intervals (e.g., 1-sec, 10-sec, 1-min, 10-min, etc.). (absolute value).
- Compare distributions of ramp rates for different unit sizes (irradiance sensor, single inverter, multiple inverters, etc.)

Part 3

- Analysis of PV output variability for two existing PV systems.
  - Small system (30kW)
  - Very large system (many MWs)

Example of PV Output Variability Reduction for 30 kW Latitude-Tilt System



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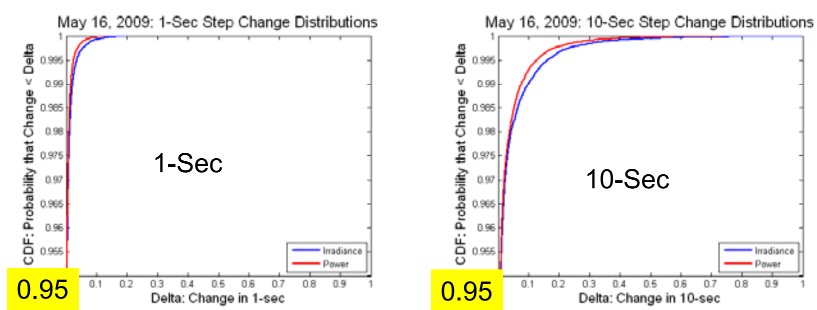
How Much Reduction?



- **For small systems ramp rate reduction is measurable for intervals between 1-10 sec but essentially disappears when 1-min ramps are analyzed.**

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Variability Analysis of Large PV Plant Output

- PV plant is multi-megawatt in capacity.
- 1-sec irradiance and power output has been normalized.
- Explore variability reduction with increasing plant size.
  - Irradiance (cm^2)
  - Single inverter output (hundreds of kWs)
  - Half of plant's inverters (multi MW)
  - Total plant output (multi MW x 2)

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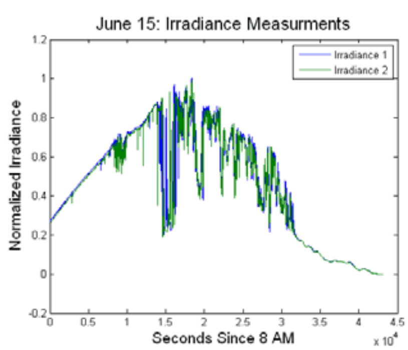
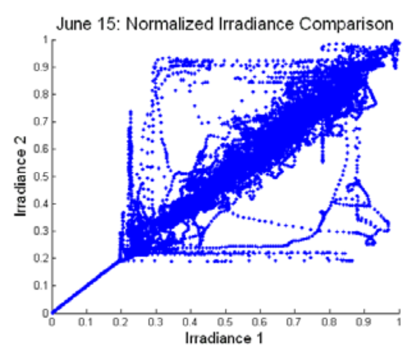
Irradiance Measurements

- June 15, 2009: Partially cloudy day selected for analysis
- Two irradiance measurements (opposite ends of plant)
- Irradiance is normalized.





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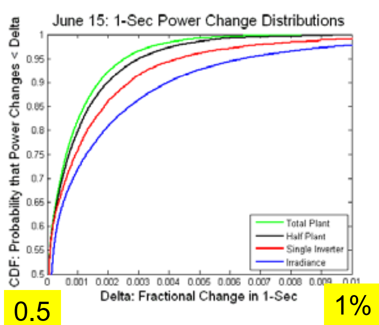
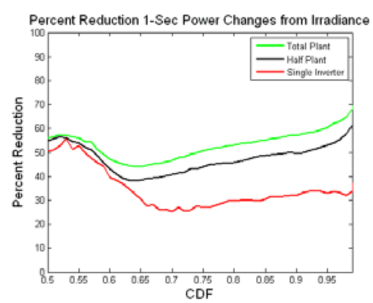
Analysis Method

- Compare distributions of power changes for different combinations of unit sizes and time intervals
  - Irradiance → Single Inverter → Half Plant → Whole Plant.
  - 1 sec → 10 sec → 1 min → 10 min

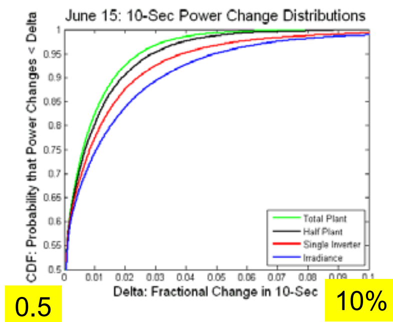
1-Sec Changes

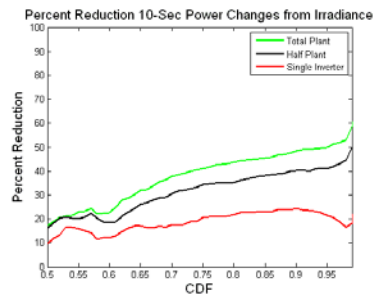




- 1-Sec power variability relative to irradiance decreases as a function of unit size.
- Single Inverter = ~30% reduction of large ramps
- Total Plant = >60% reduction of large ramps

10-Sec Changes





- 10-Sec power variability relative to irradiance decreases as a function of unit size.
- Single Inverter = ~20% reduction of large ramps
- Total Plant = >40% reduction of large ramps

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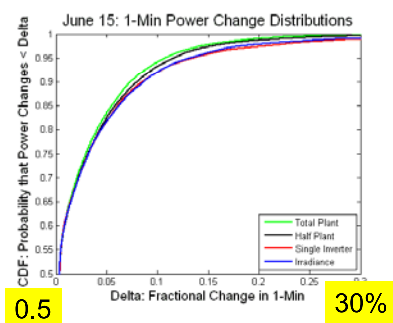
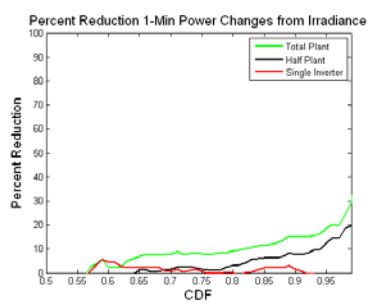
1-Min Changes





- At 1-Min, variability difference between unit sizes is not as significant as for shorter time intervals.
- Single Inverter = ~5% reduction of large ramps
- Total Plant = >10% reduction of large ramps

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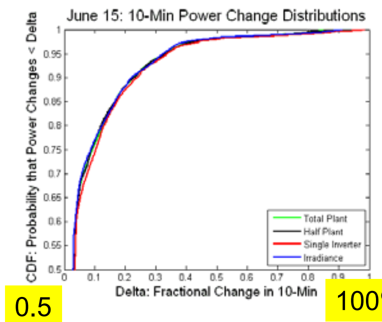
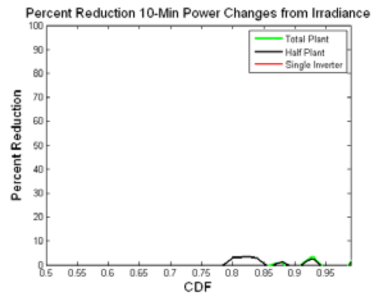
10-Min Changes





- **10-min power variability is not influenced by unit size and is essentially equivalent to 10-min irradiance variability.**

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Summary

- **Variability of PV power output is not a simple linear function of variability in plane-of-array point irradiance, especially on partly cloudy days.**
- **Preliminary results suggest that >10 min variability of multi-MW PV plants can be approximated by the variability of point irradiance averaged over a similar time window.**
- **Short term (<10 min) variability is influenced by the size of the plant, with variability decreasing with increasing size.**

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nvenergy.com

October 2009

The Need for PV Output Data

Travis Johnson, PE

Manager, Substation Construction & Maintenance
NV Energy

❖What is the Need?

- There is still much to be learned about large scale penetration of PV into the utility grid.
- There is **fear** among utility leadership that variability will cause problems including:

  System Stability, Flicker, Voltage Regulation, CPS2 (ACE) Violations, Possible Increase in Required Reserves
- These fears must be addressed to remove **arbitrary caps** on PV deployment.
- How can we address the fear?
- We need DATA!

FEAR!

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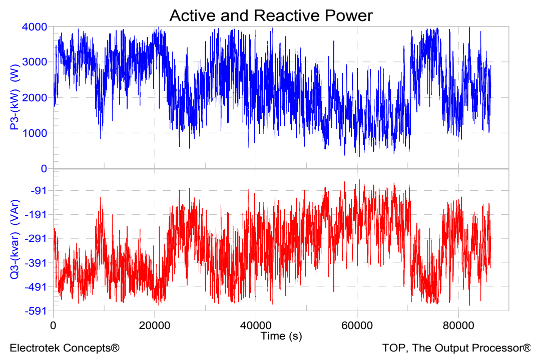
❖What Type of Data is Needed?

- Frequency (for high penetration systems)
- Irradiance (to understand ramp rates & variability issue)
- **Watts**
- **Vars**
- Voltage



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❖What Resolution is Needed?

- 1 second data is best
- 5 second data is good
- Dead-band settings can limit file size and still provide adequate resolution
- Interval can be a function of array size (large arrays respond more slowly than small arrays)

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❖What are we Willing to Share?

- PV Variability Ad Hoc Group Developed a Metadata Standard
- Standard addressed “metadata” of PV sites more than the actual “data”
- Standard was divided into 3 groups of metadata:
- **1) Public Data**
  - DC Plant Rating (STC DC Rating)
  - Type (if various technology, specify splits - mono-crystalline, thin film, etc.)
  - Rating of panels
  - Number of inverters
  - Location (latitude, longitude, and elevation) of site
  - Sampling rate & recording rate
  - Irradiance sensor type, orientation, and number
  - Power system voltage at point of delivery (or interconnection)

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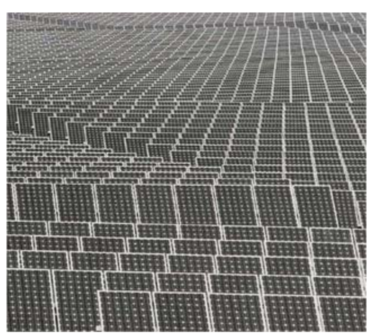
❖What are we Willing to Share?

- PV Variability Ad Hoc Group Developed a Metadata Standard
- Standard addressed “metadata” of PV sites more than the actual “data”
- Standard was divided into 3 groups of metadata:
- **2) Optional Public Data**
  - Array tilt angle and azimuth
  - Spacing of module rows
  - Tracking characteristics of array



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❖What are we Willing to Share?

- PV Variability Ad Hoc Group Developed a Metadata Standard
- Standard addressed “metadata” of PV sites more than the actual “data”
- Standard was divided into 3 groups of metadata:
- **3) Private Data (never shared)**
  - Inverter logic/control/programming
  - Design specifics (wire size, structure type, civil design)
  - Levelized cost of energy (LCOE)
  - Name of site owner
  - Street address of project
  - Cost of system components
  - Manufacturer
  - Date of installation
  - Price of installation

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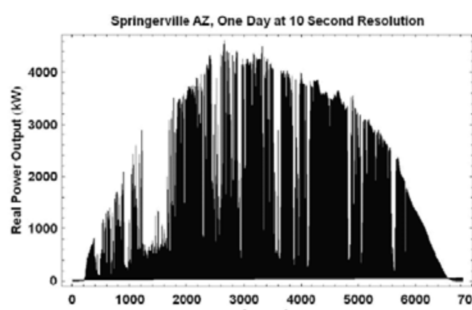
❖What are we Willing to Share?

- **What Was Missing? Data!!**
  - Watts
  - Vars
  - Irradiance
  - Frequency
  - Voltage



- The standard simply addressed that this data is considered confidential and may be addressed on a case by case basis.
- **It <u>also states</u> “sharing monitored data with third parties, such as national laboratories, research organizations, and industry partners, may result in benefits that accrue to the industry as a whole.”**

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❖Who Will Use the Data?

- Utilities only?
- Industry?
- National Labs?
- Industry Partner?

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NREL National Renewable Energy Laboratory
Innovation for Our Future

EPRI
Electric Power Research Institute

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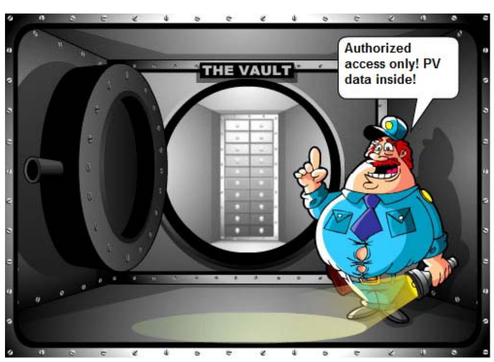
❖Where Should the Data Reside?

- Secure site?
- Data warehouse?
  - NDA required?
  - Other conditions?



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❖Data Set

- Flat ASCII file (comma delimiter, etc.)
- Excel not really a good option
- Files should be daily – one day per file.
- Time zone issues – need proper time stamp (GMT offset required)

Less desirable flat file formats.

❖Data Set

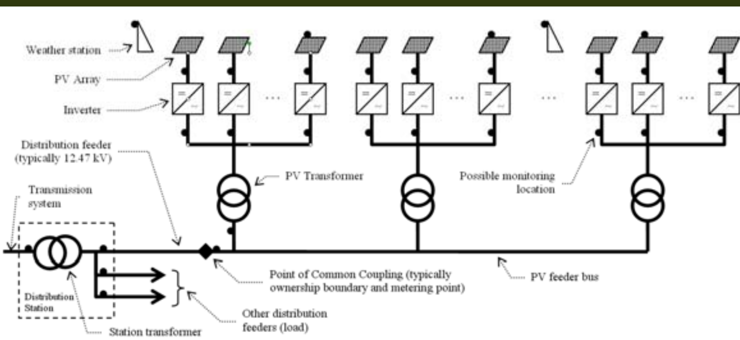

Figure 1 – Distribution-connected utility-scale PV system

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	YYYY	MM	DD	HH	MM	SS	Freq_Hz	PCC_Kw	PCC_Kvar	Inv1T1_KW	Inv1T1_kVar	Inv2T1_KW	Inv2T1_kVar	Inv2T3_kV	Inv3T3_KW		PCCVa_kV	PCCVb_kV	PCCVc_kV	POAeast_Wm2	POAWest_wm2	POANorth_wm2	POASouth_	GHIEast_\	DifEast_Wm2	
2	2009	7	4	0	0	1	60	9.391	9.437	6.037	3.462	9.347	7.797	8.159	1.146		7.2	7.2	7.2	100	200	300	500	600	50	
3	2009	7	4	0	0	2	59.999	4.809	5.235	4.921	4.04	7.765	0.827	3.253	0.008		7.204	7.198	7.196	100	200	300	500	600	50	
4	2009	7	4	0	0	3	59.994	9.934	0.553	2.579	7.61	8.269	2.795	1.63	1.062		7.206	7.202	7.193	100	200	300	500	600	50	
5	2009	7	4	0	0	4	59.993	7.424	4.061	3.272	3.905	2.503	6.17	8.96	6.863		7.203	7.198	7.189	100	200	300	500	600	50	
6	2009	7	4	0	0	5	59.989	7.385	0.66	4.462	1.941	6.623	2.849	0.857	8.814		7.198	7.195	7.188	100	200	300	500	600	50	
7	2009	7	4	0	0	6	59.989	7.26	0.319	4.701	5.891	9.646	9.189	6.13	6.847		7.203	7.193	7.189	100	200	300	500	600	50	
8	2009	7	4	0	0	7	59.984	6.793	9.991	5.184	8.787	7.472	7.076	3.332	8.777		7.206	7.191	7.193	100	200	300	500	600	50	
9	2009	7	4	0	0	8	59.984	3.89	1.935	4.301	2.009	5.726	9.863	2.267	1.555		7.206	7.193	7.192	100	200	300	500	600	50	
10	2009	7	4	0	0	9	59.987	9.515	4.208	3.743	6.239	8.481	2.659	9.717	1.688		7.201	7.196	7.192	100	200	300	500	600	50	
11	2009	7	4	0	0	10	59.991	8.772	9.409	1.956	2.441	7.44	3.433	4.208	1.45		7.201	7.196	7.193	100	200	300	500	600	50	
12	2009	7	4	0	0	11	59.986	3.987	4.962	0.085	2.021	5.028	3.433	2.186	2.111		7.204	7.193	7.195	100	200	300	500	600	50	
13	2009	7	4	0	0	12	59.988	6.481	7.773	2.812	9.801	6.261	7.271	7.122	1.379		7.202	7.194	7.193	100	200	300	500	600	50	
14	2009	7	4	0	0	13	59.993	3.371	0.103	4.792	0.536	2.848	8.302	3.408	8.985		7.203	7.193	7.194	100	200	300	500	600	50	
15	2009	7	4	0	0	14	59.989	3.93	5.665	9.178	2.638	7.157	8.255	3.602	4.49		7.204	7.194	7.198	100	200	300	500	600	50	
16	2009	7	4	0	0	15	59.992	4.209	1.732	4.561	9.343	6.921	4.613	4.852	9.637		7.204	7.19	7.199	100	200	300	500	600	50	

❖Data Set

YYYY	MM	DD	HH	MM	SS	Freq_Hz	PCC_Kw	PCC_Kvar	Inv1T1_KW	Inv1T1_kVar	Inv2T1_KW	Inv2T1_kVar	Inv2T3_kV	Inv3T3_KW	PCCVa_kV	PCCVb_kV	PCCVc_kV	POAeast_Wm2	POAWest_wm2	POANorth_wm2	POASouth_	GHEast_\	DifEast_Wm2
2009	7	4	0	0	1	60	9.391	9.437	6.037	3.462	9.347	7.797	8.159	1.146	7.2	7.2	7.2	100	200	300	500	600	50
2009	7	4	0	0	2	59.999	4.809	5.235	4.921	4.04	7.765	0.827	3.253	0.008	7.204	7.198	7.196	100	200	300	500	600	50
2009	7	4	0	0	3	59.994	9.934	0.553	2.579	7.61	8.269	2.795	1.63	1.062	7.205	7.202	7.193	100	200	300	500	600	50
2009	7	4	0	0	4	59.993	7.424	4.061	3.272	3.905	2.503	6.17	8.96	6.863	7.203	7.198	7.189	100	200	300	500	600	50
2009	7	4	0	0	5	59.989	7.385	0.66	4.462	1.941	6.623	2.849	0.857	8.814	7.198	7.195	7.188	100	200	300	500	600	50
2009	7	4	0	0	6	59.989	7.26	0.319	4.701	5.891	9.646	9.189	6.13	6.847	7.203	7.193	7.189	100	200	300	500	600	50
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2009	7	4	0	0	10	59.991	8.772	9.409	1.956	2.441	7.44	3.433	4.208	1.45	7.201	7.196	7.193	100	200	300	500	600	50
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2009	7	4	0	0	13	59.993	3.371	0.103	4.792	0.536	2.848	8.302	3.408	8.985	7.203	7.193	7.194	100	200	300	500	600	50
2009	7	4	0	0	14	59.989	3.93	5.665	9.178	2.638	7.157	8.255	3.602	4.49	7.204	7.194	7.198	100	200	300	500	600	50
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- ❖ **Column headers** (first row only), each string 12 characters or less.
- ❖ **Timestamp** format: YYYY, MM, DD, HH, MM, SS
- ❖ **Frequency**
- ❖ **Real and reactive power** (kW and KVar, 3 phase)
  - Total for the entire PV plant, <u>and</u>
  - At each inverter (desirable for selected large systems)
- ❖ For distribution-connected systems, **RMS voltage** (line-line or line-neutral, each phase)
  - At PCC or other PV feeder bus location (best), <u>or</u>
  - At terminals of two PV inverters connected to different transformers
- ❖ For transmission-connected systems, **RMS voltage** (line-line, positive sequence)
  - **At POI or high side of station transformer, <u>and</u>**
  - **At terminals of electrically closest and farthest inverter in the PV plant (desirable)**
- ❖ **Irradiance** - Plane of Array (POA) and Global Horizontal (GH) irradiance captured by each reference cell and pyranometer in the PV system. Column header (and possibly metadata as well) should indicate approximate location of sensors with respect to the PV array

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❖What Mechanism Will Make it Happen?

- ❖ How do we get there?
  - Need to finalize a “data” standard (quickly)
  - Should be assigned, not ad hoc group (too slow)
  - Needs to be compatible with PI Historian and other data historian software (flat file should be)

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❖What Mechanism Will Make it Happen?

- **Discussion:**
  - What model of data sharing is acceptable to manufacturers?
  - What is the preferred method for the labs?
  - What do utilities prefer?

- **Action Items:**
  - Close meeting with volunteer to set final format of data
  - Seek agreement between PV manufacturers to supply data to __________.

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