**Final Technical Report**

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## Executive Summary

The SunShot Initiative is focused on reducing cost to improve competitiveness with respect to other electricity generation options [1]. The goal of the Sandia Transmission Grid Integration (TGI) program is to reduce grid access barriers for solar generation. Sandia's three-year TGI work was divided into five objectives. These objectives, together with the high-level results of this project, are outlined below.

**Specify, validate, implement, and disseminate open electrical simulation models for transmission planning and interconnection studies**

SNL collaborated with members of the WECC Renewable Energy Modeling Task Force (REMTF) to develop generic electrical simulation models for utility-scale PV plants. These models were subjected to technical scrutiny by the WECC. These models are now publicly available to power system planners and renewable energy plant developers and are available in GE's PSLF®, Siemens PTI PSS®E, and PowerWorld.

**Benchmark and refine methods to estimate solar plant and fleet output**

We evaluated four different methods of estimating utility-scale PV plant variability given point sensor measurements. We found the most promising of these to be the Wavelet Variability Model (WVM). We refined, documented, and publically released the VWM code.

**Develop and demonstrate an advanced stochastic analysis tool to optimize system planning and operations for systems with high solar penetration**

We developed an advanced stochastic analysis tool for system planning and operations under conditions of high solar penetration. It is a stochastic production cost modeling tool with security-constrained economic dispatch and unit commitment. This tool is able to take into account not only the median solar forecast but a range of possible solar profiles when committing units for dispatch. We have called this tool PRESCIENT.

**Evaluate technical feasibility of high penetration solar scenarios with respect to small signal stability**

We have evaluated the WECC, both as it exists today and in a high solar penetration scenario, for small-signal stability. We found that high PV penetration has a negligible impact on the likelihood of instability due to small-signal oscillation in the Western Interconnect.

**Emerging standards and policies will appropriately take into account technical characteristics of solar generation**

Throughout this project we have provided technical recommendations and advocated for changes to IEEE Standard 1547 (P1547) to mandate voltage ride-through (VRF) and frequency ride-through (FRF) for distributed energy resources (DERs), including PV inverters. While the proposed VRT/FRT specifications have not been formally adopted in P1547, our technical engagement and advocacy has significantly raised awareness of this issue, and has made action much more likely.

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## Background

Sandia pursued a 3-year integrated program that started in fiscal year 2013, that incorporates elements of each of the Transmission Grid Integration (TGI) research areas: System Integration Study Template (SIST), Models and Tools Improvement (MATI), and Transmission Analysis and Transmission Alternatives ($TA^2$). Strategic stakeholder engagement and information dissemination are also an integral part of the proposed TGI activities, to ensure the broadest possible impact. The work plan is organized into four tasks: (1) Improve simulation models for solar generation interconnection and grid planning, (2) Improve methods and tools for the analysis of high penetration scenarios, (3) Evaluate the technical feasibility of high penetration solar deployment, and (4) Enhance critical stakeholder engagement to disseminate TGI information.

Sandia's TGI efforts addressed high-priority gaps and build on Sandia's unique expertise and prior accomplishments. In 2007, Sandia and the National Renewable Energy laboratory (NREL), working with and leading industry experts, completed the Renewables Systems Interconnection (RSI) study [2], which launched DOE's research activities on solar grid integration. Although the study was primarily focused on distribution-connected PV, some of the reports address transmission integration issues [2-7]. The first major DOE-sponsored grid integration initiative was the Solar Energy Grid Integration Systems (SEGIS) program, a concept developed and initially managed by Sandia [8-11]. The SEGIS program is now in its third round of public-private partnerships, and continues to be DOE's blueprint for technology development.

Large-scale integration studies such as the Western Wind and Solar Integration Study (WWSIS) [12] have helped identify technical challenges and solutions to large-scale wind and solar deployment. They have also refined grid integration study methods. Solar generation has been incorporated recently into those studies; however, the analysis was challenged by lack of knowledge about the output characteristics of large PV plants. Interest in PV transmission grid integration grew significantly, after the installation of the first transmission-connected PV plant in 2009. That year, Sandia, UVIG, NREL and SEPA hosted a seminal workshop Iowa hat propelled research efforts on large-scale PV grid integration [13]. Sandia's recent TGI research are focused on electrical simulation models, quantifying output variability of large PV plants and plant fleets, and bulk-level standards.

With respect to electrical simulation models, Sandia established and continues to lead industry efforts on PV plant modeling, under the umbrella of the Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force (REMTF). REMTF has established a technical foundation for PV plant modeling [14-16], and has produced guidelines that have been formally adopted by WECC [26]. The model development work builds on the extensive progress made with wind plant electrical modeling, an activity that Sandia also coordinates [17-21]. Models developed through the REMTF process have been incorporated in standard release versions of commercial simulation software, including Siemens PSSE, General Electric's PSLF, and Power

World programs. Work on dynamic and short circuit electrical models is on-going at Sandia.

A research area closely related to modeling is the study of grid stability with high penetration scenarios. This has been one of the major gaps identified in the large-scale integration studies that have been conducted to date. Currently, Sandia is working with the Bonneville Power Administration (BPA) and leading universities on transient and small signal stability analyses on an interconnected system (WECC), and the potential mitigation role of wide area and local controls using power electronics. Recent publications include [22, 23].

Over the last three years, the output characteristics of PV plants and solar plant fleets have become better known. This has allowed researchers to study integration cost of solar generation in more detail. Sandia and its collaborators have played a leading role in solar variability characterization and modeling [24-31]. The techniques have been successfully applied in recent solar grid integration studies [32] [17], as well as on-going studies in the Western US. The prospect of high penetration solar and wind generation has revived research in probabilistic methods in power systems operations, motivated by the need to more rigorously evaluate system reliability impacts and identify optimal operating strategies under high uncertainty.

Sandia has conducted leading research in the application of stochastic mixed-integer programming to operations problems [33-35]. Advanced methods have also been applied to the resource adequacy with variable generation [36,37]. Currently, Sandia leads a national-level multi-organization project on adapting advanced optimization for unit commitment and economic dispatch in real time environment (ARPA-E Project #0473-1601).

There is also a flurry of activity on standards for variable generation. NERC's Integration of Variable Generation Task Force (IVGTF) is defining new and revised bulk system standards that more directly and appropriately address solar and wind generation (see www.nerc.com/filez/ivgtf.html). As part of its stakeholder engagement effort, Sandia has been an active contributor to IVGTF reports on modeling, stationary/mobile storage, and balancing area solutions. Sandia is currently supporting the development of IVGTF reports on interconnection standard [30,31]. Sandia actively disseminates technical information through stakeholder groups led by organizations like UVIG, the EPRI and the Solar Electric Power Association (SEPA). As part of this work, Sandia is coordinating a large stakeholder group to incorporate voltage and frequency tolerance into the IEEE Standard 1547. Currently, Sandia and NREL chair UVIG's Distributed Generation Users Group, which served as UVIG's launching point for solar grid integration activities. Sandia also has experience conducted seminars on solar integration for utility commissions in several states. Sandia regularly disseminates technical information on TGI topics through publications and workshops [38].

## Project Objectives

The SunShot Initiative is focused on reducing cost to improve competitiveness with respect to other electricity generation options [1]. Ultimately, solar generation will have an impact on energy security, climate change and jobs only to the extent that very high deployment levels are achievable while acceptable levels of grid performance and supply reliability are maintained. Without application of best practices in existing grid planning and operations, as well as standards and policies, the cost of integrating solar could artificially restrict grid access and increase integration cost. The unifying goal of the Sandia TGI program is to reduce grid access barriers, a notion that is inseparable from the SunShot cost reduction target. Sandia's TGI work aims to accomplish five three-year objectives shown in Figure 1, covering all three TGI technical areas (MATI, SIST and $TA^2$). The significance of each objective with respect to the SunShot goals is described below.

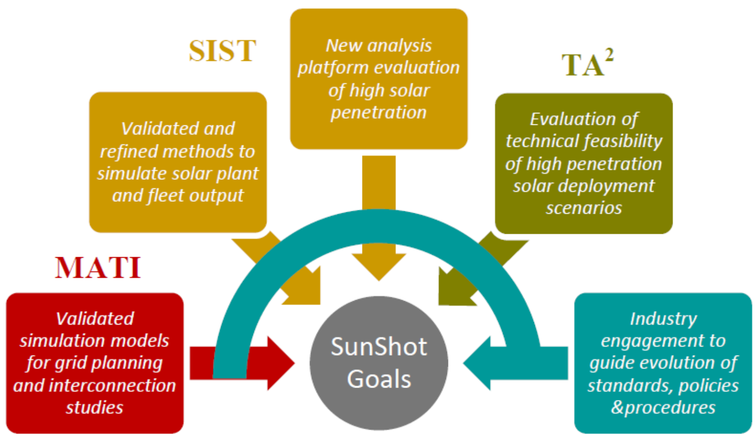



**Figure 1, Sandia TGI objectives supporting SunShot goals**

*Objective 1 – Electrical simulation models for solar integration analysis will be validated, standardized, and widely available for transmission planning and interconnection studies (see Task 1).*

Achieving this objective will enable the solar generation interconnection to proceed expeditiously and cost-effectively, and will enable solar plants to be properly modeled in grid reliability studies. This will be accomplished by ensuring that adequate electrical simulation models (specifically dynamic models and short circuit), along with input data and application guidelines, are readily available in commercial simulation platforms. Because PV plants are a new application, it is not surprising that standard models are not readily available. Existing models are user-written, proprietary extensions, which are difficult to use and are poorly documented. Also, existing models are incompatible with NERC-mandated regional transmission planning activities. This is a major a gap identified by IVGTF [39].

*Objective 2 - Methods to simulate solar plant and fleet output will be well-documented, validated, and refined (see Task 2).*

Achieving this objective will improve the quality of data used to drive planning and operations studies of high penetration solar generation. Specifically, this objective will result in transparently documented and validated methods that translate measured and/or modeled irradiance into high resolution solar plant output based on plant design parameters (solar technology, plant size, tracking method, dc/ac ratio). Existing methods to simulate data sets tend to be poorly documented and have not been validated, which compromises the credibility of the analyses insights. In addition, it is necessary to determine how methods need to be improved considering the scope and objectives of the various studies.

*Objective 3 - A new stochastic analysis platform will be available for evaluation of grid operations with high solar penetration (see Task 2).*
Achieving this objective will produce new stochastic unit commitment analysis tool that can be used to analyze in more detail system operations under a high degree of uncertainty due to variable solar (and wind) generation. The tool will allow researchers to more accurately evaluate integration cost and reliability impacts of future high SunShot scenarios. This represents an improvement over existing deterministic production cost models that are used today, which will become increasingly unable to identify optimal generation commitment strategies under a high level of uncertainty. In particular, the failure to explicitly account for uncertainty in renewables output can result in the need for higher-than-necessary operating reserves, which impacts operating cost. Software tools commonly used for grid studies generally lack extensions to solve stochastic problems using probabilistic data.

*Objective 4 - Technical feasibility of high penetration solar deployment scenarios will be better understood (See Task 3).*
Achieving this objective will addresses the need for a more rigorous assessment of bulk system performance with respect to current NERC reliability criteria. Three specific and novel studies will be conducted: 1) Small signal stability assessment 2) Stochastic unit commitment study, and 3) Long-term generation resource adequacy using probabilistic methods. These three studies will better establish the technical feasibility of future high penetration solar deployment scenarios on the WECC footprint. These technical challenges have not been thoroughly explored and are widely considered to be gaps.

*Objective 5 - Emerging standards, policies will appropriately take into account technical characteristics of solar generation (See Task 4).*
Achieving this objective addresses the need to disseminate actionable TGI technical information to stakeholders in a timely and effective manner, to ensure that revised or new standards, policies and procedures do not erect unnecessary barriers to solar deployment on transmission systems. An associated objective is to receive industry feedback on Sandia TGI technical activities. Sandia will partner with well-established organizations reach regulatory agencies, policy makers and technical working groups. The information will be disseminated through publications, technical reports, public presentations, and focused workshops. Without this type of engagement, it would not be possible for the TGI activities to have the fullest possible impact.

The next section includes a summary of the tasks within the Statement of Project Objectives (SOPO) for the three year effort, including relevant milestones and go/no-go decision points, as well as progress on each task.

## Project Results and Discussion: Tasks for Years 1 and 2

### TGI Task 1.1: Create a document with a detailed procedure for plant-level model validation of transmission-scale photovoltaic generation, and a MATLAB-based software tool to assist with carrying out the procedure

NERC MOD-026 (Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions) requires plant owners to periodically submit a validated dynamic model to the regional reliability coordinator. There are potentially more stringent requirements by the regional reliability coordinator. For example in the WECC (Western Electricity Coordinating Council), renewable plants larger than 20MW must submit an updated dynamic model every 5 years. The generic solar models are new and therefore unfamiliar to many plant owners. The goal of this task is to remove barriers to solar integration by providing a document and MATLAB tool to assist in the plant model validation process.

A block diagram of the newly developed generic solar plant models is shown in Figure 2. The components of the model include the plant level controller (REPC_A), electrical control module (REEC_B), and the generator model (REGC_A).

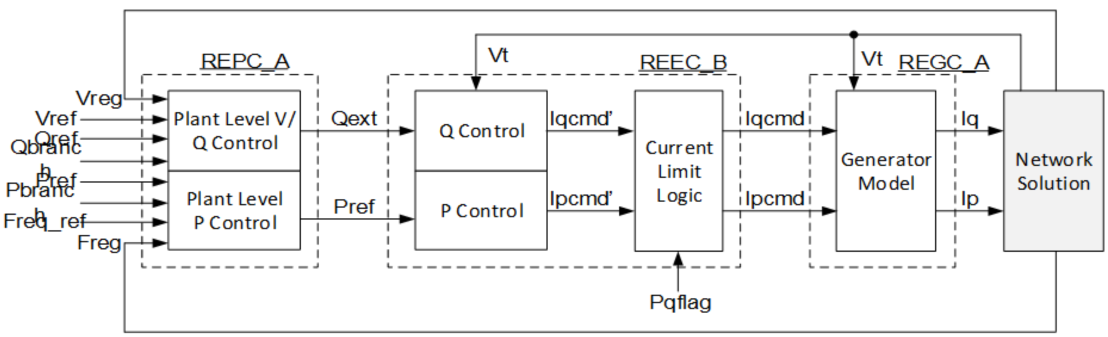



**Figure 2, Solar plant model block diagram**

Subtask 1.1.1**: Define the use-cases that will be covered in the validation guideline**
In this subtask, we identified the following use cases for plant-level validation:

(a) ability to inject signals into the system
(b) repeatable external stimulus (e.g. switched capacitor)
(c) analysis of external disturbance PMU data

From a signal processing perspective, use case (a) provides the information required for the most accurate identification of the plant-level model. The ability to inject signals at various locations in the system is a requisite to accurately identify each of the individual transfer functions in the system model. Without this ability, any system identification will be ambiguous. For example, consider the block diagram in Figure 3. Given only input/output data it is not possible to estimate the transfer functions for $P_1(s)$ and $P_2(s)$ individually unless some structure is known in advance (e.g. P1(s) and P2(s) are low pass filters, where the time constant for $P_1(s)$ is much shorter than $P_2(s)$).

Unfortunately, the most typical applications will likely not have the ability to inject signals into various points in the control system. The next best scenario for system identification is access to a repeatable external stimulus (e.g. a resistive brake insertion, a capacitor bank, etc.). This repeatable external stimulus is helpful in that the same stimulus can be used under different configurations to better isolate the performance of different system components.

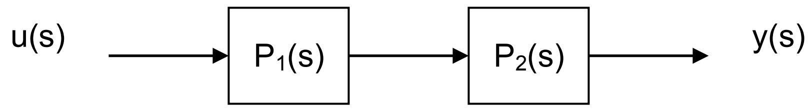



**Figure 3, System block diagram**

The third use case, analysis of external disturbance PMU data, is likely to be the most common approach, but presents the most challenges from a signal processing perspective. Using this approach, it will not be possible to uniquely identify the time constants associated with the various components of the system block diagram unless additional information is available. This additional information includes known system time constants (or ranges) to help reduce the ambiguity of the solution. We plan to allow the user to incorporate additional information (e.g. known settings or ranges) in the MATLAB tool in order to automatically arrive at the best estimate of plant parameters. Figure 4 shows an example of PMU data recorded during a fault at the Greater Sandhill Solar Plant.

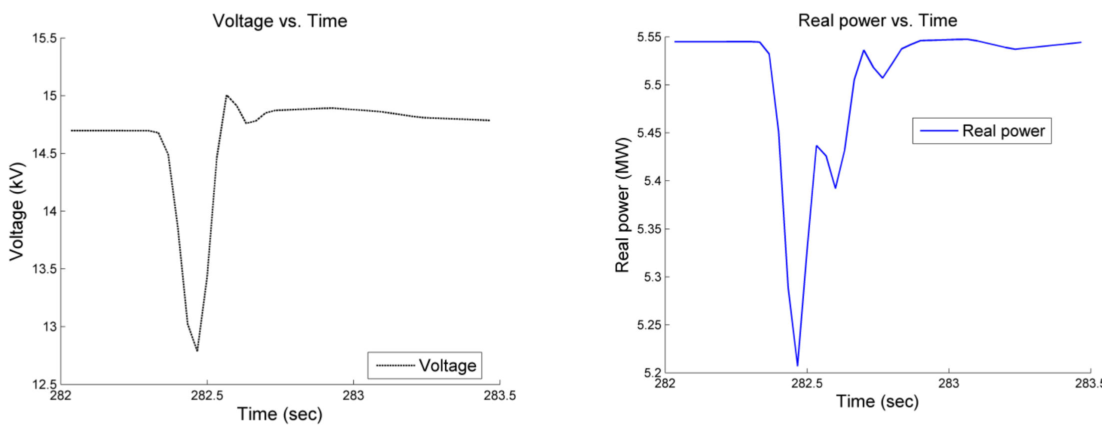



**Figure 4, PMU data recorded during a fault near the Greater Sandhill Solar Plant**

This subtask was completed.

Subtask 1.1.2**: Collect reference data that will accompany the validation procedure**
Sandia has identified PMU data containing suitable disturbances from the Alamosa and prosperity sites from January 2013 to the present. Sandia has also worked with two partners to assist them in collecting data for PV model validation. In addition, Sandia has obtained dynamic response data from several PV inverters using laboratory tests. This subtask has been completed.

Subtask 1.1.3**: Develop a software tool in MATLAB to automate the plant validation procedure**

The goal of this task was to develop a MATLAB software tool to help automate the plant model validation procedure. The inputs to the tool are: the system configuration, known settings (or ranges of settings), and system response data (falling under one of the three use cases). The output of the tool is a set of model parameters that in some sense (e.g. L1 or L2 norm) most accurately fit the observed response. A block diagram of the MATLAB tool is shown in Figure 5. The main components are the dynamic models (e.g. plant controller REPC_A, electrical control module REEC_B, and the generator/converter interface REGC_A), a power flow model (required to reflect PMU measurements to the terminal bus), and PMU data in response to a disturbance or controlled stimulus. The output of the tool is estimated/validated model parameters.

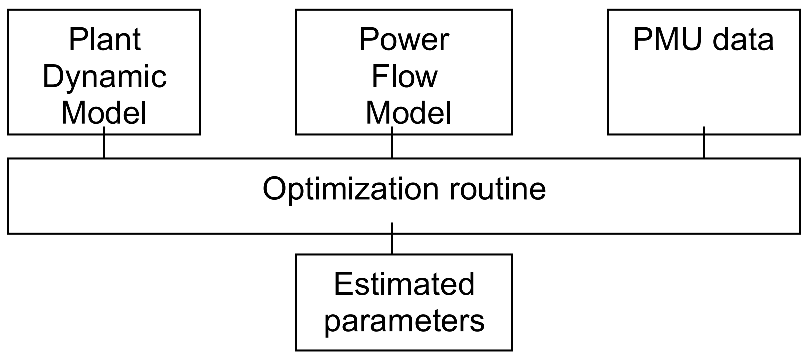



**Figure 5, MATLAB tool block diagram**

The power flow model is critical because dynamic models used to capture the behavior of PV solar plants rely on the voltage measured at the terminals of the inverter(s) to translate current commands into the active and reactive power produced by the generator/converter. In practice, a large plant may contain many power electronic converters, and the voltages inside the plant are seldom recorded. Even though the terminal voltage is not typically measured, it can be deduced with high accuracy using measurements made at the substation and an equivalent model of the collector system. For model validation tasks requiring high sample rates, PMU data captured at 60sps or higher is preferred. Most PMUs deployed in PV plants are configured to monitor both the primary and secondary of the substation transformer.

An equivalent model of a collector system comprises a representation of the substation transformer, the distribution network inside the plant, and the generator step-up transformer. In practice, the steady-state model for the transformers is distinct from the distribution line model. The line model represents the equivalent impedance of the distribution network inside the plant, and is well-described by a standard PI-model. A PI-model features series impedance and two symmetric shunt admittances. In contrast, a voltage regulating transformer, or any transformer with an off-nominal tap ratio, must be modeled differently to account for reactive asymmetry. A voltage regulating transformer acts like a VAR "pump" absorbing reactive power on one side and delivering it on the other. In this way, they can regulate the voltage at the “point of common coupling."

We have completed the dynamic plant models as well as the power flow model and are coding up the PMU interface module. We have also identified the optimization approach that we plan to use. We demonstrated a command line driven tool and shared it with two external experts (Dr. Pouyan Pourbeik and Dr. Bernard Lesieutre) for feedback.

Another benefit of this development effort has been the application of the MATLAB models to verify the generic models developed by commercial vendors (e.g. General Electric, Power World, and Siemens). Using these MATLAB models, we were able to identify three bugs in the PSLF generic model implementation:

1. Reference active power (Pref) not connected (REPC_A->REEC_B)
2. Local PF (power factor) initialization
3. Current limit adherence

Sandia worked with GE to rectify these bugs. The solution to Pref not connected is illustrated in Figure 6. This was also identified as a problem in the Power World implementation and was corrected by Power World.

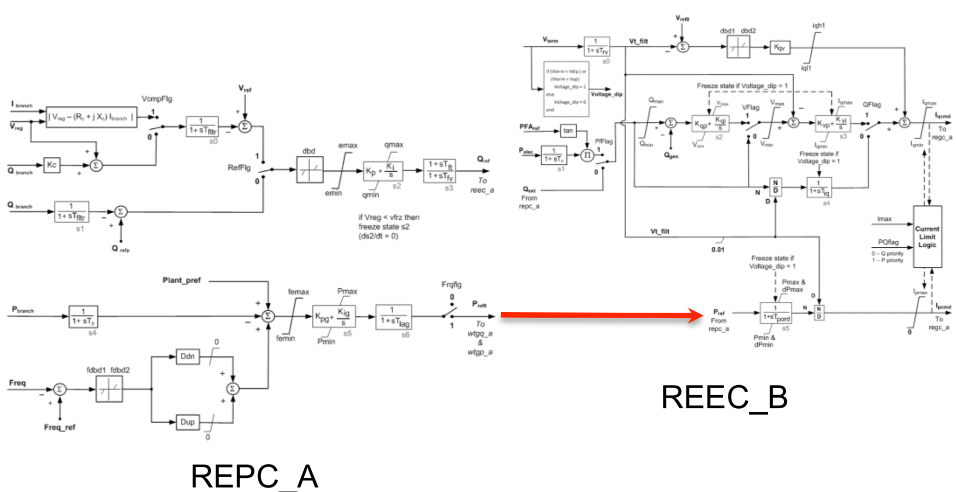



**Figure 6, PREF not connected**

The local power factor initialization problem is captured in Figure 7.

**Before**: Unsteady initial **After**: Model initializes correctly

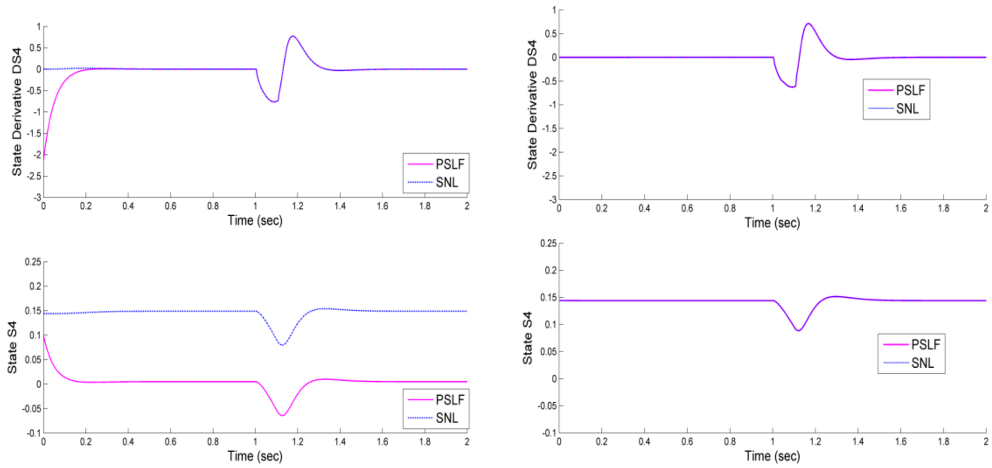
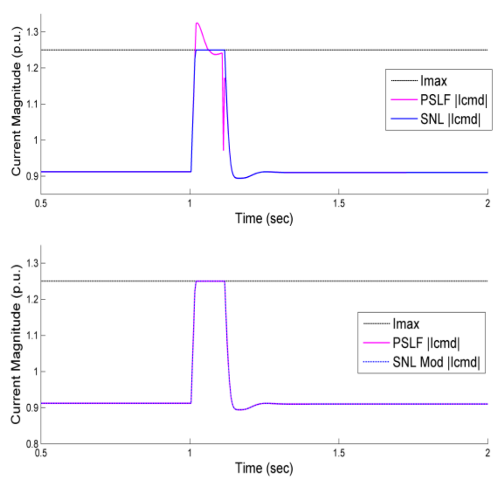



**Figure 7, local PF (power factor) initialization**

The current limit adherence issue is summarized in Figure 8.




**Before**: Current limit violation upon saturation

**After**: Saturation characteristic implemented correctly

**Figure 8, Current limit adherence**

The communication of these findings was accomplished through participation in the WECC Modeling and Validation Working Group (MVWG) Renewable Energy Modeling Task Force (REMTF) meetings. The tool was also presented at the November 2014 WECC REMTF meeting in Albuquerque.

Subtask 1.1.4**: Develop detailed plant model validation examples to illustrate the procedure**

Figure 9 depicts a model validation example using simulated data. A fault was simulated using a given parameter set, and then the optimization routine was implemented using a "blind" parameter set as an initial guess, i.e., no information about the true parameters was passed to the parameter-fitting algorithm.

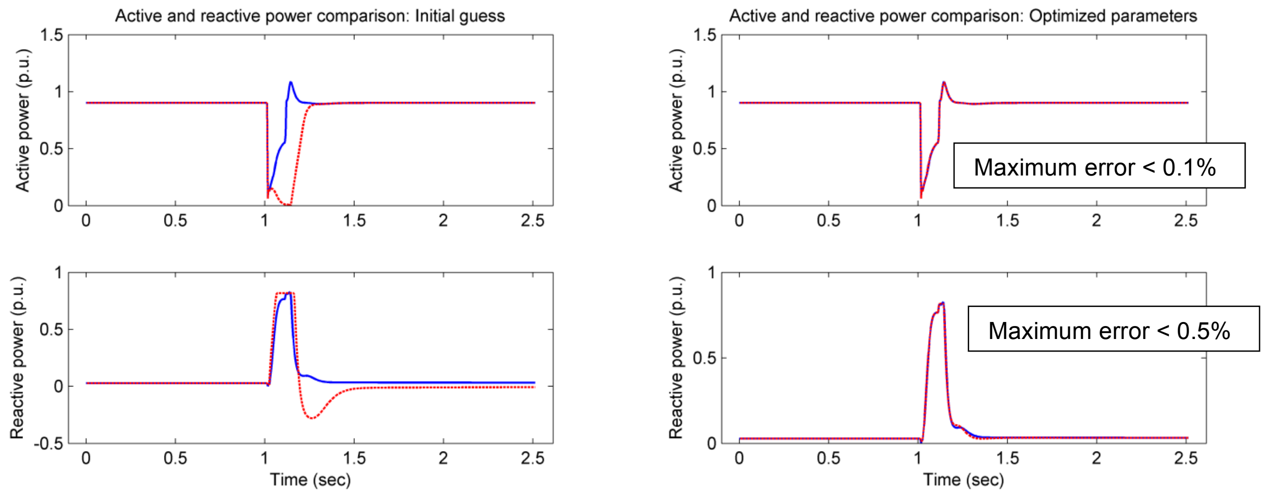



**Figure 9, Model validation example using simulated data and a blind parameter set**

This subtask was completed in the March 2015 WECC REMTF meeting.

Milestone 1.1**: Quantify percent error (model versus actual) for the reference data**
Comparing the actual performance over the reference data set (PSLF example), the maximum percent error was less than 0.5% for the reactive power output, and less than 0.1% for the active power output. These results are shown in Figure 9. The averages were considerably smaller. There is very little bias, if any.

Milestone 1.2**: Adoption by a reliability entity**
In FY14 we wrote a draft document titled, "Central Station Photovoltaic Power Plant Model Validation Guideline." This draft model validation guideline document was presented and distributed to the WECC REMTF at the M&VWG meeting held in Albuquerque in November of 2014. We received very constructive feedback which was used to revise and improve the document. Added sections describing how to set up the models in detail and the appropriate range of values for the dynamic model parameters were particularly important.

In FY15 Q2, we greatly expanded upon the original draft and distributed a complete version to the WECC REMTF in advance of the M&VWG meeting held in Salt Lake City in March of 2015. Among the important advancements in the document was a section which clearly laid out which parameters should be available for tuning in each mode of operation. These parameters are illustrated in Table 1

**Table 1, Tunable parameters**

| REEC_B | | | Tunable Parameters |
|---|---|---|---|
| **Pfflag** | **vflag** | **qflag** | **Local** |
| 0 | 0 | 1 | Kqv, Kvp, Kvi |
| 0 | 1 | 0 | Kqv |
| 0 | 1 | 1 | Kqv, Kqp, Kqi, Kvp, Kvi |
| 1 | 1 | 0 | Kqv |

In Q3 FY15, we worked with software developers at GE to resolve a problem identified by Sandia. Software developers at GE interpreted user-defined flag combinations differently than developers at PSS/E and PowerWorld, leading to problematic behavior when translating data between programs. Sandia's work on the model validation guideline brought this discrepancy to light, and allowed the industry consortium to reach a consensus on the appropriate way to interpret the user-defined flag settings. Before Sandia brought this problem to the attention of the task force, a single flag combination could correspond to different modes of operation on different software platforms.

This document, the "WECC Central Station Photovoltaic Power Plant Model Validation Guideline," was unanimously approved by the WECC REMTF and M&VWG in June of 2015. Correspondingly, GE released a version of PSLF that corrected the aforementioned problem. Sandia modified the final draft to reflect the correct parameter flag interpretation.

Final Deliverable**: Publically available use cases, web tools, and a report for plant-level model validation of transmission-scale photovoltaic generation, analysis**
Once the procedure and documents are approved by the MVWG/REMTF, they will be posted on the WECC web site. We will also consider making the tool available through Sandia's website, strictly as a research tool (as opposed to a finished product).

**TGI Task 1.2: Develop and publish a set of application guidelines for dynamic simulation analysis**
Transmission planning and interconnection studies conducted by regional reliability coordinators, independent system operators, and utilities must incorporate the newly developed generic solar models. Since these models are new, the goal of this task was to develop and publish a set of application guidelines for dynamic simulation analysis. By promoting the proper use of these models, we are removing barriers to the integration of solar resources as explained in the following subtasks.

Subtask 1.2.1**: Identify a set of default model parameters for each of the generic model modules**
Sandia identified a set of reference parameters to use as a starting point in simulating plant behavior. These model parameters can be used as a starting point (e.g. initial guess) when performing model validation. The parameters were identified based on internal testing and user feedback (e.g., CAISO).

Subtask 1.2.2**: Correlate each distinct plant control mode with a specific model configuration**
We incorporated a table in the guidelines document that identifies the model configuration for each plant control mode. This subtask was completed.

Subtask 1.2.3**: Create a set of use cases for transmission planning engineers**
We incorporated use cases in the guidelines document. This subtask was completed.

Subtask 1.2.4**: Create a WECC technical guideline**

We created a WECC technical guideline that was submitted to the WECC Technical Studies Subcommittee (TSS) for approval at the May meeting. The guidelines were approved. This subtask has been completed.

Final deliverable**: Guideline for photovoltaic dynamic simulation analysis**
The "WECC Solar Plant Dynamic Modeling Guidelines" have been approved and adopted by the WECC and are posted on the WECC website. The URL is:
https://www.wecc.biz/Reliability/WECC%20Solar%20Plant%20Dynamic%20Modeling%20Guidelines.pdf

**TGI Task 1.3: Conduct a workshop in each of the major electrical interconnections to disseminate the recent advancements in electrical modeling of photovoltaic solar generation**

Subtask 1.3.1**: Conduct a PV modeling workshop with WECC and document the proceedings**
Sandia conducted a workshop in conjunction with the June WECC MVWG meeting. Approximately 60 people participated (50% in person, 50% via web). There was a good representation of various stakeholders (plant owners, utility engineers, WECC planners). Feedback was aggregated and provided to DOE, along with recommendations on incorporating the suggestions.

Subtask 1.3.2**: Conduct a PV modeling workshop with PJM and document the proceedings**
This subtask was covered by milestone 1.4 as detailed below. A webinar open to all audiences was performed instead of having individual workshops at each region.

Subtask 1.3.3**: (STRETCH GOAL) Conduct a PV modeling workshop with ERCOT and document the proceedings**
This subtask was covered by milestone 1.4 as detailed below.

Milestone 1.3**: Completion of the WECC workshop demonstrating models/tools and compilation of user feedback**
This subtask was covered by milestone 1.4 as detailed below.

Milestone 1.4**: Completion of the PJM workshop demonstrating models/tools and compilation of user feedback**
A webinar was conducted on Thursday, July 16$^{th}$ covering model validation for renewable energy plants. It was hosted by WECC, but open to everyone across the country, including PJM and ERCOT.

Milestone 1.5**: Completion of the ERCOT workshop demonstrating models/tools and compilation of user feedback**
This subtask was covered by milestone 1.4 as detailed below.

Final Deliverable**: Completed workshops and documented proceedings and feedback from participants**
This milestone was completed in the third quarter of FY15.

**TGI Task 1.4: Perform a study to establish how distributed PV voltage and frequency ride-through capability (VRT, FRT) need to be reflected in baseline assumptions used for voltage stability, transient stability and other transmission planning studies**
If an appreciable amount of distributed PV with active inverter controls is not accurately modeled in transmission planning studies, it will create a scenario in which transmission planners are operating under a false perception of how the system will behave under various contingencies. This mismatch between model and reality would have serious implications, including increasing the risk of a major power system breakup. In FY14, IEEE Standard 1547 (DG interconnection standard) is up for revision. However, there are no studies that can inform stakeholders on reasonable default settings for VRT and FRT. This study will fulfill this need.

This task was canceled in accordance with customer feedback on how to prioritize carryover funds.

**TGI Task 1.5 (STRETCH GOAL): Develop a reference website, in wiki format, for dynamic and short circuit modeling of photovoltaic solar generation**
Developing a reference website will raise awareness of the new generic models by providing a forum where interested parties can participate in a two-way exchange of information. In addition, the website will improve the ability of engineers to accurately model PV plants by providing use-cases and a model data repository. It will also help accelerate adoption of the models. This task will leverage a model wiki for wind models, which is currently being built by UVIG. The UVIG PV/wind modeling wiki site is operational, and contains a wealth of information on PV inverter short circuit characteristics.

**TGI Task 2.1: Improved Solar Plant Input Data and Analysis Tools to Optimize Power System Operations**
In FY13, Sandia documented different methods for reproducing PV plant output variability. Sandia evaluated how each method performs for different applications, by comparing modeled data with actual field measurements. This task will leverage the work done thus far to identify opportunities for improving the methods themselves. Improved methods for generating PC and CPV output profiles will improve plant modeling, enabling more accurate analysis, which will ultimately lower system costs.

Subtask 2.1.1**: Analyze errors in several variability methods**
In this subtask, we have quantified the errors in four different variability simulation methods at matching the measured cumulative distribution of ramp rates. Four different variability simulation methods were considered. Each method starts with the measurements from an irradiance point sensor time series and then applies smoothing

to the time series to simulate the spatially-averaged irradiance over the footprint of a PV plant. The four methods considered were:

1) No smoothing: the irradiance point sensor time series was used directly.
2) Time averaging: the point sensor time series was smoothed by taking a moving averaged with time window $\overline{t} = \frac{\sqrt{A}}{CS}$, where $A$ is the PV plant area and $CS$ is the cloud speed.
3) Marcos: The method described in [40] of a low-pass filter where the cutoff frequency, $f_c = \frac{0.02}{\sqrt{A}}$.
4) WVM: The wavelet variability model (WVM) [41], which applies different smoothing at different timescales based on the distance across the plant and the cloud speed.

The output of each method was the simulated plant-average irradiance. Previously, linear irradiance to power models were most often used to convert this simulated plant-average irradiance to plant power output. However, as seen in Figure 10, linear models do not account for temperature, inverter clipping, and other non-linear effects which affect PV plant power generation. Thus, we improved on previous models by using the Sandia Array Performance Model [42], which accounts for temperature effects, to convert the irradiance to DC power, and the Sandia Inverter Model [43], which accounts for inverter behavior such as clipping, to determine the AC power output. This resulted in a spatially scaled simulated AC power output for each of the four methods.

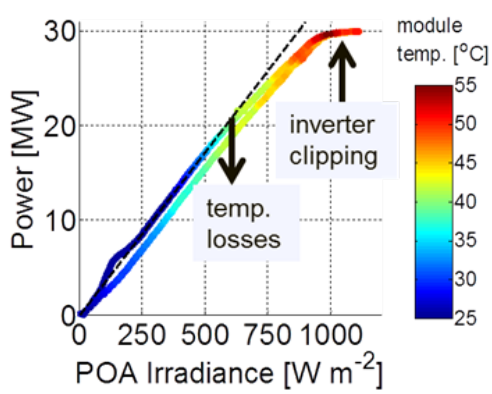



**Figure 10, Plot of PV plant power output versus POA irradiance**

Figure 11 shows the comparison of the cumulative distributions of 1-minute ramp rates for each of the four simulation methods compared to the actual measured plant power output of a 19MW PV plant. The top left plot in Figure 11 gives the probability of occurrence of large 1-minute ramp rates. For example, the no smoothing simulation predicted that 1% of the ramps would be larger than 35% of capacity; in the measured power data, only 0.2% of ramps were larger than 35% of capacity.

The top right plot in Figure 11 shows the difference between the simulated cumulative distributions and the measured cumulative distribution. A perfect simulation would be a horizontal line at zero: values above zero had positive errors and values above zero had negative errors. For example, in simulating the occurrence of ramp rates larger than 10% of capacity (as would be relevant to projects in Puerto Rico [44]), the no smoothing case overestimated the number of such ramps by over 2%. In general all methods have smaller errors at estimating the largest ramp rates (e.g., they all correctly simulate no ramps larger than 80% of capacity). The no smoothing and time averaging methods typically over estimate the number of large ramps, while the Marcos method typically underestimates the number of large ramps. The WVM also underestimates the number of ramps that are 5-15% of capacity, but has good agreement for larger ramp magnitudes.

To quantify the average errors at large ramp magnitudes, the bottom left and bottom right plots in Figure 11 show the mean absolute error at matching the cumulative distribution of ramps larger than (bottom left) 10% of capacity and (bottom right) 20% of capacity. These plots again show that the time averaging, Marcos, and WVM methods perform significantly better than the no smoothing method. The WVM is found to have the smallest errors, indicating it is likely the best method to use for variability simulation.

A factor that negatively affected this subtask was the unavailability of data to allow for method validation at more PV power plants. We spent significant effort contacting utilities, PV plant owners, and PV plant developers, but all were either (a) unable to spend the time to establish a nondisclosure agreement and coordinate data transfer due to other time commitments with higher priority or (b) unwilling to share their data due to proprietary concerns. Due to limited access to data, the comparison of different methods was done against a limited data set. This subtask has been completed.

Subtask 2.1.2**: Develop MATLAB code for PV output variability simulation and make code publically available**

This subtask has focused on developing an easy to use, publically available version of the wavelet variability model (WVM). We developed a “beta” version of the WVM code that was shared with partners who used the code to analyze their own data and then provided feedback on bugs in the code and additional features they desired. This feedback was very useful, and additional functionality was added to the WVM based on user feedback.

For example, to address situations where the WVM is used to simulate the average irradiance of a discrete irradiance point sensor network (rather than the average irradiance over a continuous PV plant footprint), for example as done in [45], we added a “discrete” mode in addition to the “square” and “polygon” modes already implemented to simulate continuous PV plant footprints.

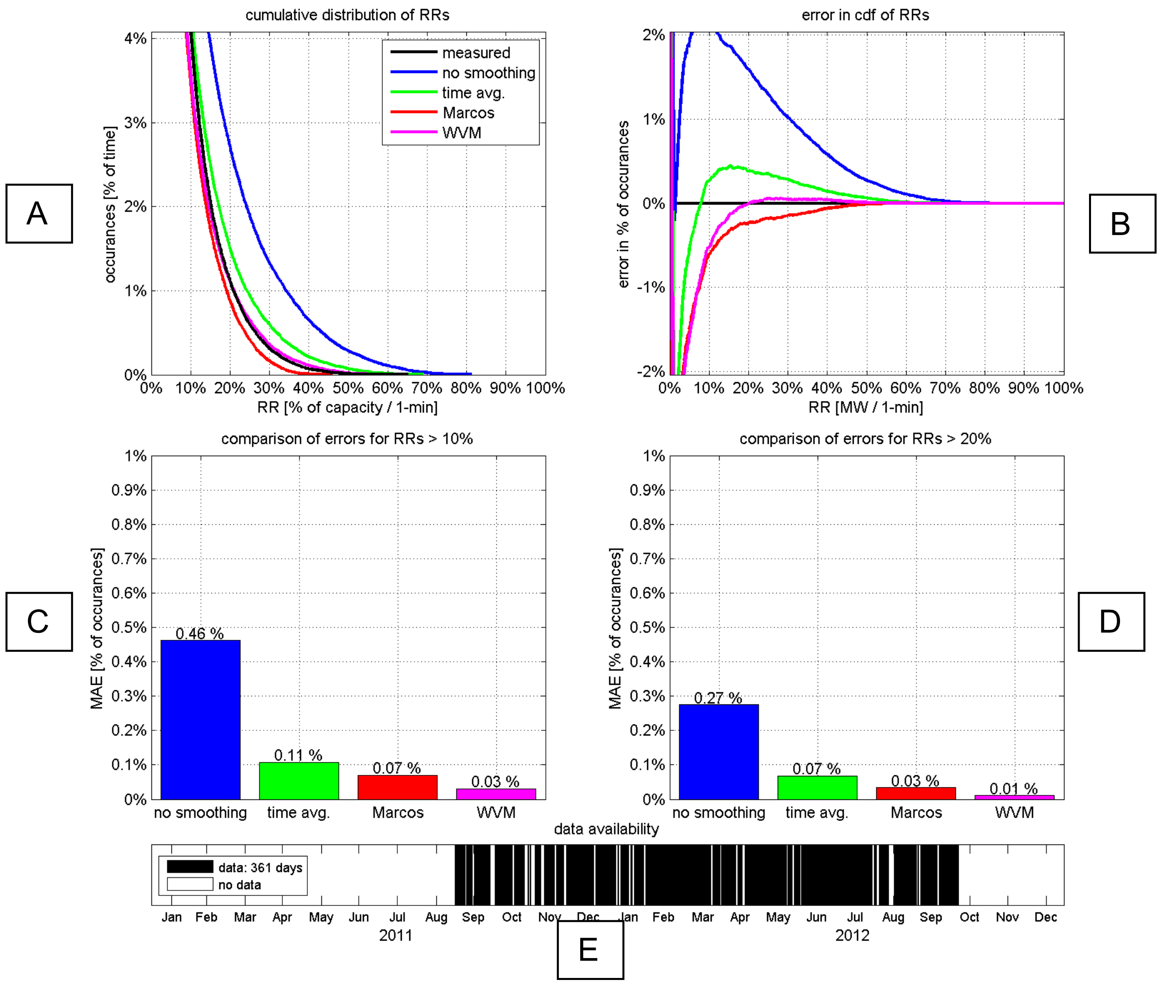



**Figure 11, A: Probability of occurrence of 1-minute ramp rates, B: Error in matching cumulative distribution function (CDF) of ramp rates, C: Mean absolute error in matching CDF of ramp rates >10% of capacity, D: Mean absolute error in matching CDF of ramp rates >20% of capacity, E: Data availability.Another common user concern was how to determine an appropriate cloud speed based on their location and time of year.**

To address this, we implemented a new subprogram that allows the user to compute the cloud speed based on a network of ground irradiance sensors, as shown in Figure 12.

User feedback also helped to identify parts of the code that were not well documented or confusing to operate. To address these concerns, we developed an html help file that includes a description of the WVM code and examples of how the code is used in a variety of scenarios (e.g., to simulate a square PV plant or to simulate a user-defined polygon PV plant footprint). Screenshots of the help file are shown in Figure 13.

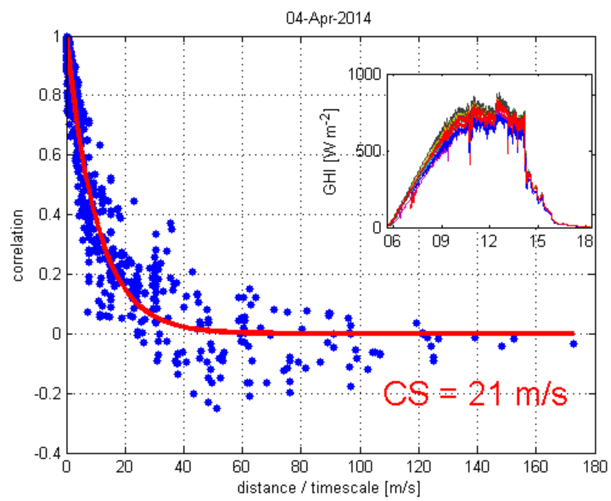



**Figure 12, Cloud speed determined from a network of irradiance sensors**

The WVM MatLab code and associate help file is compiled and ready for public release. It has already been shared on-demand by email with research, university, and utility partners. We intend to include the WVM code in a future release of the PV_Lib MatLab toolbox to allow it to reach a broader audience. The PV_Lib is well-known online resource that contains other Sandia MATLAB modules and tools applicable to PV performance and grid integration analysis. This subtask has been completed.

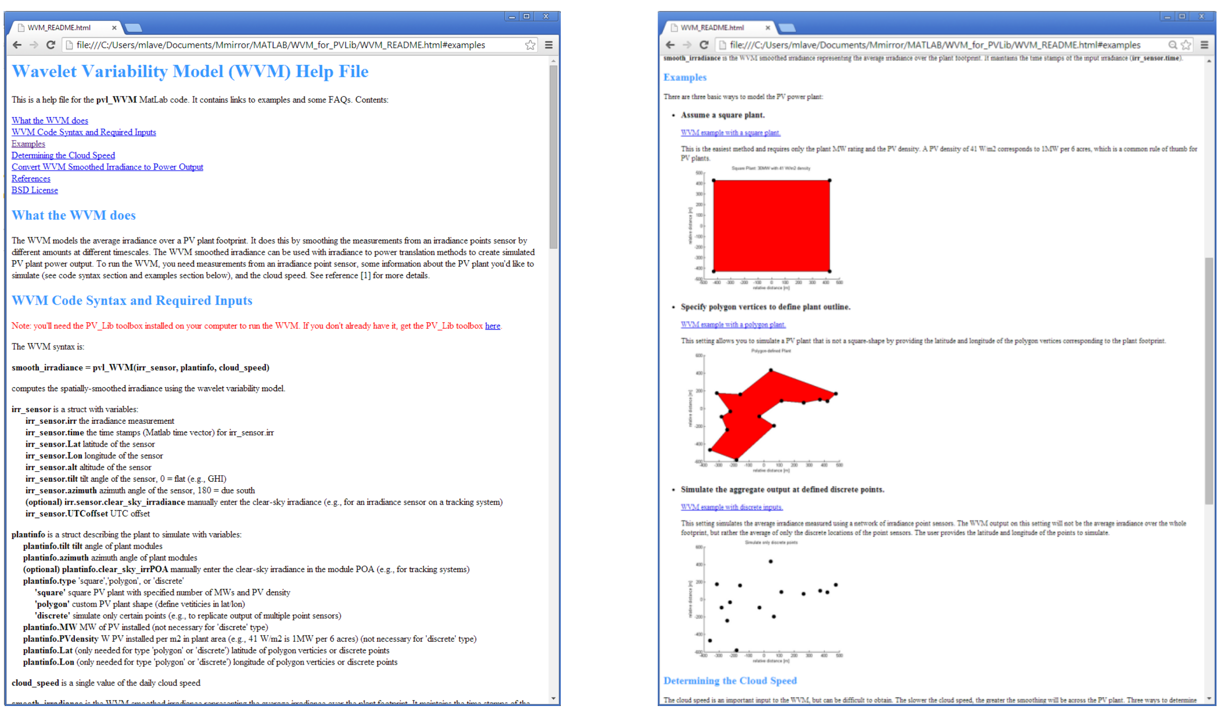



**Figure 13, Screenshots of the WVM html help file**

Milestone 2.1**: Mean absolute error in matching cumulative distribution of ramp rates quantified**

This milestone has been achieved. The MAE in matching the cumulative distribution of ramp rates is quantified in the lower plots of Figure 11, and clear differences between the different variability scaling methods were observed.

Milestone 2.2**: Release code for variability simulation methods based on ground irradiance measurements (i.e., wavelet variability model – WVM)**
The WVM code has been developed and tested with partners. It is compiled and ready for public release. We are targeting a future PV_Lib version for WVM release.

Final Deliverable**: Identify and document necessary improvements in the methods to simulate plant output and seek consensus on standard methods for simulations**
The final deliverable will be a report documenting the results described under subtask 2.1.1. Significant findings include a large improvement when using a non-linear irradiance to power translation model, and that the WVM appears to have the lowest errors at matching ramp rate distributions. This will be documented in the report to allow for an understanding of the magnitude of typical model errors, and to suggest improvements to models. The final report will be completed by September 30.

**TGI Task 2.2: Develop an advanced stochastic optimization planning toolkit for power system operators**
The goal of this task is to develop an advanced stochastic optimization planning toolkit for power system operations.

Subtask 2.2.1**: Form a technical review committee**
The complete list of members was given in the FY14 final report. Two teleconferences with the TRC took place, the first one on March 28 and the second one on July 30 of 2014.
**Subtask 2.2.2: Literature review**
A literature review was performed and presented in the final report for year 2014.

Subtask 2.2.3**: Determine the modules that will compose the toolkit**
The stochastic optimization toolkit is composed of the following modules: stochastic process model, stochastic unit commitment (UC), and economic dispatch (ED). A diagram of the architecture showing how these components interface is found in Figure 14. The stochastic UC implementation follows [51] which uses a scenario-based decomposition technique in order to increase the scalability. This implementation has been demonstrated to be able to solve UC problems with hundreds of generators in tens of minutes using commercially available MIP solvers (e.g., CPLEX, GUROBI) using modest scale parallel computing platforms (i.e., less than 100 cores). The ED implementation uses a linear optimal power flow approximation (i.e., DCOPF), which also results in tractable times for problems with a very large number of generators.

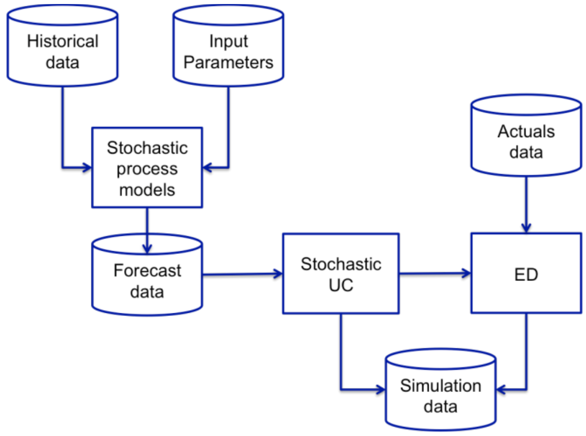



**Figure 14, Architecture of stochastic optimization toolkit**

This diagram also shows the type of information flowing in and out of each of the modules. The stochastic process models take as inputs either historical solar power production and forecast data or a set of parameters regarding the location, altitude, size and other relevant information about the solar power plant under study. With this information, the stochastic process model toolkit generates a day-ahead (*D*-1) probabilistic forecast that serves as input to the stochastic UC module. The stochastic unit commitment model creates a schedule of online units for the operating day (*D*). The economic dispatch module steps forward through time using results from the stochastic UC and actual load and solar power production to adjust generation units, thus simulating the operating day. Information regarding dispatch set points, production costs, solar energy usage, curtailed solar energy, load shedding and other relevant quantities are saved as simulation results in order to facilitate comparisons with a deterministic approach. Further Information the stochastic process model, stochastic UC and ED modules is provided in the following section. This subtask has been completed.

Subtask 2.2.4**: Develop customized stochastic models and algorithms corresponding to toolkit modules**
This section discusses the algorithms developed for each of the toolkit modules starting with the stochastic process model module and ending with the stochastic UC and ED.

*Creating Solar Power Production Forecasts when Historical Forecast Data is Unavailable*
The stochastic process model module uses historical solar power production and solar production forecast data to generate forecasts solar production forecast scenarios based on previous forecast performance.

When no forecast data is available, persistence using a clear sky index is assumed as forecast. The clear sky index is calculated as follows:

1. The clear sky global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) are computed based on latitude, longitude and altitude of a solar power plant using the Ineichen and Perez clear sky model

[46, 47] as implemented in [48] for the time period under study (e.g., each of the hours in the day-ahead or the operational day).

2. We calculate the clear sky plane of array irradiance $CSI_{poa}$ as follows:

$$CSI_{poa} = E_g + E_b + DI$$

where $E_g$ is the ground reflected irradiance on the tilted surface of the solar arrays, $E_b$ is the beam irradiance and $DI$ is the diffuse irradiance form the sky on a tilted surface. The ground reflected irradiance $E_g$ is the portion of irradiance on a tilted surface due to ground reflections and is calculated as [49]:

$$E_g = GHI \cdot A \cdot (1 - \cos(T))$$

where $A$ is the albedo (i.e., ground reflectance) and T is the array surface angle. The beam irradiance $E_b$ is calculated as:

$$E_b = DNI \cdot \cos(AOI)$$

where $AOI$ is the angle of incidence between the surface normal vector and the sun beam vector [50]. The diffuse irradiance is calculated as [49]:

$$DI = DHI \cdot \left[ AI \cdot RB + \left(1 - AI\right) \cdot 0.5\left(1 + \cos(T)\right)\right]$$

where $AI$ is the anisotropy index and $RB$ is the ratio of beam irradiance on the tilted surface to the beam irradiance on a horizontal surface.

3. Next, we calculate the clear sky index as the ratio of normalized solar power output of the solar power plant to the normalized clear sky plane of array irradiance. The normalized solar power output of the solar power plant is obtained by dividing the power output $P_{out}$ at a given time step $t$ by the rating of the power plant $P_{rating}$. The normalized clear sky plane of array irradiance can be calculated by dividing it by 1000. This results in the following expression for calculating the clear sky index at time $t$:

$$CSI(t) = \frac{1000}{P_{rating}} \cdot \frac{P_{out}(t)}{CSI_{poa}(t)}$$

Once the clear sky index for each hour $h$ of the day-ahead ($D$-1) actual power production is calculated, a persistence forecast can be generated using the day-ahead clear sky index values for each hour of $D$-1 and projecting them into the operating day $D$ irradiance. Hence, for each hour of the operating day h the forecasted power is:

$$P_{out}(h, D) = CSI(h, D-1) \cdot CSI_{poa}(h, D) \cdot P_{rating}$$

An example of the clear sky index calculation using historical data for a 30MW solar power plant in NM is shown in the top portion of Figure 15. The bottom portion shows the persistence forecast using the clear sky index calculation projected into the operating day as described above.

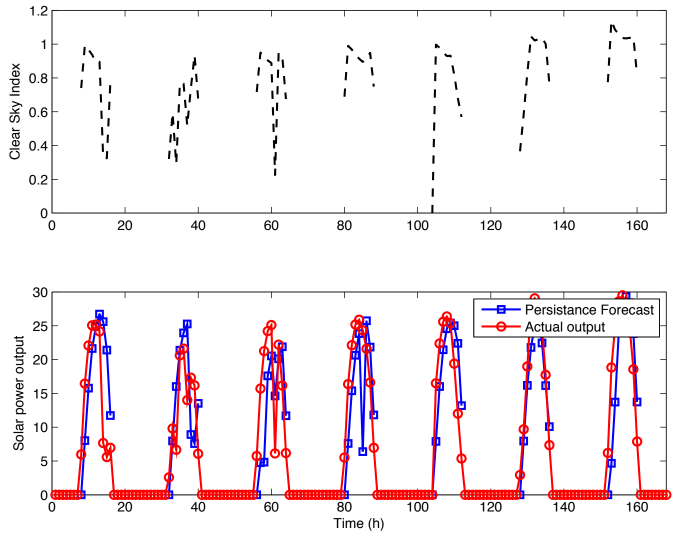



**Figure 15, Example of clear sky index (top) and its use in day-ahead persistence forecast**

*Solar Forecasts Stochastic Process Model*

Once a deterministic forecast is obtained either using historical solar power production or as input by the user as part of the historical data set, the stochastic process model module can generate a probabilistic forecasts to be employed by the stochastic UC as follows:

1. The historical data set of solar power forecast and corresponding actual power production is segmented based on forecast performance. To demonstrate this segmentation we will use 4 segments, but this procedure can be applied to any arbitrary number of segments, limited only by the size of the data set given that an statistically significant number of days should be maintained within each of the segments. The four segments are: (i) the forecast indicates a production of energy equal or greater to 80% of the maximum energy that can be produced on an perfectly sunny day ("sunny" day prediction), and the forecast is correct; (ii) the forecast predicts a "sunny" day but the prediction is incorrect; (iii) the forecast indicates a production of energy lower than 80% of the maximum energy that can be produced in a perfectly sunny day ("cloudy" day prediction), and the forecast is correct; and (iv) the forecast predicts a cloudy day but the prediction is incorrect. Figure 16 illustrates the 4 segments using data for a one-year period.
2. The probability of a day falling into each of these segments is calculated based on historical data.

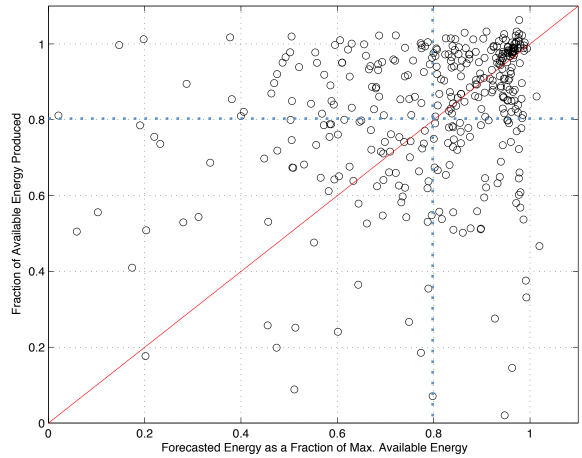



**Figure 16, Example of segmentation based on forecast performance**

3. Conditioned on the day-ahead deterministic forecast, scenarios are sampled using the probabilities calculated in step 2 and from historical data within the segments created in step 1. One way to sample is based on the shortest distance to the fraction of energy predicted by the deterministic forecast. Scenarios are also adjusted using the clear sky plane of array irradiance for the operating day as explained above.

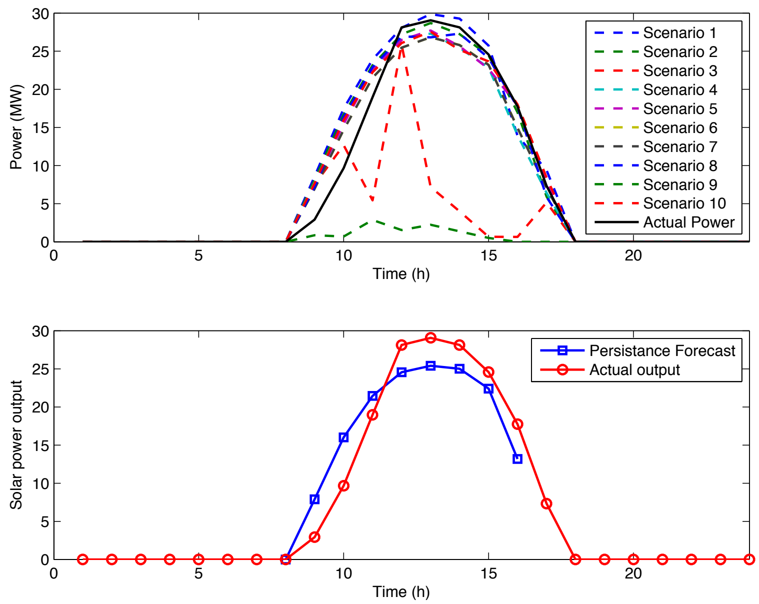



**Figure 17, Example of scenarios generated by the stochastic process model when the deterministic forecast predicts a "sunny" day**

Examples of scenarios generated by the stochastic process model when the deterministic forecast predicts a sunny day and a cloudy day are shown in the top portion of Figure 17 and Figure 18, respectively. The bottom portion of those figures shows the corresponding deterministic forecast.

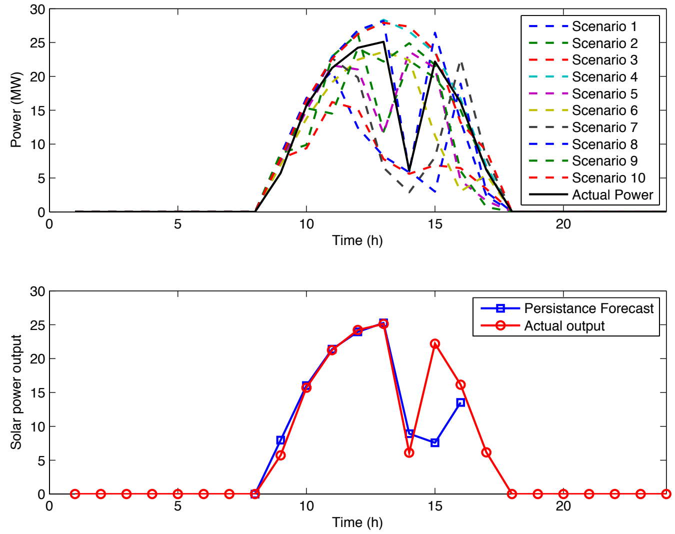



**Figure 18, Example of scenarios generated by the stochastic process model when the deterministic forecasts predicts a "cloudy" day**

*Stochastic Unit Commitment*

Briefly described, the UC problem schedules the on/off states of generating units for the next operating day to minimize total production costs based on load and non-dispatchable generation forecasts subject to power balance, power transfer limits and other operational and economic constraints. This can be formulated as:

$$\arg\min \sum_{t\in T}\sum_{g\in G} CC_g(t) + PC_g(t)$$

subject to:

$$\sum_{g\in G} p_g(t) = D(t), \quad \forall t\in T$$

$$p_g(t)\in \Pi, \quad \forall g\in G, \forall t\in T$$

where *G* is the set of generators in the generation mix, *T* is the set of time steps in the problem time span, *CC* represents the commitment costs and *PC* represents the production costs for each generator *g*. The power set point for a generator g at time step t is represented by $p_g(t)$ and Π represents the region of feasible production of all generating units in all time periods. The net demand forecast (e.g., forecast of demand minus solar power production) is represented by *D*.

A two-stage stochastic unit commitment formulation is defined as follows: (i) the first-stage decision variables are unit on/off and related state variables; (ii) the second-stage (scenario-specific) decision variables include generator power output levels and transmission power flows; and (iii) the optimization objective is to minimize the first stage cost plus the expected second stage cost [51]. This results in the reformulation of the UC problem as:

$$\arg\min \sum_{t\in T}\sum_{g\in G} CC_g(t) + \sum_{s\in S}\sum_{t\in T}\sum_{g\in G} \pi_s \cdot PC_{s,g}(t)$$

subject to:

$$\sum_{g \in G} p_{s,g}(t) = D_s(t), \quad \forall s \in S, t \in T$$

$$p_{s,g}(t) \in \Pi_s, \quad \forall s \in S, g \in G, \forall t \in T$$

where $S$ is the set of net demand scenarios and $\pi_s$ is the probability associated with scenario $s$.

*Economic Dispatch*

The ED module takes the commitment schedule produced by the stochastic UC problem and steps forward through time using the actual net demand to dispatch generators and calculate production costs. Simulation results showing economic dispatch set points for a five-generator test system are shown in Figure 19, and corresponding total production costs divided into variable costs (i.e., generation costs) and fixed costs (i.e., commitment costs) are shown in Figure 20.

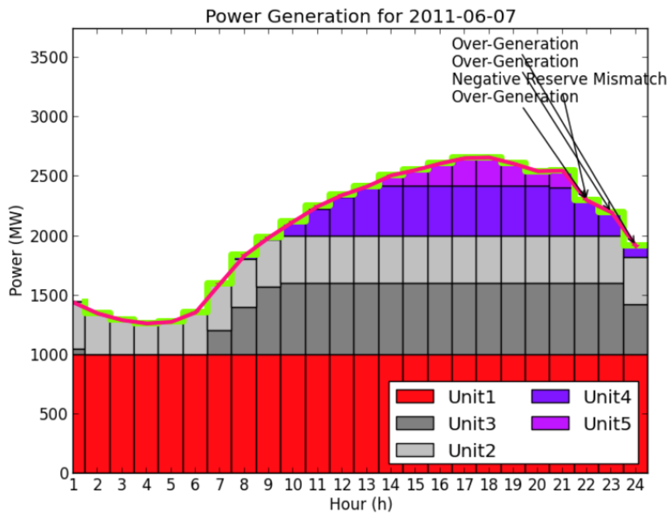



**Figure 19, Economic dispatch simulation results from stochastic UC toolkit**

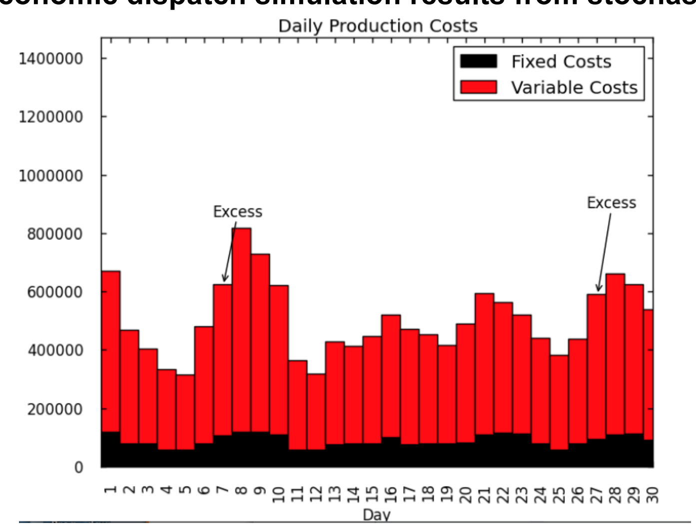



**Figure 20, Production costs corresponding to the ED results in Figure 19**

Subtask 2.2.5**: (STRETCH) User interface development**

Currently user input is done via command line. A user interface for inputting data is part of future work. On the other hand, visualization of output data is provided. Figure 19 and Figure 20 illustrate some of those visualization capabilities where economic dispatch set points and production costs are displayed.

Subtask 2.2.6**: Establish reference case for validation of toolkit**
Three main components form the base case to be employed for validation of the toolkit: (i) generator characteristics, (ii) solar generation time series, and (iii) demand time series. A base case with data representative of the Arizona Public Service (APS) territory has been assembled from different sources as explained in the following paragraphs.

Main generator characteristics such as generator type, fuel, power rating, and technology were extracted from the APS Integrated Resource Planning report [52]. Generator costs curves, ramp rates and other parameters necessary in the formulation of the unit commitment problem were extrapolated from those main generator characteristics in order to maintain the consistency of the data.

Solar generation time series for existing plants in the APS territory were obtained from the Western Wind and Solar Integration Study (WWSIS) phase 2 by approximating their current location [53]. These time series correspond to the calendar year 2006 and represent the close to 500 MW of currently installed solar generation in APS. Additional time series for 32 new potential solar power plant locations were also obtained, corresponding to an additional 3 GW of installed capacity (see Figure 21 for an example). These time series allowed for simulation of very high solar energy penetration levels. Energy demand time series were obtained from APS.

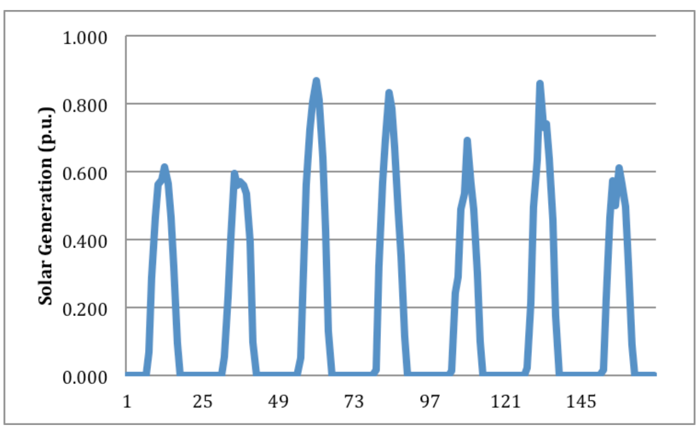



**Figure 21, Solar time series sample from a new potential solar power plant site in the APS territory for a one-week period**

Subtask 2.2.7**: Validation of toolkit using reference case**
We performed validation of the toolkit using the base case mentioned in the previous section.

Subtask 2.2.8**: Documentation and dissemination of software and results**

A talk about the toolkit was presented at the Technical Conference to Increase Real-Time and Day-Ahead Market Efficiency through Improved Software organized by FERC June 23-25. Many in the audience were interested. A similar talk including simulation results was given at the UVIG Fall meeting in San Antonio in October.

Subtask 2.2.9**: Update software and documentation based on user feedback from the October 2014 UVIG workshop**
Feedback was received during the UVIG workshop regarding reserve rules for deterministic operation with very high penetration of renewables. It is clear that current reserve values will be insufficient to deal with very high penetration of solar and that new rules must be employed in order to maintain the reliability of the system. A couple of papers outlining methodologies to calculate reserve requirements was reviewed and changes to the toolkit were performed.

Milestone 2.2**: Demonstrate accuracy or stochastic process models (SPM) for solar plant output and solar plant forecast compared to historical data**
We investigated metrics for assessing solar forecast accuracy. Several metrics exist originated from different backgrounds such as statistical metrics, variability estimations, uncertainty quantification, ramping metrics and economic metrics [54]. We employed a set of them to compare the set of solar forecast scenarios against their corresponding point forecast. In general, the stochastic process models performed within the error distributions given by the available historical data.

Milestone 2.3**: For a case study, demonstrate a reduction in system price variability compared to a deterministic operation of the system (standard deviation)**
After validation of the toolkit, we simulated a one-year period. Production costs from this one-year study were employed to compare system energy prices when deterministic and stochastic UC approaches are employed. Results showed a general trend were energy system clearing price volatility was reduced.

**Final Deliverable: A first version of the toolkit and its corresponding documentation will be made available to stakeholders. A webinar showcasing the toolkit's functionalities will take place a few weeks after the completion of milestone 2.2. Suggestions will be collected from stakeholders for future improvements.**
As demonstrated in the previous sections addressing each of the subtasks, we completed the stochastic operations toolkit and named it PRESCIENT. We did a two-hour session at the UVIG Fall Technical Workshop (Oct. 15-17) to introduce the toolkit to the audience, generally composed of utility staff involved in the integration of renewable energy.

**TGI Task 3.1: Small signal stability analysis for high penetrations of distributed solar**
The goal is to quantify the impact of large-scale behind-the-meter solar penetration on small signal stability of the WECC. This will be accomplished by performing PSLF

simulations of the WECC with newly developed composite load models (CMPLDWg). The composite load model parameters will be adjusted to reflect a large penetration of distributed solar generation. In addition, we will analyze PMU data to correlate the presence of an East-West mode that has been observed in PSLF simulations with high penetrations of renewables.

This task was pushed back into FY15 because of delays in receiving probe test data from Peak Reliability Corporation. Data from previous years is not suitable because it does not contain PMU data from Colorado and Wyoming necessary to complete this study.

We worked with Kara Clark and Nick Miller and requested permission to use the high-mix renewable base cases with the composite load model that were developed by GE for the WWSIS Phase 3 project. Kara supplied SNL with the cases in January 2015. The cases have been evaluated and simulations have been performed. Analysis is underway.

SNL collaborated with Dr. Dan Trudnowski from Montana Tech University in the analysis of PMU data to evaluate the characteristics of the East-West mode in measured data from the actual system. Probe test data was received from BPA and Peak RC. The intent of the probing tests is to modulate the real power flow on the PDCI in such a way that the frequency domain characteristics of the system can be estimated. There were many days which yielded useful results for the analysis of the East-West mode. In simulation, the East-West mode was estimated at 0.41Hz and in measured data the mode was estimated at a frequency of 0.42Hz. Figure 22 below shows a comparison of the mode shape of the East-West mode derived from measured data and simulation respectively.

The mode shape estimates presented in Figure 22 are in strong agreement. The primary difference in the shape estimates is not the observed behavior, but the points at which the mode was observed. This stems primarily from the fact that in simulation it is possible to monitor every bus in the system, whereas in the real system we are limited to the locations which have PMUs or similar devices installed.

In FY15 Sandia worked with NREL and GE to obtain high penetration WECC base cases produced for the Western Wind and Solar Integration Study Phase 3 (WWSIS3). These base cases are currently being used to assess the change in small signal stability in response to an increase in PV penetration. One of the key differences with these cases is that they employ the WECC composite load model. How the load is represented dynamically has a non-negligible impact on the simulated system response. This represents an important sensitivity to be explored in this effort.

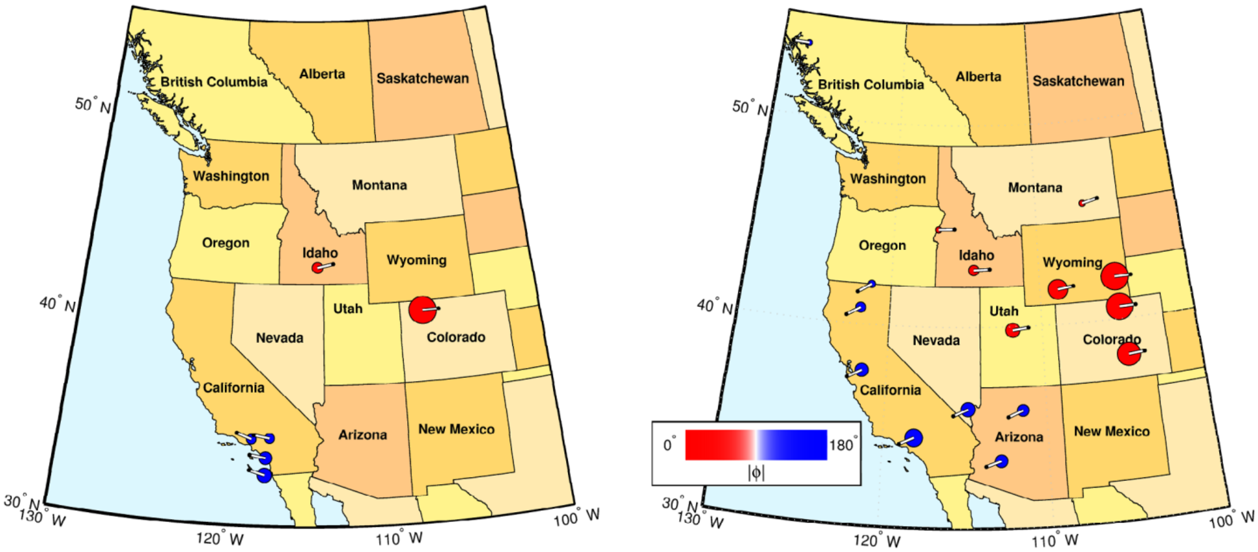



**Figure 22, East-West mode shape estimation derived from measured data (left) and simulation (right)**

Figure 23 presents an illustration of the differences in the system response as measured at two substations during a Chief Joseph Brake insertion. In Southern California the frequency nadir was observed to be lower with the composite load model than with a traditional ZIP model.

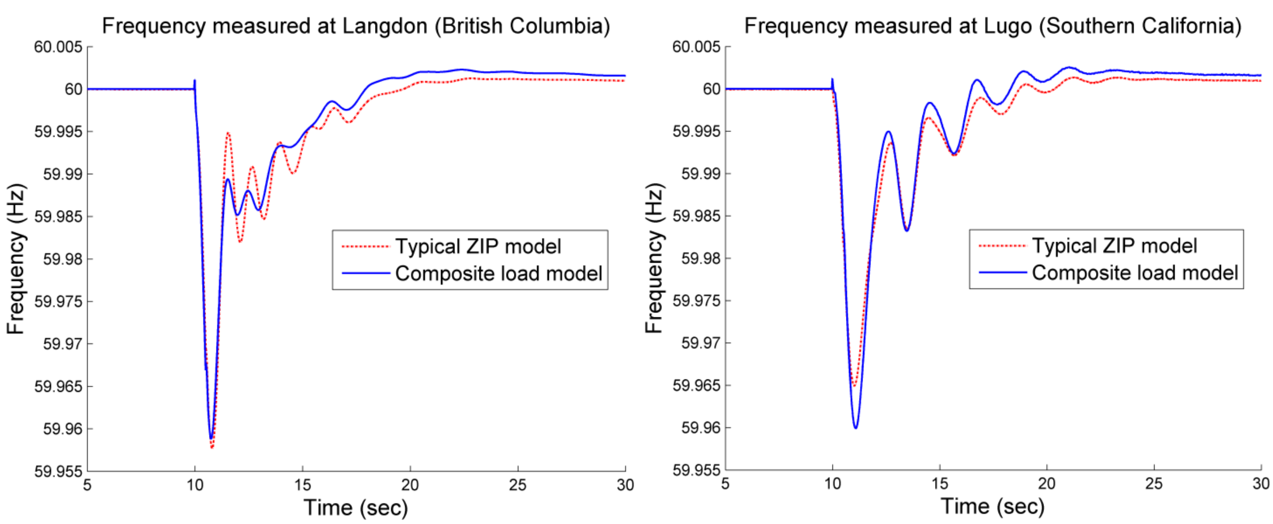



**Figure 23, Measured frequency in response to a Chief Joe Brake insertion**

## TGI Task 3.2: Develop a stochastic resource adequacy study with significant solar energy penetration

Capacity Planning is a highly complex problem that must consider the output uncertainty associated with high penetration of variable generation (such as those envisioned in SunShot scenarios), in addition to uncertainties in peak demand, generator reliability, evolving policy relative to carbon emissions, and fuel price volatility. In contrast with current planning methodologies, a stochastic planning model allows for explicit consideration of these uncertainties in order to mitigate the risk by minimizing both expected cost and conditional value at risk (CVaR). This will result in a generation expansion plan that is more robust and which is not limited to a very small number of arbitrary capacity planning expansion scenarios. This effort involved a close collaboration with Lawrence Berkeley National Laboratory. This task leveraged some of the tools (e.g., stochastic process models and optimization code) developed in Task 2.2 above.

Subtask 3.2.1**: Literature Review**
A summary of the literature review was presented in the first TRC. It focused on works from the last 7 years and included generation expansion and combined generation and transmission expansion methodologies, with and without renewables.

Subtask 3.2.2**: Extract data for base case that will serve as test case for our model using Arizona Public Service (APS) 2012 Integrated Resource Planning (IRP). Have APS review the data and assumptions**
Data was collected from the APS Integrated Resource Plan report [52] in order to create a base case for use with the stochastic resource adequacy model presented below. The main data components of this base case were explained in the final FY14 report.

**Subtask 3.2.3: Review completeness of base case with Technical Review Committee (TRC) and propose ways to substitute missing data**
A preliminary test case is complete. We presented an overview of the test case and associated assumptions in the TRC conference call at the end of July.

Subtask 3.2.4**: Formulate a resource planning model that incorporates fuel prices, peak demand, variable generation, generator reliability and other relevant quantities as inputs**
One option for including Variable Energy Resources (VER) in traditional capacity expansion models, an option often used in practice by planners, is to assign fixed, pre-determined capacity credit to VER based on historical information. In this case any amount of VER built by the model will contribute this fixed amount to meeting the planning reserve margin. This is a reasonable first approximation, but it suffers from two major shortcomings:

- The true capacity credit of VER depends on the overall conditions of the system (e.g. the capacity credit of PV may depend on the amount of wind in the system).
- The true capacity credit, particularly for solar, is known to decline with increasing penetration levels. As penetration levels increase, solar generation displaces the peak net load from the late afternoon to the early evening, when solar resources are no longer available. This results in a significant reduction of the marginal capacity value of new solar resources, a feature that is not captured using standard planning methods that rely on pre-computed capacity credits. A constant assumption for that capacity credit will not reflect this reality and therefore lead to suboptimal investment decisions.

One of the main challenges of this task is the development of a new methodology capable of endogenously computing the capacity value of solar resources within the investment-planning model. We have developed two methods to capture this feature within our stochastic capacity planning model.

Our first approximation is aimed at computing the average capacity factor of solar resources within a certain fraction of the peak net load hours. This approach endogenously captures the negative effect of increasing penetration levels on the capacity value of solar technologies. However, maintaining linearity in the formulation of the stochastic capacity planning model involves the introduction of several hundred new auxiliary binary variables and constraints, which makes computation of an optimal investment solution significantly harder. A second disadvantage of this approach is its sensitivity to rare events in the input data when identifying the average time window of the daily peak net load hour. For instance, a single cloudy afternoon, when solar resources are not available during the peak load of the day (i.e., peak net load equals to peak load), automatically biases the selection of the average peak net load for the entire year. Due to these limitations, we develop an alternative approximation method that is both computationally simpler and more robust to rare events in the input data than the one descried in this paragraph.

The second approach is based on the intuition behind a reliability metric called the “expected unserved energy” (EUE). EUE measures the amount of demand that needs to be shed when demand exceeds generation. We use the concept similar to the EUE measure to create a constraint that ensures similar adequacy across all solutions to the investment problems.

In particular, we model a demand response program where DR is put on standbv (or “deployed”) in case of a generator outage any time that the net load exceeds the available capacity, where available capacity is defined as the total aggregate conventional capacity derated by the traditional planning reserve margin. In effect, DR is put on standby during times when the system is at high risk of being inadequate. We then replace the conventional peak load plus planning reserve constraint with a constraint that limits the total amount of DR that can be put on standby over a year (i.e. a DR budget, similar to a constraint that requires a constant EUE).

This definition of DR deployment and the DR budget are sufficient to specify the total amount of generation capacity that needs to be built to maintain adequacy in a particular scenario.

Figure 24 shows peak load days, and the installed capacity that is required so that the DR budget is equivalent to 0.01% of the annual demand.

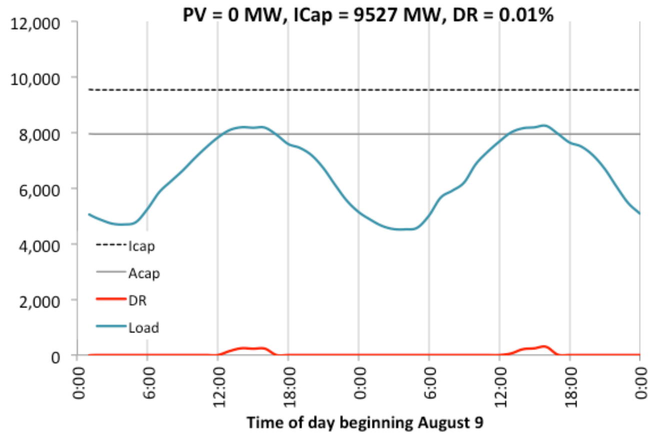



**Figure 24, Deployment of DR on peak load days without any PV**

If the model were to choose to build additional PV, less DR would need to be deployed if the installed conventional capacity were also to be kept constant as shown in Figure 25.

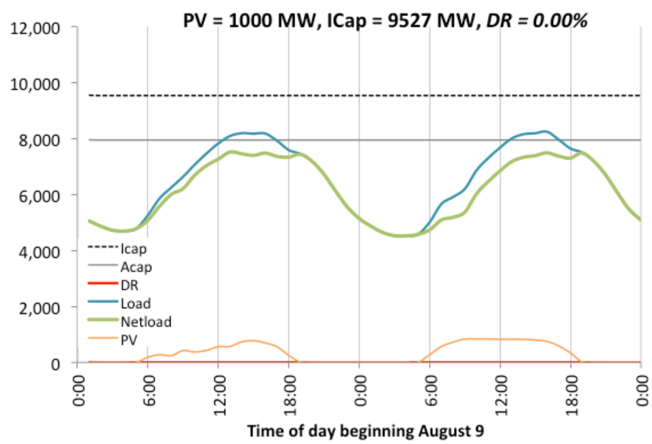



**Figure 25, Adding PV without changing the installed capacity of conventional generation leads to low deployment of DR**

Since the model is trying to minimize cost, it will choose to build less conventional generation until the DR budget is once again a binding constraint as shown in Figure 26.

This leads to less installed conventional capacity when PV is added while maintaining the same DR budget. This DR budget and definition of when DR needs to be deployed are added as constraints to the long-run planning model. We do not need to externally specify the capacity credit, it is endogenously calculated.

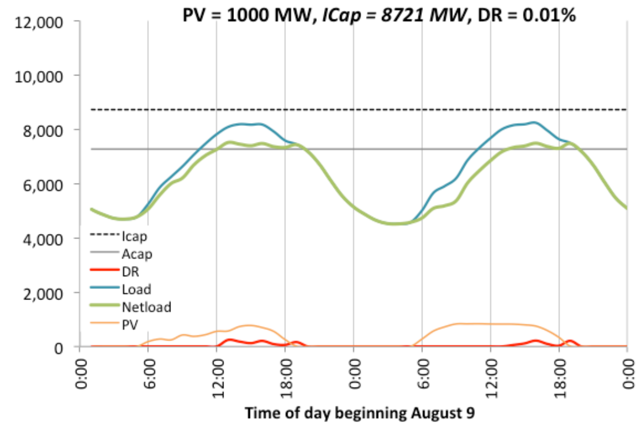



**Figure 26, Installed capacity can be reduced by 800 MW before bringing the DR deployment back up to 0.01% of the annual load**

We validate this formulation by setting up a simple version of the model with high costs of VER (such that none are built by the model) then add an increasing RPS requirement that is met by wind or PV. We estimate the implied capacity credit calculated in the model by comparing the amount of conventional generation built with and without VER as shown in Figure 27.

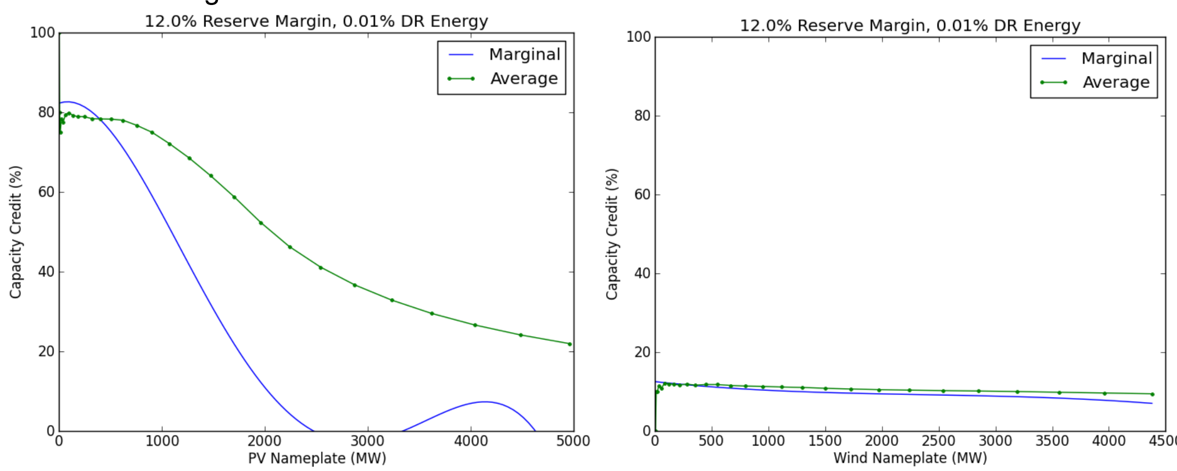



**Figure 27, Implied capacity credit estimated with increasing penetration of PV (left) and wind (right)**

The endogenous capacity credit estimated in the model matches the general expectations from other detailed analysis of the changing capacity credit of PV. One survey of the literature [55] shows a similar decline in the capacity credit of PV to what is calculated in this model. This is illustrated in Figure 28.

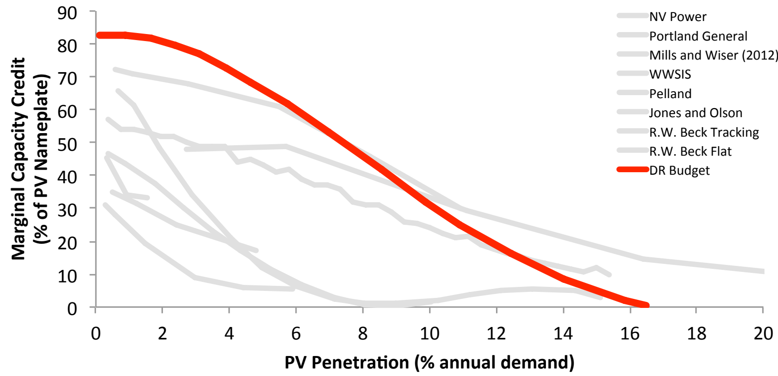



**Figure 28, Estimates of the capacity credit of PV with increasing penetration levels [55]**

**Subtask 3.2.5: Implementation in Pyomo**
The formulation has been implemented in Sandia's python optimization modeling language (Pyomo). Figure 29 shows results from a deterministic run using the Pyomo implementation.

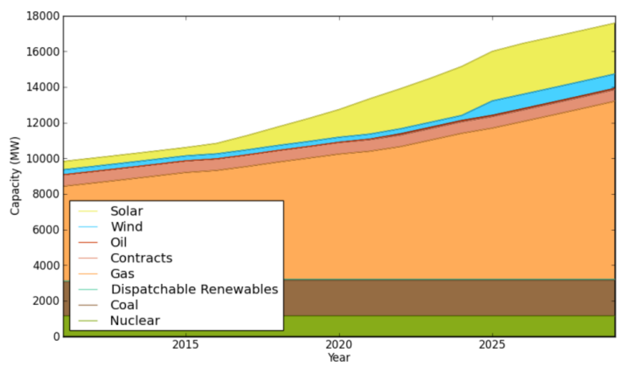



**Figure 29, installed capacity results for a deterministic run using the capacity plan formulation implemented in Pyomo**

Subtask 3.2.6**: Determine data set to employ for stochastic process models**
Data was collected from different sources to develop the different stochastic process models. Solar power production data corresponds to historical APS solar production and to potential new sites, and is also being used in the stochastic toolkit development. Fuel price information was obtained from the Energy Information Agency (EIA) for the state of Arizona. Load growth data was extracted from the 2014 APS IRP report and capital costs of solar plants were gathered from several sources such as the projections NREL and the EIA.

Subtask 3.2.7**: Review data set for 3.2.6**
The base case data and stochastic process models data was presented at our second TRC teleconference which took place on July 30. The TRC provided positive feedback. This subtask has been completed.

Subtask 3.2.8**: Develop stochastic process models**

Capacity planning is a process with a great deal of uncertainty in its inputs due to the long planning horizon, generally in the 15-30 year range. In the following sections we explain how the uncertainty of those inputs can be captured by stochastic process models and similar methods.

*Solar Energy Uncertainty*

Our problem formulation calculates the capacity factor endogenously, eliminating the need for assuming a constant value of it. We have developed two scenario-reduction frameworks to accurately compute production costs and net load profiles where reliability might be threatened, while reducing the computational complexity of the multi-stage stochastic capacity planning model. Both scenario-reduction algorithms use the full distribution of loads, wind, and solar parameters as inputs (e.g., 8,736 observations for a representative year) and provide a set of representative scenarios as outputs (e.g., 100 representative observations). The first method is based on the k-means clustering algorithm, which groups scenarios of similar characteristics into “clusters” (e.g., high load and high wind conditions or low load and low solar availability). The second method selects the sample of observations that best matches the statistical characteristics of the full dataset (i.e., means, standard deviations, and correlations). Our next goal is to compare the performance of these two scenario-reduction frameworks in the stochastic capacity planning model. Figure 30 illustrates how k-means clustering is applied to renewable energy and load profiles.

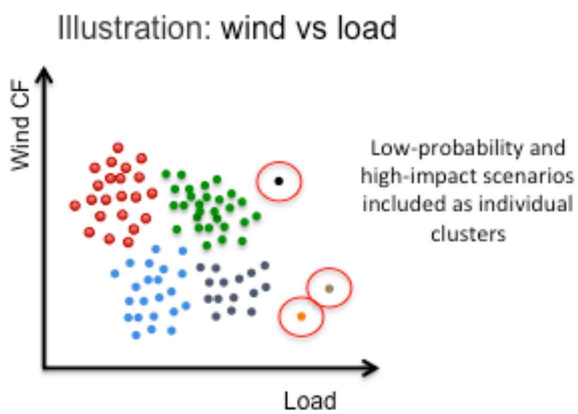



**Figure 30, Illustration of k-means clustering applied to wind and solar profiles**

*Fuel Price Stochastic Process Model*

Fuel price scenarios are generated using a mean reverting model. In short, a mean reverting model uses historical price data to predict future prices. Therefore, the assumption made is that future prices will behave in a similar fashion to the historical data. The mean reverting process also has a random component that simulates short-term deviations from average trends. A detailed discussion on the implementation of a mean reverting model for natural gas prices, its advantages and disadvantages is found in [56].

Price data for different types of fuel can be obtained from the Energy Information Agency (EIA) and the mean reverting model is fit to it. An example of a lognormal fit to historical natural gas prices in Arizona adjusted for seasonality is shown in Figure 31.

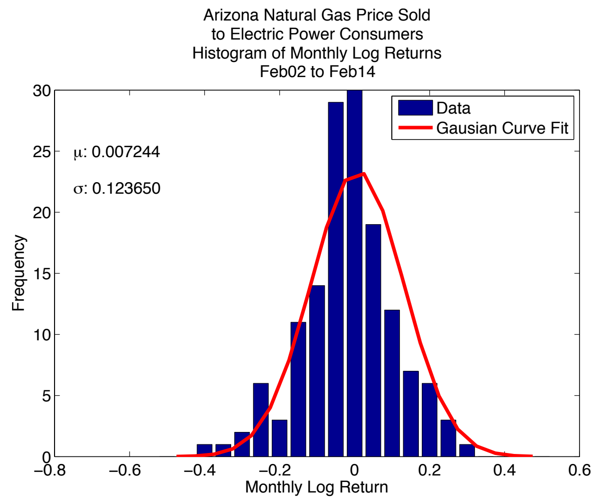



**Figure 31, log-normal fit to historical natural gas prices in Arizona adjusted for seasonality**

Once the model is fit to the historical data, scenarios can drawn by running the model multiple times to obtain random sample paths with prediction of future prices. Figure 32 shows ten price scenarios for natural gas prices predicted 15 years into the future.

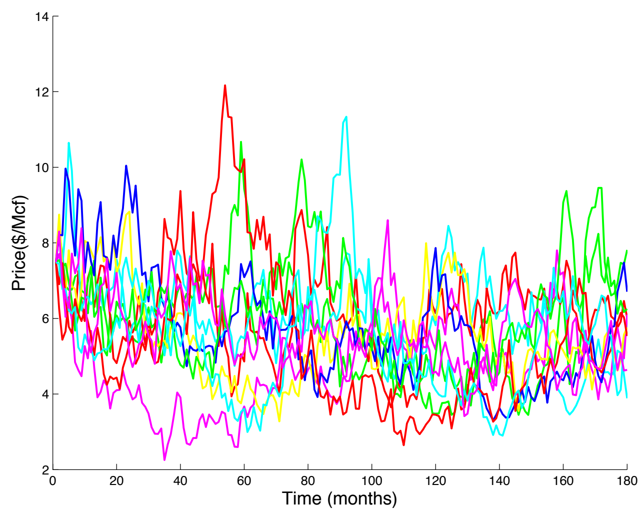



**Figure 32, Fuel price scenarios for natural gas prices in Arizona generated using a mean reverting model**

*Load Growth Stochastic Process Model*

Load growth depends upon many factors such as economic growth, population growth, weather patterns and events, and many more. Additionally, current advances in energy efficiency and distributed generation also affect the overall energy demand and peak load that a utility experiences. APS acknowledges the uncertainty in load growth due to all these factors by producing a probabilistic load growth forecast as shown in Figure 33, where confidence intervals are provided in terms of quantiles around the forecast.

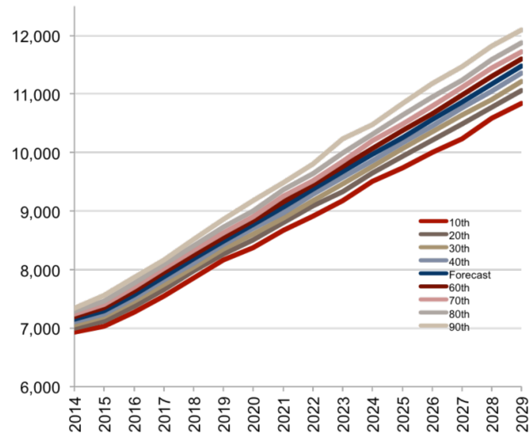



**Figure 33, APS load growth forecast with confidence levels provided as quantiles**

A stochastic process model can be developed based on the probabilistic load growth forecast provided by APS in order to obtain peak load scenarios through all years in the problem horizon. This model generates scenarios as follows:

1. Since the quantile boundaries are given for confidence levels between 0.1 and 0.9, sample a uniform distribution between 0.1 and 0.9 *n* times to create *n* peak demand scenarios.
2. For each of the *n* samples, calculate the peak demand for each year as the linear combination of the upper and lower 10% quantiles. This ensures that correlation is maintained from year to year.
3. A scenario is composed by collecting the peak demand values over all the years in the planning horizon resulting in a time series. Each scenario has a probability of 1/*n*.

*Capital Costs of Solar Plants*

A literature survey revealed that (i) estimates of future capital costs of solar vary greatly, and (ii) the capital costs of solar power plants may vary across regions and plant sizes. For these reasons three potential scenarios were extracted from literature projections to capture this uncertainty. These scenarios were presented in the final FY14 report.

Subtask 3.2.9**: Perform initial analysis using between 10-100 total scenarios to estimate computational effort**

Subtasks 3.2.9 – 3.2.11 and their corresponding milestones were canceled by the DOE technical monitor due to reduction in carry-over funds.

Go/No-Go Decision**: Successful completion of the subtasks 3.2.1-3.2.7 mentioned above, culminating in the exercise of the stochastic model using deterministic base case data. Because of the difference in methodologies it is unpractical to compare results between the deterministic approach in the APS IRP and the solutions obtained from exercising the stochastic model in "deterministic mode." However, unexpected results can point at errors in the model.**

Subtasks 3.2.1-3.2.7 were completed as demonstrated in the previous sections. A base case has been assembled and the implementation of the stochastic capacity planning formulation has been tested in "deterministic mode" with a summary of results shown in Figure 29.

Final Deliverable**: We will deliver a report that includes descriptions of the stochastic resource planning model and stochastic process models developed. The report will also include results demonstrating the robustness and sensitivity of the solution. This report will be the basis of at least one peer-review publication. In addition to the report, software implementation of optimization and stochastic process models will be made available to stakeholders.**
The final deliverable was canceled by the DOE technical monitor due to a reduction in carry-over funds.

**TGI Task 4.1: Technical Engagement**
Sandia will contribute to ongoing bulk system standards development and engage in strategic technical outreach targeting stakeholders involved in bulk system planning and operations. Specifically, Sandia will work with NERC/FERC to address and resolve bulk system reliability issues related to solar (e.g. response to disturbances). Improved standards will facilitate greater penetration of photovoltaic generation, reduce integration costs, and improve reliability. Increased awareness by system operators and planners will facilitate quicker adoption of photovoltaic generation and better integration into existing systems.

Subtask 4.1.1**: Workshop on PV plant model validation per NERC MOD standards**
This workshop was conducted after the MATLAB model validation tool and associated guidelines were published.

Subtask 4.1.2**: Technical presentation at the UVIG annual meeting, UVIG technical workshop, IEEE PVSC, or IEEE PES**
Sandia made a technical presentations on interconnection standards affecting PV (and PV/wind) modeling and validation at the UVIG spring meeting in June. An abbreviated version was presented at the WECC June meeting. Sandia also delivered technical presentations at the IEEE PES meeting on the status of PV and wind generic model development.
Sandia has led a significant effort that includes participation from NERC and other stakeholders to incorporate voltage and frequency ride-through (V/FRT) requirements for PV and other distributed generation (DG) into the IEEE Standard 1547 (P1547). During the P1547 full amendment meeting kick-off meeting (April 2014), Sandia presented the technical principles that would allow V/FRT requirements to be harmonized with existing interconnection requirements. The framework is based on the notion that sensible V/FRT requirements can avoid stability concerns due to tripping, while avoiding unwanted interaction with protection systems. In support of this effort, Sandia completed and disseminated to the P1547 stakeholder group a V/FRT white paper proposing approaches required to harmonize voltage and frequency tolerance with other technical requirements. Following the initial consensus, Sandia coordinated

a core group that includes manufacturers, utilities and other stakeholders and jointly developed a proposed amendment to be included in IEEE 1547. This proposal was further refined during the June P1547 meeting, and a formal drafting team has been established to complete the draft language. In order to drive this effort to completion, Sandia intends to remain in a coordination role during the next two P1547 meetings.

Milestone 4.1**: Hold technical presentations/publications educating the community on how to properly model solar**

Sandia has conducted the following technical presentations at public meetings:

*WECC Variable Generation Modeling Webinar (November, 2013)*

- A total of 6 presentations were given, including one from Sandia, who also coordinated the webinar.

*WECC Modeling Workshop, Salt Lake City, UT (June 2014)*

- "PV Power Flow Modeling" (Ellis)_
- "Summary of PV Dynamic Models" (Ellis)
- "Model Validation for Large Scale PV Plants" (Elliott)

*UVIG Short Course on Integration of Variable Generation on Power Systems, Portland, Oregon (June, 2014)*

- "Solar Plant Model Development and Validation" (Ellis)
- "PV Plant Technology, Design and Operations" (Ellis)
- "DG Interconnection Screening, Study Procedures and IEEE Standard 1547" (Ellis)

*Sandia presented the following material at the IEEE PES meeting in Washington DC (July 2014)*

- "Experience with Model Validation of PV Power Plants" (Ellis/Elliott)
- "Small Signal Stability with High Penetration of Solar Generation" (Elliott)

*Presentations at the Sandia/EPRI PV Modeling and Reliability Symposium in Santa Clara, CA (May, 2014)*

- "PV Plant Variability" (Lave)
- "High Penetration PV – A Transmission Perspective on DG Standards" (Ellis)

To be completed by September 30

- " Implementation of Voltage and Frequency Ride-Through Requirements in Distributed Energy Resources Interconnection Standards " (SAND report)
- "PV Generic Modeling Guidelines" (SAND report)

In addition, Sandia has been working with the Center for Public Utilities Advisory Council to organize the “Current Issues 2014” meeting in Santa Fe on March 9-12, 2014. Sandia hosted a tour of the Photovoltaic Systems Evaluation Laboratory and the Distributed Energy Technology Laboratory, and organized a panel discussion on various technical issues. The panel discussion was attended by approximately 50 people. One common theme was that an unbiased source of technical information would greatly benefit regulators who are regularly pitched ideas from different organizations with a financial or political motive.

Final Deliverable**: Materials from the workshop and technical presentations (e.g. conference paper).**

Workshop and technical presentation materials were packaged and delivered to DOE.

## Project Results and Discussion: Tasks for Year 3

### TGI Task 1.5: Develop and publish a set of modeling guidelines for short circuit analysis

**Subtask 1.5.1: Perform a technical review of existing short circuit models**
A technical review was performed and presented in the Q2 report for FY15.

**Subtask 1.5.2: Collect laboratory data against which models can be validated. If test data is not available, employ manufacturer specific models in PSCAD or data from manufacturers.**
In order to understand and characterize the dynamics of a fault and its impact on the components of an inverter, simulations will be performed on different inverter topologies starting with one of the simplest (Real Power Control Only) according to the different Inverter Control Schemes and ending with a more complex topology that encompasses the control of real and reactive power by means of current d-q decomposition commonly known as constant current control. All the simulation models were developed in Simulink with the aid of the SimPowerSystems (SPS) library. Due to space limitation, only a couple of the configurations studied are presented. Further details were provided in the slides for the Q3 FY15 review.

***Basic inverter with only real power control and no saturation limits***
Figure 34 shows a basic configuration of a grid-tied inverter where the only controlled parameters are: the real power by means of a PI controller, and the inverter's frequency by means of a Phase Locked Loop (PLL).

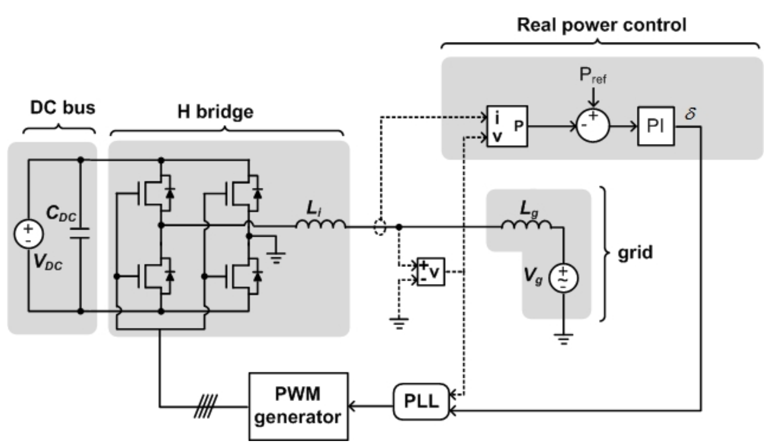



**Figure 34, Basic inverter topology**

The main components of the aforementioned system are described as follows:

- **DC bus.** This part is characterized by using a DC power supply that represents the DC output from the solar array and the corresponding power conditioning units such as a high frequency isolation transformer. At this point it is important to point out that the main purpose of the front end power conditioning units that follow the solar array is to provide a regulated DC input to the inverter (H Bridge), therefore and for simplification of the analysis (mathematical modeling), a DC power source is used [57, 58]. Another important element is the capacitor $C_{DC}$ usually used for filtering purposes because of the intrinsic switching nature of the inversion process.

- **H bridge and inductor filter.** The H bridge is the device that actually performs the inversion from DC to AC, based on the order of commutation (modulation) of the four IGBT's which in this analysis will be the Sinusoidal Pulse-Width Modulation (SPWM) scheme. Inductor $L_i$ serves as a current smoothing device that filters out the high harmonic content and provides a clean 60 Hz current to the grid. For a detailed analysis of the H bridge and SPWM theory see reference [59].
- **Real power control.** As stated before, this is one of the simplest topologies based upon the control schemes used during the dynamical behavior of the inverter. In this particular topology, a real power reference is set by the user and if the amount is whit in the power limits of the inverter the PI controller tracks this reference by actuating over the power angle δ of the system via the PLL until the desired real power output is reached. Moreover, since the output of the PI is not upper bounded (saturation limit), the inverter can increase the power angle as much as $P_{ref}$ demands at the expense of leading the system to instability as in the case of a synchronous machine connected to an infinite bus.
- **PLL.** Regardless of the power control strategy of the inverter, a PLL device will always be present on every grid-tied inverter. Its sole purpose is to synchronize the frequency of the inverter with the frequency of the grid by means of the reference voltage provided at the interconnection point between the inverter and the grid. The PLL implementation, either by merely hardware, or by software (DSP), must be adequate to handle and process the fundamental frequency and filter out its harmonics. Therefore special attention must be taken when designing the internal low pass filter of the PLL. Reference [60] covers this PLL theory in full detail.
- **PWM generator.** The PWM generator coordinates the switching of the IGBTs of the H bridge based on the synthesized frequency value provided by the PLL. The scheme used will be SPWM in which a high frequency triangular waveform is compared with a low frequency (60 Hz) sinusoid and the result (output) of this comparison drives the switching of the IGBTs [Mohan].
- **Grid.** This block represents an infinite bus along with the transmission line inductance of the system $L_g$.

For this topology a continuous time mathematical (average) model was derived. The analysis gave a set of 7 space-state equations that, when solved numerically, fully matched the average dynamic behavior of the inverter with the switching devices. One of the main advantages of the average model is that the simulation times are 3 to 5 times faster than the complete switching model.

Figure 35 shows the current of this type of inverter under faulty conditions. Before fault inception the inverter was delivering 10kW to the grid with no control over the reactive power. The fault lasted for 5 cycles and since there is not any type of protective limiter it can be notice that the current reaches up to 4 times the steady state current.

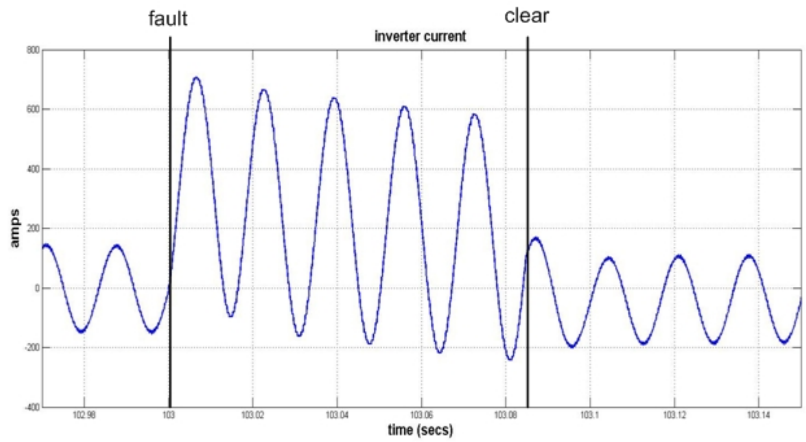



**Figure 35, Inverter with only real power control and no saturation limits**

### *Advanced inverter control (d-q current control with hysteresis)*

This topology is quite similar to the one on the previous section except for the fact that it uses a comparator with hysteresis to trigger the IGBT's instead of using a PWM switching scheme. Figure 36 shows the diagram of this topology where it can be noticed that the two inputs to the hysteresis comparator are: the reference current, and the actual current sensed at the inverter's terminals. It can also be noticed that the reference current is synthesized by means of $I_{d-ref}$ and $I_{q-ref}$ and their respective PI controllers.

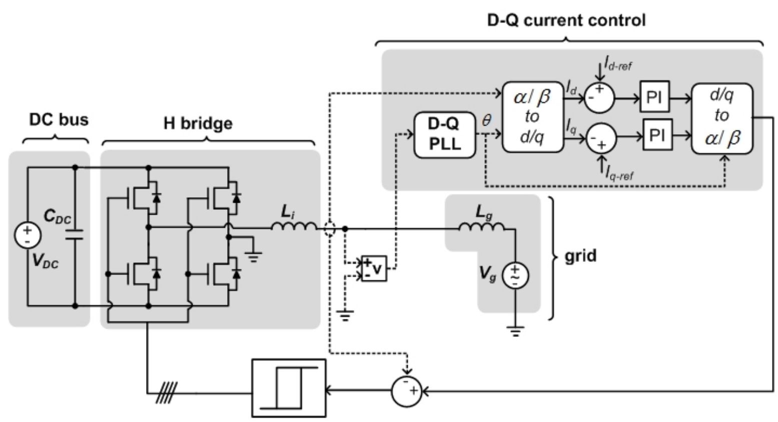



**Figure 36, Inverter with hysteresis switching scheme**

The logic behind this switching scheme is as follows:

- If $I_i \leq I_{ref} - \delta$ then IGBT's A and A' will turn on, and B and B' will turn off.
- If $I_i \geq I_{ref} + \delta$ then IGBT's B and B' will turn on, and A and A' will turn off.

Figure 37 helps to visualize the previous switching logic. The plot in the bottom shows a zoom in of one portion of the upper figure where the two compared currents $I_{ref}$ and $I_i$ are plotted. Point A in the plot helps to identify the point of occurrence of the first statement of the aforementioned switching logic and point B accounts for the second statement. Notice how at these points the slope of the inverter current changes abruptly due to the comparator action and how the reference current tracking is performed within the hysteresis band.

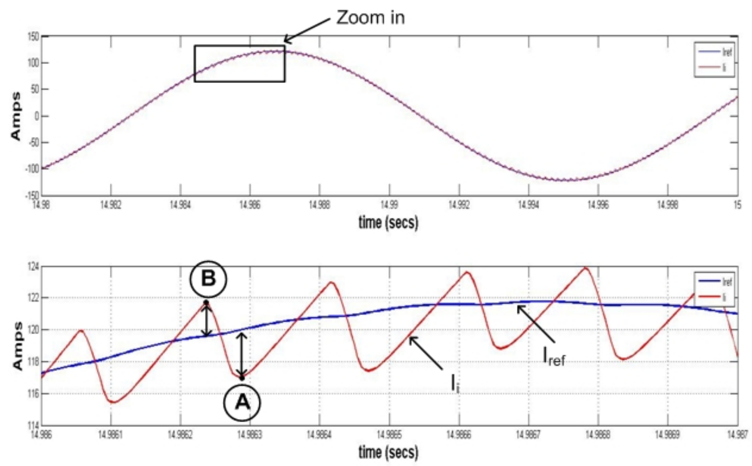



**Figure 37, Inverter with hysteresis currents**

Since the control scheme is exactly the same as with the PWM switching scheme, the dynamics of the hysteresis inverter under faulty conditions are basically the same as with the PWM scheme. Figure 38 shows three plots of the hysteresis inverter under a fault that lasted 5 cycles: the upper plot shows the fault current, the plot in the middle shows the voltage at the inverter's terminals, and the lower plot shows the inverter current. From this figure it can be noticed that at fault inception the inverter voltage is collapsed and the fault current increases significantly but the inverter contribution to the fault current is basically zero since there is not significant increase on its magnitude during the fault. Therefore, the fault current is merely provided by the grid. The in deep analysis explained for the PWM scheme applies for this topology as well, thus, the d-q current control scheme is inherently protecting the inverter by limiting its current capacity during faulty scenarios.

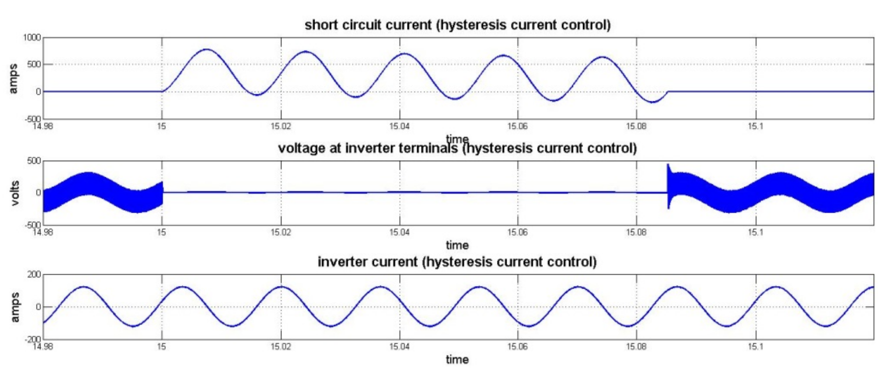



**Figure 38, Inverter with hysteresis under faulty conditions**

**TGI Task 1.6**: Continue to provide leadership and strategic advice to the WECC Renewable Energy Modeling Task Force in FY15

The process of revising IEEE Standard 1547 is well underway, with the Sandia team[1] continuing to be strategically engaged in ensuring that this revision process provides a balanced consideration of bulk power system security concerns related to distributed generation interconnection. This engagement includes drafting proposed standard clauses, leadership of the standards writing process related to disturbance ride-through and drafting of proposed standards text, participation and technical leadership in the technical debates surrounding these issues, and generally building consensus across the working group's varied interests.

The focus of the Sandia-supported effort is now on ensuring that the disturbance ride-through standards developed are both effective in meeting the goal of supporting bulk grid security, and are not so excessively stringent that approval of the final standard draft by the broader industry balloting group is jeopardized. This was complicated by the conflicting interests of an internal-combustion engine generator constituency whose existing equipment are inherently limited in their capability to withstand long-duration low-voltage periods without losing synchronism (transient instability) and certain utility constituencies desiring very extreme fault ride-through standards. The latter is not so much driven by bulk system security, but rather the extreme ride-through this group desires relates to mitigating distribution power quality issues related to high penetration of DER. Leadership provided by the Sandia team has diplomatically crafted an approach that can satisfy these diverse interests and facilitate progress in the standard development.

The new IEEE P1547 working group has met three times during 2014, and once in 2015 with two additional meetings scheduled for 2015. The bulk of the standards development drafting activity now delegated to sub-groups focused on specific areas. The Sandia team is particularly focused on Clause 4.2, which specifies DER behavior during faults and other system disturbances. Reigh Walling has been designated as a co-facilitator of this sub-group, and has been responsible for developing the actual standards wording considered by the group.

The participation of the Sandia team has been critical to the goal of producing a clear, effective, and acceptable standard. One challenge is that the majority of IEEE 1547 working group participants do not have formal standards writing expertise, and thus have not honed the art of crafting clear, unambiguous, and loophole-free technical requirements that will ensure that future DER will be designed, interconnected, and operated such that the DER do not unduly compromise the security of the bulk grid. The Sandia team has been providing the detailed draft standard writing support, attentive to the desires of the working group membership while keeping focus on the target objectives. Balance and introspective analysis and evaluation of these provisions have been offered by the Sandia team to coax the standard's trajectory toward a focus

[1] The Sandia Team for this IEEE 1547 revision activity consists of Abe Ellis and Sig Gonzalez, along with Reigh Walling of Walling Energy Systems Consulting, LLC under contract to Sandia National Laboratories.

on a standard that can be successfully balloted and adopted, across the U.S. in areas of both high and low DER penetration.

The continued participation of the Sandia Team, and the technical study support the team will provide to the working group, are essential in bringing this standard revision process to a successful completion.

**TGI Task 3.3: Perform a probabilistic production cost study**

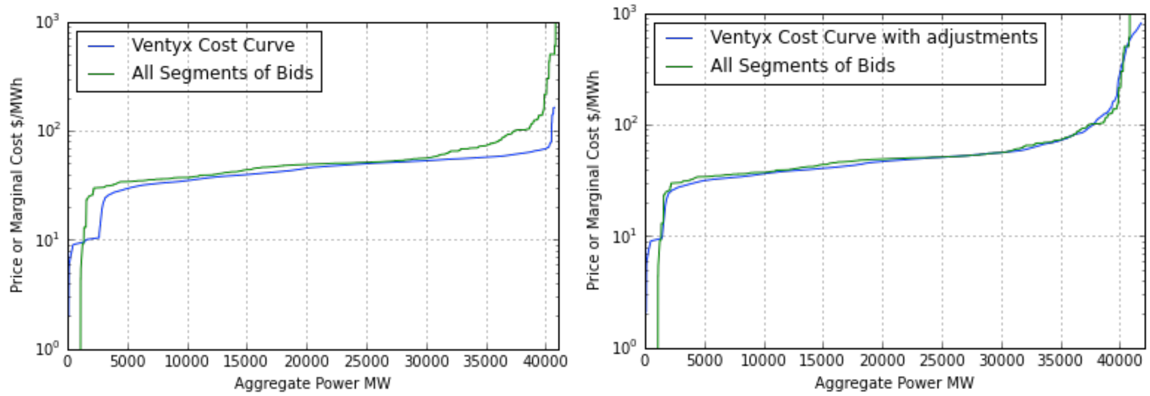
**Subtask 3.3.1: Identify data set for use in stochastic process modeling**
CAISO bid data provides the most realistic view of the characteristics of generation participating in the CAISO market. Public bid data, however, does not include all of the relevant parameters needed to simulate the commitment and dispatch of the generation. Ventyx Velocity Suite, on the other hand, collects physical unit-by-unit data on a broad range of specific generators. These include coefficients that describe fuel consumption as a function of dispatch,[2] maximum generation, ramp rates, etc. There is no guarantee that market participants create market bids using the physical characteristics of plants reported by Ventyx. The solution to this problem is to match the detailed unit-by-unit Ventyx data to the overall behavior of the CAISO bid curve data.

The first step is to create a supply curve from all CAISO bids. To do this we sorted each segment of a bid from lowest price to highest price for all bid segments in the CAISO market covering the peak hour of 2014. This bid curve is shown in green in Figure 39.

The second step was to create a similar supply curve from the unit-by-unit Ventyx data. First each unit was sorted from lowest variable cost to highest variable cost, then for each demand level a marginal unit was found. Infra-marginal units were then dispatched at full output and the marginal unit was set to cover the remaining load for all demand levels. The resulting variable cost of the whole system (including no-load costs) was then smoothed using a moving average function. The slope of this variable cost curve is then the marginal cost curve from the Ventyx data (Figure 39a).

This approach leads to good agreement with the bid curve except at low demand and high demand. To fix the load demand, one nuclear unit was removed from the Ventyx dataset. To fix the high demand, the A2 parameter was scaled up for units that were above 30,000 MW in the merit-order ranking, and additional high heat rate CTs and internal combustion units were added. The final adjusted Ventyx cost curve (Figure 39b) is in close alignment with the CAISO bid curve data across a wide range of demand levels.

[2] These coefficients are A0 – the no load fuel consumption, A1 – the coefficient between fuel consumption and dispatch level, and A2 – the coefficient between fuel consumption and the square of the dispatch level.




(a) (b)

**Figure 39. Supply curves for CAISO based on bid data, Ventyx data (a), and adjusted Ventyx data (b)**

**Subtask 3.3.3: Formulate appropriate model for stochastic variables, including load and variable generation**

This capability was demonstrated in subtask 2.2.4 in FY 14. Further improvements were described in the Q3 FY15 report.

**Subtask 3.3.4: Solve the SUC problem with respect to a set of scenarios, using a computationally efficient and robust sampling and clustering technique that uses a reduced number of scenario samples.**

We used the CAISO test case to run several simulations with scenario samples representative of several loading and weather conditions. The results show that savings in the order of 2-4% of total production costs are attainable with stochastic operations. The savings vary depending on PV penetration levels, reserve policies and fuel costs. Additionally, lower volatility of energy prices, and lower curtailment of renewable energy were also achieved.

**TGI Task 4.1: To disseminate technical information about high penetration solar to key stakeholders**

Sandia participated in the 2014 UVIG workshop by organizing a two-hour Stochastic Unit Commitment Tutorial (Cesar A. Silva-Monroy and Jean-Paul Watson) and participating in the Distributed Generation Applications session (chaired by Abraham Ellis). Sandia also submitted a manuscript titled “Endogenous Assessment of the Capacity Value of Solar PV in Generation Investment Planning Studies” (Francisco Munoz, Andrew Mills) to the IEEE Transactions in Power Systems Journal. Abraham Ellis also presented at the IEE PES General Meeting on “PV plant modeling and model validation”, at the 2015 UVIG technical workshop on “Contemporary Issues on PV Integration,” and presentation at the WECC SPSG subcommittee meeting on Nov. 2015.

## Conclusions

The unifying goal of the Sandia Transmission Grid Integration (TGI) program has been to reduce grid access barriers to solar generation, a notion that is inseparable from the SunShot cost reduction target. Sandia’s TGI work was planned to achieve five three-year objectives, starting in 2013, covering all three TGI technical areas (MATI, SIST and $TA^2$). These objectives, together with a summary of what has been accomplished on each of them, are outlined below.

**Objective 1: Specify, validate, implement, and disseminate open electrical simulation models for transmission planning and interconnection studies**
SNL collaborated with members of the WECC Renewable Energy Modeling Task Force (REMTF) to develop generic electrical simulation models for utility-scale PV plants. These models were subjected to technical scrutiny by the WECC. These models are termed "generic" to allow parameter tuning within the models to represent different plant manufacturers and operation. These are reduced-order, positive-sequence models suitable for large area transmission studies that are performed by grid operators and planners. These models are publicly available to power system planners and renewable energy plant developers and are available in GE's PSLF®, Siemens PTI PSS®E, and PowerWorld.

**Objective 2: Benchmark and refine methods to estimate solar plant and fleet output**
We evaluated four different methods of estimating utility-scale PV plant variability given point sensor measurements. We found the most promising of these to be the Wavelet Variability Model (WVM). We refined and documented the WVM code (which was open-source), and released it publicly.

**Objective 3: Develop and demonstrate an advanced stochastic analysis tool to optimize system planning and operations for systems with high solar penetration**
We developed an advanced stochastic analysis tool for system planning and operations under conditions of high solar penetration. It is a security-constrained economic dispatch and unit commitment tool which is able to take into account not only the median solar forecast but a range of possible solar profiles when committing units for dispatch. We have called this tool Prescient.

**Objective 4: Evaluate technical feasibility of high penetration solar scenarios with respect to small signal stability**
We have evaluated the WECC, both as it exists today and in a high solar penetration scenario, for small-signal stability. We found that high PV penetration has a negligible impact on the likelihood of instability due to small-signal oscillation in the Western Interconnect.

**Objective 5: Emerging standards and policies will appropriately take into account technical characteristics of solar generation**
Throughout this project we have provided technical recommendations and advocated for changes to IEEE Standard 1547 (P1547) to mandate voltage ride-through (VRF) and frequency ride-through (FRF) for distributed energy resources (DERs), including PV inverters. Over the last three years, Sandia has led initiatives under NERC, UVIG, IEEE, and other stakeholder groups to establish the technical basis from the bulk systems perspective. Under this project, Sandia was a key contributor to a NERC

report (IVGTF 1.7). The lack of a DER VRT/FRT mandate is already of great concern to NERC, regional reliability organizations, and utilities. States such as California and Hawaii, where solar penetration is high and reserve generation is limited, have already established explicit VRT/FRT requirements. In these areas, a system-wide blackout is possible because distributed PV generation is likely to cut out when it is needed the most.

Given that solar penetration is growing fast in the continental U.S., a change in P1547 now can make a large difference in the reliability and stability of our power grids in the future. While the proposed VRT/FRT specifications have not been formally adopted in P1547, our technical engagement and advocacy has significantly raised awareness of this issue, and has made action much more likely. Under a parallel effort (Advanced Inverters), Sandia has worked with PV inverter manufacturers to implement VRT/FRT without compromising other functionality such as anti-islanding, which is a critical requirement for the industry to adopt VRT/FRT requirements.

We believe that this project has allowed us to make significant progress towards advancing transmission grid integration through lowering barriers, developing software tools to aide in the integration of high penetrations of solar, and creating/disseminating technical information to stakeholders involved in bulk system planning and operations.

## Path Forward

On PV system modeling (Task 1), Sandia, through REMTF, has developed aggregated PV models that are now approved for use in WECC, but there is an acute need to validate and refine those models in the near future. We are exploring possible avenues to work with EPRI in this area of high priority to utilities. Additionally, accounting for short circuit contribution from current-limited devices in interconnection and general transmission planning studies remains a challenge. The short circuit modeling platforms do not do a good job for two reasons: Firstly, the state-of-the-art modeling technique is based on a Thevenin approach (voltage behind fixed impedance) as opposed to a controlled current source. Secondly, the short circuit behavior of inverter-based generation varies rather significantly depending on the specific controls used, especially under unbalanced fault conditions. This is exacerbated by the lack of standards that specify short-circuit behavior. This applies to distribution as well as transmission.

On stochastic methods for planning and operations (Task 2-3) we forsee the value proposition for stochastic methods will increase because increased uncertainty in fuel costs, emissions policies and cost/penalty exposure, increased variable generation, and increase decision variables involving storage, demand response (including EV). The challenge now is to get system operators to adopt the advanced tools optimization tools over time.

On critical follow-through on V/FRT (Task 5) we need to ensure that the proposed modifications to IEEE 1547 get approved. If the proposed changes are not approved, it will be several more years before we can revisit, which puts distributed PV deployment at risk due to industry pushback on potential bulk system reliability issues.

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