The Photovoltaic Performance Modeling Collaborative (PVPMC)

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Abstract — **Sandia National Laboratories is forming the PV Performance Modeling Collaborative (PVPMC). This effort is aimed at improving confidence in PV performance model predictions by bringing traceability and transparency to the modeling process and encouraging third party validation of existing algorithms. Activities currently being pursued in this collaborative include: (1) developing a website (http://pvpmc.org), (2) developing a Matlab™ PV Performance Modeling Toolbox (PV_LIB), and (3) sponsoring periodic PV performance modeling workshops and events. Contributions are welcomed from stakeholders in PV or related industries.**

Index Terms — **Photovoltaic systems, solar energy, modeling, prediction algorithms, uncertainty, collaborative work, collaborative tools**

I. INTRODUCTION

Sandia National Laboratories (Sandia) is facilitating the formation of a collaborative group of photovoltaic (PV) professionals (PV Performance Modeling Collaborative or PVPMC) interested in improving the accuracy and technical rigor of PV performance models and analyses. Such models are used to determine the future value of PV generation projects (expressed in the total annual predicted energy) and, by extension, influence how PV projects and technologies are perceived by the financial community in terms of investment risk. Greater confidence in the accuracy of performance models will lead to lower financing costs and an increase in the number of projects that are built. The PVPMC provides a collaborative venue for working towards these goals.

In September 2010, Sandia hosted the PV Performance Modeling Workshop in Albuquerque, NM [1]. This event brought together 50 stakeholders representing independent engineers, model developers, manufacturers, integrators, academics, and research scientists. The outcomes of this workshop are detailed in a report [2] and are summarized below.

- Models are not consistent. Even the same model run by different users may produce different answers.
- Performance models are a collection of separate model algorithms linked together.
- Performance models typically require many input parameters and variables, many of which are not know with high accuracy.
- Third party validation of models and modeling algorithms is not common but is needed.
- Models are frequently tuned or calibrated to measured field data, which is not widely available.
- Model results rarely include estimates of uncertainty or provide confidence bounds.

Prior to the workshop, attendees were asked to use the PV performance model of their choice to estimate the annual energy produced by three PV systems using standard c-SI module technologies. The 20 participants who volunteered for this "blind" study were given measured weather and irradiance data as well as PV system design information needed for input to performance models. The each ran their models and provided their results to Sandia prior to attending the workshop. The predicted annual generation for each of these model runs was compared to the measured output from the systems. An example for one of the system comparisons is shown in Fig 1.
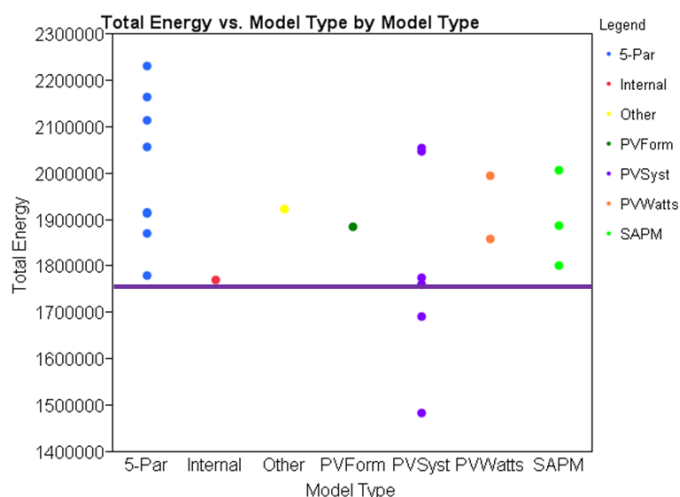

Fig 1. Variation in modeling results for annual energy from blind study [2]. Horizontal line is measured energy.

II. PV PERFORMANCE MODELING COLLABORATIVE

The idea for the PV Performance Modeling Collaborative or PVPMC arose from the results of the 2010 workshop. Existing information about available PV system modeling algorithms is not easy to find. Much of this knowledge is scattered across years of conference proceedings, journal papers, internal reports, and implemented in sparsely-documented modeling applications. This general lack of transparency contributes to diminished confidence in modeling

results and increased uncertainty. In an effort to bring light to this information, Sandia National Laboratories has started developing a website (http://pvpmc.org) that will host a range of technical information about PV performance modeling algorithms. The initial site is built and can be accessed currently with a password. Contact author (jsstein@sandia.gov) for password. Eventually, password requirement will be removed once site design is stable.

Website content includes:

A. Detailed technical information on standard modeling steps for predicting PV performance.
B. Detailed technical information on various system architectures.
C. Information about specific modeling applications, including comparisons between different software packages as well as different uses for PV performance models.
D. Member services, including mailing lists.
E. Online document library for sharing information (papers, data, etc.).
F. Access to a PV modeling toolbox for Matlab (PV_LIB Toolbox) developed by Sandia.
G. Technical nomenclature glossary.
H. Blog to share news items and events of interest to the PV performance modeling community.

The site has recently been launched but much of the technical content still needs to be added. Content addition is planned to continue for the next several years and Sandia is making a concerted effort to encourage members of the PVPMC to contribute content. To ensure consistency and control content organization on the site, Sandia will oversee editorial responsibilities and be responsible for posting technical information to the site. However, much of the technical content will be solicited from members. The home page for the site is shown in Fig. 2.
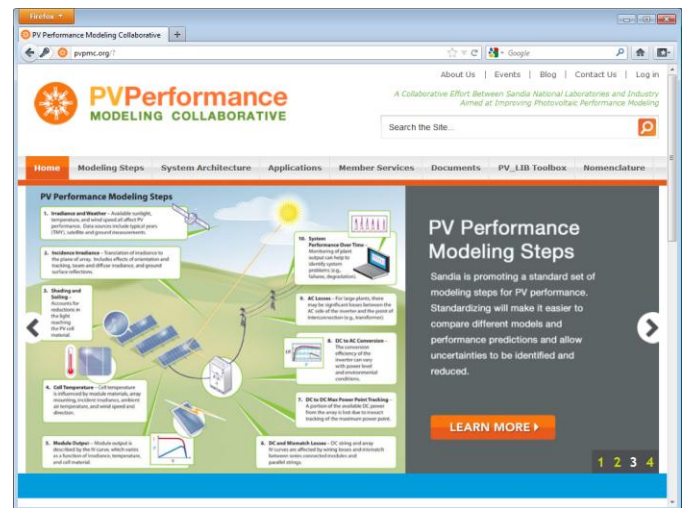

Fig. 2. Home Page for the http://pvpmc.org website

A. Standard PV Performance Modeling Steps

In order to begin the process of documenting the state of the art in PV performance modeling it is helpful to define a set of standard steps with which to organize the discussion. We propose the following nine steps for modeling a PV system's performance. In many cases, existing PV performance models skip one or more of these steps by making an assumption or adding a derate factor. As PV system design options become ever more complicated with new components (e.g., DC-DC converters), many of these previously overlooked steps will likely see more attention.

1. **Irradiance and Weather** – This step involves choosing a source for defining the irradiance and weather conditions expected for the site. Typical sources include: Typical Meteorological Years, satellite derived data, on-site ground measurements, etc. There are numerous possible approaches for choosing weather inputs for performance modeling studies. This section provides details and links to help identify and distinguish between available data.

2. **Incident Irradiance** – This step aims to translate irradiance measured at standard orientations (horizontal, plane of array, and normal to the sun) to beam and diffuse components on the plane of the array. There are numerous algorithms available to perform these translations. This section describes the differences between these methods and links to original papers and PV_LIB Toolbox functions, which offer implementation examples.

3. **Shading, Soiling, and Reflection Losses** – If the array is partially shaded or the modules are soiled then the amount of the incident irradiance that is available for conversion to electrical energy is reduced. Various algorithms

exist to calculate shading and its effect on the system. Fewer methods exist to predict the amount of soiling on the array with time. Usually this step is treated with a constant derate factor. This section provides detailed information on modeling algorithms and concepts related to these losses.

4. **Cell Temperature** – The PV cell temperature is influenced by a number of factors including module materials and construction, mounting and racking configurations, the incident irradiance (modified by shading and soiling), the wind speed, and ambient temperature, among other variables. There are many methods that have been proposed to estimate cell temperature from these variables. This section provides a detailed description of and comparison between these methods, including methods for obtaining model parameters.

5. **Module IV Output** – This step involves prediction of the IV curve of the module under the conditions described previously: irradiance (including spectrum) and cell temperature. There are various types of model forms that have been applied (single diode, semi-empirical, etc.). This section describes in detail the available model forms, including methods for measuring and estimating model parameters.

6. **DC and Mismatch Losses** –This step involves estimating the losses on the DC circuit(s) due to resistive wire losses and mismatch between series connected modules and parallel strings. Few performance modeling applications include this step explicitly except by means of a scalar derate factor. Treating this part of the performance modeling problem is especially important in order for PV performance models to accurately represent performance of array technologies designed to reduce such mismatch losses (DC-DC converters, string –level inverters, microinverters, etc.)

7. **DC to DC Maximum Power Point Tracking** – Most if not all modeling applications assume that the DC voltage on the array can be held at the maximum power point for the array at all times. In fact, there are differences between maximum power point tracking (MPPT) algorithms that are implemented in inverters and other converter components. Furthermore sometimes PV systems may operate off of the maximum power point. Few, if any, current performance models can distinguish between the effectiveness of different MPPT algorithms or represent performance under non-maximum power-point conditions (e.g., operation at non-unity power factor).

8. **DC to AC Conversion** – This step accounts for the conversion efficiency of the inverter. This efficiency can vary with environmental parameters such as temperature and well as electrical conditions, such as DC power level. This section describes and compares available model algorithms to represent this conversion efficiency.

9. **AC Losses** –Once the power has been converted to AC it must be transmitted to a point of interconnection. Any losses along this transmission path (wire losses, transformer losses, etc.) are accounted for here. Few existing models represent this process in any detail [3]. As utility-scale plants become more popular, these losses will have to be considered in more detail. This section will describe emerging methods to estimate these losses.

10. **System Performance Over Time** – Monitoring of plant output can help to identify system problems (e.g., degradation, component failures, etc.). There are a number of metrics used to track and evaluate system performance (e.g., performance ratio, performance index, etc.). This section will describe these monitoring methods and metrics.

B. System Architectures

This part of the website will host technical information related to system designs and their influence and impacts on performance. For example, the choice between central inverters, string inverters, and module-scale, microinverters will have an impact on performance due to the different effects of mismatch depending on system architecture. Other topics that might be considered in this section would be the effect of system design on DC wiring losses, shading, etc.

C. Applications

This part of the website will consider topics related to how PV performance models are used in general, differences between specific modeling applications, and best practices related to documenting analyses.

PV performance models are used different applications. For example, models are used to predict future energy yields for proposed PV power plants, they are used to assess the pros and cons of different design options, including tradeoff studies comparing different PV technologies (e.g., c-SI vs. thin-film, central vs. string inverters, etc.)

Available PV performance models have a variety of features that help to distinguish them. Sandia published a comparison between available PV performance models [4] and will continue to monitor and document developments in the field.

D. Member Services

The member services section of the website will allow users to join the collaborative. To join, participants must supply their name, email, and professional affiliation. Other information is optional. By joining, members will have access to all of the content on the site. Member lists will be used to distribute periodic newsletters with announcements and updates.

E. Document Library

The document library part of the web site is designed to hold and catalog documents and files meant to be shared with the PV performance modeling community. Only material that can be shared legally (not copyrighted) will be included in the document library.

Another application for the document library will be to host publically–available PV performance datasets for use in model validation activities. This need was highlighted at the 2010 workshop [2].

F. PV_LIB Toolbox for Matlab

While an organized source of reference information on PV performance modeling is certainly valuable, there is nothing to match the availability of actual examples of modeling algorithms being used in practice. To meet this need, Sandia has developed a PV performance modeling toolbox (PV_LIB) for Matlab. It contains a set of well-documented functions and example scripts showing the functions being used in practice. This toolbox is meant to help make the multi-step process of modeling a PV system more transparent and provide the means for model users to validate and understand the models they use and or develop. It makes use of Matlab's help and documentation utilities (Fig 3).

The *PV_LIB Toolbox* Version 1.0 provides 32 functions that are sorted into four categories:

1. **Time and Location Functions** – These include functions to manage time and date issues such as the conversion of dates and times between Excel and Matlab standards, and build and manage site location data (latitude, longitude, elevation, time zone).

2. **Irradiance and Atmospheric Functions** – This set of functions includes the ability to read standard weather file formats (e.g., TMY2 and TMY3), calculate the solar position, calculate extraterrestrial radiation, calculate relative and absolute air mass, and estimate direct radiation from global measurements.

3. **Irradiance Translation Functions** – These functions implement a number of common and not-so-common algorithms to estimate diffuse irradiance on a tilted plane, and the angle of incidence between the sun and the PV array.

4. **Photovoltaic System Functions** – This final set of functions focus on models for the electrical performance of the PV system in response to the irradiance and other environmental conditions. These functions currently focus on implementing the Sandia PV Array Performance Model [5] and the Sandia Photovoltaic Inverter Model [6], but will eventually include other model forms. In addition, functions to calculate the orientation angles for tracked systems (including back tracking) are included.

5. **Example Scripts** – As part of the PV_LIB Toolbox example scripts are provided to show users practical examples of the toolbox functions in use to model a complete PV system.
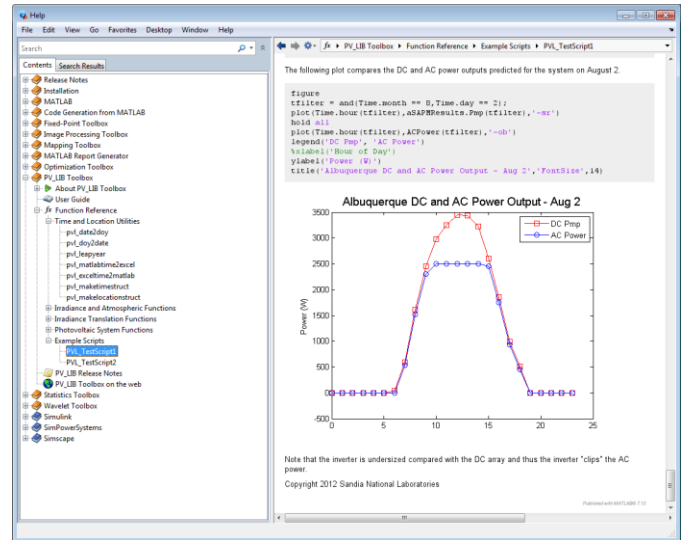

Fig. 3. Example of PV_LIB Toolbox integration with Matlab's help utility.

F. Nomenclature

The nomenclature section of the site contains an alphabetical list of technical terms with associated definitions, pictures, figures, links, etc. This section will help the collaborative maintain consistent terminology across the site.

G. PVPMC Blog

A blog element has been included in the site as a means of communicating news items and announcements to PVPMC members. Sandia will moderate the blog posts to ensure the content is relevant and accurate. Blog posts will include categories so that posts can be sorted by subject and keywords.

III. ADDITIONAL PVPMC ACTIVITIES

In addition to the website, the PVPMC will host and sponsor a number of future activities including workshops, webinars, and special sessions at national and international conferences.

The session organized around this paper at the 38th IEEE PV Specialists Conference is the first in a series that are being planned. Future conference workshops may include training sessions for the PV_LIB Toolbox, technical working groups

IV. How to Get Involved?

As a collaborative, this effort will require many stakeholders to engage and participate in order for it to be as successful as possible. The process for engagement will likely evolve with time, but currently Sandia is maintaining editorial control of the material and organization on the site. Currently the site has more than 180 separate pages, most in the Modeling Steps section. Sandia has developed a preliminary outline for the modeling steps but will likely add many more pages once more content is added. In the near future templates will be posted for members to use to submit content for existing pages or proposals for new pages. Contributed content will be subject to editing by Sandia but authorship of all contributed content will be acknowledged on the site.

The vision for the detailed content in the Modeling Steps section is that one day it might form the basis for a textbook, technical manual, or handbook on PV performance modeling. The PV_LIB Toolbox could be included as a means to develop problems sets and examples for such a project. Such a resource will help train future engineers and scientists to support a vigorous and competitive PV energy industry. By contributing to the PVPMC, you ensure that such training will include accurate and relevant information.

References

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