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Models Used to Assess the Performance of Photovoltaic Systems

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Models Used to Assess the Performance of Photovoltaic Systems

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Abstract

This report documents the various photovoltaic (PV) performance models and software developed and utilized by researchers at Sandia National Laboratories (SNL) in support of the Photovoltaics and Grid Integration Department. In addition to PV performance models, hybrid system and battery storage models are discussed. A hybrid system using other distributed sources and energy storage can help reduce the variability inherent in PV generation, and due to the complexity of combining multiple generation sources and system loads, these models are invaluable for system design and optimization. Energy storage plays an important role in reducing PV intermittency and battery storage models are used to understand the best configurations and technologies to store PV generated electricity. Other researcher's models used by SNL are discussed including some widely known models that incorporate algorithms developed at SNL. There are other models included in the discussion that are not used by or were not adopted from SNL research but may provide some benefit to researchers working on PV array performance, hybrid system models and energy storage. The paper is organized into three sections to describe the different software models as applied to photovoltaic performance, hybrid systems, and battery storage. For each model, there is a description which includes where to find the model, whether it is currently maintained and any references that may be available. Modeling improvements underway at SNL include quantifying the uncertainty of individual system components, the overall uncertainty in modeled vs. measured results and modeling large PV systems. SNL is also conducting research into the overall reliability of PV systems.

Acknowledgments

The authors would like to thank Charles Hanley, Christopher Cameron, Dan Riley, Abraham Ellis, Richard Chapman, David Trujillo, Dave Menicucci, David King, Tom Hund, John Boyes, Rudy Jungst, Terry Aselage, David Ingersoll and William Beckman for providing information on models used to simulate performance in PV, hybrid and battery storage systems.

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Acronyms and Abbreviations

Ah	Amp-hour
AIAA	American Institute of Aeronautics and Astronautics
ANN	artificial neural network
aSi	amorphous silicon
BIPV	building integrated photovoltaic
BOS	balance-of-system(s)
CdTe	cadmium telluride
CEC	California Energy Commission
CIEMAT	Centro de Investigaciones Energeticas, Medioambientales y Technologicas
CiS	copper-indium (di)selenide *or* copper-indium gallium (di)selenide technologies
CPE	Clean Power Estimator
CPV	concentrating photovoltaic (crystalline unless stated otherwise)
cSi	crystalline silicon
CSI	California Solar Initiative
CSV	comma separated value
CVA	canonical variate analysis
CWEC	Canadian Weather for Energy Calculations
DOE	Department of Energy
EPRI	Electric Power Research Institute
EPW	EnergyPlus Weather
EU	European Union
EV	electric vehicle
HDKR	Hay, Davies, Klucher, Reindl
HIT	hetero-junction intrinsic thin layer
IEA	International Energy Agency
IMBY	In My Backyard
Imp	current at maximum power point
IMS	internet map server
INSEL	Integrated Simulation Environment Language
IPAL	Intellectual Property Available for Licensing
IRR	internal rate of return
Isc	short-circuit current
ISE	Institute for Solar Energy
ISES	International Solar Energy Society
IWEC	International Weather for Energy Calculations
LCOE	levelized cost of energy
mj	multi-junction
µc	micro-crystalline
MPPT	maximum power point tracking
MSEC	Maui Solar Energy Software Corporation
MUERI	Murdoch University Energy Research Institute

NASA	National Aeronautics and Space Administration
NASA SSE	NASA Surface Meteorological and Solar Energy Program
NIST	National Institute for Standards and Technology
NPV	net present value
NREL	National Renewable Energy Laboratory
NRSDB	National Solar Radiation Data Base
NSHP	New Solar Homes Partnership
O&M	operations and maintenance
POA	plane of array
PPA	power purchase agreement
PV	photovoltaic
PVSC	Photovoltaic Specialists Conference
PVSS	Photovoltaic System Simulation Program
RAPSIM	Remote Area Power Simulator
RER	Renewable Energy Research
RERL	Renewable Energy Research Laboratory
RISE	Research Institute for Sustainable Energy
RPS	renewable portfolio standard
SAM	Solar Advisor Model
SEL	Solar Energy Laboratory
SERI	Solar Energy Research Institute
SOC	state-of-charge
SOMES	Simulation and Optimization Model for Renewable Energy Systems
STC	standard test conditions
SWERA	Solar and Wind Energy Resource Assessment
TMY	Typical Meteorological Year
USHCN	US Historical Climatology Network
Voc	open-circuit voltage
Vmp	voltage at maximum power point
WRDC	World Radiation Data Center

1. Introduction

Sandia National Laboratories (SNL) plays a leading role in the development and application of photovoltaic (PV) technology used for generating electricity. These efforts include research, development and performance modeling of crystalline silicon, thin-film, concentrating PV, and inverter technologies and working to transfer this knowledge to end-users in a way that will increase the utilization of PV systems for generating electricity.

In order to support this work, SNL has been instrumental in developing computer modeling tools that can be used to design, monitor and predict PV and energy storage system performance for specific research needs. Some of these tools have been incorporated into third-party software that includes both free and commercial applications, while others have been developed and applied exclusively by researchers at SNL.

The photovoltaic industry is poised to undergo a period of rapid growth due to many factors, including but not limited to the following: A growing desire by people to reduce their carbon emissions, establishment of state renewable portfolio standards (RPS), use of third-party power purchase agreements (PPAs), new federal tax incentives for manufacturing and installation, new PV cell, inverter and storage technologies, and a decrease in the cost of PV system components.

As more PV systems are installed, there will be an increase in demand for software that can be used for design, analysis and troubleshooting. One example outlining the importance of PV performance monitoring is that new regulatory devices are being put into place that make the amount of tax credit returned from an installation conditional on the amount of electricity generated by a PV system. An incomplete assessment of a PV system's capabilities can underestimate system payback and affect possible financing. When new PV technologies are deployed, predicted and actual performance data will be included in databases, and other assumptions may require significant changes to the existing empirical and analytical techniques that are currently used. Folding in the PV performance algorithms into hybrid simulation models for micro-grid applications is important as distributed generation and renewable energy use becomes more established in the U.S. The use of batteries for both small and large-scale energy storage and power conditioning will also be important as PV grid penetration increases.

A comprehensive understanding of available models, capabilities, tradeoffs and shortcomings will be necessary to keep up with changes in technology and differing needs by end-users both now and in the future. This new phase of PV deployment in the U.S. will be successful if the photovoltaic, hybrid simulation and battery modeling tools can address these new challenges.

The paper is divided into three main sections: 1) PV performance models 2) hybrid system performance models and 3) battery storage models. There is some overlap between the sections due to the fact that hybrid systems incorporate both individual PV performance and battery storage algorithms. It is likely that there are some models used by academia or industry that are not widely advertised, and therefore are not included in this discussion. In addition, this paper does not represent an exhaustive search of models used to simulate other energy storage technologies such as flywheels, capacitors, compressed air, or pumped hydro. References are provided within each section and at the end of the paper. Any available hyperlinks are included and represent the location of reports publically available at the time this paper was written in late 2009. A summary table is presented in Appendix A to differentiate PV and hybrid model types in terms of system components or entire systems models. Finally, we present a discussion of current work being done at SNL in the areas of PV performance model enhancements and improvements.

2. PV Performance Models

Photovoltaic performance models are used to estimate the power output of a photovoltaic system, which typically includes PV panels, inverters, charge controllers and other "balance of system" (BOS) components (Figure 1). These models create a generation profile based on a specific geographic location which helps determine how much solar irradiance is available for harvesting. The meteorological inputs for any given location vary by latitude, season and changing weather patterns; being able to accurately determine the generation profile due to these changing variables results in better matching of system load with expected generation. Some models make general assumptions about system components and ratings while other more complex models take into account manufacturer parameters, derived parameters and empirically derived data. These models can also be used to evaluate system performance over time by providing a baseline to compare with if performance suddenly decreases and troubleshooting is necessary.

Financial considerations are also important when considering PV; some models are considered "system" models due to the inclusion of capital and operating costs as well as expected benefits in terms of payback period, avoided costs, internal rate of return, levelized cost-of-energy (LCOE), cash flow and depreciable basis, just to name a few. System derate factors are also important as equipment degrades over time resulting in a power output decrease.

This section begins with models developed and used by researchers at Sandia National Laboratories presented in chronological order, then discusses models other researchers utilize when evaluating PV system performance, and ends with a discussion of simplified PV performance models. Only models with English language versions are included in this assessment. A table of the PV models and important characteristics is presented in Appendix A.

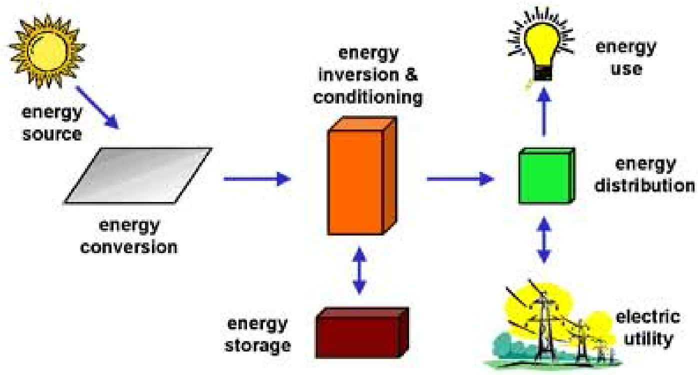

Figure 1. Photovoltaic Balance-of-Systems (Credit: Florida Solar Energy Center)

2.1 Sandia National Laboratories PV Modeling Timeline

An annotated history of the many early models developed at SNL used to predict PV performance is presented by King et al. (2004). There are however many other algorithms developed at SNL that go back to the 1970's and are summarized below. A detailed description of these models is presented in the following subsections in chronological order.

The earliest efforts at SNL for modeling PV cells, arrays and system cost can be found in the PVSS program by Goldstein and Case (1977), the SOLCEL systems analysis program by Linn (1977) and Hoover (1979), and followed by Evans et al. (1978; 1980), and Evans (1981). Around the same time, SOLSTOR (Aronson et al., 1979; Aronson et al., 1982) was created as a hybrid system model that could look at wind and energy storage in addition to PV. The PV performance algorithms in SOLSTOR were expanded from work done in SOLCEL. The model PVForm (Menicucci 1985, 1986; Menicucci and Fernandez, 1988) was built to improve and simplify the codes developed in SOLCEL and provide a systems modeling approach. Some of the array performance algorithms developed in PVForm have been widely incorporated into a number software programs that will be discussed in more detail later in this paper.

These models were followed in 1996 with an effort to better characterize and describe cell and module electrical performance with a model called PVSIM (King et al., 1996) which used empirically derived module parameters to better define cell or module performance for a wide range of temperatures. PVMOD was developed through a separate effort in 1998 from module testing that started in 1991. The purpose of this testing was to empirically derive performance estimates from PV modules under a variety of operating conditions. PVMOD uses a simplified solar radiation algorithm and is still used in 2009 for analysis.

The Sandia PV Array Performance Model resulted from further refinements of the work initially done in PVMOD. SNL worked with the Maui Solar Energy Software Corporation (MSESC) in 1998 to include its array and inverter performance algorithms into the commercially available PVDesignPro software (MSESC, 2004), and worked on validating the model as well as providing supporting documentation. The SNL model is also included in the systems level Solar Advisor Model (SAM) maintained by the National Renewable Energy Laboratory (NREL).

Around the same time PVSIM and the Sandia PV Array Performance Model were in development, two hybrid system models were being designed. The first model Hysim, by Chapman (1996) was designed for remote stand-alone military facilities using a PV-diesel-battery configuration. The second model HybSim, by Kendrick et al. (2003) models remote hybrid systems and adds wind as an additional generation source. Both HybSim and Hysim represent independent modeling efforts.

2.2 PV Models Developed and Used by Sandia National Laboratories

2.2.1 PVSS

Description

The Photovoltaic System Simulation Program (PVSS) developed by SNL is a simple component model built in FORTRAN to simulate PV system performance by allowing the user to choose a variety of different system configurations for both on and off-grid PV systems.

A plane of array (POA) radiation model was not used in this model. Array performance is based on a one-diode equivalent circuit equation for determining the current-voltage (I-V) curve. Temperature effects on irradiance are based on equation that is a function of the band-gap, a silicon specific constant, Boltzmann's constant and the cell temperature. (Lewis and Kirkpatrick, 1970). Based on the year the model was developed, Flat plate crystalline silicon (cSi) is probably the only modeled PV technology. The user manual does not mention the use of any common weather databases for weather or insolation, though it appears these values can be altered easily by the user to incorporate site-specific information. This model does not perform any economic or financing analysis.

For lead-acid battery storage, state-of-charge and power delivered or received is tracked.

Availability and Maintenance

PVSS was developed in the 1976-1977 timeframe based on the references described below. The program is no longer used, updated or supported by SNL.

References

- Goldstein, L. H, and G. R. Case, 1977, *PVSS – A Photovoltaic System Simulation Program Users Manual*, SAND77-0814. Sandia National Laboratories, Albuquerque, NM, June 1977.

- Goldstein, L. H., and G. R. Case, 1978, *PVSS – A Photovoltaic System Simulation Program*, Solar Energy, Vol. 23, No. 1, pp.37-43.

- Lewis, C. A., and J. P. Kirkpatrick, 1970, *Solar Cell Characteristics at High Solar Intensities and Temperatures*, 8th IEEE PVSC, Seattle, WA, August 4-6, 1970.

2.2.2 SOLCEL

Description

SOLCEL is a system-level model used for both grid-tied and off-grid (battery storage) PV systems. It is implemented in FORTRAN and can run simulations down to an hourly time-step.

A simple equivalent circuit model as described in PVSS (Section 2.2.1) is used to model array performance. Temperature effects on array performance are determined using a temperature-corrected efficiency model based on PVSS and modified based on different passive and active cooling configurations. The program can model both flat-plate and concentrating PV (CPV) incorporated onto trackers or fixed arrays. Weather and solar insolation data for the model is obtained using the SOLMET Typical Meteorological Year (TMY) database.[1]

SOLCEL is set up to look at different scenarios to determine the best system design for a desired range of costs including, but not limited to PV energy cost, total system cost, life-cycle cost, and rate of return. The two economic-evaluation techniques the program implements are the life-cycle costing methodology and the Department of Energy (DOE)/Electric Power Research Institute (EPRI) required revenue methodology. SOLCEL can also find the optimal configuration with the lowest life-cycle cost (Hoover, 1980).

Availability and Maintenance

SOLCEL consisted of three versions. SOLCEL-I was developed around 1976-1977 timeframe, followed by an updated version, SOLCEL-II in 1979-1980. SOLCEL-III is mentioned by SERI (1985) in an early computer models directory, and was available for use around 1985 though no formal documentation is available. SOLCEL is no longer being used, updated or supported by SNL. Some equations used in the models can be found in the following references.

References

- Linn, J. K., 1977, *Photovoltaic System Analysis Program – SOLCEL*, SAND77-1268. Sandia National Laboratories, Albuquerque, NM, August 1977.

- Evans, D. L., W. A. Facinelli and R. T. Otterbein, 1978, *Combined Photovoltaic/Thermal System Studies*, SAND78-7031. Sandia National Laboratories, Albuquerque, NM, August 1978.

[1] The 26 SOLMET sites gathered hourly measurements from 1952-1975 and was replaced by the National Solar Radiation Data Base (NSRDB) measurements for the time period of 1961-1990.

- Hoover, E. R., 1980, *SOLCEL-II An Improved Photovoltaic System Analysis Program*, SAND79-1785. Sandia National Laboratories, Albuquerque, NM, February 1980.

- Solar Energy Research Institute (SERI), 1985, *Solar Energy Computer Models Directory*, SERI/SP-271-2589. Solar Energy Research Institute, Golden, CO, August 1985.

2.2.3 Evans and Facinelli Model

Description

A photovoltaic performance model for PV systems was developed by Arizona State University under contract with Sandia National Laboratories. In the model, system performance is analyzed when using a battery or converted energy from the array for maximum power point tracking (MPPT). The assumption in this model is that the PV arrays only generate power at the maximum power point on the I-V curve (Evans et al., 1981).

The model runs on a monthly time-step and is implemented in the TRNSYS environment (see Section 3.2.3 for more discussion on TRNSYS). For POA irradiance, a tilt correction factor is used and the arrays are either tracking or moved monthly to optimize energy production. For array performance, a power temperature coefficient model considers the efficiency, temperature and tilt correction factor. Technologies modeled include cSi and CPV with weather and insolation data taken from the SOLMET TMY database.

Availability and Maintenance

This model was developed in the late 1970s and early 1980s and is no longer used, updated or supported by SNL. Many of the equations used to develop the model are described in the references below.

References

- Evans, D. L., W. A. Facinelli and R. T. Otterbein, 1978, *Combined Photovoltaic/Thermal System Studies*, SAND78-7031. Sandia National Laboratories, Albuquerque, NM, August 1978.

- Evans, D. L., W. A. Facinelli, and L. P. Koehler, 1980, *Simulation and Simplified Design Studies of Photovoltaic Systems*, SAND80-7013. Sandia National Laboratories, Albuquerque, NM, September 1980.

- Evans, D. L., W. A. Facinelli, and L. P. Koehler, 1981, *Simplified Design Guide for Estimating Photovoltaic Flat Array and System Performance*, SAND80-7185. Sandia National Laboratories, Albuquerque, NM, March 1981.

- Evans, D. L., 1981, *Simplified Method for Prediction Photovoltaic Array Output*, Solar Energy, Vol. 27, No. 6, pp. 555-560.

2.2.4 PVForm

Description

PVForm by Menicucci (1985) was one of the first "system" models for PV applications that can analyze and compare system performance in one or many locations with the benefit of incorporating system costs. The model has the ability to look at both grid-tied and stand-alone systems (with battery storage) and can allow a user to model system degradation, and the effects of load and component changes.

PVForm was also built to both simplify and improve the SOLCEL model (Section 2.2.2) by Linn (1977) and Hoover (1979). Some of the major technical improvements as compared to earlier models developed by SNL include changing solar insolation calculations for flat plate and POA orientations using the newly developed Perez model (Perez et al., 1987, 1988), a simpler modified power temperature coefficient model for array performance, and inclusion of a thermal model for module temperature by Fuentes (1987). PVForm appears to only model flat plate cSi. For weather and solar insolation, the TMY dataset is utilized. For financial information, PVForm gives users the ability to understand important metrics such as LCOE for comparing the cost of other electricity generating technologies with PV.

A validation test of the battery modeling algorithm in PVForm is described by Chamberlin (1988) where performance from flooded, gelled and absorbed-electrolyte lead-acid batteries was evaluated when coupled with a PV system.

Availability and Maintenance

PVForm was created in 1985 as a stand-alone program for PC computers running MS-DOS. Version 3.3 as described in Menicucci and Fernandez (1988) was the last update to PVForm. The program is no longer being used or maintained by SNL, but is available at IPAL for licensing http://ipal.sandia.gov/Default.php.

Programs that Use PVForm

Because of its simplicity, many different programs utilize portions of PVForm, especially PVWatts, one of the more widely known and utilized models discussed below in Section 2.3.2. Figure 2 shows the many PV and hybrid systems models that incorporate the POA and array performance algorithms from PVForm. These models are discussed in more detail in subsequent sections.

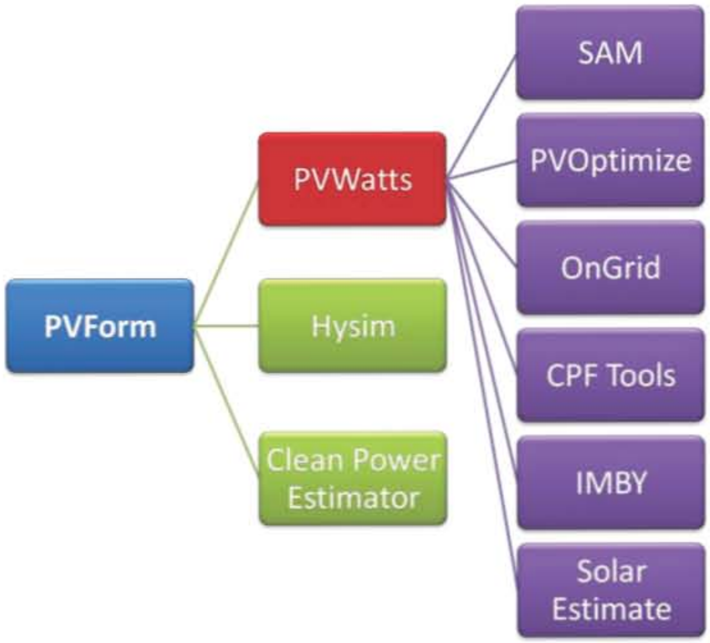

Figure 2. Hierarchy of PV and hybrid system models that use PVForm

References

- Linn, J. K., 1977, *Photovoltaic System Analysis Program – SOLCEL*, SAND77-1268. Sandia National Laboratories, Albuquerque, NM, August 1977.
- Hoover, E. R., 1980, *SOLCEL-II An Improved Photovoltaic System Analysis Program*, SAND79-1785. Sandia National Laboratories, Albuquerque, NM, February 1980.
- Menicucci, D. F., 1985, *PVFORM – A New Approach to Photovoltaic System Performance Modeling*, 18th IEEE PVSC, Las Vegas, NV, October 21-25, 1985.
- Menicucci, D. F., 1986, *Photovoltaic Array Performance Simulation Models*, Solar Cells, Vol. 18, pp. 383-392.
- Fuentes, M. K., 1987, *A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays*, SAND85-0330. Sandia National Laboratories, Albuquerque, NM, May 1987.
- Perez, R., R. Stewart, C. Arbogast, R. Seals and D. Menicucci, 1987, *A New Simplified Version of the Perez Diffuse Irradiance Model for Tilted Surfaces*, Solar Energy, Vol. 39, pp. 221-231.
- Perez, R., R. Stewart, R. Seals, T. Guertin, 1988, *The Development and Verification of the Perez Diffuse Radiation Model*, SAND88-7030. Sandia National Laboratories, Albuquerque, NM, October 1988.

- Menicucci, D. F., and J. P. Fernandez, 1988, *User's Manual for PVFORM: A Photovoltaic System Simulation Program for stand-alone and grid-interactive applications*, SAND85-0376. Sandia National Laboratories, Albuquerque, NM, April 1988.

- Chamberlin, J. L., 1988, *Performance Modeling of Lead-Acid batteries in Photovoltaic Applications*, 20th IEEE PVSC, Las Vegas, NV, September 26-30, 1988. [SAND88-0594C]

2.2.5 PVSIM

Description

PVSIM was developed at SNL by King et al. (1996) to better understand the electrical behavior between each module in an array. Specifically, it was built to take a look at module mismatch and shading loss. This analysis is done using a two-diode equivalent circuit model with empirically derived parameters from dark I-V measurements at a low (25°C) and high (50°C) cell temperatures. The software program allows for users to enter their parameters to create cell I-V curves determined through testing. From there, users can see how an array would perform at a variety of different operating temperatures.

Availability and Maintenance

The basic two-diode equivalent circuit equations in PVSIM are presented in the paper. PVSIM is not currently being distributed or used by SNL, although renewed interest from the PV industry is leading to efforts to translate the software to a new platform for future analysis.

References

- King, D. L., J. K. Dudley, and W. E. Boyson, 1996, *PVSIM: A Simulation Program for Photovoltaic Cells, Modules, and Arrays*, 25th IEEE PVSC, Washington, DC, May 13-17, 1996. [SAND95-2673C]

2.2.6 Sandia Photovoltaic Array Performance Model

Description

The Sandia PV Array Performance Model (King et al., 2004) utilizes a database of empirically derived PV module parameters developed by testing modules from a variety of manufacturers. The data can be used to evaluate the performance of PV systems in three ways:

1) Design a PV system to properly match desired generation with load information on timescales that vary from one hour to one year;

2) Calculate the system power rating from module-specific empirically derived formulas developed at SNL, and

3) Provide long term analysis capabilities that are useful for measuring array performance and troubleshooting support.

Where other algorithms attempt to determine array performance in conditions that are not optimal (most of the time), using theoretical and semi-empirical methods, the Sandia PV Array Performance Model is a departure from many of the earlier equations used to derive power from a PV system as it is based on empirical measurements made for modules in conditions other than the manufacturer provided standard test conditions (STC).

This model calculates the Isc, Imp, Vmp, Voc, and two other current values at intermediate points. This is accomplished with a curve-fitting process using coefficients derived from module testing. Empirical coefficients are also developed to calculate parameters that are temperature dependent (including a module specific thermal model), effects of air mass and angle of incidence on the short-circuit current, and type of mounting (whether rack mounted or BiPV). This model also allows for the determination of an “effective irradiance”, which is the amount of irradiance that actually reaches the cells after other losses are taken into consideration.

This model is considered a component model as it only models PV Arrays. Besides cSi, the model has been applied to thin films including cadmium telluride (CdTe) copper-indium selenide (CiS) and amorphous silicon (aSi), CPV, and multi-junction (mj) CPV. Weather and insolation data can come from any source. As implemented in PVDesign Pro (Section 2.2.8) and the Solar Advisor Model (Section 2.2.9), it can use TMY2, TMY3 and METEONORM weather and solar insolation data.

This approach has its limitations in that the modules have to undergo additional testing to obtain parameters other than what is provided by the manufacturer. However, validation of the model performed by National Institute for Standards and Technology (NIST) and SNL shows the model can predict power output to within 1% of measured power in different geographic locations (Fanney et al., 2006). In addition, the model has also been applied to Building Integrated PV (BIPV), and when compared with the 5-parameter model described later in Section 2.3.1, the SNL model better predicts measured power output (Fanney et al., 2002). The SNL model is also being used extensively by NIST for evaluating performance of cSi and tandem-junction aSi BIPV modules (Fanney et al., 2009).

Availability and Maintenance

This software was developed in many stages between 1991 and 2004. All of the equations used by the current PV Array Performance Model (and early prototype PVMOD) are described in the King et al. (2004) paper and are utilized in both PVDesignPro (Section 2.2.8) and the Solar Advisor Model (Section 2.2.9). This is the primary model used by researchers at SNL to calculate array performance at the time of this publication. As of 2009, testing is being conducted in Tempe, Arizona for new PV modules by TUV Rheinland PTL. These results will go into the SNL module database, which is accessible within the Solar Advisor Model and PVDesign Pro.

References

- Fanney, A. H., B. P. Dougherty, and M. W. Davis, 2002, *Evaluating Building Integrated Photovoltaic Performance Models*, 29th IEEE Photovoltaic Specialists Conference, New Orleans, LA, May 17 and 24 2002.

- King, D. L., W. E. Boyson and J. A. Kratochvil, 2004, *Photovoltaic Array Performance Model*, SAND2004-3535. Sandia National Laboratories, Albuquerque, NM, August, 2004.

- Maui Solar Energy Software Corporation (MSESC), 2004, PV-DesignPro v6.0 & Solar Design Studio, Available at: http://www.mauisolarsoftware.com.

- Fanney, A. H., M. W. Davis, B. P. Dougherty, D. L. King, W. E. Boyson, and J. A. Kratochvil, 2006, *Comparison of Photovoltaic Module Performance Measurements*, J. of Solar Energy Engineering, Vol. 128, No. 2, pp. 152-159.

- Fanney, A. H., B. P. Dougherty, and M. W. Davis, 2009, *Comparison of Predicted to Measured Photovoltaic Module Performance*, Solar Energy Engineering, Vol. 131, No. 2, 10p.

2.2.7 Sandia Inverter Performance Model

Description

The Sandia Inverter Performance Model for grid-tied systems (King et al., 2007) characterizes efficiencies in the conversion process from dc-power to ac-power using an empirical method (like the Sandia PV Array Performance Model) through the testing of operating inverters. Inverter performance is characterized as a function of input power and voltage, and coefficients are derived that can be used in the model. The results of the testing include an inverter parameter database with equations that can be utilized with the Sandia PV Array Performance Model. This model is included in PVDesignPro (Section 2.2.8) and the Solar Advisor Model (Section 2.2.9).

Availability and Maintenance

The database as compiled by King et al. (2007) is the original version. The inverters in this database were selected as part of a long-term effort to study how performance changes through time. Additional parameters from testing by the California Energy Commission (CEC) are included in updates to the databases used in the Solar Advisor Model and available at: https://www.nrel.gov/analysis/sam/download.html. This is the primary model used by researchers at SNL to calculate inverter performance at the time of this publication.

References

- King, D. L., S. Gonzalez, G. M. Galbraith, and W. E. Boyson, 2007, *Performance Model for Grid-Connected Photovoltaic Inverters*, SAND2007-5036. Sandia National Laboratories, Albuquerque, NM, September 2007.

2.2.8 PVDesignPro

Description

PVDesignPro software is a commercially available software model developed by the Maui Solar Energy Software Corporation (MSESC) and SNL for photovoltaic systems modeling. The software incorporates algorithms from both of SNL's PV array and inverter performance models as well as SNL's database of PV module and inverter parameters. NIST uses a custom version of PVDesignPro for comparing different PV technologies and predicting PV module performance for BIPV applications. Some of these tests using PVDesignPro are described above in Section 2.2.6.

The program uses an hourly time-step for modeling system performance. Two solar radiation models are available: the Hay, Davies, Klucher, Reindl (HDKR) model (Duffie and Beckman, 1991) and the Perez et al. (1987, 1988) model. Array performance is modeled using the Sandia PV Array Performance Model. Modeled technologies include cSi, thin-film (CdTe, CiS, and aSi), CPV, and mj-CPV. For weather and solar insolation, PVDesignPro uses TMY2, EPW (TMY3) and METEONORM data.

If financial analysis is desired, the software will take system cost inputs to determine cash flow, payback period, internal rate of return, and utility avoided costs. Battery state-of-charge can be tracked for systems with battery backup.

Availability and Maintenance

PVDesignPro is available at http://www.mauisolarsoftware.com in various configurations for small systems and large utility systems. It also has the ability to model battery storage, off-grid systems, water pumping, and solar water heating. The software was developed in 1998 with the most recent version of the software (v6.0) updated in 2004 at the time of this report. The climate and module database were kept up-to-date at the time of this report.

References

- Maui Solar Energy Software Corporation (MSESC), 2004, PV-DesignPro v6.0 & Solar Design Studio, Available at: http://www.mauisolarsoftware.com

2.2.9 Solar Advisor Model

Description

The Solar Advisor Model or SAM, as it is commonly referred to, is a stand-alone software program created in 2006 by a partnership with the National Renewable Energy Laboratory (NREL) and SNL through the DOE Solar Energy Technologies Program. The model is being continuously updated and improved and has an active user community that can be accessed at: http://groups.google.com/group/sam-user-group. The early concept name for this program was PVSunVisor and a report by Mehos and Mooney (2005) prior to full model release discusses the impetus for creating a comprehensive modeling tool.

This model is considered a “system” model because it has the ability to model PV system performance, and perform financial analysis. A useful feature in SAM is that it provides access to many different array performance models described below in Table 1.

POA radiation models in SAM include Isotropic Sky (Liu and Jordan, 1963), Hay and Davies (Davies and Hay, 1980), Reindl (1988) and Perez et al. (1987, 1988) Modeled technologies include cSi, thin-film (CdTe, CiS, and aSi), CPV, mj-CPV and hetero-junction intrinsic thin layer (HIT). SAM can also look at other solar technologies such as Dish Stirling, parabolic trough and power tower systems. For array performance, Table 1 below shows the four different options. SAM uses the Transient Systems Simulation (TRNSYS) code developed by the Wisconsin Solar Energy Laboratory as the ‘engine’ for implementing the array performance models. For weather and solar insolation, SAM uses TMY2, TMY3, EnergyPlus Weather (EPW) and METEONORM data. Financial analysis capabilities include looking at energy costs, financing options, system depreciation, tax credits, cash flow, and LCOE.

Other useful features include the ability to perform sensitivity analysis and optimize against a selected output. An internal scripting language is available for custom program design and also gives the user the ability to run many simulations.

Table 1 shows the many algorithms developed by different authors and available for use in SAM. In terms of radiation inputs, the model will accept either beam and diffuse and calculate total radiation, or total and beam and calculate diffuse radiation.

Table 1. Algorithm Options in SAM for Solar Radiation, Array and Inverter Performance

Solar Radiation	Array Performance	Inverter
• Isotropic Sky • Hay and Davies • Reindl • Perez et al.	• Sandia PV array performance model (empirical) • 5-parameter performance model (semi-empirical) • PVWatts • Simple-efficiency model	• Sandia inverter performance model • Single-point efficiency

A study conducted at SNL by Cameron et al. (2008) compares the output of the three array performance models in SAM to output from PVWATTS (Section 2.3.2) and PVMOD (Section 2.2.6). The paper also compared the output of the different solar radiation models used within SAM and the simplified PVMOD version. The study showed similar predictions of monthly performance of crystalline silicon systems when modeled annual output was normalized to measured annual output. However for non-crystalline technologies the percentage difference between each model's outputs was often much higher.

Availability and Maintenance

SAM was created in 2006 and is maintained by NREL. The program can be downloaded at https://www.nrel.gov/analysis/sam/. A major upgrade to the software occurred in 2009 and the version available at the time of this report is 2009.10.2.

References

- Mehos, M., and D. Mooney, 2005, *Performance and Cost Model for Solar Energy Technologies in Support of the Systems-Driven Approach*, NREL/CP-550-37085. National Renewable Energy Laboratory, Golden, CO, January 2005.

- Cameron, C. P., W. E. Boyson, D. M. Riley, 2008, *Comparison of PV System Performance-Model Predictions with Measured PV System Performance*, 33rd IEEE PVSC, San Diego, CA, May 12-16, 2008. Available at: https://www.nrel.gov/analysis/sam/pdfs/2008_sandia_ieee_pvsc.pdf

- Gilman, P., N. Blair, M. Mehos, C. Christensen, S. Janzou, and C. Cameron, 2008, *Solar Advisor Model User Guide for Version 2.0*, NREL/TP-670-43704. National Renewable Energy Laboratory, Golden, CO, August 2008.

- Additional SAM-related publications are available at: https://www.nrel.gov/analysis/sam/publications.html

2.3 Other PV Performance Models

2.3.1 5-Parameter Array Performance Model

Description

The 5-Parameter array performance model was developed from research conducted at the Wisconsin Solar Energy Laboratory (SEL). This model utilizes the well known one-diode array performance model for evaluating PV array performance. It was initially described as the 4-parameter or equivalent one-diode model by Townsend (1989). The model was incorporated into TRNSYS by Eckstein (1990), and is described by Duffie and Beckman (1991). Further validation and analysis by DeSoto (2004) at the SEL led to the 5-parameter version (DeSoto et al., 2006). In general, like the Sandia PV Array Performance Model, the 5-parameter model was developed to better predict power output from PV under non-standard test conditions.

The 5-parameter model was intended to predict both maximum power and current-voltage characteristics using only data normally supplied by manufacturers. At the time of model development, manufacturers typically supplied values of: short circuit current, open circuit voltage, voltage at maximum power point, current at maximum power point, and the temperature coefficients of both open circuit voltage and short circuit current. This available data was then used to determine the ideality factor, light current, diode reverse saturation current, series resistance, and shunt resistance (DeSoto et al., 2006). It is considered a semi-empirical model as some of these 5 parameters are theoretical and some are calculated from known relationships and equations derived from previous studies. When shunt resistance is very high, its impact tends to be very small and the model is then described as a 4-parameter model. This model can be used to predict performance for cSi, ribbon cSi, and thin film (CdTe, and aSi), however work is currently underway to improve the model accuracy for the thin-film technologies.

This algorithm is one of four implemented in the SAM system program as described above in Section 2.2.9. The California Energy Commission (CEC) uses the 5-parameter model and an inverter model to estimate system performance for the New Solar Homes Partnership (NSHP) program. The estimated performance is used to determine the state rebate to the homeowners This NSHP program is only for new houses in the State of California.

Availability and Maintenance

The 5-parameter model is constantly evolving from its inception in 1989 to its most current version as implemented in SAM and the CEC models. Additional work is being done at the SEL to improve the model for analyzing thin-film modules.

The 5-parameter model is available as a free download at:
http://sel.me.wisc.edu/software.shtml

The CEC implementation of the 5-paramater model is available at:
http://www.gosolarcalifornia.org/nshpcalculator/index.html

The 5-parameter model is implemented in SAM:
https://www.nrel.gov/analysis/sam/

References

- Townsend, T. U., 1989, *A Method for Estimating the Long-Term Performance of Direct-Coupled Photovoltaic Systems*, M.S. thesis, University of Wisconsin-Madison, Madison, WI. Available at: http://sel.me.wisc.edu/theses/townsend89.zip

- Eckstein, J. H., 1990, *Detailed Modeling of Photovoltaic System Components*, M.S. thesis, University of Wisconsin-Madison, Madison, WI. Available at: http://sel.me.wisc.edu/theses/eckstein90.zip

- Duffie, J. A. and W. A. Beckman, 1991, *Solar Engineering of Thermal Processes*, Second Edition, John Wiley & Sons, Inc., New York, NY.

- DeSoto, W., 2004, *Improvement and Validation of a Model for Photovoltaic Array performance*, M.S. thesis, University of Wisconsin-Madison, Madison, WI. Available at: http://sel.me.wisc.edu/theses/desoto04.zip.

- DeSoto, W., S. A. Klein, and W. A. Beckman, 2006, *Improvement and Validation of a Model for Photovoltaic Array performance*, Solar Energy, Vol. 80, No. 1, pp. 71-80.

2.3.2 PVWatts

Description

PVWatts is a grid-connected photovoltaic modeling tool developed by NREL that is based on the PVForm algorithms developed at SNL (Section 2.2.4). This includes the POA radiation model (Perez et al. 1987, 1988) and the modified power temperature coefficient model for array performance. A hierarchy of programs that descended from PVForm and from its predecessor, PVWatts is shown above in Figure 2.

PVWatts is available as a web-based application in two different versions. Version 1 allows the user to choose from preset locations and PV system values that include the DC rating, derate factors, array type (fixed tilt, 1-axis or 2-axis tracking), array tilt and azimuth. It also assumes -0.5%/C which is reasonable for cSi but not for thin-film technology.

Output includes monthly averages of solar radiation, AC energy and the energy value (kWh x cost/kWh) all of which can be exported on an hourly basis. Version 2 uses an internet map server (IMS) to allow the user to choose a more site-specific location than what is available in version 1. The user can zoom in on an area, click on the PVWatts icon, then click on a desired grid cell. The same input parameter window from version 1 appears and the user can input the parameters described above.

NREL recently created a program called In My Backyard (IMBY) that runs on the PVWatts platform and allows a user to zoom in on a specific location and draw a shape that resembles the outline of a PV array. This specific area is translated into a system size in kilowatts with a default derating factor, latitude tilt and assumed azimuth angle of 180 degrees. The model uses Perez satellite derived radiation input. Output includes the standard PVWatts information with added information on system payback and the ability to change all input variables for a more customized output. The user can then compare generation with electricity consumption by uploading a load profile and also compare monthly electric bills before and after PV installation based on electric rates. Geographic coverage includes North America, Central America and the northern extents of South America.

PVWatts is also used in the California Solar Initiative (CSI) EPBB Calculator to determine incentives for PV on existing buildings (See discussion of a different California benefit calculator for new homes in Section 2.3.1 above).

Availability and Maintenance

PVWatts is available in two versions. Version one can be used to evaluate system output for locations around the world: http://www.nrel.gov/rredc/pvwatts/version1.html

Version 2 is for the U.S. and its territories and can provide more site-specific meteorological input than version 1: http://www.nrel.gov/rredc/pvwatts/version2.html

The IMBY tool is available at: http://www.nrel.gov/eis/imby/

The CSI EPBB Calculator can be found at: http://www.csi-epbb.com/default.aspx

References

- Marion, B., M. Anderberg, P. Gray-Hann, and D. Heimiller, 2001, *PVWATTS Version 2 – Enhanced Spatial Resolution for Calculating Grid-Connected PV Performance: Preprint*, NREL/CP-560-30941. National Renewable Energy Laboratory, Golden, CO, October 2001.

- Marion, B., M. Anderberg, and P. Gray-Hann, 2005, *Recent and Planned Enhancements for PVWATTS*, NREL/CP-520-38975. National Renewable Energy Laboratory, Golden, CO, November 2005.

2.3.3 PVSYST

Description

PVSYST is a photovoltaic system analysis software program developed by the Energy Group at the University of Geneva in Switzerland and can be used at any location that has meteorological and solar insolation data. It is widely used due to the many parameters available for the user to modify. The complexity of the input parameters makes it suitable for expert users.

For POA radiation, the default is the Hay (1979) model, however the user can also specify the Perez et al. (1987, 1988) model. PVSYST uses the one-diode equivalent circuit model for calculating performance in cSi and HIT modules, and a modified version for what they consider "stabilized" thin film modules, such as aSi, CiS and CdTe. The program allows input from many different weather and solar insolation datasets, including Meteonorm, Satellight, TMY2/3, ISM-EMPA, Helioclim-1 and -3, NASA-SSE, WRDC, PVGIS-ESRA and RETScreen. There is also a custom input option that allows for importing the required data from a comma-separated value (csv) file format. PVSYST can work with many different currencies from around the world, and can model system lifecycle costs, financing, and feed-in tariffs.

Other interesting features include a 3-D shading tool that allows a user to draw a structure with PV arrays and see potential shading impacts from simulated obstructions. There is an option to analyze array mismatch to determine more specific Isc and Voc parameters, as well as look at cell/module shading and other voltage losses due to wiring, and soiling. Other useful features include an incident angle modifier and an air mass spectral correction for thin-film modules, as well as the ability for the user to input known parameters and coefficients if measured data is available for both PV modules and inverters.

Availability and Maintenance

PVSYST is available at the following website: http://www.pvsyst.com/ch/index.php. A 15-day trial version can be downloaded for evaluation purposes. It appears the software was developed in the mid-1990s, though the exact date is unknown. The most recent version (5.05) was released in late 2009.

References

- Mermoud, A., 1995, *Use and Validation of PVSYST, A User-Friendly Software for PV-system Design*, 13th European Photovoltaic Solar Energy Conference, Nice, France, October 23-27, 1995.

- Van der Borg, J. J. C. M., and M. J. Jansen, 2003, *Energy Loss Due to Shading in a BIPV Application*, 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan, May 11-18, 2003. Available at: http://www.ecn.nl/docs/library/report/2003/rx03024.pdf

2.3.4 PV F-Chart

Description

PV F-Chart is a PV array performance modeling software developed at the University of Wisconsin SEL and licensed through F-Chart software.

For POA radiation, it uses a simple isotropic sky model (Liu and Jordan, 1963). Array performance of cSi modules is calculated as a function of cell temperature, efficiency, and incident angle. For weather and solar insolation, TMY2 data is utilized. Economic analysis results including life-cycle and equipment costs are also included in the analysis.

Equations used for radiation analysis and array performance are provided in a literature review of PV F-Chart completed by Texas A&M in 2004.

Availability and Maintenance

PV F-Chart is a commercial software product available from F-Chart software: http://www.fchart.com/pvfchart/pvfchart.shtml. The program was created in 1985 and the last update to this software appears to be in 2001.

A demonstration version is available at:
http://www.fchart.com/pvfchart/pvfchartdemo.shtml

The user manual is available at: http://www.fchart.com/download/pvfchart_manual.exe

References

- Evans, D. L., W. A. Facinelli and R. T. Otterbein, 1978, *Combined Photovoltaic/Thermal System Studies*, SAND78-7031. Sandia National Laboratories, Albuquerque, NM, August 1978.

- Siegel, M. D., S. A. Klein, and W. A. Beckman, 1981, *A Simplified Method for Estimating the Monthly-Average Performance of Photovoltaic Systems*, Solar Energy, Vol. 26, No. 5, pp. 413-418.

- Clark, D. R., S. A. Klein, W. A. Beckman, 1984, *A Method for Estimating the Performance of Photovoltaic Systems*, Solar Energy, Vol. 33, No. 6, pp. 551-555.

- Publications describing the use of and outputs from PV F-Chart are available at the SEL publications page: http://sel.me.wisc.edu/publications.shtml

- A detailed history of PV F-Chart and the equations drawn upon by other researchers is provided in a report by the Texas A&M Energy Systems Laboratory for the Texas Commission on Environmental Quality, available at: http://repository.tamu.edu/handle/1969.1/2069

2.3.5 RETScreen Photovoltaic Project Model

Description

RETScreen is a program developed by Natural Resources Canada for evaluating both financial and environmental costs and benefits for many different renewable energy technologies. RETScreen has a specific Photovoltaic Project Model that can model PV array performance for many locations around the world.

For POA radiation, it uses a simple isotropic sky model (Liu and Jordan, 1963). The array performance model used by RETScreen is based on the power temperature coefficient model by Evans (1981) (Section 2.2.3). The software has the ability to model many different types of PV modules including cSi, CdTe CiS and aSi. For weather and insolation data, it can use TMY2 and NASA-SSE. Financial output includes project cost and savings, financial feasibility and lifecycle cash flows.

Availability and Maintenance

It appears that RETScreen was developed around 1997. RETScreen v4 was last updated in 2009 and is the most recent version at the time of this report. It runs within Microsoft Excel and can be downloaded at the following location: http://www.retscreen.net/ang/home.php

References

- Evans, D. L., 1981, *Simplified Method for Prediction Photovoltaic Array Output*, Solar Energy, Vol. 27, No. 6, pp. 555-560.

- Braun, J. E., and J. C. Mitchell, 1983, *Solar Geometry for Fixed and Tracking Surfaces*, Solar Energy, Vol. 31, No.5, pp. 439-444.

- Duffie, J. A. and W. A. Beckman, 1991, *Solar Engineering of Thermal Processes*, Second Edition, John Wiley & Sons, Inc., New York, NY.

- Equations used in developing the PV Project Model for RetScreen can be found at: http://www.retscreen.net/ang/textbook_pv.html

- General references for tutorials and case studies are available at: http://www.retscreen.net/ang/g_photo.php

2.3.6 PVSol

Description

PVSol is a photovoltaic systems analysis software program developed by Valentin Energy Software in Germany with an English language version distributed by the Solar Design Company based in the UK. The first version of PVSol was released in 1998. The Expert edition has the most features, including a 3-D shading program.

For POA radiation, it uses the Hay and Davies (Davies and Hay, 1980) anisotropic sky model. Array performance is calculated as a function of incoming irradiance, module voltage at STC and an efficiency characteristic curve. PVSol can use either a linear or dynamic temperature model. There is also an incident angle modifier for determining how much is radiation is reflected. The software can model performance for the following PV technologies: cSi, CdTe, CiS, aSi, HIT, µc-Si, and Ribbon. For insolation and weather data, the program uses MeteoSyn, Meteonorm, PVGIS, NASA SSE, SWERA and custom inputs. The software has a great deal of economic analysis capabilities, including determining economic efficiency for cash value, capital value, amortization and electricity production costs. As with other PV software programs developed in Europe, feed-in tariffs can be incorporated.

Availability and Maintenance

PVSol is a commercial software product maintained by Valentin Energy Software. The most recent version of PVSol Expert 4.0 was released in 2009. According to the Solar Design Company, an English language version of Expert will be available in late 2009.

A limited feature demo version is available for download:
http://www.solardesign.co.uk/index.htm

PVSol is also available at:
http://www.valentin.de/

References

- An internet search of PVSol brings up journal articles of system modeling applications primarily applied in Europe.

2.3.7 Polysun

Description

Polysun is a photovoltaic systems analysis software program designed by Vela Solaris in Switzerland. The company began operation in 2007 and started releasing its software to U.S. customers in May 2009. The program does not give any detail on what type of POA radiation or array performance models are used in the calculations. The software can model performance from the following PV modules: cSi, CdTe, CiS, aSi, HIT, µc-Si, and Ribbon. For insolation and weather data, the program uses Meteotest. Economic analysis includes financing, operations and maintenance (O&M) costs, incentives, energy prices, fuel cost savings and system value.

Availability and Maintenance

Polysun is a commercial software program available from Vela Solaris. The most recent version available is 5.2.

A limited feature demo version is available for download: http://www.velasolaris.com

References

- An internet search of Polysun brings up journal articles of system modeling applications primarily applied in Europe.

2.3.8 INSEL

Description

The Integrated Simulation Environment Language (INSEL) solar electricity toolbox from Doppelintegral GmbH in Germany is a photovoltaic systems analysis program. It appears the software was initially developed in 1991. INSEL is modular in the sense that it can be linked to other programs and can be customized by an advanced user.

INSEL gives users 10 options for radiation conversion on a tilted surface and include: 1) Isotropic Sky (Liu and Jordan, 1963), 2) Temps and Coulson (1977), 3) Bugler (1977), Hay and Kambezidis, 4) Klucher (1978), 5) Hay (1979), 6) Willmott (1982), 7) Skartveit and Olseth (1986), 8) Gueymard (1987), 9) Perez et al. (1987, 1988), and 10) Reindl (1988). For PV performance modeling, INSEL uses a one-diode or modified two-diode model as described by Obst (1994) and Jakobides (2000). There are four different options for modeling incident angle losses. A module thermal model is used to describe heat gain and loss. Modules that can be utilized include cSi; however other technologies such as thin-film are probably in the database. For insolation and weather data, the program uses its own weather database. Economic analysis includes installed system cost, O&M costs, net-present value (NPV), electricity costs and feed-in tariffs.

Availability and Maintenance

INSEL version 8.0 pre-release was released in late 2009 at the time of this report and is available for a free 30-day trial version: http://www.insel.eu/index.php?id=79&L=1

References

- Obst, C., 1994, *Kennlinienmessung an Installierten Photovoltaik-Generatoren und deren Bewertung*, M.S. thesis, University of Oldenburg, Germany.

- Jakobides, F., 2001, *Nutzung empirischer Datensätze zur Bestimmung der Modellparameter für Solarzellen auf der Basis von kristallinem und amorphen Silizium*, M.S. thesis, Fachhochschule Magdeburg, Germany. Available at: http://www.insel.eu/fileadmin/insel.eu/diverseDokumente/Diplomarbeit_Fr.Jabobides.pdf

- A general list of publications using INSEL can be found at: http://www.insel.eu/index.php?id=40&L=1

- Equation descriptions are available at: http://www.insel.eu/fileadmin/insel.eu/softwareLE/inselBlockReference.pdf

- Calculations for incoming solar radiation module are available at: http://www.insel.eu/fileadmin/insel.eu/diverseDokumente/inselTutorial/module09.pdf

- Examples of grid-connected and off-grid battery storage applications are available at: http://www.insel.eu/fileadmin/insel.eu/diverseDokumente/inselTutorial/module10.pdf

2.3.9 SolarPro

Description

SolarPro software is a PV system simulation program from Laplace System based in Kyoto, Japan. The first version of the software appears to have been released in 1997.

The user must first define the system in terms of mounting, array layout and orientation, then develop a 3-D layout that can have shading objects built-in. Interesting features include detailed analysis of module-specific shading within an array by looking at module I-V curves.

Based on the demonstration version, it is not clear what type of radiation processor or POA radiation algorithm is used. It appears that the one-diode equivalent circuit model is used to calculate array performance. Temperature effects are modeled as a function of temperature, irradiance and wind speed. System derates are lumped into one coefficient for soiling and electrical losses. Inverter losses are determined by an inverter specific efficiency, which can be changed. Based on the module database for the demonstration version, cSi, thin-film (aSi, CdTe), and HIT modules can be utilized, as well as the ability to input user-defined modules. System construction and O&M costs can be included in the analysis.

Availability and Maintenance

The most recent version of SolarPro is 3.0. It appears to be maintained and updated and is available in an English language version. The software is available for a 90-day trial version. http://www.lapsys.co.jp/english/

References

- The software is available at: http://www.lapsys.co.jp/english/

2.4 Simplified PV Performance Models

2.4.1 Clean Power Estimator

Description

Clean Power Estimator (CPE) is a customizable web-based PV system and financial analysis program. It can be tailored by Clean Power Research to provide a site specific interface that can be designed as a quick look at system performance and financial analysis for a PV system. This tool is marketed to the consumer who wants an easy to use program with a minimal number of inputs. The array performance and POA algorithms are based on SNL's PVForm code (Section 2.2.4) and has been tested and validated by the Clean Power Research Company. For insolation and weather data, CPE uses TMY2 as well as proprietary satellite based estimates of insolation. Financial analysis includes system financing, payback, cash flow, O&M and depreciation.

Availability and Maintenance

Clean Power Research can provide a customized web-based tool for specific customers and is used in many locations around the U.S.: http://www.cleanpower.com/

An example of a specific application developed for the State of California is the CEC Clean Power Estimator:
http://cec.cleanpowerestimator.com/cec.htm

A CPE application built for the state of New York is available at: http://nyserda.cleanpowerestimator.com/nyserda.htm

References

- Clean Power Estimator provides reports describing the use and application of its software. A paper that describes the array performance portion “Validation of a Simplified PV Simulation Engine” can be found at: http://www.clean-power.com/research/customerPV/PVModelValidation.pdf

2.4.2 PVOptimize

Description

PVOptimize is a software tool developed for the California market by KGA Associates and is geared towards installers for generating system quotes and design.

The program uses PVWatts (Section 2.3.2) for solar resource data and array performance modeling. Modules available for analysis include cSi, CdTe, aSi, CPV and Ribbon. For weather and insolation, the program uses PVWatts (TMY2) data. There are many forms and inputs specific to the incentives and rebates offered by the State of California. Therefore the model may have limited utility to locations outside of California.

Availability and Maintenance

PVOptimize is a commercial software program from KGA Associates, LLC. A 7-day trial version is available for evaluation purposes.

References

- http://www.pvoptimize.com/index.html

2.4.3 OnGrid

Description

OnGrid is a software tool developed for use in the U.S. by Andy Black of OnGrid Solar in California and is focused on what installers need for system quotes and design.

The program uses PVWatts (Section 2.3.2) for the array performance calculations. Module technologies available for analysis include cSi, aSi, CdTe and Ribbon. This software consists of a macro-enabled Excel spreadsheet that can be customized for any incentive program available in the U.S. Incentives for the State of California are included by default. The spreadsheet can look at system cost, incentives, depreciation, cash flow, O&M costs, and internal rate of return.

Availability and Maintenance

A time-limited demonstration version along with monthly or annual subscriptions is available at: *http://www.ongrid.net/payback/signup.html*

References

- The software developer has a link to many papers and presentations that discuss the use of OnGrid for system sizing and PV economics. http://www.ongrid.net/papers/index.html

2.4.4 CPF Tools

Description

CPF Tools is a software program developed in 2007 by Energy Matters LLC for Clean Power Finance. The software is aimed towards system installers for system design, economics and financing. CPF tools also leverages the technology in RoofRay, which is an on-line interactive tool that allows a user to easily draw an outline of a potential PV array to explore the potential costs and benefits. RoofRay is similar to the IMBY tool developed by NREL for an interactive analysis of potential PV system size (Section 2.3.2). CPF Tools was previously known as Solar Pro Tools.

For array performance, CPF Tools uses PVWatts. Module technologies available for analysis include cSi, aSi, CdTe and Ribbon. Insolation and weather data are taken from the NCDC U.S. Historical Climatology Network (USHCN).

Availability and Maintenance

CPF Tools is available for download on the internet. At the time of this report, the company has a variety of subscription plans for customers. According to Energy Matters LLC, the next generation of the software will be called Energy Periscope.

A 7-day trial version is available for evaluation at:
http://www.cleanpowerfinance.com/solar/installer-tools/pricing/

References

- See software description at: http://www.cleanpowerfinance.com/
- Next version of software: http://www.energyperiscope.com/
- RoofRay is available at: http://www.roofray.com/

2.4.5 Solar Estimate

Description

Solar Estimate is a web-based tool developed by Energy Matters LLC for both residential and commercial solar resource estimation. The user enters in a zip code and chooses the utility that they purchase power from. Assumptions include a total energy delivered of 78%, which includes derates for panel, inverter, wiring and panel soiling. For POA radiation and array performance, PVWatts is used. The model does not specify a PV technology, although it is likely based on flat plate cSi modules. Because the model uses PVWatts for determining solar energy, it probably uses TMY2 data for weather and insolation measurements.

Output includes an estimated system size, cost, financial incentives based on location and utility, cash flow, and savings and benefits over system lifetime. Assumptions used in the model are available for the user to review at the end of the "Your Solar Electric Estimate" page.

Availability and Maintenance

Solar Estimate was developed in 2000 and is currently maintained and updated to take advantage of the many local, state and federal tax credits and incentives that are available to residential and commercial customers. Because it is web-based, there is nothing to download.

References

- Solar Estimate is available at: http://www.solar-estimate.org/

3. Hybrid System Models

Hybrid system models are used to simulate the performance of "hybrid" or "distributed energy resource" systems that typically include one or more renewable sources of electricity combined with a traditional fossil based fuel source. These models were built initially to look at the use of PV or wind as a backup source for small and remote off-grid applications. Battery storage and lifetime (primarily from lead-acid) is simulated due to the need for a continuous source of power. More recent models can incorporate sources such as biomass, hydro, and other energy storage devices such as non lead-acid batteries, fuel cells, capacitors, flywheels and compressed air. These models can also look at grid-tied systems and attempt to capture interactions at the utility scale.

The International Energy Agency (IEA) is funding a program through the Photovoltaic Power Systems Programme (PVPS) as Task 11 – PV Hybrids and Mini Grids as a multi-year project that started in 2006 and will continue until 2011. Their research aims to document the many hybrid system models and compare their structure, inputs and outputs. More specifically, the IEA is looking at market penetration and technical issues surrounding PV-hybrid systems. This work can be viewed at: http://www.iea-pvps-task11.org/. The models described below that are a part of this research effort include: Homer, ViPOR, Hybrid2, RetScreen, IPSYS, ISE, and HySys.

Hybrid system modeling is becoming more important as the idea of microgrid generation and delivery in a grid-tied system becomes a more recognized and adopted infrastructure. Microgrids are the integration of hybrid systems to an existing grid-tied infrastructure, or in other cases, a more complex off-grid system. Recent reports from the DOE's Renewable Systems Interconnection Study (RSI) by Whitaker et al. (2008) and Ortmeyer et al. (2008) address the possible issues arising from high penetration of PV in distributed generation and microgrid applications. This paper does not discuss microgrid system models and needs as those are addressed in detail by Ortmeyer et al. (2008).

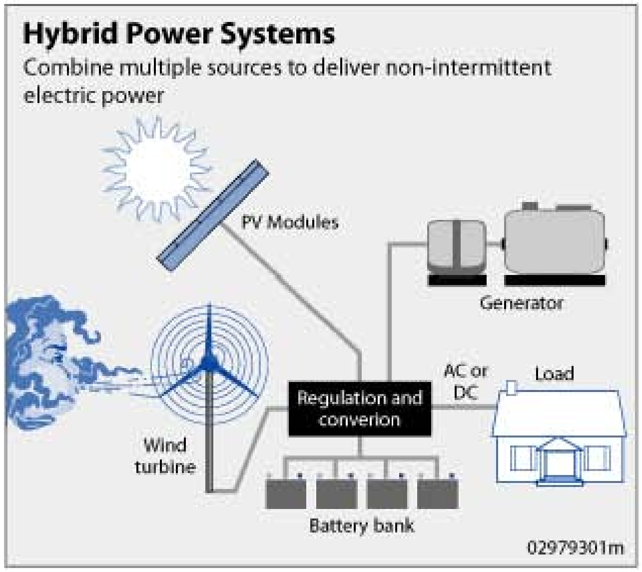

Figure 3. Illustration of a Hybrid Electric Power System

3.1 Hybrid System Models Developed and Used by Sandia National Laboratories

3.1.1 SOLSTOR

Description

SOLSTOR is a model developed at SNL for looking at the overall economics and optimization strategies of different hybrid system configurations. Components include PV arrays, wind turbines and generators. Storage is in the form of batteries and flywheels. Power conditioning options are also available. The model can be run with a utility connection or stand-alone with a backup generator.

The program incorporates some of the PV array performance algorithms as described in SOLCEL (Section 2.2.2). PV technologies that can be modeled include cSi and CPV. SOLSTOR uses the SOLMET database for weather and insolation data. Economic output includes capital costs, O&M costs, energy purchase costs, depreciation, investment tax credits, salvage value and financing.

Availability and Maintenance

SOLSTOR was developed and used in the 1979-1982 timeframe. It was written in Fortran77 and is no longer used or maintained by researchers at SNL. The equations used in the program are documented by Aronson et al. (1981) and Aronson et al. (1982).

References

- Aronson, E. A., D. L. Caskey and B. C. Caskey, 1981, *SOLSTOR Description and User's Guide*, SAND79-2330. Sandia National Laboratories, Albuquerque, NM, March 1981.

- Caskey, D. L, E. A. Aronson, and K. D. Murphy, 1981, *Parametric Analysis of Stand-Alone Residential Photovoltaic Systems and the SOLSTOR Simulation Model*, 15th IEEE PVSC, Kissimmee, FL, May 12-15, 1981. [SAND81-1130C]

- Aronson, E. A., D. L. Caskey and K. D. Murphy, 1982, *SOLSTOR II Description and User's Guide*, SAND82-0188. Sandia National Laboratories, Albuquerque, NM, June 1982.

3.1.2 HybSim

Description

HybSim is a hybrid energy simulator developed and copyrighted at SNL for looking at the costs and benefits of adding renewable energy to a fossil fueled electrical generation system in a remote location. The model requires knowledge of the existing load profile, weather, battery characteristics and a few economic details. At the moment, solar PV is the only renewable energy source available for comparison however wind power will be another choice in a future versions of the model. Current license holders include the University of Michigan and a few corporate customers.

The system is designed to model cSi modules. For weather and insolation, HybSim can use data measured at 15-minute intervals. Lifecycle costs are analyzed for system components including PV modules, generators and batteries. Capabilities include comparing cost and performance differences with a diesel only system with one using a combination of diesel, PV, wind and battery storage.

Availability and Maintenance

HybSim version 1 (2005) is currently available for license from SNL. At the time of this report, the model is still undergoing development to add additional features. See the intellectual property available for licensing (IPAL) site for detail on how to license HybSim: http://ipal.sandia.gov/Default.php.

References

- Kendrick, L., J. Pihl, I. Weinstock, D. Meiners, and D. Trujillo, 2003, *Hybrid Generation Model Simulator (HYBSIM)*, EESAT Conference, San Francisco, CA, October 27-29, 2003. [SAND2003-3790A]

3.1.3 Hysim

Description

Hysim is a hybrid energy simulation model developed at SNL for analyzing the combination of PV, diesel generators and battery storage for stand-alone systems in remote locations. The purpose of this model was to look at increasing overall system reliability by adding the PV and battery storage, as well as the economics associated with PV and batteries compared to existing generator only systems. Hysim uses a modified version of the battery model in SOLCEL (Section 2.2.2).

For POA radiation and PV array performance, Hysim uses PVForm (Section 2.2.4). The only PV technology modeled in Hysim is cSi. For weather and insolation data, Hysim uses TMY2. Financial analysis includes LCOE, lifecycle, fuel and O&M costs, as well as cost comparisons between different configurations.

Availability and Maintenance

Hysim was developed around 1987 and appears to have been used up until 1996. It is not currently being used, supported or updated by researchers at SNL. Those interested in this hybrid simulator should see the references below for more information.

References

- Jones, G. J., and R. N. Chapman, 1987, *Photovoltaic/Diesel Hybrid Systems: The Design Process*, 19th IEEE PVSC, New Orleans, LA, May 4-8, 1987. [SAND87-1203C]

- Chapman, R. N., 1996, *Hybrid Power Technology for Remote Military Facilities*, Powersystems World '96, Las Vegas, NV, September 7-13, 1996. [SAND96-1867C]

3.2 Other Hybrid System Models

3.2.1 HOMER

Description

HOMER is a hybrid system model developed at NREL in 1993 for both on-grid and off-grid systems. A unique capability that HOMER offers is the ability to find the optimal configuration based on price estimates as well as perform sensitivity analysis to help understand tradeoffs between different technologies and economic considerations. The software has the ability to compare multiple system configurations as well as different battery types. HOMER uses the KiBaM code for battery life modeling as described below in Section 4.2.1. The model can incorporate the following components: PV, wind, hydro, fossil fuel generator, battery, AC/DC converter, electrolyzer, hydrogen tank and reformer. The loads that it can simulate include primary, deferrable, thermal and hydrogen.

POA radiation is modeled using the HDKR model (Duffie and Beckman, 1991). For PV array performance, the program uses an equation that describes power output as function of incident radiation. Temperature effects are not considered in the performance calculation, however they can be accounted for as a part of the total system derate. HOMER uses a generic module type for analysis. For weather and insolation, HOMER can use TMY2 formatted data or custom user inputs.

The help file within the program describes each calculation and its reference, if available.

Availability and Maintenance

HOMER is maintained by HOMER Energy (as of 2009) and the most current version of the program (2.67) is available for download at: http://www.homerenergy.com/. According to HOMER Energy, future versions will have an associated cost.

References

- Documentation is available at: http://www.homerenergy.com/documentation.asp

- A HOMER bibliography of publications compiled by NREL is available at: http://www.homerenergy.com/pdf/HOMERPublications.pdf

3.2.2 Hybrid2

Description

Hybrid2 is described as a probabilistic time series computer model for evaluating the performance and economics of hybrid electricity generating systems. It was developed by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts Amherst with support from NREL. This program is an engineering design model for hybrid systems consisting of PV, wind, generators and battery storage for both on-grid and off-grid systems.

For POA radiation, the model uses the HDKR model (Duffie and Beckman, 1991). For PV array performance, Hybrid 2 uses a version of the 5-parameter model developed by SEL as described in Section 2.3.1. Module technologies that can be modeled include cSi, CdTe, CiS and aSi. The format for weather and insolation data is unknown. Financial analysis includes lifecycle cost, cash flow, NPV, payback, internal rate-of-return (IRR) as well as tradeoffs between different hybrid system configurations.

Availability and Maintenance

Hybrid2 was initially developed in 1994 as Hybrid1, then as Hybrid2 in 1996. The most current version is 1.3e (2004). At this time, there are no plans to update the model past the current version. Hybrid2 is maintained by the RERL and can be downloaded at: http://www.ceere.org/rerl/projects/software/hybrid2/

References

- A list of publications related to Hybrid2 is available at: http://www.ceere.org/rerl/rerl_publications.html

- A detailed theory manual with software description and equations is available at: http://www.ceere.org/rerl/projects/software/hybrid2/Hy2_theory_manual.pdf

3.2.3 UW-Hybrid (TRNSYS)

Description

The UW-Hybrid simulation model is described as a quasi-steady performance simulation tool for looking at hybrid systems consisting of solar, wind, diesel generators and battery storage. This hybrid simulator is part of the TRNSYS software program but can be run alone under a demonstration editor version called TRNSED.

Running the hybrid model in TRNSYS, POA radiation models include simple isotropic sky (Liu and Jordan, 1963), Hay and Davies (Davies and Hay, 1980), Reindl (1988) and Perez et al. (1987, 1988) For array performance, TRNSYS uses the 5-parameter array performance model (Section 2.3.1). PV technologies include cSi, CPV and aSi. Weather and insolation data includes TMY, TMY2, Meteonorm, EnergyPlus and the International Weather for Energy Calculations (IWEC) database.

Availability and Maintenance

UW-Hybrid as implemented under TRNSED is available from the SEL at: http://sel.me.wisc.edu/trnsys/downloads/trnsedapps/demos.htm. The program was written in 1998 under TRNSYS version 14.2 and there are not many manufacturer options for the PV array, wind turbine, generator or battery. More detailed information is likely to be included in the most recent version of TRNSYS.

An evaluation version of TRNSYS is available at:
http://sel.me.wisc.edu/trnsys/downloads/#EvaluationVersion.

Details about the full version of TRNSYS can be found at:
http://sel.me.wisc.edu/trnsys/default.htm

References

- Detailed references and publications using TRNSYS for hybrid system modeling can be found at: http://sel.me.wisc.edu/publications.shtml.

3.2.4 RETScreen

Description

RETScreen is a program developed by Natural Resources Canada for evaluating both financial and environmental costs and benefits for many different renewable energy technologies for any location in the world. The Photovoltaic Project Analysis module was covered in Section 2.3.5. Electricity generation options include solar, wind, fuel cells, gas or diesel generators, gas turbines, geothermal, tidal power, wave power, hydro turbine, and ocean current power. For combustible fuels, fossil, biomass, waste and hydrogen are listed in terms of inputs for modeling. Energy storage options include batteries.

For POA radiation, it uses a simple isotropic sky model (Liu and Jordan, 1963). The array performance model used by RETScreen is based on the power temperature coefficient model by Evans (1981). The software has the ability to model many different types of PV modules including cSi, CdTe CIS and aSi. For weather and insolation data, it can use

TMY2 and NASA-SSE. Financial output includes project cost and savings, financial feasibility and lifecycle cash flows.

Availability and Maintenance

RETScreen 4 last updated in 2009 is the most recent version at the time of this report. It runs within Microsoft Excel and can be downloaded at the following location: http://www.retscreen.net/ang/home.php

References

- The different power options that can be modeled in RETScreen are discussed at: http://www.retscreen.net/ang/power_projects.php

- RETScreen has an E-Textbook that describes many of the equations for some of the different power source options. http://www.retscreen.net/ang/12.php

- More references are described above in Section 2.3.5

3.2.5 PVToolbox

Description

PVToolbox is a hybrid system model developed for the Natural Resources Canada CANMET Energy Technology Centre – Varennes (CETC-Varennes). The program is written for use within Matlab Simulink and has been validated using bench tests which describe the model vs. measured performance under different load scenarios. The model looks specifically at PV, diesel generator and battery systems designed for Canadian latitudes and weather conditions.

It is unknown what type of POA radiation model is used in PVToolbox. PV performance is calculated with a one-diode equivalent circuit model similar to that described by Duffie and Beckman (1991). PV technologies include cSi and aSi. The format for weather and insolation data inputs is unknown. Financial information includes an O&M calculator for lifecycle cost analysis.

Availability and Maintenance

This program was likely developed in the early 2000s with updates that appear to have been made around 2007. It is unknown if the software is actively being maintained.

References

- Duffie, J. A. and W. A. Beckman, 1991, *Solar Engineering of Thermal Processes*, Second Edition, John Wiley & Sons, Inc., New York, NY.

- Thevenard, D., and M. M. D. Ross, 2002, *Validation and Verification of Component Models and System Models for the PV Toolbox*, Report to CETC-Varennes (Natural Resources Canada), Varennes, Quebec. Available at: http://www.rerinfo.ca/english/publications/pubReport2002PVToolboxValid.html

- Ross, M. M. D, 2003, *Validation of the PVToolbox Against the First Run of the Battery Capacity Cycling Test*, Report to CETC-Varennes (Natural Resources Canada), Montreal, Quebec. Available at: http://www.rerinfo.ca/english/publications/pubReport2003PVTboxValidBCap.html

- A comprehensive list of other references including papers and publications regarding PV Toolbox is available at the Renewable Energy Research (RER) consulting company website: http://www.rerinfo.ca/english/publications/all.html

3.2.6 RAPSIM

Description

The Remote Area Power SIMulator (RAPSIM) is a hybrid system model developed in Australia at the Murdoch University Energy Research Institute (MUERI). This program simulates systems comprising of PV arrays, wind turbines and diesel generators with battery storage. The organization that currently houses the work at the university is called the Research Institute for Sustainable Energy (RISE).

The type of POA radiation and performance models are unknown, as well as modeled PV technologies and weather and insolation data inputs.

Availability and Maintenance

It appears the software was developed in 1996, with version 2 available in 1997. It is unknown if updates have been made to the software. It does not appear the software is available for download although references to the program are shown in the link below.

References

- Publications describing RAPSIM research performed at the RISE are available at: http://www.rise.org.au/pubs/index.html

- Patel, M. S., and T. L. Pryor, 2001, *Monitored Performance Data from a Hybrid RAPS System and the Determination of Control Set Points for Simulation Studies*, ISES 2001 Solar World Congress, Adelaide, Australia, November 25-December 2, 2001.

- Jennings, S. U., 1996, *Development and Application of a Computerised Design Tool for Remote Area Power Supply Systems*, Ph.D. dissertation, Murdoch University, Perth, Australia.

3.2.7 SOMES

Description

SOMES is also known as the Simulation and Optimization Model for Renewable Energy Systems. It was created at the Utrecht University in The Netherlands. The simulation program can look at hybrid systems that utilize PV arrays, wind turbines and generators for generating electricity and batteries for storage. Both technical and economic parameters can be modeled as well as an optimization model to help figure out the best configuration at a specific cost.

The type of POA radiation and performance models are unknown, as well as modeled PV technologies and weather and insolation data inputs.

Availability and Maintenance

SOMES was initially developed in 1987 with version 3.0 following in 1993 and version 3.2 in 1997. It is unknown if the software has been updated past version 3.2.

References

- SOMES is described at the following website. It is unclear if the software is still available for use or purchase. http://www.chem.uu.nl/nws/www/publica/Publicaties%201997/97020.htm

- SOMES v. 3.2 is also described at: http://www.web.co.bw/sib/somes_3_2_description.pdf

- Van Dijk, V., 1996, *Hybrid Photovoltaic Solar Energy Systems, Design, Operation, Modelling and Optimization of the Utrecht PBB System*, PhD dissertation, Utrecht University, The Netherlands.

3.2.8 IPSYS

Description

IPSYS is a hybrid simulation modeling tool for remote systems. The program has a component type library and can model electricity generation through PV arrays, wind turbines, diesel generators, fuel cells as well as natural gas. Energy storage can be modeled using batteries, hydro reservoirs and hydrogen. The model is written in C++ and there is no current graphical user interface, however there are scripts that can be used to analyze model output within graphs.

The type of POA radiation and performance models are unknown, as well as modeled PV technologies and weather and insolation data inputs.

Availability and Maintenance

IPSYS is available from the Riso National Laboratory Wind Energy department. It appears the first version of the software was developed in 2000. It is unclear if the software has been updated since 2004. Contact information about the software is available at this page: http://www.risoe.dtu.dk/research/sustainable_energy/wind_energy/projects/ipsys.aspx?sc_lang=en

References

- Applications of IPSYS are available at: http://www.risoe.dtu.dk/research/sustainable_energy/wind_energy/projects/ipsys.aspx?sc_lang=en

- A description of IPSYS as part of the IEA's PV task 11 can be found at: http://www.iea-pvps-task11.org/HTMLobj-167/Gehrke_IPSYS_Valencia08.pdf

3.2.9 HySys

Description

The Hybrid Power System Balance Analyser, or HySys is a hybrid simulation tool developed at the Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT) institute in Spain by their wind technology group. The software is primarily for isolated systems and includes electricity from PV arrays, wind turbines and diesel generators. According to the IEA 2008 report as shown in the reference below, the software appears to be under development to operate primarily within Matlab.

The type of POA radiation and performance models are unknown, as well as modeled PV technologies and weather and insolation data inputs.

Availability and Maintenance

Version 1.0 was developed in 2003. As of 2008, it appears the software is currently being used internally by CIEMAT and is undergoing a transition from Excel to Matlab.

References

- See link for A. Costa, CIEMAT for a description of the HySys tool: http://www.iea-pvps-task11.org/id39.htm

3.2.10 Dymola/Modelica

Description

The Fraunhofer Institute for Solar Energy (ISE) in Germany uses the Modelica/Dymola object oriented programming language for modeling PV-hybrid systems. The electricity sources include PV, wind turbines, generators and fuel cells along with storage in the form of batteries.

The type of POA radiation and performance models are unknown, as well as modeled PV technologies and weather and insolation data inputs. It appears the program can evaluate lifecycle costs and calculate LCOE.

Availability and Maintenance

The software development date is unknown. Based on the IEA 2008 report described in Section 3.2.9, it is unclear when the software was last updated. A search on the

Fraunhofer ISE website for terms Hybrid and Dymola give references to work being done at:
http://www.ise.fraunhofer.de/welcome-to-the-web-pages-of-the-fraunhofer-institute-for-solar-energy-systems?set_language=en&cl=en

References

- See link for Matthias Vetter, Fraunhofer ISE for a description of the HySys tool: http://www.iea-pvps-task11.org/id39.htm

- Modelica is an object-oriented modeling language and can be found at: http://www.modelica.org/

- The Dymola software, which uses the Modelica modeling language is from Dynasim AB in Sweden and can be found at: http://www.dynasim.se/dymola.htm

4. Battery Performance Models

Photovoltaic systems provide varying amounts of power throughout the day due to the intermittent nature of sunlight reaching PV panels. Cloudy days, varying temperatures, system latitude, module configuration and shading effects directly affect the amount and timing of photovoltaic energy that can be produced.

To help smooth out the variability in power production and satisfy system loads, batteries are used to store excess energy and use it when system loads are greater than PV output. Batteries used in PV systems are subject to different stresses as compared to traditional battery applications due to shallow charge-discharge cycling, among other things. Initially, automobile and boat lead-acid batteries were used for energy storage, however due to the unique demands imposed by PV generated electricity, manufacturers are developing batteries specifically for use in PV systems. Battery chemistries besides lead-acid are undergoing research and in some cases currently being used to store energy from distributed sources like PV and wind (Kivya and Ostergaard 2009).

To better understand how batteries store and release electricity, models were developed based on a variety of methodologies and can be generally grouped into the following: 1) performance-based lifetime or physico-chemical 2) cycle counting or weighted Ah throughput and 3) event-oriented (Sauer and Wenzl, 2008; Wenzl et al. 2005).

Recently the European Union (EU) led an international benchmarking project for hybrid power systems in 2005 to better understand battery model limitations and potential fixes (Bindner et al., 2005). Also, work by Sauer and Wenzl (2008) identifies the need for better modeling techniques and other models that can simulate performance on chemistries other than lead-acid. In addition, newer battery technologies are being introduced for hybrid and electric vehicles (EV's), which may eventually be appropriate for PV systems when these technologies are better understood, are tested in PV and hybrid systems, and costs decrease.

Most of the battery models discussed in this section are implemented in the hybrid system models described in Section 3, as these models are well known and have undergone extensive testing and validation. This discussion on battery storage models will first look at what SNL has done in terms of modeling energy storage for PV systems, and then go into battery models used by other researchers.

4.1 Battery Performance Models Developed and Used by Sandia National Laboratories

4.1.1 SIZEPV

Description

SIZEPV was developed by Chapman (1987) the author of Hysim described in Section 3.1.3. The purpose of SIZEPV was to determine the optimal configuration of a PV system with battery storage using a loss-of-load probability model. The results of this model were by comparing with loss-of-load probabilities calculated with PVForm. The advantage of using SIZEPV for PV systems with battery storage is the ability to run multiple iterations much quicker than if set up using PVForm.

The model is limited to lead-acid batteries. Required input data includes battery capacity, minimum allowable state-of-charge (SOC), equalization SOC, backup capacity, equalization schedule, beginning SOC, maximum charge efficiency and maximum discharge efficiency.

Availability and Maintenance

The equations for SIZEPV are presented in the report by Chapman (1987). The program is not currently available for use.

References

- Chapman, R. N., 1987, *Sizing Handbook for Stand-Alone Photovoltaic/Storage Systems*, SAND87-1087. Sandia National Laboratories, Albuquerque, NM, April 1987.

- Menicucci, D. F., and J. P. Fernandez, 1988, *User's Manual for PVFORM: A Photovoltaic System Simulation Program for stand-alone and grid-interactive applications*, SAND85-0376. Sandia National Laboratories, Albuquerque, NM, April 1988.

4.1.2 Artificial Neural Network Technique

Description

Urbina et al. (1998) developed a probabilistic model for determining battery behavior when connected to a PV system. This technique uses an artificial neural network (ANN) to look at the probabilistic nature of battery operation. Input data for solar radiation is modeled using either a bivariate, first order Markov chain or canonical variate analysis

(CVA). The resulting modeling for the PV-battery system is performed using a Monte Carlo analysis.

This type of modeling is considered inductive or non-phenomenological because the inputs and outputs are statistically derived through training behavior rather than the more traditional observed mathematically derived process. SNL has performed this type of inductive modeling with lead-acid as well as lithium-ion batteries.

Availability and Maintenance

The equations are described in papers by Urbina et al. (1998) and Urbina et al. (2000).

References

- Urbina, A., R. Jungst, D. Ingersoll, T. Paez, G. O'Gorman, and P. Barney, 1998, *Probabilistic Analysis of Rechargeable Batteries in a Photovoltaic Power Supply System*, 194th Electrochemical Society Meeting, Boston, MA, November 1-6, 1998. [SAND98-2635C]

- Urbina, A., T. Paez and R. Jungst, 2000, *Stochastic Modeling of Rechargeable Battery Life in a Photovoltaic Power System*, 35th Intersociety Energy Conversion Engineering Conference, AIAA-2000-2976, Las Vegas, NV, July 24-28, 2000. [SAND2000-1541C]

4.2 Other Battery Performance Models

4.2.1 KiBaM

Description

The Kinetic Battery Model (KiBaM) is a lead-acid battery modeling application developed by Manwell and McGowan (1993) at the University of Massachusetts RERL. The charging analysis portion of the model is based on the dissertation by Facinelli (1983) and the discharge analysis is based on the BEST model by Hyman (1986). KiBaM is considered a phenomenological model where many of the battery parameters are derived from extensive testing, and uses a modified amp-hour (Ah) cycle counting method to model battery performance and lifetime. The original version was built for wind/diesel systems with PV added in later versions. HOMER, as discussed above in Section 3.2.1 uses a simplified version of the KiBaM model.

The Hybrid2 software program (Section 3.2.2) uses KiBaM for modeling battery performance. A recent benchmarking program undertaken by the EU (Bindner et al., 2005) led to improvements in the model. The model available for download is the revised version of KiBaM which incorporates recommendations made by the benchmarking project. Some of these improvements include better tracking of cycle charge and discharge rates, and expansion of the lifetime model to look at both cycle means and ranges (Bindner et al., 2005).

Availability and Maintenance

The program is available from RERL at:
http://www.ceere.org/rerl/projects/software/batteryModel.html

A theory manual is also available for Hybrid2 and describes the algorithm used by KiBaM: http://www.ceere.org/rerl/projects/software/hybrid2/Hy2_theory_manual.pdf

The improvements to KiBaM based on the benchmarking activities is available at:
http://www.ceere.org/rerl/publications/published/2005/AWEA05BatteryModel.pdf

References

- Facinelli, W. A., 1983, *Modeling and Simulation of Lead-Acid Batteries for Photovoltaic Systems*, Ph.D. dissertation, Arizona State University, Tempe, AZ.

- Hyman, E., 1986, *Modeling and Computerized Characterization of Lead-Acid Battery Discharges*, BEST Facility Topical Report RD 83-1, NTIS Report DOE/ET/29368-T13.

- Manwell, J. F. and J. G. McGowan, 1993, *Lead Acid Battery Storage Model for Hybrid Energy Systems*, Solar Energy, Vol. 50, No. 5, pp. 399-405.

- Bindner, H., T. Cronin, P. Lundsager, J. Manwell, U. Abdulwahid, I. Baring-Gould, 2005, *Lifetime Modelling of Lead Acid Batteries*, Riso-R-1515. Riso National Laboratory, Roskilde, Denmark, April 2005.

- Other references to KiBaM can be found at: http://www.ceere.org/rerl/rerl_publications.html

4.2.2 FhG/Riso

Description

The FhG/Riso model utilizes an equivalent circuit battery performance (weighted-Ah) and lifetime model developed by Puls (1997) and is derived from PV system modeling by Fraunhofer-Gesellschaft (FhG). The voltage equation in the Puls model is based off of early work by Shepherd (1965). A detailed description of model assumptions and equations is given by Bindner et al. (2005) as part of the EU benchmarking project.

Recommendations for model improvement as identified in the benchmarking project included the addition of additional testing data, creating a validation model, implementation of more stress factors and damage mechanisms, and incorporating other tests for input data. The group at Riso National Laboratory mentions including this battery model into IPSYS (Section 3.2.8) (Bindner et al. 2005).

Availability and Maintenance

Model equations are presented in detail in the Benchmarking report by Bindner et al. (2005). Detailed equations can be found in the thesis by Puls (1997).

References

- Shepherd, C. M., 1965, *Design of Primary and Secondary Cells, II. An Equation Describing Battery Discharge*, J. Electrochem. Soc., Vol. 112, pp 657-664.

- Puls, H. G., 1997, *Evolutionsstrategien zur Optimierung autonomer Photovoltaik-Systeme*, diploma thesis, Albert-Ludwigs University, Freiburg, Germany.

- Bindner, H., T. Cronin, P. Lundsager, J. Manwell, U. Abdulwahid, I. Baring-Gould, 2005, *Lifetime Modelling of Lead Acid Batteries*, Riso-R-1515. Riso National Laboratory, Roskilde, Denmark, April 2005.

- Baring-Gould, I., H. Wenzl, R. Kaiser, N. Wilmot, F. Mattera, S. Tselepis, F. Nieuwenhout, C. Rodrigues, A. Perujo, A. Ruddell, P. Lundsager, H. Bindner, T. Cronin, V. Svoboda, and J. Manwell, 2005, *Detailed Evaluation of Renewable Energy Power System Operation: A Summary of the European Union Hybrid Power System Component Benchmarking Project*, Preprint, NREL/CP-500-38209. National Renewable Energy Laboratory, Golden, CO, May 2005.

4.2.3 CIEMAT

Description

The Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT) in Spain has a battery storage model based on work by Copetti et al. (1993), and partially based on work by Shepherd (1965). The model was built to predict charge and discharge for lead-acid batteries produced by many different manufacturers rather than the more costly and time consuming effort of developing parameters for each brand of battery (Copetti et al., 1993; Achaibou et al., 2009). The application of this model to a hybrid PV/wind system is described by Gergaud et al. (2003), and is likely the battery model used in HySys (Section 3.2.9), although not confirmed.

Availability and Maintenance

Equations used by the CIEMAT model are available in the reference section.

References

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4.2.4 CEDRL

Description

The CEDRL model was developed for Natural Resource Canada's CEDRL Photovoltaic and Hybrid Systems group by Ross (2001a, 2001b). This semi-empirical model is a modified version of work by Shepherd (1965) and by Copetti et al. (1993) for the relationship between state of charge and current/voltage. The model is written for use within the Matlab Simulink environment. Equations for this model are used in HybSim, the hybrid system model developed at SNL (Section 3.1.2) and the PVToolbox program (Section 3.2.5).

Availability and Maintenance

Equations describing the battery model can be found in the references below, as well as the publications of the Renewable Energy Research (RER) consulting company webpage: http://www.rerinfo.ca/english/publications/all.html.

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5. PV Modeling Effort Improvements Underway at Sandia National Laboratories

SNL is actively working to improve the accuracy and value of PV performance models by focusing on a number of related technical areas listed below.

- Developing standardized techniques for PV performance model validation

- Characterizing PV performance model uncertainty and sensitivity

- Building models capable of simulating performance of large PV plants

5.1 PV Model Validation

Model validation is the process of evaluating the degree to which a performance model accurately represents the actual performance of a fielded PV system. SNL researchers are developing a standard validation process that compares measured performance data with the performance predicted by a model in order to better understand how to use and interpret model results. A standardized validation approach will allow different models to be compared with a set of quality controlled data from well instrumented fielded systems in a variety of climates. Model users can examine these validation results to evaluate the strengths and weaknesses of different models for different applications. Model developers can apply these standardized validation methods.

SNL's standardized approach to model validation for PV performance models focuses on comparing measured and modeled data in a number of different ways that provide insights into the accuracy of the model under different conditions. Perhaps the most obvious comparison that is made is for the total amount of energy produced by the system over different time periods (e.g., annual and monthly). Other comparisons examine measured and modeled energy output under specific ranges of environmental conditions (e.g., temperature, irradiance, winds speed, etc.). This comparison provides model developers with important information about how a particular model compares with other models, and under what specific set of conditions might result in poor model performance. One challenge with developing a meaningful comparison between measured and simulated data is that most quantitative comparisons assume there is no uncertainty in the data. Appropriate treatment of uncertainty both in measured and modeled data is an important aspect of model validation this is usually overlooked when models are validated. SNL's effort towards evaluating the sources and magnitudes of uncertainties in PV performance modeling is outlined in the next section.

5.2 Model Uncertainty and Sensitivity

PV performance models all rely on some set of parameters that describe the ability of a given PV array or module to produce power under a given set of environmental and site conditions. These parameters are typically determined from tests run at known conditions in the laboratory (e.g., standard testing conditions (STC)) or at outdoor testing laboratories where environmental conditions are measured with high accuracy (e.g., Sandia National Laboratories' PV Systems Optimization Laboratory). As with any test, there are uncertainties related to the measurement and interpretation of data (e.g., regression analyses) that can propagate and contribute to uncertainties in the predicted output from a model. In addition, different models and modeling approaches exist for predicting PV performance and therefore the choice and application of a model adds a degree of model uncertainty. SNL is currently working to apply standard methods of uncertainty analysis to evaluate parameter and model uncertainties associated with current practices for PV performance modeling.

The approach being pursued by SNL is to employ stochastic methods (e.g. Monte Carlo analysis) to propagate parameter uncertainties in several of the available models discussed in this report. Current efforts are focused on evaluating uncertainty in the Sandia PV Array Performance Model and the other models included as part of the Solar Advisor Model (SAM) as well as for PVSYST. In addition to estimating uncertainty, these analyses will use methods such as stepwise regression to identify and rank the sensitivity of model results to each of the uncertain input parameters. Such results will help researchers and industry identify areas where increased accuracy of measurements would have the greatest positive impact on model accuracy.

5.3 Modeling Large PV Plants

All models included in this survey assume that the PV array is small enough such that a single irradiance value (along with co-located weather parameters) is representative of the conditions across the entire array for each time step in the calculation. As large, multi-megawatt PV plants begin to proliferate, the fact that irradiance patterns over these large arrays are not uniform in time and space becomes important. Updated modeling approaches are necessary in order to more accurately represent the performance of such systems. SNL is actively involved in deploying networks of irradiance sensors to evaluate the spatial and temporal patterns in irradiance at the sites of large PV arrays. The result of this research is aimed at developing a model of PV performance that can represent, and/or use as input, spatially and temporally complex patterns of irradiance and still provide accurate estimates of aggregated PV plant performance. Such a model is needed to better understand the impact of integrating large PV plants into the existing distribution and transmission grids.

6. Assertion of Copyright

Some of the codes evaluated in this report were developed in the 1970's and 1980's, prior to the processes now in place that require SNL to assert copyright of these codes with the Department of Energy before releasing or licensing them to the public. For SNL employees, complete instructions for the assertion of copyright can be found on the internal (restricted) SNL network, at:

Internal: http://www.irn.sandia.gov/legal/intellectual/copyright.html

Information regarding licensing intellectual property (including software and codes) from SNL can be found at the following external website:

External: http://ipal.sandia.gov/

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APPENDIX A

PV and Hybrid Model Table

The following table shows the difference in capabilities of both PV and hybrid system models. Battery models are not included in this matrix. The order of the models follows the same order as the report. These categories allow for comparison between each model and include the following: Type of model, plane-of-array radiation model, array performance, modeled technologies, weather and insolation, economics/financing and model status. A key is provided at the end of the table to describe certain terms in more detail. It is exceedingly likely that information was not discovered, or not made available to the authors during the compilation of this report that would indicate an update, improvement or provide additional information about a specific model. Therefore, this compilation does not represent an exhaustive effort and should be considered a working draft as some models are constantly updated and changed, and new models are introduced. Contacting the organization that manages each model will provide the most up-to-date information.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
PVSS	component	N/A	One-diode equivalent circuit and simple temperature model.	cSi	unk	N/A	Developed around 1976-1977. No longer used or maintained.
SOLCEL	system	N/A	One-diode equivalent circuit, simple temperature model, passive or active cooling.	cSi, CPV	SOLMET	Basic cost and LCOE.	Developed and used from the mid-1970s to the mid-1980s. No longer used or maintained.
Evans and Facinelli	component	Array tilt correction factor	Power temperature coefficient model (efficiency, temperature, array tilt correction factor).	cSi, CPV	SOLMET	N/A	Developed in the late 1970s to early 1980s timeframe. No longer used or maintained.
PVForm	system	Perez et al.	Modified power temperature coefficient model (efficiency, temperature and POA). Different equation used for two low and high irradiance levels. Fuentes thermal model.	cSi	TMY	Basic input and lifecycle cost, LCOE.	Developed in 1985 with the last update made in 1988. No longer maintained. PVForm can still be licensed from SNL.
PVSIM	component	N/A	Two-diode equivalent circuit.	All PV technologies	N/A	N/A	Developed in 1996. No longer used or maintained.
Sandia PV Array Performance Model	component	N/A	Empirically derived coefficients for the following: I-V curve, module temperature (thermal model), angle of incidence, air mass, and effective irradiance.	cSi. CPV, mj-CPV, TF (CdTe, CiS, aSi)	TMY 2/3, METEONORM, custom locations.	N/A	Developed between 1991 and 2004. Currently used and maintained at SNL with new modules being added to database. Used in SAM.
PVDesignPro	system	HDKR, Perez et al.	Sandia PV Array Performance Model.	cSi, CPV, mj-CPV, TF (CdTe, CiS, aSi)	TMY 2/3, METEONORM, custom locations.	Financial analysis including lifecycle and energy costs.	Developed in the late 1990s. Maintained by the developer with v6.0 released in 2004.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
Solar Advisor Model	system	Isotropic Sky, Hay and Davies, Reindl, Perez et al.	Sandia PV Array Performance Model, 5-Paramater Array Performance Model, simple-efficiency model, PVWatts.	cSi, CPV, HIT, TF (CdTe, CiS, aSi)	TMY2, EPW (TMY3), METEONORM.	Energy cost, financing options, depreciation, tax credits/incentives, cash flow, LCOE. Residential, commercial and utility financing.	Developed around 2006. Maintained by NREL. Last update in 2009 with version 2009.10.2.
5-Parameter Array Performance Model	component	N/A	Semi-empirical 5-parameter one-diode model.	CEC implementation: cSi, BiPV, Ribbon, TF (aSi, CdTe)	N/A	N/A	Code is currently being updated by Wisconsin SEL to add more parameters. Used in SAM.
PVWatts	system	Uses PVForm (Perez et al.)	Uses PVForm Equation.	cSi	TMY 2 for US. For international sites, SWERA, CWEC, IWEC.	Calculates electricity cost and energy value.	Maintained by NREL. Last update in 2008. Used in SAM.
PVSYST	system	Hay, Perez et al.	One-diode equivalent circuit. Modified one-diode for stabilized aSi, CiS and CdTe thin-film modules. Also, Incident angle modifier, and air mass correction.	cSi, μc-Si, HIT, TF (CdTe, CiS, aSi)	Meteonorm, Satellight, TMY 2, ISM-EMPA, Helioclim-1 and 3, NASA-SSE, WRDC, PVGIS-ESRA, RETScreen.	System financing, feed-in tariffs, annual and used energy costs.	Developed in the mid 1990s. Currently updated in 2009 with version 5.05.
PV F-Chart	system	Isotropic Sky	Monthly average of Instantaneous array output (function of efficiency and cell temperature). Also see Evans and Facinelli above.	cSi, CPV	TMY2	Life-cycle costs, equipment costs and cash flow.	Developed in 1985. Last update was in 2001.
PVSol	system	Hay and Davies	Based on irradiance and module voltage at STC and efficiency characteristic curve. Linear or dynamic temperature model. Incident angle modifier.	cSi, μc-Si, Ribbon, HIT, TF (CdTe, CiS, aSi)	MeteoSyn, Meteonorm, PVGIS, NASA SSE, SWERA, custom locations.	Economic efficiency for cash value factor, capital value, amortization period and electricity production costs.	Developed in 1998. Last update of Expert was in 2009 with version 4.0.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
Polysun	system	unk	unk	cSi, µc-Si, Ribbon, HIT, TF (CdTe, CiS, aSi)	Meteotest, custom locations.	Financing, O&M costs, incentives, energy prices, fuel cost savings, system value.	Developed in 2007. Last update was in 2009 with version 5.2.
INSEL	system	Isotropic Sky, Temps and Coulson, [Bugler, Hay and Kambezidis], Klucher, Hay, Willmott, Skartveit and Olseth, Gueymard, Perez et al., and Reindl et al.	One and two-diode equivalent circuit model. Four incident angle modifier models.	cSi, others unknown	Worldwide InselWeather database.	Installed system cost, O&M costs, NPV, electricity cost, feed-in tariffs.	Developed in 1991. Pre-release of version 8.0 was available in late 2009.
SolarPro	System	Unk	One-diode equivalent circuit. Simple temperature model.	cSi, HIT, TF (CdTe, aSi)	Worldwide – provided by Japan Meteorological Agency.	System O&M costs.	Developed in 1997. Current version at time of this report is 3.0.
Clean Power Estimator (CPE)	system	Uses PVForm (Perez et al.)	Uses PVForm Equation.	cSi, others unknown	TMY2, Proprietary satellite measurements.	financing, tax credits, utility rates, payback, cash flow, O&M costs, depreciation.	Software is current. Clean Power Research can customize the CPE for any location in the US and has been in operation since 1998.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
PVOptimize	system	Uses PVWatts (PVForm)	Uses PVWatts (PVForm) Equation.	cSi, CPV, Ribbon, TF (CdTe, aSi)	PVWatts (TMY2)	Generates reports for State of California specific incentives (Performance Based Incentives), utility interface cost and credits.	7-day evaluation version 1.0.46 available at the time of this report.
OnGrid	system	Uses PVWatts (PVForm)	Uses PVWatts (PVForm) Equation.	cSi, Ribbon, TF (aSi, CdTe)	Uses PVWatts	Generates reports for State of California specific incentives (Performance Based Incentives), utility interface cost and credits. Also works with other states incentive systems. Looks at system costs, federal incentives, depreciation, cash flow, IRR, and O&M costs.	This software was released in 2005 and consistently updated with options for monthly or annual subscriptions. Version 3_4a is the version available at the time of this report.
CPF Tools	system	Uses PVWatts (PVForm)	Uses PVWatts (PVForm) Equation.	CEC implementation: cSi, Ribbon, TF (aSi, CdTe)	NCDC USHCN	Generates custom reports. Federal and state incentives, cash flow, IRR, financing, LCOE, lifecycle payback, system resale value.	Software is current with a monthly subscription cost. A 7-day trial is available. CPF started operations in 2007.
Solar Estimate	system	Uses PVWatts (PVForm)	Uses PVWatts (PVForm) Equation.	cSi, others unknown	PVWatts (TMY2)	System cost, federal, state and local financial incentives, cash flow analysis, savings and benefit analysis.	On-line application was released in 2000. Web-based software is currently updated at the time of this report.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
SOLSTOR	Hybrid system	N/A	See SOLCEL	See SOLCEL	See SOLCEL	lifecycle costs including capital cost, O&M, and energy purchase cost. Depreciation, ITC, salvage value, financing.	Software was developed and maintained between 1979 and 1982. It is no longer updated or supported.
HybSim	Hybrid system	unk	unk	cSi	15 minute max insolation, temperature and wind speed.	Lifecycle costs for system components, such as PV, generator and batteries. It can look at cost and performance differences between a diesel only system with one consisting of different renewable sources (PV, wind) combined with storage (battery) and backup generators.	Version 3.3 available for license. Work is on-going (as of 2009) to add more hybrid system components. Version 1 was released in 2005.
Hysim	Hybrid system	Uses PVForm (Perez et al.)	Uses PVForm Equation.	cSi	TMY 2	LCOE, lifecycle cost, fuel cost, O&M cost, cost comparison between alternative configurations.	Hysim was available for use in 1987 with some applications as late as 1996. It is no longer used or updated.
HOMER	Hybrid system	HDKR	Power calculated as a function of incident radiation, derating, rated array capacity and PV cell temperature.	Uses some input data from module manufacturer and other available data.	Scaled data in a text file. User can select locations in software, use TMY 2 data or input custom data.	Inputs include annual real interest rate, project lifetime, system fixed capital costs and O&M costs and capacity shortage penalty. Main outputs include total Net Present Cost (NPC), and LCOE.	HOMER was developed in 1993, and is available as of 2009 through HOMER Energy. Version 2.67 beta (April 2008) was the most recent version at the time of this report.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
Hybrid2	Hybrid system	HDKR	5-parameter array performance model.	cSi, TF (CdTe, CiS, aSi)	unk	lifecycle cost, cash flow, NPV, payback, IRR, tax credits, tradeoffs between different hybrid configurations.	This program was developed in 1994 as Hybrid1, and then updated to Hybrid2 in 1996. The most recent version at the time of this report is 1.3e (2004).
UW-Hybrid (TRNSYS)	Hybrid system	Isotropic Sky, Hay and Davies, Reindl, Perez et al.	5-parameter array performance model (4-parameter for crystalline, 5-parameter for TF).	cSi, CPV, TF (CdTe, CiS, aSi)	TMY, TMY 2, Meteonorm, EnergyPlus, IWEC.	lifecycle cost analysis including cash flow, savings, payback period, rate of return. User can input state and federal tax incentives.	TRNSYS was developed in 1975 and continues to be utilized and updated for a variety of energy analysis capabilities. The most recent version at the time of this report is version 17.
PVToolbox	Hybrid system	unk	One-diode equivalent circuit.	cSi, TF (aSi)	unk	O&M calculator for lifecycle cost analysis.	It appears that the PVToolbox was initially created in the early 2000s for research in Canadian climates. The last updates to the model appear to have been made in 2007.
RAPSIM	Hybrid system	unk	unk	cSi assumed, others unknown	unk	unk	This software was developed in 1996 for use in Australia. Version 2.0 was available in 1997. It is unknown if updates were made past 1997.
SOMES	Hybrid system	unk	unk	cSi assumed, others unknown	unk	unk	SOMES was developed in 1987, with version 3.0 available in 1993, and version 3.2 available in 1997. It is unknown if updates were made past 1997.

	Type of Model	POA Radiation Model	Array Performance	Modeled PV Technologies	Weather and Insolation	Economics/Financing	Model Status
IPSYS	Hybrid system	unk	unk	cSi assumed, others unknown.	unk	unk	Development for IPSYS appears to have started in 2000, with a more formal discussion of the software in 2004. It is unknown if updates were made past 2004.
HySys	Hybrid system	unk	unk	cSi assumed, others unknown.	unk	unk	HySys version 1.0 was developed in 2003. Further research is identified by the IEA PVPS Task 11 in 2008. It is unknown if updates are available past the 2003 version.
Dymola/Modelica	Hybrid system	unk	unk	cSi assumed, others unknown.	unk	Lifecycle costs, LCOE.	2008 is the last known date of the software from an IEA PVPS conference.

Key for PV and Hybrid Model Table:

unk - unknown
N/A - not applicable
Component - models individual or all components in a PV system such as array, inverter, charge controllers, batteries and system load.
System - models all components of a PV or hybrid system and includes economic and financial analysis capabilities. May also include battery storage.
ISM - EMPA - Switzerland meteorological data.
PVGIS ESRA - GIS interpolated meteorological layer for Europe and Africa.
Helioclim - Europe and Africa Meteostat meteorological data.
RETScreen - Worldwide meteorological dataset uses best location from 20 sources.
Meteonorm - Worldwide meteorological dataset.
Satellight - European meteorological dataset.
MeteoSyn - Worldwide meteorological dataset.
PVGIS - EU spatially enabled geobrowser for European and African meteorological data.
Meteotest - Worldwide meteorological dataset.

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