Improvements to PVWatts for Fixed and One-Axis Tracking Systems

Preprint

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Improvements to PVWatts for Fixed and One-Axis Tracking Systems

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***Abstract*—This work presents improvements to the widely used NREL PVWatts photovoltaic system energy model to improve modeling accuracy for typical fixed and one axis system designs. The aim is to calculate losses in the PV system assuming typical modern system design practices, while maintaining simplicity by keeping the required set of input parameters small. These improvements allow users to more credibly and quickly evaluate competing system designs in early stage feasibility. Common submodels for module cover, spectral, snow, tracker, transformer, plant controller, and self-shading losses, in addition to a bifacial gain option, are incorporated into the PVWatts model, and are shown to improve PVWatts' system performance prediction capabilities without major impact to ease of use. We anticipate including these improvements in a future release of NREL's open source PVWatts code, and some of the features may become available in the System Advisor Model (SAM) desktop software as well as the popular PVWatts web application.**

***Index Terms*—photovoltaic modeling, PVWatts, NREL, energy model, bifacial, self-shading**

I. INTRODUCTION

The NREL PVWatts model is a simple-to-use photovoltaic system energy model that is widely accepted in the industry for initial feasibility assessment and quick analysis. PVWatts was first developed in the late 1990s, and was improved over many years, with the most recent version 5 released in 2014 [1]. To keep the model simple, many losses were simply entered as an input originally as the PVWatts "derate" (well known default value of 0.77 prior to 2014), or the aggregate "system loss" (default of 14 % in versions 5 and 6). The derate or system loss assumptions included soiling, shading, snow, mismatch, wiring and connections, and other categories. In this work, we incorporate models for self-shading, snow loss, and other common losses to enable better prediction of energy output as a function of system design without additional model input complexity. For example, our revised PVWatts model can be used to optimize initial design parameters (ground coverage ratio, DC/AC ratio, fixed or tracking, monofacial or bifacial) to maximize energy yields for a given land area. Consequently, PVWatts can be applied as a true first cut feasibility tool to balance high level system design trade-offs in a credible way.

This work was done using the open-sourced version of PVWatts version 5 as a starting point, available online from the NREL GitHub repository at github.com/nrel/ssc. We anticipate that the full enhanced feature set will be made available via the open-source code and in the SAM software development kit, and a subset of the features described here will be added to the implementation in the SAM desktop software, PVWatts application programming interface (API), and the PVWatts web application.

II. MODEL ENHANCEMENTS

Our changes to the standard PVWatts Version 5 model presented in this work include:

1) Updated module and system loss assumptions.
2) Addition of self-shading calculations for fixed and one-axis tracking systems assuming typical modern system design parameters. The self-shading model accounts for non-linear electrical losses when appropriate.
3) Improvement to the module cover losses to account for diffuse blocking effects.
4) Addition of a spectral loss calculated via a standard air mass modifier equation.
5) Addition of a snow loss model for when daily snow depth data is available.
6) Addition of new output variables to facilitate creation of Sankey diagrams of modeled losses.
7) Addition of the Marion rear side irradiance and bifacial model [2].
8) Estimation of one axis tracker wind stow losses.
9) Estimation of gains from diffuse light stowing optimization.
10) Interconnection limit plant controller losses.
11) Step-up transformer losses.
12) Optional monthly or daily soiling and albedo input parameters.

A. Module types and loss assumptions

The assumptions for the three different module types in PVWatts are listed in Table I, and are updated relative to PVWatts V5 to be more representative of recent module characteristics. These values were selected by inspection from among recent mid-size nameplate modules from three Tier-1 manufacturers. In general, the efficiencies are improved compared with parameter values in PVWatts V5, and the temperature coefficient for the thin film module is slightly worse than previously.

Type	STC η	Cover	γ_{mpp}
Standard	∼17.0 %	Glass	-0.38 %/°C
Premium	∼20.1 %	AR Glass	-0.30 %/°C
Thin film	∼15.6 %	Glass	-0.28 %/°C

TABLE I
MODULE TYPES IN PVWATTS

The lumped DC system loss parameter is also revised in this work to approximately 6 %. This value represents non-modeled losses including mismatch, wiring, and light induced degradation (LID). System availability may be lumped in with

DC system loss, or applied separately in the performance adjustment or curtailment factor input. Also, depending on the particular site under evaluation, an estimate of far shading losses may be added into the lumped loss as well.

B. Self-shading loss

The self-shading losses are calculated using the semi-empirical model of Deline, et. al. [3]. Reasonable assumptions about module geometry and array layout must be made when the PVWatts array type is a fixed open rack or a one axis tracker. Note that the fixed roof mount array type option assumes modules arranged in a single plane mounted close to a roof, and so no self shading occurs.

The ground coverage ratio (GCR) is the key parameter defining the array layout. Individual modules, regardless of type, are assumed to have an aspect ratio of 1.7 and an STC rating of 300 Watts. Given the total system size, the number of modules can be calculated, as well as an approximation of the number of rows assuming a "square" array layout in which each row has a single line of modules. Assuming a representative V_{mp} (maximum power voltage) of 60 V, 7 modules per string gives a nominal DC voltage of about 420 V.

For crystalline silicon modules (standard or premium), fixed systems are assumed to have a 2-up portrait configuration, while one axis trackers are in a 1-up portrait setup, typical of commonly used tracker technology. For thin film modules, the array design is assumed to take advantage of the long parallel cell structure to minimize nonlinear electrical shading losses.

C. Module cover loss

The module cover model is improved beyond PVWatts version 5 to include diffuse angular effects according to the approach describe in Duffie & Beckman's *Solar Engineering of Thermal Processes* [7]. For premium modules with anti-reflective coatings, the PVWatts version 5 two slab physical model is used for the beam component of the irradiance.

D. Spectral loss

A simple air mass modifier spectral correction is added according to the approach of Desoto [6]. The air mass modifier polynomial coefficients are not impacted in the current implementation by the choice of module type, although this could be an area for further improvement.

E. Snow loss

Snow losses are accounted for using the Marion, et. al. model, as implemented in NREL's System Advisor Model (SAM) software [4]. The model is applied to both fixed and one axis tracking systems, and incorporates the instantaneous tilt angle, snow depth, and ambient temperature. Snow depth data must be available in the weather file to run the snow model; however, historical snow depth data can be found in various public sources and databases, including the NREL 1961-1990 historical weather dataset used to create the TMY2.

F. Loss diagram

A common way to visualize energy flows in PV systems is through Sankey loss/gain diagrams. PVWatts Version 5 did not include the necessary detailed outputs to create these visualizations. The individual loss percentages calculated by PVWatts, as shown in Fig. 1, are relative to the previous energy value (the percent values are not additive). In addition, it is not straightforward to truly disaggregate all of the individual effects, and so the losses percentages should be treated as fairly credible, if not 100 % exact.

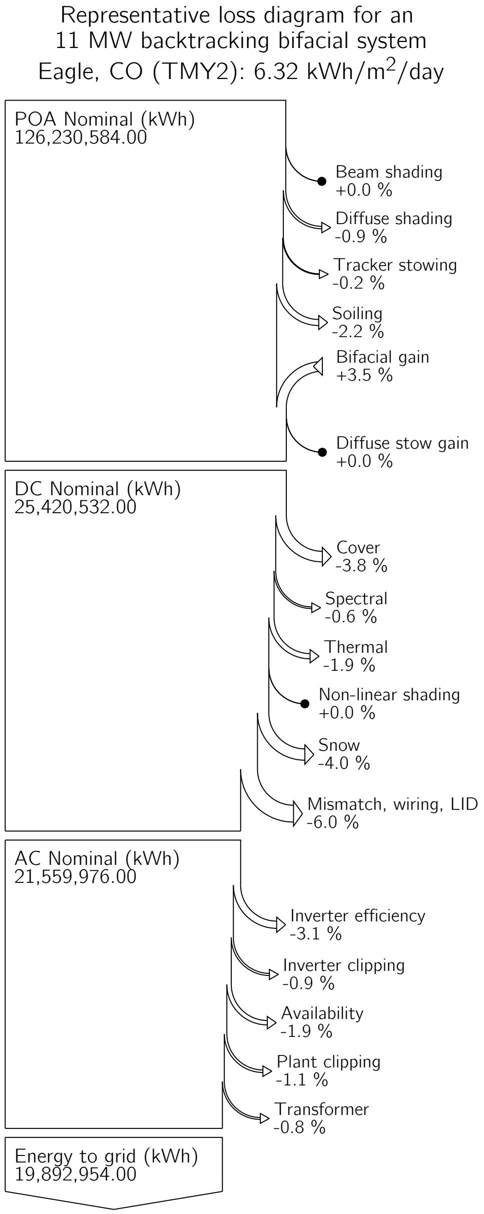

Fig. 1. Representative Sankey loss diagram showing modeling improvements in PVWatts for a system in Eagle, CO. Note in particular the 4 % loss due to snow.

G. *Bifacial gain*

By setting a new module *bifaciality* input parameter to greater than zero, the Marion, et al. [2] view factor model is enabled for back side irradiance gain estimation. In addition to the bifaciality (rear side efficiency) parameter, the model uses the system GCR, assumes a 1 m height, and a 0.13 light transmission factor through the module. The total gain is reported as a positive value in the loss diagram.

H. *Tracker wind stowing*

In high wind conditions, one axis trackers are designed to stow to prevent damage to the system installation. The reduced plane of array irradiance received compared to optimal tracking results in an energy production loss. We can estimate this loss by forcing a fixed tracker wind stow angle if the average hourly wind speed, multiplied by a gust factor, exceeds a tracker wind stow threshold setting. Default values are a wind stow threshold of 10 m/s, a gust factor of 1.28 [11], and a default tracker stow angle of approximately 30 degrees [10].

I. *Step-up transformer*

In larger system installations, a step-up transformer is needed to connect a PV system to the grid. A simple two parameter model is implemented to account for load and no-load loss behavior of typical transformers. Default parameters follow the PVsyst [14] recommendations, of a no-load loss (iron core) of 0.1 %, and a load loss (ohmic winding) of 0.66 %.

J. *Plant controller*

In some larger systems, a plant-level controller may limit total inverter output to a maximum of the grid interconnection limit. This is separate from inverter level clipping that occurs as a result of DC/AC ratio design considerations. The AC maximum delivery power (interconnection limit) is set as a fraction of the rated system AC power (which is defined internally from the DC system size and DC/AC ratio parameters). By default, no plant controller is enabled (AC plant maximum fraction is 1.0).

K. *Diffuse stow*

Modern single axis trackers sometimes use additional sensors and algorithms to actively adjust the tracker rotation angle to maximize plane of array irradiance capture beyond simply pointing directly at the sun. At locations where diffuse light comprises a significant portion of the total available irradiance, it can benefit annual energy yields to turn trackers to a more horizontal position during cloudy periods to increase the view factor to the sky dome. In PVWatts, we implement a simple algorithm that finds the best tracker angle at every time step to maximize total POA irradiance. For the case of one axis trackers with bifacial modules, we design the algorithm to maximize total (front & rear side) irradiance, noting that this may represent an upper bound on the potential improvement, as it may be too complex or costly to implement active sensors in a real system to optimize both side irradiance collectively.

L. *Soiling and albedo*

As experience from operating plants in various locations increases, better seasonal information on soiling loss and albedo may be available. Monthly and daily soiling input options allow for users of PVWatts to estimate optimal washing schedules given observed soiling rates and rain fall patterns, and more flexibility on albedo allows consideration of potential bifacial system scenarios. By default, the soiling loss is a single annual value of 2 %, while default albedo is still 0.2. If the snow loss model is enabled, and snow depth is detected greater than 0.5 cm, the model does increase albedo from 0.2 to 0.6 by default to properly account for the increased reflected irradiance.

III. RESULTS

A. *Self-shading behavior*

Figs. 2-3 show losses for different system designs as a function of the ground cover ratio (GCR), relative to a nearly completely unshaded condition (GCR=0.1). For premium silicon modules, the row-to-row shade impact on a one-axis tracker is quite pronounced as non-linear electrical losses quickly predominate as the GCR is increased, and employing a backtracking strategy can reduce losses. For the thin-film modules, which are assumed to respond linearly to shade due to long cells parallel to the axis of tracker rotation, backtracking may incur greater losses than standard tracking. Note that these figures show relative loss - not actual energy generated: the energy output of a one axis tracked system at GCR of 0.4 may well still produce more energy than a fixed system even if the losses relative to the unshaded condition are higher.

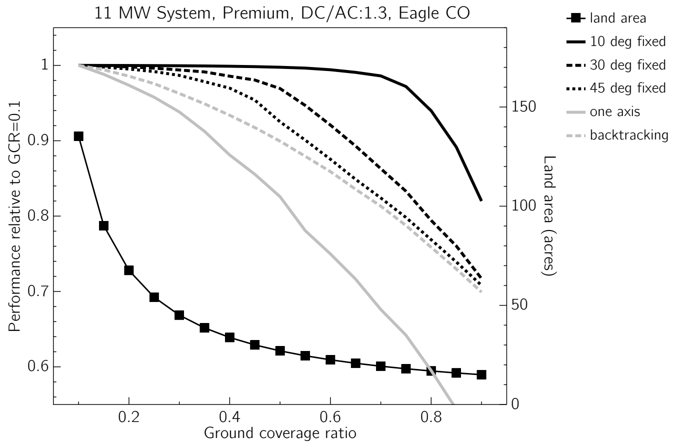

Fig. 2. Relative performance for different system designs using premium crystalline silicon modules with respect to the unshaded condition. Note that system energy production is not relative among the different system designs shown - only the self-shading impact is indicated.

B. *Impact of snow fall*

Fig. 4 shows annual energy output for five different system designs. For locations in the world where snowfall occurs, it

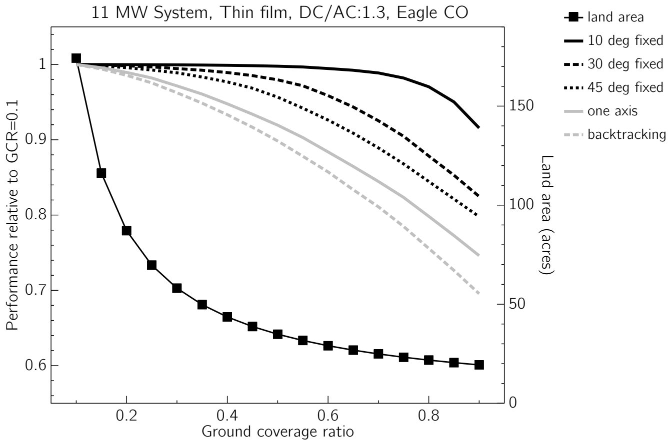

Fig. 3. Relative performance for different system designs using thin film modules with respect to the unshaded condition. Note that system energy production is not relative among the different system designs shown - only the self-shading impact is indicated

is important to quantify the energy loss as it can be quite significant. Adding a snow loss model to PVWatts allows estimation of the impact of snow, provided that historical daily snow depth data is available. For a low tilt fixed system, the loss can be over 9 % for a typical year in Eagle, CO.

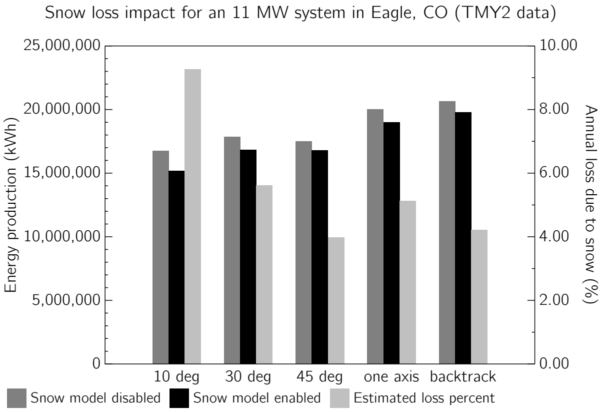

Fig. 4. Estimation of energy losses due to snow for a system in Eagle, CO.

C. *Diffuse stow tracking*

We evaluate our diffuse stow one axis tracking algorithm in Wilmington, Delaware, which experiences a greater fraction of diffuse light than Eagle, Colorado. On an annual basis, PVWatts predicts that a monofacial tracking system with diffuse light stow optimization yields about 0.6 % more energy in Wilmington. This is roughly consistent with recent information from the tracker industry [9]. The same system, but with bifacial modules (bifaciality factor of 0.65), shows a bifacial gain of 3.9 %, but the diffuse stowing gain is reduced to about 0.3 %. As a tracker with bifacial modules attempts to stow horizontally to maximize the front side sky view factor, the rear side view factor is simultaneously reduced, thereby reducing the potential total irradiance gain from stowing relative to a true-tracked position.

This behavior is clearly visible in Fig. 5, which shows tracker angles on four representative days in January. The first and second days are primarily cloudy, and the monofacial diffuse stow-enabled tracker spends more time close to a zero degree angle compared with the normal true-tracking of the sun position. With bifacial modules, the optimum position is somewhere in between the true-tracked and monofacial case, explaining the reduced potential gain from diffuse stowing with bifacials. The third day shows behavior under high wind stow, and on the fourth day, all tracker angles are the same and point to the sun due to the relatively high beam irradiance conditions.

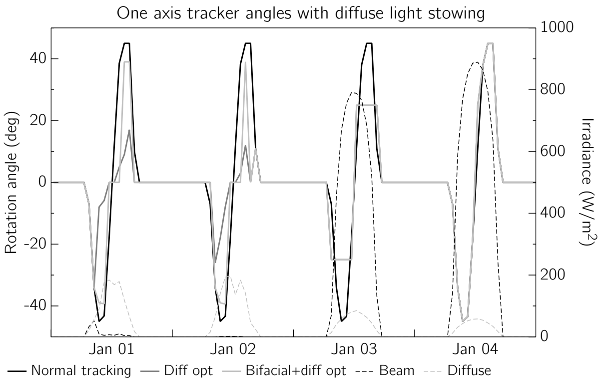

Fig. 5. Tracker rotation angles for different tracking strategies across four representative days.

D. *Comparison with Single-diode models*

In this section, we compare the simple linear module model in PVWatts with the industry standard single diode Mermoud-Lejeune (SDM-ML) model used for detailed system design modeling in PVsyst [5]. For this exercise, we select three representative modules from the PVsyst database to correspond to the three PVWatts module types. Only the electrical I-V curve model is used - the module cover, spectral, shading, and thermal models are the same for both cases.

PVWatts Module (Linear)	PVsyst Module (SDM-ML)
Standard	Trina TSM-330DD14A(II)
Premium	SunPower SPR-X20-327-COM
Thin film	First Solar FS-4112-3

TABLE II

REPRESENTATIVE MODULES FOR COMPARISON WITH THE PVSYST SINGLE DIODE MODEL.

In general, Fig. 6 shows good agreement between the PVWatts simple linear model and the single diode model. The most notable difference is for the thin film modules, for which the single diode model predicts a smaller spread in power at any irradiance - hence a lower impact of module temperature. This discrepancy needs further more investigation, as the max power point temperature coefficient indicated by PVsyst for the First Solar module is the same as the PVWatts assumption of -0.28 %/°C.

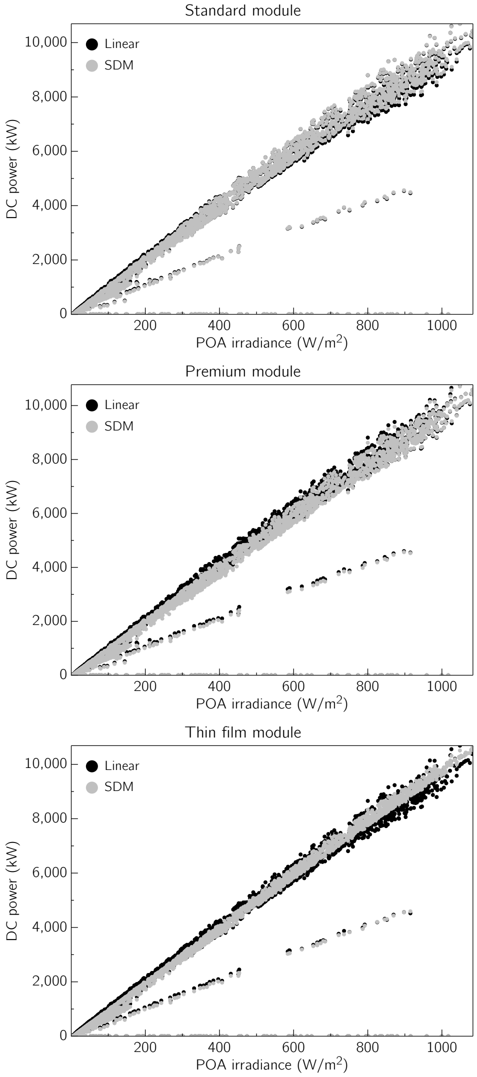

Fig. 6. Comparison of simple linear vs. single diode model behavior for three different module types.

E. Comparison with real systems

We leverage past NREL PV model validation work [12] [13] to compare our expanded PVWatts model with measured system performance data for nine operating photovoltaic plants. Details of the nine systems are available in [12]. We assign a DC loss factor of 6%, consistent with the recommendations in this paper, and set the new soiling input to a constant 2% to be consistent with previous work. Due to a lack of snow depth data, we did not enable the snow model. None of the systems, which are older, are bifacial, so that model was not enabled, and we do not have any information on plant controller or step-up transformer losses, so those features were likewise not used. However, the new module type assumptions, self-shading calculations, module cover and spectral losses, and wind stow model with its default values for single axis trackers were enabled in this analysis. Table III shows the results of these simulations.

System	PVWatts Version 5 (%)	Improved Version (%)
STF	-1.4	1.1
Forrestal	-6.9	-3.1
RSF1	-0.9	1.6
RSF2	-3.2	0.2
VisitorParking	-0.5	2.8
MesaTop	0.1	2.1
FirstSolar2	-4.0	-5.6
DeSoto	-9.6	-7.4
FirstSolar1	-6.9	-8.7
Average	-3.7	-1.9

TABLE III

COMPARISON OF ANNUAL ENERGY MODEL PREDICTION ERROR WHEN COMPARED WITH TO MEASURED SYSTEM PERFORMANCE DATA.

In general, we see that the errors are similar to PVWattsV5 for most cases. The average error across the 9 systems for PVWatts V5 is -3.7%, while for the improved PVWatts model it is -1.9%. Note that the exact GCR is unknown for many of these systems, or the installed GCR may differ from the system specifications. This was not a handicap for PVWattsV5, which only used that information for single-axis tracking systems, but will now affect the self-shading algorithms for all systems in the updated model code. We also do not have any details on the wind stow behavior of the trackers for the two single-axis tracking systems (MesaTop and DeSoto). Nonetheless, it is a good result that even with limited information about a particular system, PVWatts can offer a credible estimate of annual energy output and realistically model various system design trade-offs as articulated in the preceding sections.

IV. CONCLUSION

Improvements to the PVWatts algorithms for modeling typical fixed and one-axis tracking photovoltaic system designs were presented. The enhancements allow PVWatts to better predict energy output as a function of typical design parameters and environmental conditions with minimum set of input parameters. New modeling capabilities for bifacial modules, as well as tracker operation including wind stowing and diffuse light capture optimization, enable users to rapidly understand the complex trade-offs between various system design choices before investing in extremely detailed and precise systems modeling efforts. While a cursory comparison with measured performance data from nine operating plants shows that our presented model improvements reduce model prediction errors relative to previous versions of PVWatts, additional validation is always warranted and in particular for some of the newer system design options for which copious performance data is not readily available. We anticipate that these model algorithm updates will be made available in a future release of the open source NREL PVWatts code and SAM software development kit, and a subset of these features will be added to the SAM desktop software and the PVWatts web application and API.

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