

TECHNOLOGY REVIEW OF FIRST SOLAR'S PV SIMULATION
SOFTWARE PLANTPREDICT

PlantPredict Review

First Solar, Inc.

Document No.: 10031850-HOU-R-01

Issue: C, **Status:** FINAL

Date: 22 May 2017



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List of abbreviations

Abbreviation	Meaning
ACP	Alternating Current Power
BT	Backtracking
DNI	Direct Normal (beam) Irradiance or Irradiation
DNV GL	DNV KEMA Renewables, Inc.
FT	Fixed Tilt (array)
GCR	Ground Coverage Ratio
GHI	Global Horizontal Irradiance or Irradiation
GMT	Greenwich Mean Time
GWh	GigaWatt-hours
HT	Horizontal Tracker
I-V	Current versus voltage (relationship)
Kc	Linearized fixed thermal resistance coefficient (a.k.a. Uc)
Kv	Linearized wind-dependent thermal resistance coefficient (a.k.a. Uv)
MismFV	Fixed Voltage Mismatch parameter
MismMPP	Mismatch at MPP parameter
MN6	Meteonorm version 6
MN7	Meteonorm version 7
MPP	Maximum Power Point
MST	Module Surface Temperature
MWp	MegaWatts at peak power (STC-rated PV power capacity)
NNE	(facing) North by North-East
PlantPredict	Designation for First Solar performance modeling tool
POA	Plane-of-array (irradiance or irradiation)
PV	Photovoltaic
R	Ohmic resistance (as in I^2R losses)
QC	Quality Control
SSE	(facing) South by South-East
STC	Standard Test Conditions (1000 W/m ² , 25 °C cell temperature, AM 1.5 spectrum)
TMY2	NREL Typical Meteorological Year version 2
Voc	Open-circuit Voltage
WindCool	Non-zero Kv such that there is a dependence of PV system output on wind speed

EXECUTIVE SUMMARY

Introduction

This Report presents DNV GL's findings for the Technology Review of First Solar's PV Simulation Software PlantPredict (or "PlantPredict Review"). PlantPredict is a web-based simulation software for simulating the energy generation and performance of photovoltaic (PV) power plants.

Software overview

PlantPredict implements a general-purpose simulation processing engine for solar photovoltaic (PV) power generating plants in a web browser user interface. The modeling input data (e.g., weather data, project information data, and module and inverter characterization data) are stored in databases that allow straightforward retrieval and update from any physical location. On May 31, 2016, First Solar released version 3.0.0 of PlantPredict for public use.

Although industry-standard PV simulation software such as PVsyst is already used by many developers, engineering and procurement contractors, and independent engineers to model system equipment and designs, PlantPredict offers certain logistical and technical advantages.

From a logistical perspective, the use of PVsyst is very closely coupled with specific workstations, and the sharing of up-to-date results with both technical and non-technical users in a timely fashion is challenging. During a project development phase, updates to modeling assumptions may occur in rapid sequence. With PlantPredict, management and sales departments can obtain the latest consistent results with a simple browser refresh.

From a technical perspective, PlantPredict offers First Solar a direct path to introducing and testing modeling algorithms specific (but not limited) to the First Solar technology. Updates to general-purpose simulation software such as PVsyst tend to be delayed, if only due to balancing resource limitations with upgrade needs in a broad spectrum of PV-related technologies besides those of First Solar.

Validation overview

A risk presented by the use of any new PV modeling software is that the results of the simulations might not be accepted as valid by all parties in a given power plant construction deal, due to concerns including model applicability, model accuracy, or model consistency between runs. This report addresses the technical merits of the PlantPredict model, including model applicability and accuracy for versions 3.11.0.24737 (3.11.0), 3.12.0.28019 (3.12.0), and 3.13.0.39595 (3.13.0) of the PlantPredict software. DNV GL also ran one simulation in version 4.5.0.33429 (4.5.0) to confirm the time zone updates made in version 4.0.0.

The evaluation proceeds with a comparison to PVsyst version 6.43, which allows detailed comparisons of standard modeling comparison points. For typical modeling, the overall discrepancies in first year annual energy projections have a mean bias error of -0.6% (PlantPredict less than PVsyst) and a root-mean-square error of 1%.

Results overview

Figure ES-1 displays a summary of the deviations in annual AC energy output for the several test cases that were independently simulated by DNV GL in both PlantPredict and PVsyst. The range of results is from about -1.5% to 1.5% including test cases that are unlikely to occur in practice, which in DNV GL's view indicates that PlantPredict is a well-constructed PV performance prediction software package that is in most aspects comparable to or better than the industry-standard PVsyst modeling package. Some unexplained discrepancies do occur in the areas of near shading, reflection losses, and inverter losses, which are discussed in this report.

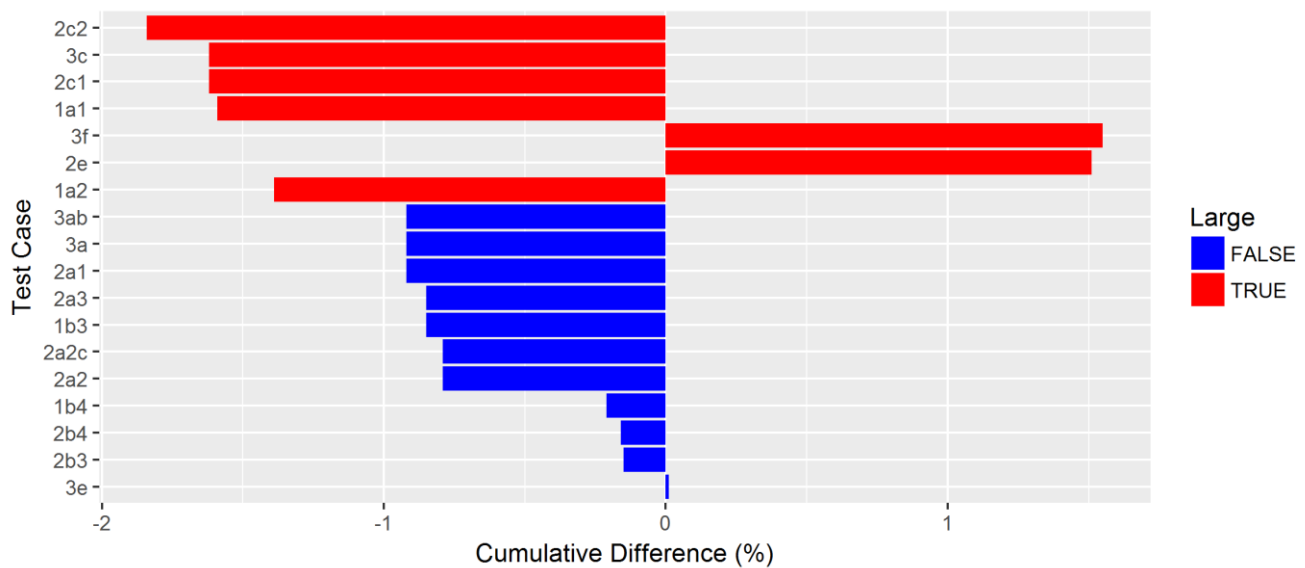


Figure ES-1. Primary Loss Trees Discrepancy Summary (True indicates >1%).

First Solar is conducting research both independently and in collaboration with research organizations such as Sandia National Laboratories to improve the models used in PlantPredict. These new models may lead to more accurate predictions by PlantPredict before similar models are implemented in PVsyst.

Twenty-one comparisons of PlantPredict outputs to field performance measurements were conducted by First Solar, with results indicating that modeled results are within 2.0% of field-measured annual energy generation with a mean bias error of -0.1%. These results are highly encouraging, and there may be room for additional improvement. First Solar noted that the distribution of residuals is not obviously normal and there may be dependencies correlated with climate and installation type (e.g., fixed vs. horizontal tracking).

1 INTRODUCTION

First Solar (the "Sponsor"), has retained DNV KEMA Renewables, Inc., a DNV GL Group member, (hereafter "DNV GL"), to perform a technical due diligence Technology Review of First Solar's PV Simulation Software PlantPredict (the "Project", or "PlantPredict Review"). This review is performed predominantly under First Solar Purchase Order 4800036188 and Task Order 131030, pursuant to the Professional Services Agreement (PSA) between DNV KEMA Renewables, Inc. and First Solar, Inc. dated 3 June 2016 (collectively the "Governing Agreement").

This technical due diligence report (the "Report") is provided to the Sponsor per the terms and conditions of the PSA and disclosure of the Report by the Sponsor to other potential investors and/or lenders is subject to provisions of the Governing Agreement.

The purpose of this Report is to summarize DNV GL's review of the PlantPredict modeling tool and the documentation received and reviewed through the date of this Report; to evaluate technical risks and mitigation measures relative to typical industry practice; and to advise on the status of any issues that appear technically incorrect, inconsistent with tool documentation, or that remain unresolved at the time of the preparation of this Report.

1.1 Objective and Scope of Review

The objective of DNV GL's role in the Project is to provide the Sponsor and such interested parties with whom they share the report with an opinion as to the technical validity of using the PlantPredict software for projecting energy production. Such opinion will be supported by DNV GL's review of the aspects of the Project as stipulated by the scope of work in the Governing Agreement, which is consistent with the Table of Contents herein.

This Report is limited to the scope of review specified herein and does not address legal or regulatory issues, nor financial implications of any specific results generated by the software.

1.2 Approach

To confirm that PlantPredict can produce results comparable with typical performance models used in project finance, DNV GL compares results obtained from PlantPredict with PVsyst at various stages of the simulation as discussed in Section 2 to identify potential areas of discrepancy and confirm similarity of results.

Since PlantPredict includes some models and features that are not necessarily comparable with PVsyst directly, Section 3 discusses the origin and nature of certain models implemented by PlantPredict.

To address consistency with field performance, DNV GL reviews a field benchmarking study performed by First Solar in Section 4.

2 COMPARISON WITH PVSYST

PVsyst is a widely-used, commercially-available photovoltaic power plant simulation tool. No simulation software can exactly predict the performance of any real-world process, but PVsyst is an industry-standard tool that includes many sub-models for the significant processes of the photovoltaic power modeling sequence, and includes options for entry of adjustments that can account for minor mechanisms not specifically modeled in PVsyst version 6 (e.g., Module Quality Factor and monthly soiling).

2.1 Test Cases

There are several key stages in the PV power production simulation process, including: sun geometry, horizontal to plane-of-array irradiance transposition, estimation of irradiance reduction effects, irradiance-to-electricity conversion, inverter power conversion, transformer losses, and wiring losses. The validation plan DNV GL developed is based on three tables of information: sites, test cases, and results presentation.

The first table (Table 1) shows the chosen sites (numbered 1-3) featured in the analysis results: two in the USA (both northern/western hemisphere, namely, Phoenix with low diffuse and Newark, New Jersey with high diffuse) and one in the southern/eastern hemisphere (Perth). The test case configurations at these three sites are listed in Table 2, Table 3, Table 4, and Table 5. These parameters represent key model settings applied in the simulations.

Two types of structures, fixed tilt (FT) and horizontal tracker (HT) were modeled at each location, in some cases with different azimuth configurations, with each structure/orientation combination assigned a letter (a-f). Minor modeling variations including horizon shading, ground coverage ratio, and irradiance transposition models were also defined and labeled with an additional digit. The combinations of location, structure/orientation, and minor variations lead to digit-letter or digit-letter-digit test case identifiers that are used to annotate the input and results data files. One typical-year weather data set per site was chosen as a common (identical) input to both PlantPredict and PVsyst.

Initially four sites were chosen for review. One site (Mumbai) was selected in the northern/eastern hemisphere but south of the Tropic of Cancer so that summer sun azimuths remain north of the local zenith all day. However, version 3 of PlantPredict did not properly handle half-hour time zones, so the results for this location are not included in this report. First Solar corrected the issue in the version 4.0.0 release. DNV GL re-ran one Mumbai simulation in version 4.5.0 and confirmed that the weather data imported properly and in closer alignment with PVsyst.

The general principle of the evaluation is to plot loss tree comparisons as well as selected hourly comparison points together in one of several formats and to look for any lack of agreement. The primary format of the latter is a plot of 8760 data points with values from the PlantPredict simulation on the y-axis and values from the PVsyst corresponding times on the x-axis. Where discrepancies are likely to show a dependence on time of day, plots that combine one day of summer (solstice) and one day of winter (solstice) are plotted. A third type is the plot of the difference between PlantPredict and PVsyst versus time of day for each of the solstice days. A fourth type of plot is a heat map of month vs. time of day with color indicating the mean bias error in that bin of data. Only select plot types are featured in this report.

Each test case represents some degree of similarity or difference to other test cases, and where details of any pair of test cases are highly similar some respect, only one representative test case is used to compare PlantPredict and PVsyst. Thus, each test case has a set of “Y”/“N” flags that indicate whether that test case is interesting (and thus should have plots generated) in a particular context. For example, with respect to comparing the computation of geometric positions (row “Geom”), only Phoenix and Perth are reviewed because Newark is not considered to be significantly different from Phoenix in this respect. The comparison categories highlighted in Tables 2-5 are defined as:

- Geom: Incidence angle
- GeomS: Tracking angle
- GeomN: PVsyst Tracking Angle compared with the negative of PlantPredict Tracking Angle to account for differences in the sign convention between the two simulation programs
- Irr: Global, Beam, Diffuse Sky, and Albedo irradiance quantities
- IrrHR: Horizon-reduced global POA irradiance
- Tmod: Module temperature
- Pwr: DC Ohmic losses, Virtual (Ideal) DC power, MPP Tracked DC power, Inverter DC voltage, Off-MPP Losses (including both power and voltage clipping), Inverter Power Conversion Losses, Inverter (AC) Output Power

Table 1. Sites Used in Comparison

Site	Lat	Lon	Zone	Alt	Weather	Comment
Newark, New Jersey	40.70	-74.17	-5	9	TMY2:14734	High diffuse northern location, western hemisphere; zone detail: Etc/GMT+5, America/New_York, GMT/UTC offset -5, DST -4
Phoenix, Arizona	33.43	-112.02	-7	339	TMY2:23183	Low diffuse northern location, western hemisphere; zone detail: Etc/GMT+7, America/Phoenix, GMT/UTC offset -7, DST -7
Perth, Australia	-31.95	115.87	8	19	MN6:Perth	Southern location, eastern hemisphere; zone detail: Etc/GMT-8, Australia/Perth, GMT/UTC offset +8, DST +8

In all test cases, the FS-385 Q211 PAN file was used in a system with 1300 strings of 15 modules each with one Conversol NA-1350F-3V-2011-10c inverter.

Horizon (far shading) was tested in some cases with a 5° “wall” from south to west (“Trunc”) or from south to northwest (“Half”). GCR was either “Normal” (0.57 for fixed tilt, 0.44 for horizontal tracker) or “High” (0.68 for fixed tilt). The mismatch assumed under maximum power was 1.5% for both PVsyst and PlantPredict. However, under off-maximum-power (also referred to as “fixed voltage”) conditions the mismatch was set to 3% for PVsyst per recommended practice, but PlantPredict offers no option to vary the mismatch assumption this way so it remained at 1.5% at all times.

DNV GL did not evaluate the degradation or plant output control models in PlantPredict to see how they act independently or how they interact.

Table 2. Test Cases (Part 1/4)

	1a1	1a2	1b3	1b4	2a1
Comment	Newark FT	Newark FT High GCR	Newark HT w BT MismFV=MismMPP	Newark HT No BT	Phoenix FT
Site	Newark	Newark	Newark	Newark	Phoenix
Tilt	25	25	0	0	25
Az	180	180	180	180	180
Structure	FT	FT	HT	HT	FT
IrrModel	Hay	Hay	Hay	Hay	Hay
Geom	N	N	N	N	Y
GeomN	N	N	N	N	Y
GeomS	N	N	N	N	N
Irr	Y	Y	Y	Y	Y
IrrHR	N	N	N	N	N
Tmod	N	N	N	N	N
PV	N	N	N	N	N
Pwr	Y	N	Y	Y	Y
Horizon	None	None	None	None	None
BackTracking	NA	NA	Yes	No	NA
Uv.Uc	29/0	29/0	29/0	29/0	29/0
GCR	Normal	High	Normal	Normal	Normal
MismMPP	1.5	1.5	1.5	1.5	1.5
MismFV	3	3	1.5	3	3

Table 3. Test Cases (Part 2/4)

	2a2	2a2c	2a3	2c1	2c2
Comment	Phoenix FT Half Horizon	Phoenix FT Truncated Half Horizon	Phoenix FT High GCR	Phoenix FT East	Phoenix FT East Perez
Site	Phoenix	Phoenix	Phoenix	Phoenix	Phoenix
Tilt	25	25	25	25	25
Az	180	180	180	90	90
Structure	FT	FT	FT	FT	FT
IrrModel	Hay	Hay	Hay	Hay	Perez
Geom	N	N	Y	Y	N
GeomN	N	N	Y	Y	N
GeomS	N	N	N	N	N
Irr	Y	Y	Y	Y	Y
IrrHR	Y	Y	N	N	N
Tmod	N	N	N	N	N
PV	N	N	N	N	N
Pwr	N	N	N	Y	N
Horizon	Half	Trunc	None	None	None
BackTracking	NA	NA	NA	NA	NA
Uv.Uc	29/0	29/0	29/0	29/0	29/0
GCR	Normal	Normal	High	Normal	Normal
MismMPP	1.5	1.5	1.5	1.5	1.5
MismFV	3	3	3	3	3

Table 4. Test Cases (Part 3/4)

	2b3	2b4	2e	3a	3ab
Comment	Phoenix HT	Phoenix HT WindCool	Phoenix HT SSE	Perth FT	Perth FT MismFV=MismMPP
Site	Phoenix	Phoenix	Phoenix	Perth	Perth
Tilt	0	0	0	25	25
Az	180	180	150	0	0
Structure	HT	HT	HT	FT	FT
IrrModel	Hay	Hay	Hay	Hay	Hay
Geom	Y	N	Y	Y	N
GeomN	Y	N	Y	N	N
GeomS	N	N	N	Y	N
Irr	Y	N	N	Y	N
IrrHR	N	N	N	N	N
Tmod	Y	Y	N	Y	N
PV	N	N	N	Y	N
Pwr	Y	N	N	Y	Y
Horizon	None	None	None	None	None
BackTracking	No	No	No	NA	NA
Uv.Uc	29/0	25/1.2	29/0	29/0	29/0
GCR	Normal	Normal	Normal	Normal	Normal
MismMPP	1.5	1.5	1.5	1.5	1.5
MismFV	3	3	3	3	1.5

Table 5. Test Cases (Part 4/4)

	3c	3e	3f
Comment	Perth FT East	Perth HT	Perth HT NNE
Site	Perth	Perth	Perth
Tilt	25	0	0
Az	90	0	30
Structure	FT	HT	HT
IrrModel	Hay	Hay	Hay
Geom	Y	Y	Y
GeomN	N	N	N
GeomS	Y	Y	Y
Irr	N	N	N
IrrHR	N	N	N
Tmod	N	N	N
PV	N	N	N
Pwr	N	N	N
Horizon	None	None	None
BackTracking	NA	No	No
Uv.Uc	29/0	29/0	29/0
GCR	Normal	Normal	Normal
MismMPP	1.5	1.5	1.5
MismFV	3	3	3

2.2 Theory

The following sections discuss the comparisons between PlantPredict and PVsyst for each of the key stages in the simulation. Since values computed in each stage build on values computed in the preceding stage, discrepancies in later stages become progressively larger due to cascading errors, so the conclusions that can be reached become weaker as more discrepancies are identified in data that the results depend on.

2.2.1 Sun Geometry

The position of the sun relative to surface-oriented coordinates at any project site on Earth is very predictable by computations based on time. There are comparatively simple formulas based on spherical coordinate transformations, as well as more complicated formulas that take the oblate spheroid shape of the earth into account. That is, given date/time, latitude, longitude, and time zone, the sun position relative to local coordinates can be calculated using equations as documented by e.g., Reda and Andreas [1]. The sun position is typically given in polar coordinates, relative to gravitational "straight up" (the zenith) and geometric north (direction to the north rotational axis of Earth). Sometimes the zenith angle is quoted as elevation above the horizon ($90-z$), where the elevation is negative when the sun is below the horizon (blocked by the earth). However, more typically the zenith angle is used in spherical geometry calculations, and in fact the zenith angle is more frequently reported than sun azimuth due to its value in relating direct normal irradiance to direct horizontal irradiance.

The sun position formulas are sometimes implemented with special-case logic to handle multi-quadrant use (e.g., south of the equator, or merely within tropical latitudes where the sun may remain north of the zenith all day during some days of the year). Such logic is subject to programming errors, so sites that exercise calculations in non-US locations were included in the validation test cases. (Newark was considered similar enough to Phoenix in this regard that geometry was not reviewed for that site).

The sun incidence angle may be thought of as the angular offset from the optimum sun angle (perpendicular to the array surface). When the incidence angle is zero, the array receives maximum possible beam irradiance. When the incidence angle is equal to 90 degrees, the sun shines on the array "edge-on" and no beam irradiance is received. When the incidence angle is greater than 90 degrees, the sun shines (at best) on the back of the array, which for most PV module technologies is inert, or (for the purposes of energy modeling) equivalent to an incidence angle of 90 degrees.

Comparing the test cases showed equivalent sun incidence angle results were within 0.5° of PVsyst results when the sun was in front of the array.

In general, when the sun is near the horizon there is a distinct "bend" in the sun beam, such that the sun does not appear to set until its geometric position is approximately 5° below the horizon, or at a 95° zenith angle. PlantPredict accounts for this while PVsyst does not appear to do so. The energy discrepancy associated with this is negligible since this computation only affects the division of input GHI between beam and diffuse irradiance components, and beam irradiance is significantly reduced when the sun is near the horizon.

2.2.2 Tracking Angle

Tracking angle is another value for which special case programming to handle unusual sun quadrants could lead to errors if not implemented correctly.

Our review found that although the computed tracker positions from each program agree, they are of opposite sign in the northern and southern hemispheres. This is simply a difference in sign convention and does not appear to lead to subsequent errors in incidence angle. There are also differences in the assumed tilt position at night, but this will have no effect on energy production estimates.

2.2.3 Incidence Angle

The PVsyst convention is to set incidence angle equal to 90 degrees when the sun is below the horizon while in PlantPredict the convention is to set the incidence angle equal to the negative value of the incidence angle with respect to the back of the module.

The test cases showed good agreement for incidence angle when the sun was in front of the array.

2.2.4 Irradiance Transposition

If all irradiance used for converting power in a flat-plate PV power system came from the beam irradiance from the sun, then estimating the irradiance available at the (unshaded) plane-of-array would be a straightforward multiplication of the beam value times the cosine of the incidence angle.

Unfortunately, 15-30% of the overall irradiation available throughout the year may arrive from “diffuse” sources, such as the blue sky, white clouds, or particulate reflection. The unpredictable geometric distribution and magnitude of diffuse irradiance means that analytical prediction of the irradiance that will reach a POA surface is impractical. However, measurements have determined that diffuse irradiance is often increased around the sun and near the horizon which leads to empirical models (such as those by Hay or Perez) developed to estimate the diffuse irradiance on sloped surfaces at various tilts. These models are rather inaccurate for any particular measurement point in time due to unevenly distributed diffuse such as from clouds, but on a monthly or annual basis the translation uncertainty can be better than the typical irradiance instrument measurement accuracy.

Regardless of how well the estimated POA irradiance agrees with real-world values, the model computations are in principle deterministic. The goal of this comparison was to verify the similarity of the model implementations embedded in PVsyst and PlantPredict. Toward this end, since only Hay and Perez options are available in PVsyst these were the only options exercised in PlantPredict as well.

One potential area for concern in this area of modeling is that transposition from horizontal to tilted or tracked configurations requires either diffuse or direct irradiance in addition to the usual global horizontal irradiance. There are very few weather sites that include measurement of these auxiliary quantities, so it is typical to use a mathematical model to estimate diffuse irradiance. Some sources of irradiance data include pre-computed estimates of diffuse irradiance, while others do not. If either PVsyst or PlantPredict are provided with weather that is missing this data, they will fill it in, but there are a variety of levels of sophistication in models that can be used. Regardless of which transposition model is chosen, PVsyst uses the Erbs diffuse estimation model. PlantPredict offers the Erbs [2], Reindl [3], DISC [4], and DIRINT [5] models for diffuse estimation.

If the chosen weather data already includes an estimate of diffuse irradiation, this information may be communicated through pairs of data columns, one of either GHI+DHI, or GHI+DNI. If all three columns are available then rounding errors or other inconsistencies can cause choosing either of these pairs to give different results, so we recommend including only the pair of interest in the input file or confirming that the desired columns have been selected before comparing results. In this comparison, the GHI+DHI combination was used. In PlantPredict, the “weather file DNI” option under “model choices” was set to “off”.

2.2.5 Irradiance Losses

Once the irradiance that could be available in the POA is identified, several effects may reduce this value: far shading, near shading, soiling, and reflection. Of these, all but soiling can in general interact, so a separate evaluation of these quantities may only be useful for indicative purposes. For example, once a horizon shade object is blocking the sun, near shading no longer applies to the beam irradiance.

Near and far shading may be treated as fully blocking the beam component of irradiance, and blocking part of the diffuse irradiance. Similarly, reflection is typically addressed on the beam and diffuse components separately, where diffuse reflection is estimated using analytical or numerical integration over the array surface.

2.2.6 Module Temperature Estimation

In general, the temperature of modules placed in the sun is higher than the ambient temperature. The magnitude of this temperature rise can depend on the degree of airflow restriction or amount of ambient wind, but utility-scale system designs typically avoid restricted-airflow configurations. In this evaluation the constant thermal factor of 29 recommended by PVsyst is used¹.

An additional complication in this regard is the distinction between cell temperature and back-of-module temperature. As radiation is absorbed by the cells within the PV module, the power not converted to electricity is converted to thermal power that must conduct to the outer surfaces of the module. Since thermal conduction requires a temperature gradient, the back surface of the module where sensors can be placed in the field will be a few degrees cooler than the cells inside the module. PVsyst and PlantPredict both assume that the K_v/K_c parameters are predicting cell temperatures (referred to as T_{Array} by PVsyst). PlantPredict also applies a simple thermal model to estimate how much cooler the back surface is expected to be.

2.2.7 Irradiance to Electricity Conversion

The simple view of converting irradiance to power using PV is that an array I-V curve is operated at V_{mp} and power is converted. In the real world irradiance may vary over the surface of the array due to near shading and diffuse obscuration, such that multiple I-V curves may interact with each other with some balancing between all of the I-V curves leading to reduced output.

Certain thin-film module designs (e.g., CdTe) allow the most common near shading conditions (row-to-row) to not suffer from these electrical interactions. That is, the cells are long and thin from the highest edge of the module to the lowest edge, and shade lines that fall perpendicular to these lines cause all cells to be

¹ First Solar’s current modeling guidance recommends $K_c=30.7$, but this is not a significant difference for the purpose of this review of the agreement between software results.

affected equally with no “electrical mismatch”. This allows First Solar to reasonably recommend that horizontal single-axis trackers (HT) not backtrack to avoid shading as crystalline-cell PV systems require. Note that when comparing thin-film performance with crystalline silicon mounted on fixed-tilt or non-backtracking single-axis trackers, PlantPredict’s currently-missing ability to model electrical mismatch would give c-Si some inappropriate advantage.

2.2.8 DC Wiring Losses

DC wiring losses, also known as ohmic losses, occur when current flows through imperfectly conducting wires, characterized by their resistance. Since the resistance of the wire is related to its cross-sectional area and length, small-diameter or long wires have larger resistance than large-diameter or short wires, respectively. For a given resistance, power loss increases proportionally with the square of current. DC wiring in PV systems may generally be categorized by which components they connect: module to first combiner, first combiner to second combiner (a.k.a. “recombiner”) and second combiner to inverter. The wiring is usually sized so that each of these segments loses 0.3-0.9 percent when operated at STC conditions. (Note that since normal operation does not occur under STC conditions, the corresponding loss amount shown in the loss tree is usually lower than the nominal STC loss percentage.)

In theory, not all modules are separated from the inverter by the same resistance, since the wire lengths are different. This means that some mismatch in the I-V curves may be introduced by different wire lengths, but this mismatch is significantly smaller than the wire loss itself, so it is typically neglected, or if considered it is included as part of another loss factor.

PVsyst includes some support for estimating wire losses based on diameters and lengths, but does not support American Wire Gauge so DNV GL has preferred to make this percentage loss estimate independently and enter a percentage loss under STC conditions into PVsyst.

2.2.9 Inverter Power Conversion

The inverter is tasked with converting as much DC power as feasible into AC power. To do this it must adjust the actual array voltage until it coincides with the maximum power voltage of the array, subject to limitations of the operation of the inverter. Two major limitations of inverters in performing this task are the minimum and maximum voltages that the inverter can support. The maximum DC voltage is generally set based on the material voltage ratings of the materials used in the inverter construction. The minimum DC voltage is generally associated with the voltage margin compared to the maximum AC voltage. That is, if the DC voltage is too low the inverter may produce “flat-topped” sine wave output that would exceed harmonic content requirements. In addition to voltage limits, the inverter will typically have minimum and maximum power levels, where the minimum is associated with supplying unavoidable internal losses from the array rather than AC power, and the maximum is associated with component ampacities on the DC and/or AC side. Current limits are the fundamental characteristic of inverter power components, but many inverters design with enough margin to avoid reaching current limits before power limits are reached and therefore current limits may not be specified separately in all inverter datasheets.

PlantPredict allows the user to paste in the parameters of a PVsyst inverter modeling (OND) file from the clipboard to import them into the variables of PlantPredict. This relies on the feature in PVsyst for copying the parameters to the clipboard. DNV GL notes that certain points on the inverter efficiency curve are not copied from PVsyst to the clipboard. Therefore, DNV GL manually added these points in PlantPredict,

updating the fitted inverter efficiency surface. DNV GL did not explore the impact of bypassing this manual step. Although the import feature of PlantPredict appears to be working as of version 4.5.0, the process is susceptible to PVsyst software bugs and changes. PlantPredict will need to maintain this feature to keep up-to-date with PVsyst as these undocumented input and output formats change.

Some large discrepancies in DC operating voltage occur between PlantPredict and PVsyst around twilight. This is because while both programs simulate “zero” volts on the array at night, they differ in their treatment of voltage at very low array power with PlantPredict choosing the more realistic behavior. Either way, there is no impact on annual results since in both cases the inverter is modeled as off.

2.2.10 Transformer Losses and AC Ohmic Losses

PVsyst has recently added support for night-time core loss modeling, but DNV GL has not had a chance to analyze this support or compare results with PlantPredict. As mentioned in the introduction, DNV GL performs these computations separately using the equations offered earlier. PlantPredict includes night-time loss calculations in a manner similar to PVsyst.

Note that PVsyst references AC ohmic loss percentages to STC current ratings that are inappropriate for AC wiring for two reasons: first, inverters often limit output power and prevent currents corresponding to STC conditions from ever occurring in those wires, and second that equipment such as transformers are rated at levels independent of STC and quote percentage losses relative to those equipment ratings.

2.3 Results

One simulation with each of the two programs was produced for each test case (36 simulations). Inverter output energy discrepancies for each test case are summarized in Table 6. Among the test cases considered, the mean bias error and root-mean-square deviation of the relative differences are -0.6% and 1% respectively.

Table 6. Simulation Comparisons Summary

Test Case Identifier	Description	PlantPredict Block AC Energy (GWh/yr)	PVsyst Block AC Energy (GWh/yr)	Relative Deviation (%)
2c2	Phoenix FT East Perez	2.63	2.68	-1.8
2c1	Phoenix FT East	2.60	2.64	-1.6
3c	Perth FT East	2.41	2.45	-1.6
1a1	Newark FT	2.17	2.20	-1.6
3f	Perth HT NNE	3.27	3.22	1.6
2e	Phoenix HT SSE	3.59	3.54	1.5
1a2	Newark FT High GCR	2.12	2.15	-1.4
2a1	Phoenix FT	3.12	3.15	-0.9
3a	Perth FT	2.84	2.87	-0.9
3ab	Perth FT MismFV=MismMPP	2.84	2.87	-0.9

1b3	Newark HT w BT MismFV=MismMPP	2.36	2.38	-0.8
2a3	Phoenix FT High GCR	3.08	3.11	-0.8
2a2	Phoenix FT Half Horizon	3.11	3.14	-0.8
2a2c	Phoenix FT Truncated Half Horizon	3.11	3.14	-0.8
1b4	Newark HT No BT	2.38	2.39	-0.2
2b4	Phoenix HT WindCool	3.66	3.66	-0.2
2b3	Phoenix HT	3.66	3.67	-0.1
3e	Perth HT	3.32	3.32	0.0

DNV GL ran each of the above test cases in both PlantPredict and PVsyst and independently computed the loss trees based on the one-year of hourly data (i.e., 8760) output files of both software programs.

The below Figure 2-1 is an example of a plot that DNV GL independently produced for each test case. Positive values indicate a higher PlantPredict output relative to PVsyst, while negative values indicate a lower PlantPredict output. The sub-plot on the right shows how the relative deviations in annual irradiation or energy between PlantPredict and PVsyst change at each step of the modeling sequence (correlated with each line item of the loss tree). Meanwhile, each line item of the plot on the left represents a tally of the losses or gains based on the incremental results in the plot on the right. To summarize, the right hand plot features incremental deviations in the losses or gains at each step in the modeling sequence while the left hand plot shows the cumulative results.

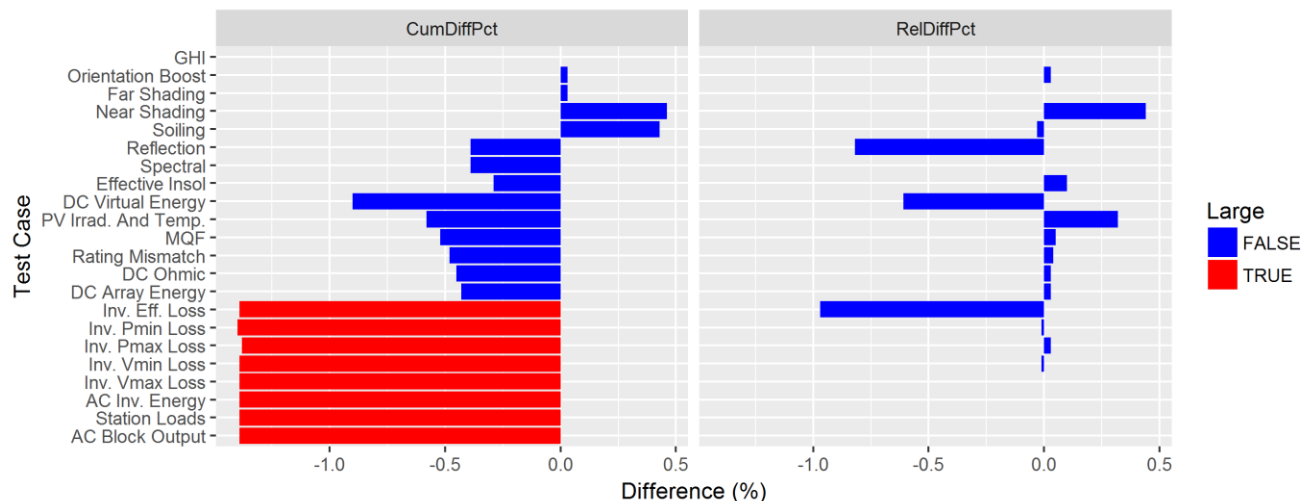



Figure 2-1. Loss Tree Comparison Plot for 1a2 Newark FT High GCR



This example Test Case 1a2 demonstrates three of the larger-than-expected discrepancies that commonly occur in the results (and remain unresolved): Near shading, inverter efficiency, and reflection results.

* Near shading: In this test case (with a high GCR), the near shading line item results in an incremental gain of approx. 0.5% in PlantPredict irradiation relative to PVsyst. More accurately, the shading losses in PlantPredict appear to be 0.5% less than in PVsyst. The simulation applies the "2D Trigonometric" shading model in PlantPredict and the fixed tilt with near shadings model in PVsyst ("slow simulation" mode).

* Inverter efficiency: In this test case, the inverter efficiency loss discrepancy approaches 1% (in absolute terms) and leads to a lower PlantPredict energy output relative to PVsyst. It is noted that PlantPredict does not employ a cubic spline fit to the inverter efficiency surface similar to PVsyst. Rather, a piecewise linear interpolation method is employed. Nevertheless, it remains unknown as to whether this difference in approach contributes in any way to the discrepancies observed. DNV GL also did not consider whether one approach has more theoretical advantages for the intended applications. Finally, as noted previously, certain efficiency set points defined in the PVsyst inverter modeling (OND) file were missing from the clipboard, which DNV GL manually populated into PlantPredict, updating the fitted efficiency surface. DNV GL did not explore the impact of bypassing this manual entry of the missing efficiency set points into PlantPredict.

* Reflection losses: In this test case, the reflection loss discrepancy exceeds 0.75% in absolute terms and leads to a lower PlantPredict irradiation relative to PVsyst. The simple ASHRAE model is applied in both software programs, so it is unclear what might be causing these discrepancies which commonly occur in the results.

The effects of these remaining discrepancies are for the most part <1% individually but they can accumulate to >1% as displayed in this example test case.

This test case also demonstrates how discrepancies can negate one another to some extent. In this case, the near shading discrepancy leads to a higher PlantPredict output relative to PVsyst while the inverter efficiency and reflection discrepancies lead to a lower PlantPredict output. Ultimately the near shading discrepancy is outweighed by the other discrepancies, leading to a lower overall PlantPredict output relative to PVsyst.

2.3.1 Typical Results

The following example in Figure 2-2 demonstrates common patterns in the results for system designs with typical orientation, GCR, and other parameters. Most notably, certain discrepancies arise in the reflection and inverter efficiency categories.

The first discrepancy we note appears in the reflection loss, computed for PlantPredict as the difference of Global POAI After Soiling and Global POAI After IAM, and for PVsyst as IAMLoss. For this case, PlantPredict computes 0.4% greater loss than PVsyst. It is not clear to DNV GL at this point which estimate is more correct.

The second discrepancy we note is in the inverter efficiency computation, computed in PlantPredict as the difference of DC Power (adjusted for clipping) and AC Power, and for PVsyst as "IL Oper". It is not clear to DNV GL at this time which estimate is more correct, though the linear interpolation of efficiency could contribute to some error in PlantPredict as compared to the spline interpolation used in PVsyst.

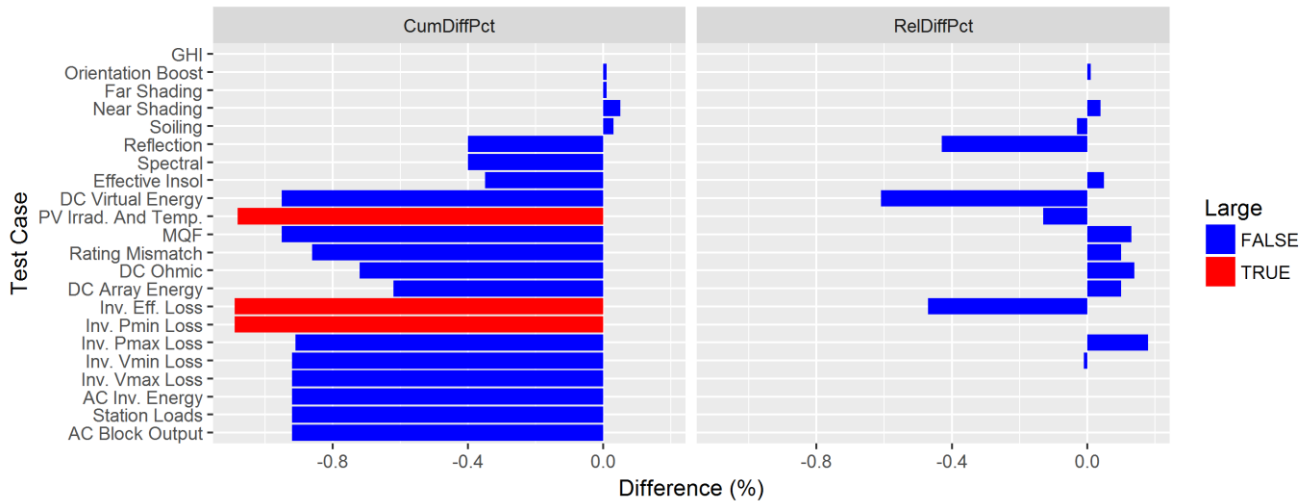


Figure 2-2. Loss Tree Comparison Plot for 2a1 Phoenix FT

2.3.2 Near Shading Discrepancies

The “2D Trigonometric” direct shading option in PlantPredict is intended to be analogous to the near shading (3-D) of row-to-row arrays in PVsyst. The 2D Trigonometric model provides results that are generally consistent with PVsyst and is what was used and displayed in the results of this report. Nevertheless, some higher-than-expected deviations in near shading remain.

The following example in Figure 2-3 demonstrates that >1% near shading discrepancies remain in certain test cases when using the active “2D Trigonometric” near shading option in PlantPredict. However, it is unusual to install single-axis trackers in other than the north-south axis alignment as exercised by this test case, so this is an unlikely result in practice.

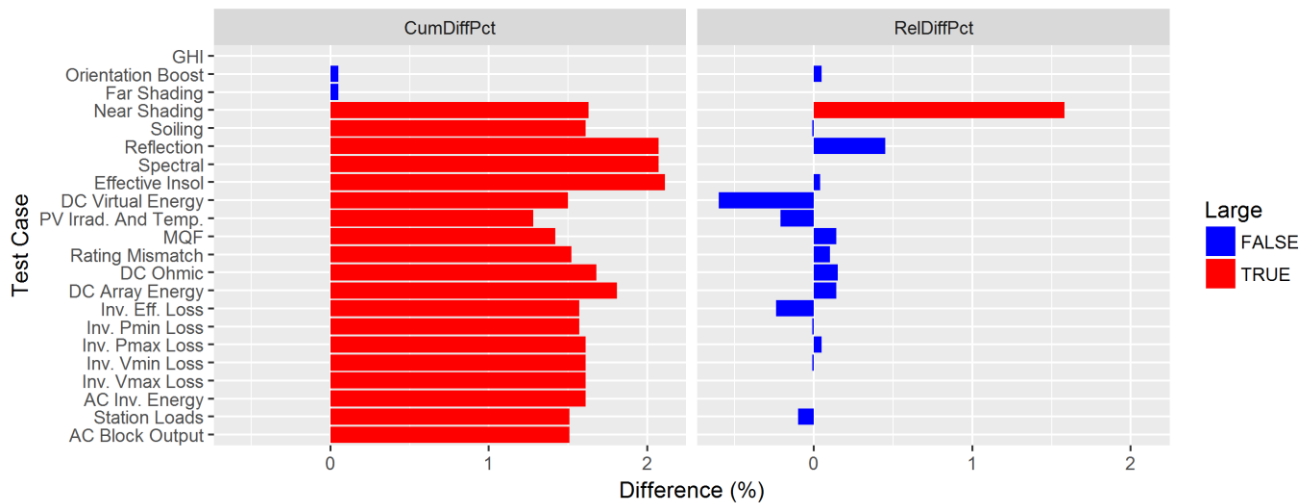


Figure 2-3. Loss Tree Comparison Plot for 2e Phoenix HT SSE

2.3.3 Ohmic Loss Discrepancies

Figure 2-4 shows instances when ohmic power loss hourly estimates are higher in PVsyst than in PlantPredict. Note that the units in the PlantPredict hourly 8760 output file appear to be incorrectly labeled as joules even though the values appear to be in units of watts (or watt-hours given that the data is hourly), just as in PVsyst. In this case, PVsyst appears to be failing to correctly model the reduced DC current that is expected when the inverter power is constrained (clipped), leading to an overestimation of I^2R losses by PVsyst. This can be seen in the pattern of discrepancies in the time of day versus time of year plot in Figure 2-4 during which they are the largest. The combination of lower ambient temperatures and possibly clearer skies (e.g., in April) lead to higher voltages and currents, respectively. The likelihood of clipping is increased under these conditions and the more clipping that occurs, the more PVsyst is expected to overestimate DC ohmic losses. In all test cases, a DC to AC ratio of 1.32 is simulated, so some clipping is expected to occur for the systems under test in these locations.

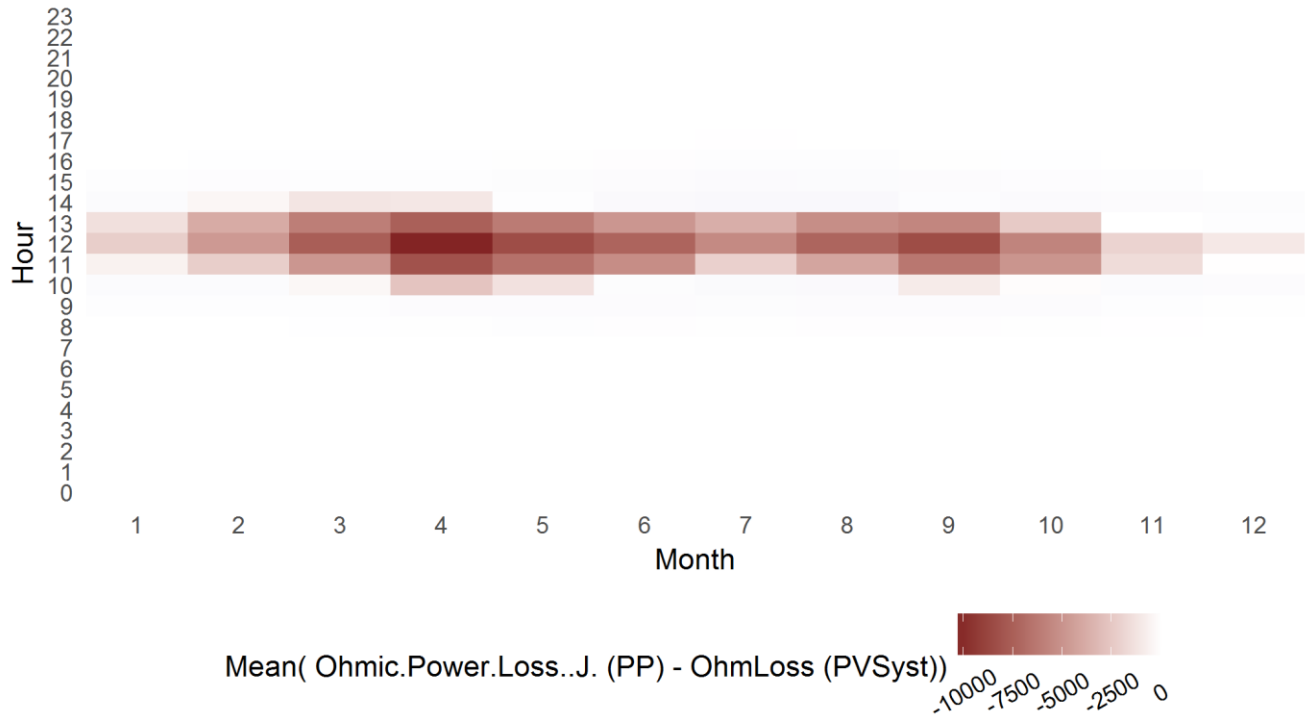


Figure 2-4. 2a1 Phoenix FT Ohmic Loss Agreement

Nevertheless, Figure 2-5 shows that the two software programs are in best agreement with one another during periods of power clipping. This is because the systems are clipped at a similar value in both programs and so the software outputs are similar for that condition. Therefore, in this example the increased ohmic losses in PVsyst do not affect the net AC energy output discrepancies though the loss tree reports losses in the wrong category.

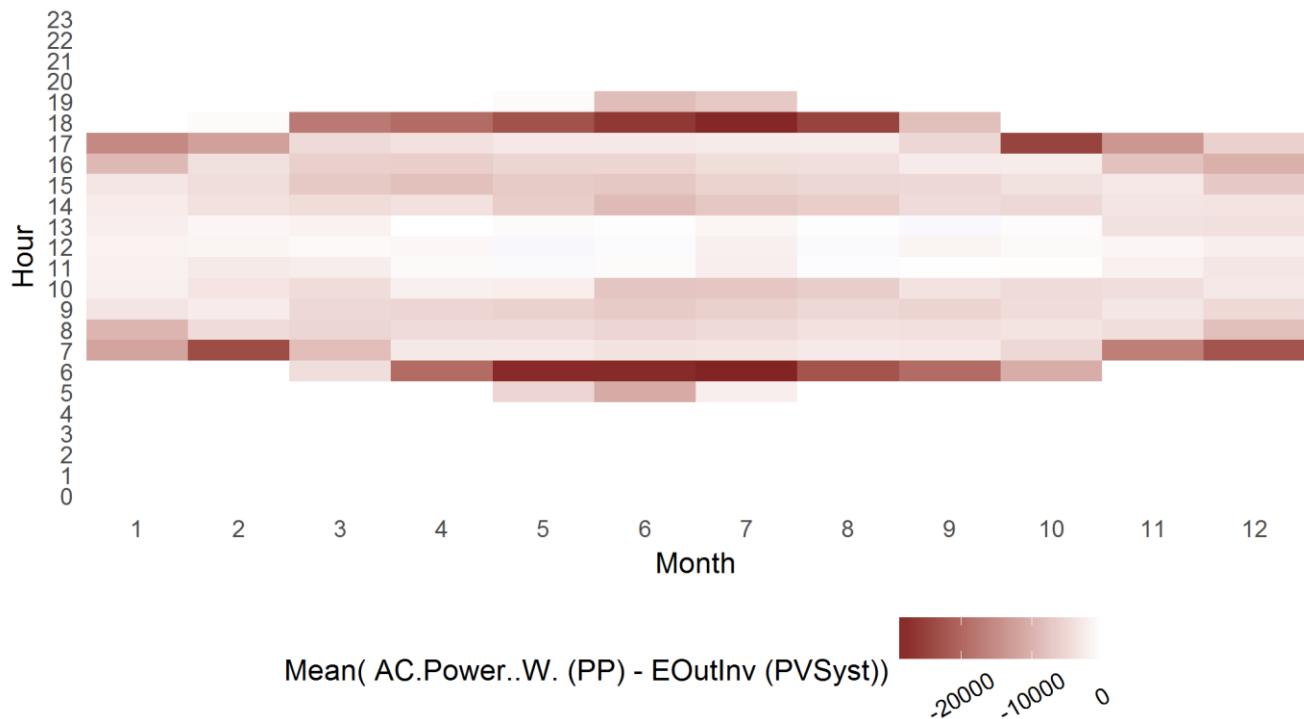


Figure 2-5. 2a1 Phoenix FT Inverter Output Power Agreement

2.3.4 Other Notable Results

The following were also noted based on the results of the analysis:

- * A non-zero U_v coefficient is working in PlantPredict as expected; for example, test cases 2b3 (not wind-cooled) and 2b4 (wind-cooled) are virtually the same (as intended, given that a combination of U_c and U_v was chosen to achieve effectively matching thermal effects on performance).
- * The overall discrepancy between PlantPredict and PVsyst is larger when running Perez in Test Case 2c2 relative to Hay in Test Case 2c1; notably Perez also leads to a 1.5% higher irradiation and energy output compared to Hay (it is expected that Perez will generally yield higher outputs relative to Hay).
- * When diffuse irradiance is larger than global in the weather data (e.g., at the edges of the day, due to error in the measurement data recorded), PVsyst replaces diffuse with the lower value (in this case, global), whereas PlantPredict uses the data as-is.
- * PlantPredict reports $V=V_{oc}$ when the system power is below the minimum inverter power threshold; PVsyst reports 0 V. This does not appear to impact the resulting energy generation because either way there is no current flowing or power generated, but the PlantPredict behavior is only representative for a very brief time each morning and evening while PVsyst is more typical throughout the night.
- * In one experiment, the annual AC energy deviation between PlantPredict and PVsyst increased by 0.7% with backtracking on (see test case 1b3 where the simulated output of PlantPredict is less than PVsyst by a larger amount with backtracking on versus 1b4 with backtracking off).

2.4 Recommendations

Some opportunities for improving PlantPredict were identified by DNV GL during this review. Namely, DNV GL recommends that First Solar:


- * Add inactive bands into the shading calculations of PlantPredict. Inactive bands are useful for modeling significant non-photoactive module edges or mounting structure components at the top or bottom (or sides) of the rows within the simulated array. Inactive bands cast shadows but are not themselves affected by shading. Crystalline silicon modules in portrait are a common use case for inactive bands given that the cell-to-frame distance(s) can be larger at the top and bottom (i.e., along the short frame members) relative to the sides.

- * Add fixed voltage mismatch (MismFV) losses into PlantPredict. These losses are expected when the array is operating at a DC voltage different than the maximum power point voltage (V_{mp}), a condition that occurs frequently in system designs with large arrays relative to the inverter capacity. PlantPredict applies a single mismatch percentage regardless of whether the array is operating at the maximum power point condition (MismMPP). The discrepancies between the software programs might be expected to be higher for crystalline silicon and high fill factor technologies. The method of implementing mismatch calculations in both PlantPredict and PVsyst is much more simplified than what occurs in practice, but the two-level approach that PVsyst uses allows for finer granularity that is particularly useful when high-fill-factor arrays are being modeled.

- * Add electrical effects into shading loss calculations in PlantPredict. These effects are especially useful in modeling crystalline silicon, as might occur in a comparative performance study. The intention of PlantPredict is to be able to accurately model all technologies. Incidentally, the lack of consideration of electrical effects works in favor of technologies like crystalline silicon and against First Solar CdTe modules (assuming shading is affecting array performance). Nevertheless, a more detailed model should result in better agreement with real-world performance.

- * Ensure that it is readily possible to reproduce simulation results produced in previous major and minor versions of PlantPredict. Especially for utility-scale applications, there is often a need to re-run the original, contractual ("Pro Forma") models at multiple times in a project's life cycle including at each transaction. Ideally the contractual modeling files can be loaded into the same software version that was originally run, to produce an unaltered baseline expectation of how the system is expected to perform. Having access to run each minor version is also useful to enable users to independently unit (a.k.a. regression) test new software versions to highlight the similarities or differences in the results between each new version and the one(s) preceding it. Currently, it is only straightforward to run the version 3 and 4 "prediction logic" in PlantPredict, but not to revert to a specific previous minor version (e.g., 3.12.0). Because of this limitation, First Solar runs their own broad set of internal regression tests to ensure that results are consistent across minor versions as intended. DNV GL did not have a chance to review the software regression test protocols in use at First Solar. At a minimum, DNV GL recommends that First Solar publish their internal regression test results generated with each version release of PlantPredict for the benefit of the community of users.

- * Migrate to third-party data hosting for PlantPredict and provide assurance that First Solar only has access to data that is self-generated or granted to First Solar with prior expressed permission. Given the need for confidentiality in DNV GL simulations, for example, the outcome of this recommendation will be a consideration in whether DNV GL adopts PlantPredict as a modeling platform for consulting work.



* Initiate a help forum for PlantPredict that is analogous to that of PVsyst. This is a powerful way to leverage the community of users to help accelerate the debugging and software documentation process. The forum not only brings the community together but also advances it by making users feel heard and personally invested in improving the software that they are opting to use (namely, when the recommendations and bug reports are reviewed and addressed by First Solar).

* Verify correct operation for all fractional time zones, to support international business development. DNV GL has used version 4.5.0 of PlantPredict to independently verify that the fractional time zone for Mumbai is now working as part of the major version 4 release of PlantPredict.

* Consider adding a simplified PVsyst-compatibility option to PlantPredict (e.g., choose irradiance as PVsyst does and disable certain advanced modeling algorithms in PlantPredict) to assist in future comparisons with energy estimates produced by independent engineers.

3 REVIEW OF ALGORITHMS

First Solar has been developing new model algorithms and implementing various published algorithms since the comparison with PVsyst began in 2012 with PlantPredict version 2.6.0.1. Other than the non-linear temperature response, none of these algorithms (described in the "PlantPredict PV Energy Simulation Algorithm Specification" [6]) were enabled for the comparison with PVsyst (which does not implement them), but most of them were enabled for the benchmarking effort discussed later. The following discussions present the DNV GL considered opinion of these calculations.

3.1 Non-Linear Module Power Temperature Response

First Solar has indicated that they have implemented a non-linear impact (with respect to irradiance level) of temperature on module power output based on CdTe test results presented by Schweiger et al. [7] In principle, this non-linearity has been known for some time (e.g., King 1997 [8] and IEC 61853-1 [9]), but most simulation tools (including PVsyst v5 and v6 and PlantPredict with the fixed temperature coefficient) treat the temperature sensitivity as independent of both irradiance and temperature. From the CdTe, CIGS, and a-Si sensitivity curves in Figure 3-1, we can see that if the bulk of energy is produced in mid- to high-irradiance conditions then the standard assumption of constant power-temperature coefficient is reasonable ($\pm 5\%$ of the temperature coefficient which corresponds to an error of ± 0.1 to 0.4% annual energy depending on system location), while in low-irradiance climates the constant temperature coefficient assumption fails (on the order of $+30\%$ of the assumed temperature coefficient which may correspond to more than 0.5% annual energy) so a model with irradiance dependence in the temperature sensitivity should provide better correspondence with measured performance. Whether such improved modeling will be measurable remains to be seen since measurement of irradiance at low levels in the field is significantly less accurate than measurements at high irradiance levels. That is, the irradiance uncertainty is likely to dominate over the temperature impact.

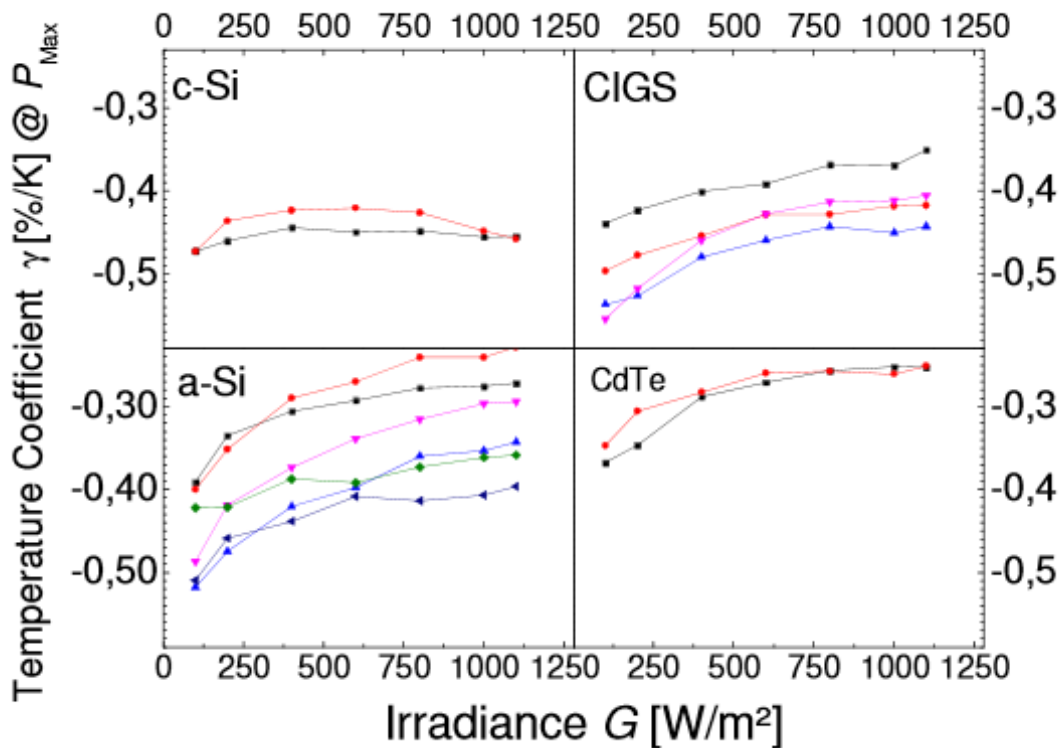


Figure 3-1. Temperature Coefficient Variation (Figure 2 in [7])

3.2 Spectral Shift – CdTe Spectral Response

The match between the spectrum of incident irradiance and the photovoltaic material sensitivity is a well-known factor that is considered in standardized flash test procedures such as those documented in the IEC 60904 series. However, since existence of associated irradiance spectra either in standard weather data sets or in field measurements is quite rare, and since the impact of spectrum is comparatively small for crystalline silicon, this effect frequently has been neglected in energy prediction software. The Sandia Photovoltaic Array Model [10] has recommended an empirical spectral correction based on air mass (the amount of atmosphere that direct irradiation passes through) for many years.

PVsyst v5 and v6 do not directly model spectral mismatch for CdTe technology². As we have discussed in another white paper [11], First Solar has addressed this limitation by offering two versions of workaround calculations for including monthly spectral impacts in PVsyst energy estimates. The first version, based on the model presented by Nelson et al. [12], addressed the impact of precipitable water on spectral sensitivity. A more recent version by Lee et al. [13][14] addresses the effects of both precipitable water and air mass on spectral mismatch. However, PlantPredict incorporates the Sandia, Nelson, or Lee models directly at each time record. While the theoretical and laboratory experience with spectral mismatch suggests it should have

² PVsyst has included a heuristic spectral effect model for amorphous silicon technology from the first versions, but not for other technologies.

a significant effect on the performance of PV modules in the field, in our opinion the effect has only been shown to be significant for CdTe primarily in typically-humid locations. However, if the Lee model is to be applied, best results will be obtained by applying it on an hourly basis as PlantPredict implements it, rather than on the monthly basis used in the PVsyst workaround. We refer the reader to our white paper on this topic for a more complete treatment of this subject.

3.3 Degradation

PlantPredict includes three options for modeling long-term degradation: linear DC, stepped AC, and linear AC. Most PV degradation occurs in the PV array, but balance-of-system effects can add to the module degradation rates, and inverter power or plant controller limits can obscure the DC degradation from appearing in the AC energy generation data. The available options are designed to allow for what-if scenarios that address simplified degradation (linear AC), warranty limitation scenarios (stepped AC), and the apparent degradation in high DC-to-AC rating ratio systems (linear DC).

Actual CdTe degradation has been observed to include an initial over-rating period of a couple of years while the rating approaches the nameplate rating, followed by a slower long-term degradation period. There are numerous factors that can affect or obscure this long-term degradation, so it may appear to curve up, be linear, or curve down depending on these other factors. Among these possibilities it can be difficult to pin down an accurate estimate for this rate, but the available options in PlantPredict can allow the user to model reasonable downside production scenarios.

One factor that can cause overall system production to drop slowly in early years is that time spent operating at the inverter maximum power output “hides” the ongoing DC degradation from appearing in the AC energy production. The PlantPredict linear DC modeling option allows this behavior to be modeled.

Recent heuristic models of degradation (e.g., Mikofski [15] and Roessler [16]) have included stochastic estimates of degradation rates at the module level, with which estimates of mismatch can be derived that show increasing mismatch in older equipment (apparent non-linear system-level degradation). Currently the PlantPredict modeling only applies electrical mismatch as a separately estimated constant impact due to production variation, so some departure from the proposed degradation model may appear late in the project lifetime. Recent versions of PVsyst provide a long-term degradation estimation option that incorporates simplified stochastic modeling for energy projections later in the project lifetime.

3.4 Inverter Temperature & Elevation De-rate

In PlantPredict, First Solar has implemented variable power limits based on ambient temperature and voltage using a model that is capable of tracking the steady-state behavior of inverters when such data is available (such as for SMA Sunny Central inverters). This inverter behavior limits power output under high temperature/high irradiance/high elevation/low voltage conditions, but the limitations tend to occur when the array output is also reduced by temperature, so these limits only come into play in very high irradiance climates. Since they can have an effect that is on the order of one percent in extreme climates, including this effect is appropriate.

The difficulties in using this particular model are a) that ambient temperature is only a rough indicator of the actual power limiting that occurs based on power circuitry temperatures, and b) characterizations such as

SMA has provided (under non-disclosure) are not generally available publicly (for external review) or for inverters supplied by other manufacturers. However, application of this model is recommended for SMA inverters, so including this model in PlantPredict avoids the manufacturer-recommended post-processing step for use when you have access to those manufacturer modeling recommendations.

Recent versions of PVsyst have incorporated similar features, but the characterization data necessary to populate the inverter models is still in limited supply.

3.5 Seasonal Tilt

Although the seasonally-adjusted fixed tilt array is quite rare in North America, a model for this type of structure was implemented in PlantPredict in response to requests from clients in areas with very low labor rates. Long-term actual energy production of such a system will be noticeably affected by how effectively this operational mode is managed. The incremental benefit of even ideal tilt-tracking beyond a fixed tilt boost (~14%) is on the order of 7% (total 21%) in high-DNI areas, with seasonal tilt (two adjustments) capturing 4-5% of that difference.

3.6 Horizon Shading


PlantPredict has a horizon shading model to account for sub-hourly sun transit time from optically-adjusted geometric sunrise/sunset to the modeled horizon line. As with most current PV performance simulation tools, hourly input data leads to computations on an hourly basis. A straightforward approach to handling horizon shading is to identify the location of the sun during the hour that contains the sunrise/sunset event, and ignore the direct beam irradiance if that position is behind the horizon. In theory, the impact of horizon will be captured on average by the day-to-day changes in sun position. For simple horizon geometries this assumption should work fine, but for complex horizons this may not work well.

First Solar has implemented a reasonable but brute-force algorithm to identify the fraction of the hour during which the direct beam irradiance is impacted. This fraction-of-the-hour is then applied to the beam irradiance for that hour, assuming constant irradiance throughout the hour. No order-of-magnitude justification for this algorithm has been provided to DNV GL, and the assumption of constant irradiance will certainly overestimate the horizon shading impact, so it is unclear whether this is a net improvement in horizon shading estimation.

3.7 Irradiance Models

First Solar has changed a published constant in the Reindl diffuse fraction decomposition model [3] to reduce the structure (systematic variation) apparent in the residuals obtained by comparison with First Solar field-acquired data. This is a significant step in identifying the plane-of-array irradiance given the location/time and global horizontal irradiance, and published improvements such as this are certainly welcome.

However, diffuse fraction estimation models are usually connected intimately with the subsequent orientation translation models due to the typical derivation of translation model coefficients from measured global horizontal and global-tilted irradiance field data. That is, it is risky to change the diffuse fraction



decomposition model and/or parameters without also changing the translation model and/or parameters, since a poorly-specified parameter in one sub-model (i.e., diffuse fraction or translation) may be (partially) compensated for in the parameters of the other sub-model. Lave et al. [17] (including W. Hayes of First Solar) investigated this interdependency and concluded that these sub-models must be evaluated together. The PlantPredict Plant Summary output indicates which decomposition and transposition models were used, but it is up to the user to select a combination that is consistent with the intended use.

4 REVIEW OF FIRST SOLAR BENCHMARKING REPORTS

First Solar has compared modeled PV system behavior to measured PV system behavior for twenty-one “benchmark” PV system production data sets, with the stated intention of expanding the number of benchmark comparisons [18]. The comparisons are conducted primarily for the plant output power and energy, but secondary comparisons with significant parameters within the PV systems are made in the interest of trying to distinguish sources of discrepancies between the measured and modeled outputs. Due to the large number of potential interference issues not under First Solar’s control, they plan to review each data set carefully before drawing conclusions. DNV GL agrees with this methodical approach, which contrasts with methods (e.g., Hasselbrink [19] or Reich [20]) that gather information from large numbers of PV systems with minimal review of each individual PV system data set and instead rely on robust statistics to identify overall model-to-actual agreement.

For benchmarking against measurement data, many data sets and PV systems are desirable, where the precise specification of “many” depends on the desired significance of the benchmark testing effort. The current 21 PV system benchmark allows empirical cumulative probability distributions to be reviewed with resolution of approximately 5%, which is on the order of magnitude of the modeling uncertainty.

The benchmarking report [18] provided to DNV GL presents a statistical overview of the results obtained for these 21 PV systems reviewed. It is based on 2013 modeling guidance provided by First Solar. These results indicate minor issues with estimating POA irradiance, module temperature, and inverter power clipping, with a net annual AC energy production modeling bias of 0.1% below measured (-0.1%), a sample standard deviation of 2%, and a range from about 4% below measured to 4% above measured. First Solar mentions concerns about performance data that are derived from inverter measurements, but we consider those questions as open until more accurate inverter input and output measurements are collected.

First Solar also asserts that the results are not normally distributed, and that the distribution is bimodal based on the two climate types in the investigation:

“The average prediction accuracy at the energy meter was -0.11% (slight underprediction) with a standard deviation of 1.97%. However, the distribution of performance was not normal; it appeared to be somewhat bifurcated by climate type. This trend was more significant on older plants; before the 2014 update, PlantPredict underpredicted temperate climate sites by an average of 2.5% (1.1% standard deviation) and overpredicted hot climate sites by 1.6% (1.8% standard deviation). With the addition of newer sites, PlantPredict underpredicted temperate climate sites by 1.9% (0.8% standard deviation) and overpredicted hot climate sites by 0.1% (1.9% standard deviation).”

Overall, First Solar concludes that PlantPredict under-predicts measured outputs in temperate climates and slightly overpredicts in hot climates based on the 2013 model settings. However, the supplied histogram does not clearly appear either bimodal or unimodal in our review. To the extent that it is not unimodal, some caution would be warranted in interpreting the low mean bias error estimate of -0.1% as any given system will be less likely to be in the center than near one of the modes above or below the mean.

Since these results do not incorporate the algorithms described in Section 3 we anticipate some degree of improvement in prediction accuracy once these recently-developed algorithms are applied. That said, the variance of individual energy predictions is comparable with normal field measurement uncertainty so the absolute accuracy of any single project production estimate is already quite good and is not likely to change very much as the PlantPredict model is improved. DNV GL recommends further investigations into the

climate-driven bimodality and recommends adding systems in other climate types besides the two included thus far, with a distribution such that the results are not too heavily weighted towards any one climate.

Figure 4-1 is taken from First Solar’s benchmarking report. We recommend that an additional (initial) entry representing GHI magnitude be included to visually confirm that both the measured and modeled columns start with the same irradiation and at the same time to make the orientation boost more apparent (since POA error is likely to increase as the tilt/tracking strategies augment the irradiation boost).

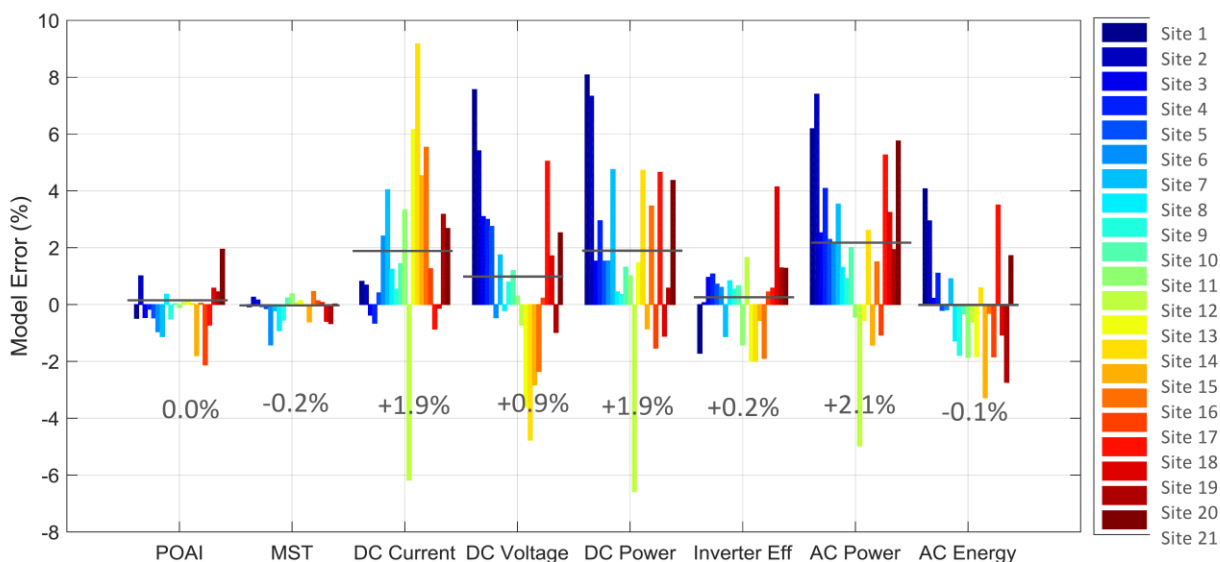



Figure 4-1. First Solar’s Graphical Summary Plot of Annual Model Errors [18]

The weakness of the depiction in Figure 4-1 is that it presents many values that are comparatively uncertain (e.g., DC Current, POA Irradiance) next to values that are much more certain (Plant AC Energy) with visually equivalent emphasis. A single biased measurement (e.g., DC Current) can affect multiple quoted measures (e.g., Inverter DC Power, Inverter Efficiency) and can have even more incremental impacts (e.g., DC Current, Inverter DC Power, Inverter Efficiency, Inverter AC Power). Some indication of uncertainty should be included in order to not mislead the reader as to where actual problems might be. For example, the AC and DC energy measurements are being made by inverters that often have a bias in their calibration (inaccurate multiplier) that can be several percent in some cases. When Inverter AC energy output is compared with the more accurate Plant AC Energy, the apparent losses in the AC collection system can be much larger (or smaller) than the true losses are. This uncertainty is quite large compared to the anticipated losses in the collection system, such that the difference may be positive or negative with little assurance that it represents the actual losses. Using the Inverter DC and AC Power values to compute “measured” inverter efficiency can lead to even more misleading conclusions, since both measures have relatively large uncertainties that combine additively when dividing one by the other. Such computations should only be performed using external (temporary or permanent) instrumentation with proper specifications. Finally, if the error in Inverter AC Power happens to be incorrect, then the error will appear in both the “measured” inverter efficiency and the apparent AC collection system loss, reducing one and increasing the other.



As a larger body of comparison reports is compiled and statistical summaries of comparison points are made across different power plants, all benchmarks undertaken should continue to be represented. However, diagnosis discussions may inform “quality” characterizations that may (later) help focus the discussion on common ways real PV system performance deviates from modeled results.

5 CONCLUSIONS

The comparison with PVsyst illustrates that PlantPredict has comparable modeling behavior with this industry-standard tool. However, it also illustrates that even an industry-standard simulation tool can oversimplify aspects of the model behavior such that close agreement at each time step would require choosing similar oversimplifications in the new software. For example, we found that PVsyst does not model the reduction of DC ohmic losses due to power-limited inverter operation. While this has a very small impact on the final answer and the computational expense of obtaining the correct answer may not change financing decisions, it does not make sense to expect PlantPredict to behave the same way.

DNV GL agrees that there are several areas in which PlantPredict can apply algorithms that estimate the impact of specific loss mechanisms more effectively than PVsyst can. For example, recent research is indicating that specific combinations of diffuse estimation and irradiance transposition models may be more accurate than the limited set available in PVsyst. It may be appropriate to adjust independent PVsyst models to include these impacts as they are highlighted by PlantPredict.

The First Solar Model Benchmarking effort is a sophisticated, comprehensive approach for comparing predicted performance with actual performance. Significant effort is being invested in automating the identification of data that represent conditions that the model is incapable of predicting, while identifying those conditions and their scope of impact to the comparison. DNV GL considers the resulting automated filters to be appropriate to the task, and expects that few manual interventions will be required to obtain credible results. In particular we observed that excessive filtering was not an issue in the two systems reviewed in detail, so these results appear to represent observed performance fairly.

As with all predictive PV performance modeling tools, variations in actual conditions away from those assumed in the performance model lead to varying discrepancies in the prediction. These discrepancies are understood to occur even with PVsyst, and some reliance on the relative variance reduction in long-term simulations is typically assumed for any model. That is, the discrepancy between predicted and measured values for any given hour may be large, but the positive and negative errors over a long interval are expected to even out if the model prediction bias is small. Following this strategy, the First Solar Benchmarking approach focuses on comparing aggregate quantities accumulated over more than one year. As additional data sets are evaluated, a distribution of annual energy prediction errors should become apparent, which will provide an indication of the overall PlantPredict combined model and measurement uncertainty for purposes of annual production prediction. Other contributing factors to production deviation from expected production will of course be uncertainty in the measurement of the true long-term weather; the typical variability of long-term weather; and the variability of factors such as equipment availability and snow impact that the benchmarking exercise has corrected for or excluded from consideration.

DNV GL has reviewed other benchmarking data sets in confidence, and notes that the variance in the twenty-one results presented so far is noticeably smaller than any of those sets to date. The combination of careful data review by First Solar, working primarily with fixed medium-tilt arrays (for which POA estimation is less difficult than steep tilts or trackers), and well-characterized models in PlantPredict are all likely contributing factors to this narrower range of results.

Within DNV GL, PVsyst is the current accepted modeling tool to maintain consistency of modeling among many types of PV power plant designs. We are currently considering the use of PlantPredict to inform the assumptions used in models that incorporate First Solar photovoltaic modules.

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