

# Performance Model Evaluation

**Project:**

Performance Model Validation

**Prepared By:**



**October 1, 2013**

***[Edited to preserve Tigo Energy confidentiality]***



## 1. Introduction

Tigo Energy, Inc. (Tigo) has worked with Folsom Labs to incorporate the power conversion characteristics of the Tigo Energy Maximizer technology into a web-based tool named HelioScope for modeling PV power generating systems. This modeling tool models the entire PV system performance just as the commonly used PVSyst 2 performance prediction software does, but does not have the breadth of testing or market acceptance that PVSyst has.

BEW Engineering (BEW) was engaged by Tigo to review HelioScope, with particular attention to the model calculations and its possible use in conjunction with PVSyst as a basis for adjusting PVSyst simulation results to account for the benefits of using the Tigo Energy Maximizer technology.

## 2. Model Review

The model review begins with a short overview of the principles of operation of the Tigo Maximizer technology, and proceeds with a discussion of the principles of operation of the modeling tool, and concludes with a comparison of results from the PVSyst and HelioScope hourly and summary simulation results.

### Tigo Principles of Operation

[Redacted]

### Modeling Tool

HelioScope is a controlled-access website that allows a user to specify a Project (location), Design (module model, racking geometry and layout, inverter model, electrical wiring characteristics, optimizer) and a Scenario (weather data, soiling, temperature variability, far and near shading) for which to simulate an annual energy estimate. The software organizes multiple designs, scenarios, and simulation result sets within a Project, and projects can be shared within a group or accessible only to one user. HelioScope simulates the performance of each module individually for every simulation, and combines these simulated values consistent with the presence or absence of optimizers.

The version of the software that was reviewed for this report (3 (cb0b98d6759f699804d0)) includes a web interface that supports the layout of the array over a Google Maps satellite image of the location. The layout is automatic, based on the area in which the array is to be located as defined by pointing and clicking in the Google Map image. This approach can require several iterations of repositioning array boundary points to obtain desired results (array size, complete rows, array positioning relative to nearby reference points such as building edges). The ability to make additional designs by modifying existing designs to, for example, add an optimizer was also not yet supported so creation of our variants always required starting over with a new HelioScope design specification.



Once a system design has been defined, a scenario must be defined. Several key assumptions are made in the definition of the scenario that can have a significant impact on the results obtained. The weather file, near shade profile, horizon profile, irradiance transposition model, module temperature model, soiling, irradiance variance, cell temperature spread, and module nameplate binning variation should all be compatible with assumptions made in PVSyst. The following paragraphs will expand on these assumptions.

For a given site, multiple weather files may be available that each purport to represent “long-term” weather resource at that site. Even if these files have the same global horizontal irradiance, they may have different diffuse irradiance, air temperature, or wind speed data. For the purposes of this comparison we require that the input weather data used when creating parallel PVSyst and HelioScope simulations be the same. An import mechanism is available for loading NREL Typical Meteorological Year CSV files (TMY3 format) into HelioScope. If a non-TMY3 weather file is being used in PVSyst, it will almost certainly be necessary to export the weather data from PVSyst (as part of a simulation) and import it into HelioScope to make sure that the same resource data are being used by the two programs. For our review we used a single TMY3 weather data file.

The near shade profile is one of the key features of HelioScope. PVSyst includes support for near shading impact estimation, but the impacts are modeled either as area-related or beam irradiance desensitizing on a string level. Area-related shade impacts are appropriate for shade modeling of most thin-film PV technologies, but this is too generous for shade impacts on most crystalline silicon PV technologies. PVSyst’s desensitizing factor is a percentage between area impact and disabling the conversion of beam irradiance for strings with any shade at all, but the choice of which desensitizing factor is appropriate requires experience or detailed modeling of the type that HelioScope does. HelioScope allows a shading profile to be generated using a plugin in Google Sketchup. The shading profile is a set of 12\*24 geolocated bitmap images indicating which portions of the array site will be affected by shading throughout the year.

PVSyst and HelioScope use the same conceptual model for horizon profiles, which is a series of azimuth-elevation points outlining mountains or distant shading objects. BEW did not exercise or verify the function of HelioScope horizon profiles.

The irradiance transposition model allows plane-of-array irradiance data to be estimated using irradiance data from the horizontal orientation. The beam irradiance can be transposed using sun elevation and sun POA incidence angle. The fact that diffuse irradiance is not equally intense from all directions means that empirical correlations must be used. Models developed by Hay and Perez are available choices in both PVSyst and HelioScope. The Perez model is recommended where accurate values of diffuse irradiance are available, but the Hay model is more robust when the diffuse data are approximate. This setting must be the same in both programs in order to obtain comparable results.



The accuracy of module (cell) temperature modeling in general is less critical than irradiance modeling, because the repeatability of cell temperatures in the field is larger than the typical modeling accuracy anyway. At the time of this review, the PVSyst thermal modeling option was not working, so we used the Sandia model and obtained fairly similar results anyway.

Soiling reduces the amount of irradiance that passes through the module glass and reaches the cells. HelioScope supports specification of monthly average soiling impact as a percentage of performance reduction, while PVSyst supports either the monthly estimates or a single annual value for convenience. The usual assumptions are that soiling is washed away by rain, and that it arises due to dust build-up at a site-dependent rate between natural or artificial (manual wash) rain events. Such build up is assumed to be uniform across the surface of the array. One concern that has been raised in support of module-level optimizers is that if soiling is non-uniform (e.g. bird droppings), then increased mismatch may affect the array operation. Neither PVSyst nor HelioScope offers direct assistance in estimating the impact of such effects.

HelioScope also provides limited support for estimating the effect of irradiance variability within the array. That is, due to clouds or variations in module orientation, the irradiance reaching the modules may not all be the same. HelioScope supports adding a random variation of irradiance from module to module to the POA irradiance estimates. Since the program is already modeling the IV curve mismatch, the impact of such variations can easily be observed in the simulation results. Unfortunately the identification of which values are appropriate representations of real conditions is not so clear. For purposes of our PVSyst comparison, this value was set to zero.

HelioScope similarly provides limited support for estimating the effect of temperature variability within the array in the form of a random adder to each module's cell temperature. It is not clear to BEW that this applies to modules *within the same string that have similar POA irradiance*. PVSyst offers no comparable feature, and for our comparison this value was set to zero.

HelioScope includes an explicit specification of uniform random variation in delivered module STC rating across a range of values (binning). Under normal business practices the delivered module rating will indeed be limited at the data sheet power tolerance, but in practice there are two concerns with this specification. First, power rating variability for some production lines is much narrower than the power tolerance limits, and will be better modeled as a normal distribution with a very small standard deviation, while for other production lines the power bin may represent a "slice" out of a wide normal distribution such that it may be skewed to the low end (high ratings) or skewed to the high end (low ratings). The second issue is that some production lines may yield high-current/low-voltage modules in a particular bin, or low-current/high-voltage modules. Since current and voltage interact differently in the IV curve mismatch calculations, the net result is that power rating may not be the best indicator of binning mismatch. Both issues could be addressed fairly easily in a future version of HelioScope. For purposes of this comparison we assumed a -0% to +3% binning range in both HelioScope and PVSyst.

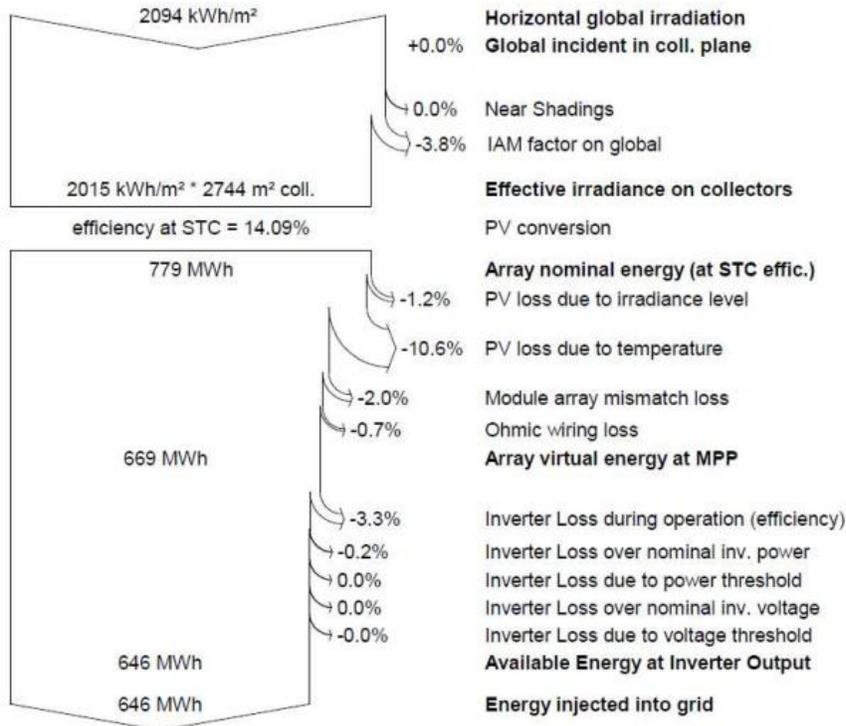


The reviewed version of HelioScope does include a fixed-tilt row-to-row shade modeling capability within the user-accessible interface. This capability is based on a mathematical derivation that makes the assumption that the rows are “long” and that incident irradiance is composed of “beam” irradiance and an isotropic (uniform across the sky dome) “diffuse” component. Most practitioners agree that this approximation is insufficient for estimating plane-of-array irradiance from horizontal irradiance because of “circumsolar” irradiance and “horizon brightening” effects, but it should be sufficient for estimating local shading impacts in a repeating row-to-row layout.

The unique contribution offered by HelioScope is the ability to model IV curve interactions based on the above inputs to identify overall system behavior. At this stage of development, it does not model the individual bypass diodes within a module, so each module is represented by a single-diode IV curve model driven by an effective irradiance on the surface of the module. Like PVSyst, the effective irradiance is modified to model the electrical impact of mismatch within the module, and then module IV curves are modeled in detail to address inter-module mismatch. In particular, the current version models each module like a PVSyst 100% near shade string, in that module-level mismatch effects show up in the “shading” category rather than the “mismatch” category. The 100% value means the module shading impact is more sensitive to sun angle modeling imperfections than a real module would be.

### **Comparison with PVSyst**

Every simulation tool should follow the progress of power through the capture, conversion and delivery stages. PVSyst introduced the idea of a “loss tree” (Figure 1) to the performance simulation market that clearly highlights how much power loss is being attributed to each simulation stage. It also allows the user to save the hourly simulation results for most of the intermediate calculation values. HelioScope includes similar loss summary and hourly results capture.



**Figure 1. Sample PVSyst Loss Tree**

PVSyst does not undertake to model PV systems from the module level up. Rather, it applies adjustments to the irradiance and power conversion stages of an array model that allow it to predict performance of the array even when certain common module-level effects are expected to occur. As mentioned earlier, the electrical mismatch arising from module-level shading appears in the PVSyst near shading loss category rather than lower in the loss tree where the other electrical effects are logically grouped.

This comparison treats PVSyst as the benchmark of correct system modeling behavior in non-optimizer designs, since the goal is to determine whether the incremental modeling improvements offered by HelioScope could be used to modify PVSyst simulation results. No comparison of modeling results with field measured data was included in this review, so the actual benefits provided by the optimizers are not addressed.

The basic comparison approach has been to confirm that HelioScope obtains intermediate modeling results comparable to those produced by PVSyst when no optimizers are included. Then the introduction of optimizers will alter the simulation results obtained with HelioScope, and in theory these changes may be applied to the PVSyst results.



## Test Cases

To confirm the similarity of results between PVSyst and HelioScope, two basic designs were simulated, with two shading variations and two cases with optimizers as shown in Table 1.

**Table 1. Test Cases**

Test Case	Site	Tilt (degrees)	Optimizer	Comment
A1	Phoenix	0	None	Horizontal
A2	Phoenix	0	None	Horizontal Shaded
B1	Phoenix	30	None	FT HighGCR
B2	Phoenix	30	None	FT HighGCR Shaded
C1	Phoenix	0	MM-ES50	Horizontal
C2	Phoenix	30	MM-ES50	FT HighGCR Shaded

Shared design characteristics included:

- Location on top of US Post Office roof (4949 E. Van Buren, Phoenix, AZ), disregarding any actual near or horizon shading. To the best of our knowledge this location does not correspond to an actual PV system, but is an example location with clear site reference points and relatively simple shading conditions suitable for this comparison.
- Perez irradiance transposition model assumed
- South facing azimuth
- Row pitch of 5m, banks of three modules per row, wired along the length of the row
- 1680ea Yingli YL230P-29b, modeled using a BEW custom PAN file in both PVSyst and HelioScope (which supports import of PVSyst PAN files)
- 120 Strings of 14 modules in series; 10 rows each with four strings along the bottom bank of modules, four more along the middle bank, and the last four along the top bank.
- Unshaded orientations modeled using sheds with 15.6cm electrical effect activation distance in PVSyst; shaded orientations were modeled using fixed tilt and near shading models at 60% string sensitivity.
- PVI-Central-300-US inverter, modeled in PVSyst with a BEW custom OND file per data sheet, and in HelioScope using inverter model as found in HelioScope (which does not at this time support import of PVSyst OND files)



- Module thermal modeling of  $K_c=25$  and  $K_v=1.2$  in PVSyst, Sandia model with no configuration options in HelioScope
- DC ohmic losses of 1% at STC in PVSyst (or 0.8% annually), internally derived within HelioScope using 10AWG module-to-combiner wiring, and 500MCM wiring between combiners and 5m of 500MCM to inverter (approximately equal to 0.9% at STC or 0.7% annually)
- No blocking diodes (0V drop in PVSyst)
- Module quality factor of -1.5% (boost) in PVSyst, binning of 0-3% in HelioScope
- Mismatch of 0.3% at MPP and 0.5% at fixed voltage in PVSyst; no specification in HelioScope.
- Soiling of 0.0% in both PVSyst and HelioScope
- ASHRAE incidence angle model of 0.05 in both PVSyst and HelioScope
- Near Shade Object: for test cases A2, B2, and C2 the northwest corner of a 10m tall, 12m E-W, 15m N-S “penthouse” was located at 33.4493.16N 111.976225W. In PVSyst, per this information the shade object was 3.3m south of the south edge of the array near the middle.

## Results

The simulation results are compared according to a loss tree breakdown that is as consistent as possible between the two programs. Table 2, Table 3, Table 4, Table 5, Table 6, and Table 7 compare annual losses computed from the hourly simulation data (which due to rounding in the hourly output data may be slightly different than the values reported by the programs). The Item column identifies the category of intermediate result or loss mechanism. The last two columns compare the cumulative and incremental differences between the loss trees. The intermediate columns are in pairs, with the left column of the pair indicating PVSyst results and the right column indicating HelioScope results. Net values are cumulative net irradiation in MWh/m<sup>2</sup> until the array area is introduced, after which they are reported in MWh. Delta values represent the incremental differences of net values. RelPct values present the Delta values as percentages. For example, the DC Virtual Energy intermediate result is the effective irradiation times the (modeled) STC rating of the module. The loss incurred in this step is 100-STC efficiency, and the incremental modeling discrepancy RelDiffPct is effectively based on comparing the modeled conversion efficiencies.

**Table 2. Test Case A1 Loss Comparison**

Item	Net.pvs	Net.hel	Delta.pvs	Delta.hel	RelPct.pvs	RelPct.hel	Area.pvs	Area.hel	NACount.pvs	NACount.hel	CumDiffPct	RelDiffPct
GHI	2094.2	2094.2	0	0	0	0	NA	NA	0	0	0	0
OrientationBoost	2094.2	2091.9	0	-2.3	0	-0.11	NA	NA	0	4153	-0.11	0
ShadingLoss	2094.2	2091.9	0	0	0	0	NA	NA	0	4153	-0.11	0
IAMLoss	2015.4	2014.3	-78.8	-77.6	-3.76	-3.71	NA	NA	0	4153	-0.05	0.05
SoilingLoss	2015.4	2014.3	0	0	0	0	NA	NA	0	4153	-0.05	0
EffectiveInsol	2015.4	2014.3	0	0	0	0	NA	NA	0	4153	-0.05	0
DCVirtualEnergy	779173.7	781252.9	-4751777	-4746634.9	-85.91	-85.87	2744.28	2744.28	0	4153	0.27	0.28
PVTmpIrrLoss	690259.6	702271.3	-88914.1	-78981.6	-11.41	-10.11	NA	NA	0	4153	1.74	1.47
MQFLoss	701947.2	702271.3	11687.6	0	1.69	0	NA	NA	0	4153	0.05	-1.66
MismatchAndOffMppLoss	696924.9	697650.9	-5022.3	-4620.4	-0.72	-0.66	NA	NA	0	4153	0.1	0.06
DCOhmicLoss	691816.5	693660.4	-5108.4	-3990.6	-0.73	-0.57	NA	NA	0	4153	0.27	0.16
DCInvEnergy	690577	693660.4	-1239.5	0	-0.18	0	NA	NA	0	4153	0.45	0.18
InvEffLoss	666985.5	670917.9	-23591.5	-22742.4	-3.42	-3.28	NA	NA	0	4153	0.59	0.14
ACInvEnergy	666985.5	670917.9	0	0	0	0	NA	NA	0	4153	0.59	0



**Table 3. Test Case A2 Loss Comparison**

Item	Net.pvs	Net.hel	Delta.pvs	Delta.hel	RelPct.pvs	RelPct.hel	Area.pvs	Area.hel	NACount.pvs	NACount.hel	CumDiffPct	RelDiffPct
GHI	2094.2	2094.2	0	0	0	0	NA	NA	0	0	0	0
OrientationBoost	2094.2	2091.9	0	-2.3	0	-0.11	NA	NA	0	4153	-0.11	0
ShadingLoss	2042.6	2072.4	-51.6	-19.4	-2.47	-0.93	NA	NA	0	4153	1.46	1.58
IAMLoss	1968	1996.4	-74.5	-76	-3.65	-3.67	NA	NA	0	4153	1.44	-0.02
SoilingLoss	1968	1996.4	0	0	0	0	NA	NA	0	4153	1.44	0
EffectiveInsol	1968	1996.4	0	0	0	0	NA	NA	0	4153	1.44	0
DCVirtualEnergy	760839.5	774199.2	-4639978.4	-4704513.4	-85.91	-85.87	2744.28	2744.28	0	4153	1.76	0.28
PVTmplrLoss	673743.7	695566.5	-87095.9	-78632.7	-11.45	-10.16	NA	NA	0	4153	3.24	1.46
MQFLoss	685156.3	695566.5	11412.6	0	1.69	0	NA	NA	0	4153	1.52	-1.66
MismatchAndOffMppLoss	680524.8	683840.4	-4631.4	-11726.1	-0.68	-1.69	NA	NA	0	4153	0.49	-1.02
DCOhmicLoss	675587.1	679932.2	-4937.7	-3908.1	-0.73	-0.57	NA	NA	0	4153	0.64	0.16
DCInvEnergy	674391.8	679932.2	-1195.3	0	-0.18	0	NA	NA	0	4153	0.82	0.18
InvEffLoss	651429.2	657757.2	-22962.6	-22175	-3.4	-3.26	NA	NA	0	4153	0.97	0.14
ACInvEnergy	651429.2	657757.2	0	0	0	0	NA	NA	0	4153	0.97	0

**Table 4. Test Case B1 Loss Comparison**

Item	Net.pvs	Net.hel	Delta.pvs	Delta.hel	RelPct.pvs	RelPct.hel	Area.pvs	Area.hel	NACount.pvs	NACount.hel	CumDiffPct	RelDiffPct
GHI	2094.2	2094.2	0	0	0	0	NA	NA	0	0	0	0
OrientationBoost	2357.7	2357.5	263.5	263.3	12.58	12.57	NA	NA	0	4153	-0.01	-0.01
ShadingLoss	2254.7	2256.5	-103.1	-101	-4.37	-4.28	NA	NA	0	4153	0.08	0.09
IAMLoss	2199.5	2201.6	-55.2	-54.9	-2.45	-2.43	NA	NA	0	4153	0.1	0.02
SoilingLoss	2199.5	2201.6	0	0	0	0	NA	NA	0	4153	0.1	0
EffectiveInsol	2199.5	2201.6	0	0	0	0	NA	NA	0	4153	0.1	0
DCVirtualEnergy	850319.5	856100.4	-5185648.2	-5185670.3	-85.91	-85.83	2744.28	2744.28	0	4153	0.68	0.57
PVTmplrLoss	752626.2	766715.9	-97693.3	-89384.5	-11.49	-10.44	NA	NA	0	4153	1.87	1.19
MQFLoss	765381	766715.9	12754.8	0	1.69	0	NA	NA	0	4153	0.17	-1.66
MismatchAndOffMppLoss	753614.5	753548.5	-11766.5	-13167.3	-1.54	-1.72	NA	NA	0	4153	-0.01	-0.18
DCOhmicLoss	747719.5	748907.2	-5895	-4641.4	-0.78	-0.62	NA	NA	0	4153	0.16	0.16
DCInvEnergy	746026.2	748907.2	-1693.3	0	-0.23	0	NA	NA	0	4153	0.39	0.23
InvEffLoss	719315.7	723424.8	-26710.5	-25482.3	-3.58	-3.4	NA	NA	0	4153	0.57	0.19
ACInvEnergy	719315.6	723424.8	0	0	0	0	NA	NA	0	4153	0.57	0

**Table 5. Test Case B2 Loss Comparison**

Item	Net.pvs	Net.hel	Delta.pvs	Delta.hel	RelPct.pvs	RelPct.hel	Area.pvs	Area.hel	NACount.pvs	NACount.hel	CumDiffPct	RelDiffPct
GHI	2094.2	2094.2	0	0	0	0	NA	NA	0	0	0	0
OrientationBoost	2357.7	2357.5	263.5	263.3	12.58	12.57	NA	NA	0	4153	-0.01	-0.01
ShadingLoss	2189	2228.9	-168.7	-128.6	-7.16	-5.46	NA	NA	0	4153	1.82	1.83
IAMLoss	2134.6	2174.7	-54.4	-54.2	-2.49	-2.43	NA	NA	0	4153	1.88	0.06
SoilingLoss	2134.6	2174.7	0	0	0	0	NA	NA	0	4153	1.88	0
EffectiveInsol	2134.6	2174.7	0	0	0	0	NA	NA	0	4153	1.88	0
DCVirtualEnergy	825224.2	845454.8	-5032620.3	-5122490.7	-85.91	-85.83	2744.28	2744.28	0	4153	2.45	0.57
PVTmplrLoss	731191.4	756826.7	-94032.7	-88628	-11.39	-10.48	NA	NA	0	4153	3.51	1.03
MQFLoss	743569.8	756826.7	12378.4	0	1.69	0	NA	NA	0	4153	1.78	-1.66
MismatchAndOffMppLoss	735257	738647.4	-8312.8	-18179.3	-1.12	-2.4	NA	NA	0	4153	0.46	-1.29
DCOhmicLoss	729560.4	734029.4	-5696.6	-4618	-0.77	-0.63	NA	NA	0	4153	0.61	0.14
DCInvEnergy	728087.2	734029.4	-1473.2	0	-0.2	0	NA	NA	0	4153	0.82	0.2
InvEffLoss	702342.8	709311.1	-25744.4	-24718.2	-3.54	-3.37	NA	NA	0	4153	0.99	0.18
ACInvEnergy	702342.7	709311.1	0	0	0	0	NA	NA	0	4153	0.99	0

**Table 6. Test Case C1 Loss Comparison**

Item	Net.pvs	Net.hel	Delta.pvs	Delta.hel	RelPct.pvs	RelPct.hel	Area.pvs	Area.hel	NACount.pvs	NACount.hel	CumDiffPct	RelDiffPct
GHI	2094.2	2094.2	0	0	0	0	NA	NA	0	0	0	0
OrientationBoost	2094.2	2091.9	0	-2.3	0	-0.11	NA	NA	0	4153	-0.11	0
ShadingLoss	2094.2	2091.9	0	0	0	0	NA	NA	0	4153	-0.11	0
IAMLoss	2015.4	2014.3	-78.8	-77.6	-3.76	-3.71	NA	NA	0	4153	-0.05	0.05
SoilingLoss	2015.4	2014.3	0	0	0	0	NA	NA	0	4153	-0.05	0
EffectiveInsol	2015.4	2014.3	0	0	0	0	NA	NA	0	4153	-0.05	0
DCVirtualEnergy	779173.7	781252.9	-4751777	-4746634.9	-85.91	-85.87	2744.28	2744.28	0	4153	1.27	0.28
PVTmplrLoss	690259.6	702271.3	-88914.1	-78981.6	-11.41	-10.11	NA	NA	0	4153	1.74	1.47
MQFLoss	701947.2	702271.3	11687.6	0	1.69	0	NA	NA	0	4153	0.05	-1.66
MismatchAndOffMppLoss	696924.9	698167	-5022.3	-4104.3	-0.72	-0.58	NA	NA	0	4153	0.18	0.14
DCOhmicLoss	691816.5	692188.4	-5108.4	-5978.6	-0.73	-0.86	NA	NA	0	4153	0.05	-0.13
DCInvEnergy	690577	692188.4	-1239.5	0	-0.18	0	NA	NA	0	4153	0.23	0.18
InvEffLoss	666985.5	669628.6	-23591.5	-22559.8	-3.42	-3.26	NA	NA	0	4153	0.4	0.17
ACInvEnergy	666985.5	669628.6	0	0	0	0	NA	NA	0	4153	0.4	0



**Table 7. Test Case C2 Loss Comparison**

Item	Net.pvs	Net.hel	Delta.pvs	Delta.hel	RelPct.pvs	RelPct.hel	Area.pvs	Area.hel	NACount.pvs	NACount.hel	CumDiffPct	RelDiffPct
GHI	2094.2	2094.2	0	0	0	0	NA	NA	0	0	0	0
OrientationBoost	2357.7	2357.5	263.5	263.3	12.58	12.57	NA	NA	0	4153	-0.01	-0.01
ShadingLoss	2234.6	2229.4	-123.2	-128.1	-5.22	-5.43	NA	NA	0	4153	-0.23	-0.22
IAMLoss	2178.9	2175.2	-55.6	-54.2	-2.49	-2.43	NA	NA	0	4153	-0.17	0.06
SoilingLoss	2178.9	2175.2	0	0	0	0	NA	NA	0	4153	-0.17	0
EffectiveInsol	2178.9	2175.2	0	0	0	0	NA	NA	0	4153	-0.17	0
DCVirtualEnergy	842374.2	845662.1	-5137180.1	-5123703.2	-85.91	-85.83	2744.28	2744.28	0	4153	0.39	0.57
PVTmpIrrLoss	746321.3	757017.1	-96052.8	-88645	-11.4	-10.48	NA	NA	0	4153	1.43	1.04
MQFLoss	758956.9	757017.1	12635.6	0	1.69	0	NA	NA	0	4153	-0.26	-1.66
MismatchAndOffMppLoss	749096.9	752620.9	-9860.1	-4396.2	-1.3	-0.58	NA	NA	0	4153	0.47	0.73
DCOhmicLoss	743255.2	742565.6	-5841.6	-10055.3	-0.78	-1.34	NA	NA	0	4153	-0.09	-0.56
DCInvEnergy	741676.5	742565.6	-1578.8	0	-0.21	0	NA	NA	0	4153	0.12	0.21
InvEffLoss	715278.3	721669	-26398.2	-20896.6	-3.56	-2.81	NA	NA	0	4153	0.89	0.78
ACInvEnergy	715278.3	721669	0	0	0	0	NA	NA	0	4153	0.89	0

Note that due to the different ways that mismatch is accounted for in the two programs, mismatch effects may appear in both the shading loss category and in the mismatch-and-off-MPP-operation category. PVSyst models within-string mismatch as “electrical effect” on the shade reduction, and HelioScope models row-to-row shading impacts the same way. PVSyst estimates inverter off-MPP-operation losses separately from on-MPP mismatch losses, but HelioScope does not so the PVSyst categories are combined for this comparison. BEW Engineering accounts for module rating bias in the module quality factor entry, while HelioScope incorporates it into the overall conversion efficiency category.

The horizontal test case with no shading, no irradiance and no temperature variability (A1) is intended to provide as few opportunities for modeling discrepancies as possible. The loss tree comparison in Table 2 (CumDiffPct) shows that HelioScope is 0.57% more generous than the PVSyst estimate in this case. Small discrepancies (on the order of 0.2%) accumulate from several loss categories, but the two most significant discrepancies are in the module quality factor (binning bias, which HelioScope obtains by simulating rating variations from module to module) and in the temperature/irradiance impact. The developer has confirmed that the impact of binning is appearing in the temperature/irradiance category, and plans to reassign that loss category in a future version of the software.

The tilted test case with no shading (A2) introduces the potential for discrepancies in the plane-of-array irradiance modeling algorithms and row-to-row shading. Table 3 demonstrates that the orientation boost is in excellent agreement, but at first review the shading loss appears to be 1.6% more optimistic. In fact, much of the discrepancy arises because PVSyst attributes additional “shading” loss to account for an electrical mismatch loss due to shading while HelioScope groups the shading-induced mismatch with other forms of mismatch further down in the loss tree. There is 0.4% additional discrepancy for a total of nearly 1.0% difference in this case. However, it is possible that HelioScope is actually obtaining a more accurate result than PVSyst does through detailed modeling of individual module irradiance conditions and electrical mismatch.

The flat test case with an external shading object (B1) is intended to introduce external shading modeling as the only addition to the simple case A1 conditions. Table 4 arrives at an identical cumulative difference as case A1, and shows that PVSyst string shade modeling with a 60% shade impact (our



estimated impact for this geometry) is only 0.1% different than the result obtained by HelioScope. Nevertheless, it is crucial that nearby shading objects be located accurately relative to the array to obtain accurate shading estimates.

Test case B2 represents a combination of row-to-row shade modeling and an external shade object leading to 7.2% shading/electrical mismatch annual loss. Table 5 shows that HelioScope maintains its 1.0% more optimistic estimate of energy generation than PVSyst, just as in case A2, even though multiple interacting effects are being modeled. As before, it is not clear which of the two modeling tools is correct, but the consistency of the results could prove useful.

Test case C1 represents a third variation of case A1, where Tigo MM-ES50 optimizers are included in the HelioScope model. (These results are compared to the same PVSyst model as used in A1.) The intent is to confirm that the introduction of additional equipment with no shading impacts to address does show a net reduction of output. The HelioScope result is still more optimistic than PVSyst, but only 0.4% rather than 0.6%, so a 0.2% net annual power consumption by the optimizers appears to be predicted by HelioScope. However, the 3 percent range in the HelioScope module binning assumption leads to mismatch, which has separately been shown to be on the order of 0.2%. So the full efficiency of the Tigo Maximizer appears to be 0.4%. This is consistent with the efficiency curves that Tigo has supplied to Folsom Labs.

Test case C2 models the impact of Tigo MM-ES50 optimizers on the shaded configuration of case B2. The PVSyst simulation in this case assumes “linear” shade impact (proportional to shaded area), since this behavior is the ideal goal of installing optimizers. The corresponding HelioScope simulation is about 0.9% more optimistic than the PVSyst simulation, which is consistent with discrepancies in other test cases. If we compare the PVSyst simulations from B2 to C2 we find a 1.8% higher energy capture with the ideal optimizer function. The corresponding comparison for HelioScope which is intended to model actual Tigo optimizer behavior is 1.7%, where the difference of 0.1% only accounts for 1/5 of the expected power consumption of the optimizers. As discussed above this could be due to the small residual mismatch from the module binning assumptions in HelioScope.

### **3. Conclusion**

HelioScope is a novel modeling tool for investigating the energy generating performance of PV systems even when subject to non-ideal solar access. It demonstrates agreement with PVSyst modeling results to within 1%, and appears to combine multiple shading effects (row-to-row and nearby object) to achieve consistent results relative to PVSyst. In addition, it shows general agreement in magnitude with the expected shade response improvement as well as the minor insertion loss from the Tigo Maximizers.

HelioScope takes an impressive technical step forward in PV system performance modeling. Features such as modeling the array from the module level, employing cloud computing resources on the fly, and interfacing with easy-to-use mapping and structure construction tools make this a package worth



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watching. Looking forward, the use of Google Maps is limiting if a system is being planned at a new location without aerial imagery of reference points, and the ability to confirm actual positioning dimensions will be a welcome improvement to the software.