Geothermal Risk Reduction via Geothermal/Solar Hybrid Power Plants

Q2 FY15 Milestone Report:
Parabolic Trough Solar-Thermal Output Model
Decoupled from SAM Power Block Assumptions

Prepared For:

The Geothermal Technologies Office
U.S. Department of Energy – Office of Energy Efficiency and Renewable Energy

March 31, 2015

Prepared By:
Craig Turchi and Ty Neises

NATIONAL RENEWABLE ENERGY LABORATORY

INTRODUCTION

Geothermal/Solar-thermal hybrid systems integrate two different renewable energy technologies that share the common feature of converting thermal energy into electric power. However, the two technologies have different time-dependent performance and thermal capabilities. Solar thermal systems collect energy during hours with good direct normal insolation (DNI). These systems may incorporate thermal energy storage, for example, by collecting a hot heat transfer fluid (HTF) in an insulated tank for later use. In contrast, geothermal systems have the ability to operate continuously.

The effective modeling of hybrid geothermal/solar-thermal facilities requires accurate modeling of each of the subsystems as well as their integrated design. As reported in prior work, NREL and Idaho National Laboratory (INL) have performed such analyses using a combination of NREL's System Advisor Model (SAM), Excel spreadsheets, and ASPEN simulation code [Turchi et al., 2014, Wendt & Mines, 2014].

While SAM is a state-of-the-art simulation package for concentrating solar power (CSP) systems, the use of SAM for modeling geothermal/solar-thermal hybrid systems is complicated by the fact that SAM's solar-thermal models are provided within systems that include a steam-Rankine power block. The user must understand the complexities added by the included steam power cycle is order to extract model results that are relevant for the case where the solar field is only providing thermal energy.

The objective of this milestone is to simplify access to SAM's powerful solar thermal collector/receiver models so that results from SAM can be used by a wider audience to simulate the solar thermal contribution to geothermal/solar-thermal hybrid systems.

APPROACH

NREL began analysis of the solar field at Enel Green Power's Stillwater Geothermal Plant in fall 2014 using SAM 2014-01-14. This work is part of the Geothermal Technologies Office task *2.5.4.2 Geothermal Risk Reduction via Geothermal/solar Hybrid Power Plants* and a CRADA between Enel, NREL, and INL. A simple representation of the hybrid integration at Stillwater is provided in Figure 1. The design employs 24,778 m^2 of parabolic troughs arranged in 11 loops. Because of the land area at Stillwater, the loops consist of two 115-m SCAs plus two shorter, 86-m SCAs. The troughs are 6-m aperture SkyTroughs supplied by SkyFuel of Arvada, CO. The specific hardware dimensions and operating conditions were set up in a SAM 2014-01-14 case file.

The release of SAM 2015-01-30, a major update from the 2014 version, required recreation of the Stillwater case. Important revisions to SAM in 2015 include greater customization capabilities and a new interface. The update required recoding SAM into C++ to allow provide faster simulation times and use of multicore, parallel processing. Three different cases were made in the new version of SAM:

1) SAM's default Physical Trough model with solar field, collector, and receiver inputs adjusted to represent the Stillwater field,
2) The inputs as in Case (1) plus modifying SAM's Power Cycle page in an effort to avoid having the power cycle code interfere with simulation of the solar field, and

3) The inputs as in Case (1) exported to TCS Console, an NREL software tool that allows manipulation of the core performance code for the Physical Trough model, so that the solar field components could be modeled in the absence of any power cycle.

These simulations proceed in increasing order of sophistication with respect to the understanding of SAM and represent what might be undertaken by a novice SAM user, a frequent SAM user, and an advanced SAM user, respectively. Our goal is to provide the best simulation from SAM with the least required knowledge on the part of the user in order to make SAM more accessible for geothermal/solar-thermal hybrid analysis.

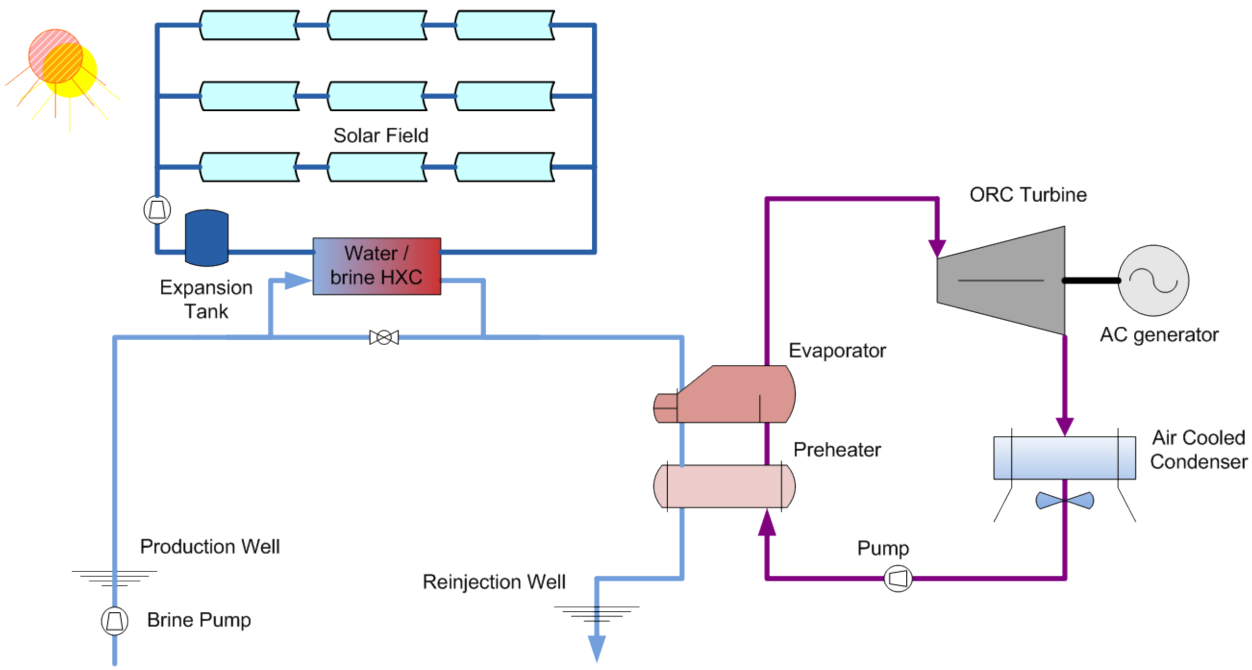

Figure 1. Geothermal/Solar-thermal hybrid configuration similar to that employed at Stillwater.

RESULTS

A comparison of SAM's annual *Field Thermal Power Produced* for the three cases is provided in Table 1. This is one of SAM's output variables for solar field performance and represents the predicted thermal energy from the solar field HTF after accounting for incoming DNI and optical and thermal losses in the solar field. Table 1 also shows the total thermal energy incident on the solar field aperture area, the total thermal energy absorbed by the solar field, and energy dumped due to forced defocusing of the solar field.

Table 1. Relevant annual solar field performance estimates from different cases. Running the solar collector code without any power cycle interference (Case 3) is required to obtain the best estimate of thermal energy potential.

Annual thermal energy estimates (MWh-th)	Case (1) Solar Field with SAM's default power cycle	Case (2) Solar Field with power cycle input changes in SAM	Case (3) Stand-alone trough modeled via TCS Console
Field thermal power incident	76,120	76,120	76,120
Field thermal power dumped	31	518	0
Field thermal power produced	35,506	38,988	41,465
Estimated generation (relative)	85.6%	94.0%	100%

The simplest way to use SAM to simulate the thermal output from a parabolic trough field is to open a default case of the Physical Trough Model and adjust the Location and Resource and solar field settings via the Solar Field, Collectors (SCAs), and Receivers (HCEs) pages to model the size and hardware details of the field in question (see Figure 2). However, as is apparent from Table 1, if the SAM user simply runs the default Physical Trough Model in this fashion without addressing the default Power Cycle inputs, SAM will underestimate energy production. It is also possible the model will not even run due to a mismatch in power cycle and solar field properties. These errant results are due to SAM trying to "force fit" the specified solar field and power cycle parameters.

Case (2) addresses many of these concerns by adjusting Power Cycle inputs to minimize the influence of the power cycle code on the solar field performance. This results in a case with less potential for convergence errors and a better estimate of the potential output from the solar field. The specific recommended changes for this case are outlined in Table 2.

Finally, Case (3) removes the Physical Trough code completely from the SAM interface and runs the code within NREL's TCS Console environment. TCS Console was developed by NREL to allow manipulation of the model systems originally developed the TRNSYS FORTRAN format. For this work, NREL developed a script within TCS Console that separates the power block controller functions from the solar field performance model and allows for recirculation of the solar field HTF as necessary.

Running the Physical Trough model in this fashion avoids any conflict with the power cycle code and provides a clean estimate of parabolic trough performance. However, the process is more complex than simply adjusting inputs within SAM's Graphical User Interface, and requires access to NREL's TCS Console tool. Instructions for extraction and use of the Physical Trough model are provided in the Appendix.

While this report documents a procedure to access accurate predictions from the Physical Trough model in the absence of a steam power cycle, the use of TCS Console is cumbersome and not a long-term solution. TCS Console was an interim fix for NREL programmers and is not intended as a public-use tool. Recognizing the need for access to SAM's collector/receiver models and the limitations of the procedure described here, NREL has proposed to develop a more intuitive SAM-based interface for accessing these tools in FY16. This request has been included in a proposal to the DOE Solar Program.

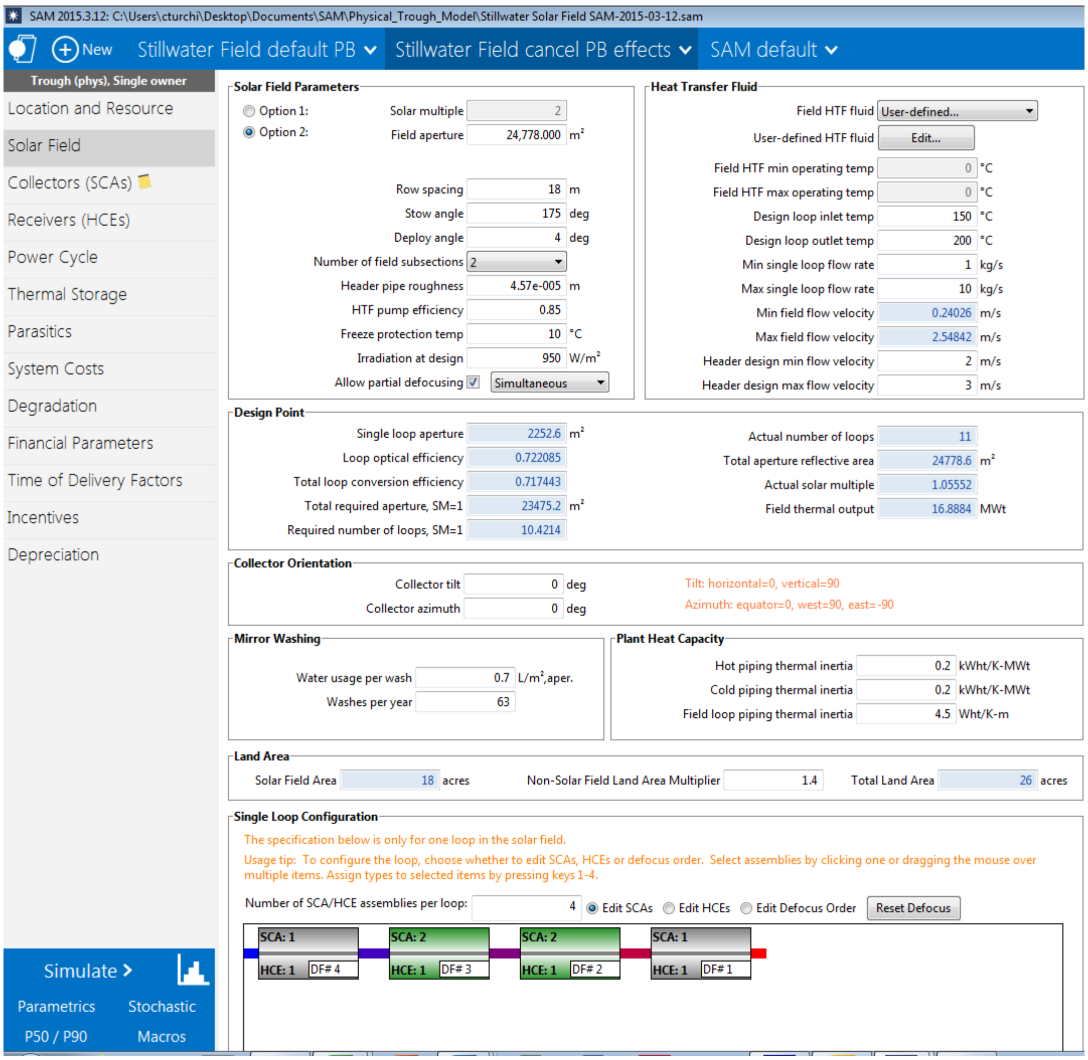

Figure 2. Solar Field inputs page in the Physical Trough Model in SAM 2015-03-12.

Table 2. Changes to SAM's Power Cycle inputs page to minimize power cycle influence over the solar field performance. If thermal storage is used, additional adjustments need to be made on the Thermal Storage page.

Power Cycle page Input	SAM default	Recommended change
Design gross output	111	Set equal to thermal power rating of solar field
Estimated gross to net conversion factor	0.9	no change
Availability and Curtailment inputs	various	no change
Rated cycle conversion efficiency	0.3774	1.0
Boiler operating pressure	100	set equal to saturated steam pressure at solar field outlet temp
Steam cycle blowdown fraction	0.02	no change
Fossil backup boiler LHV efficiency	0.9	no change
Aux heater outlet set temp	391	set equal to solar field outlet temp
Fossil dispatch mode	Min backup level	no change
Low resource standby period	2	no change
Fraction of thermal power needed for startup	0.2	0
Power block startup time	0.5	0
Minimum required startup temp	300	set equal to solar field inlet temp
Max turbine over design operation	1.05	2
Min turbine operation	0.25	0.02
Turbine inlet pressure control	Fixed Pressure	no change
Cooling System inputs	various	no change

CONCLUSIONS AND RECOMMENDATIONS

SAM's normal interface can be used to estimate parabolic trough performance for solar-thermal applications if one takes a number of steps to minimize the influence of the power cycle simulation requirements on the solar field. For the Stillwater solar field, skipping these steps results in solar field thermal-energy generation estimates that are 85% below values estimated without interference from the power cycle component model. Making a series of adjustments to SAM's default power cycle inputs improved the estimate to be within 94% of the estimated stand-alone solar field value.

For initial performance estimates, creating a case with SAM and minimizing the influence of the power cycle by the methods outlined in this report is probably sufficient. For more detailed analysis, stand-alone-trough model estimates can be developed via NREL's TCS Console environment following the process outlined in the Appendix. However, performing this analysis requires requesting access to TCS Console from NREL. TCS Console was not written as a public software tool and lacks usability features and documentation.

Recognition of this limitation has led to a FY16 proposal within the CSP program to modify SAM to allow for easier access to the solar field performance codes within SAM's user-friendly interface. Such a change will promote greater use of SAM of thermal-energy production in geothermal hybrids and for other thermal-energy applications.

Lastly, while this report deals specifically with the Physical Trough model, the same procedures would apply to SAM's linear Fresnel models.

REFERENCES

C. Turchi, G. Zhu, M. Wagner, T. Williams, and D. Wendt, "Geothermal / Solar Hybrid Designs: Use of Geothermal Energy for CSP Feedwater Heating," Geothermal Resources Council 38th Annual Meeting, Portland, Oregon, Sept 28 to Oct 1, 2014.

D.S. Wendt and G.L. Mines, "Use of a Geothermal-Solar Retrofit Hybrid Power Plant to Mitigate Declines in Geothermal Resource Productivity," Geothermal Resources Council 38th Annual Meeting, Portland, Oregon, Sept 28 to Oct 1, 2014.

Download site for System Advisor Model (SAM): https://sam.nrel.gov/

Download site for SAM's software development kit (SDK) tools: https://sam.nrel.gov/content/sam-simulation-core-sdk

APPENDIX

The set of inputs from SAM's Input Browser is provided in the following two tables. The Inputs Browser only shows values that differ from the default inputs in SAM-2015-03-12. The User-defined HTF is pressurized water, but the actual physical properties are not shown here.

Variable	Label	SAM default	Stillwater Field default PB	Stillwater Field cancel PB effects
IAMs_1	Incidence angle modifier coefficients	1;0.0506;-0.1763	1;0.0327;-0.1351;0	1;0.0327;-0.1351;0
P_boil	Boiler operating pressure	100	100	15
Row_Distance	Row spacing	15	18	18
SCA_drives_elec	Tracking power	125	68	68
T_amb_des	Ambient temp at design	20	25	25
T_fp	Freeze protection temp	150	10	10
T_loop_in_des	Design loop inlet temp	293	150	150
T_loop_out	Design loop outlet temp	391	200	200
T_set_aux	Aux heater outlet set temp	391	391	200
T_startup	Minimum required startup temp	300	300	150
T_tank_cold_ini	Initial TES fluid temp	300	100	100
cold_tank_Thtr	Cold tank heater set point	250	25	25
collector_library	Collector library	Solargenix SGX-1	SkyFuel SkyTrough (Manufacturer	SkyFuel SkyTrough (Manufacturer
combo_htf_type	Field HTF fluid	Therminol VP-1	User-defined...	User-defined...
combo_tes_htf_type	Storage HTF fluid	Hitec Solar Salt	User-defined...	User-defined...
const_per_months1	Construction Loan 1 months	24	6	6
csp.dtr.cost.bop_per_kwe	Balance of Plant Cost per kWe	110	0	0
csp.dtr.cost.epc.percent	EPC Costs % direct	11	25	25
csp.dtr.cost.htf_system.cost_per_m2	HTF System Cost Per m2	80	40	40
csp.dtr.cost.plm.per_acre	Land Cost acre	10000	0	0
csp.dtr.cost.power_plant.cost_per_kw	Power Plant Cost per kWe	830	0	0
csp.dtr.cost.site_improvements.cost_p	Site Improvement Cost per m2	30	10	10
csp.dtr.cost.solar_field.cost_per_m2	Solar Field Cost per m2	270	200	200
csp.dtr.cost.storage.cost_per_kwht	Storage System Cost per kWht	80	0	0
csp_dtr_hce_diam_absorber_inner_1	Absorber tube inner diameter	0.066	0.076	0.076
csp_dtr_hce_diam_absorber_outer_1	Absorber tube outer diameter	0.07	0.08	0.08
csp_dtr_hce_notify_text_1	Receiver name from library	Schott PTR70 2008	Schott PTR80	Schott PTR80
csp_dtr_hce_var1_abs_abs_1	Variation 1 Absorber Absorptance	0.96	0.963	0.963
csp_dtr_hce_var1_bellows_shadowing	Variation 1 Bellows Shadowing	0.96	0.935	0.935
csp_dtr_hce_var1_env_trans_1	Variation 1 Envelope Transmittance	0.963	0.964	0.964
csp_dtr_hce_var1_hce_dirt_1	Variation 1 Dirt on receiver	0.98	0.975	0.975
csp_dtr_hce_var1_rated_heat_loss_1	Variation 1 Rated Heat Loss	150	31	31
csp_dtr_hce_var2_env_trans_1	Variation 2 Envelope Transmittance	0.963	0.964	0.964
csp_dtr_hce_var2_field_fraction_1	Variation 2 Field Fraction	0.01	0.015	0.015
csp_dtr_hce_var2_rated_heat_loss_1	Variation 2 Rated Heat Loss	1100	245	245
csp_dtr_hce_var3_bellows_shadowing	Variation 3 Bellows Shadowing	0.96	0.935	0.935
csp_dtr_hce_var3_field_fraction_1	Variation 3 Field Fraction	0.005	0	0
csp_dtr_sca_aperture_1	Reflective aperture area	470.3	656	656
csp_dtr_sca_ave_focal_len_1	Average surface-to-focus path length	1.8	2.15	2.15
csp_dtr_sca_ave_focal_len_2	Average surface-to-focus path length	1.8	2.15	2.15
csp_dtr_sca_clean_reflectivity_1	Mirror reflectance	0.935	0.93	0.93
csp_dtr_sca_clean_reflectivity_2	Mirror reflectance	0.935	0.93	0.93
csp_dtr_sca_general_error_1	General optical error	0.99	1	1
csp_dtr_sca_general_error_2	General optical error	0.99	1	1
csp_dtr_sca_geometry_effects_1	Geometry effects	0.98	0.952	0.952
csp_dtr_sca_geometry_effects_2	Geometry effects	0.98	0.952	0.952
csp_dtr_sca_length_1	Length of collector assembly	100	115	115
csp_dtr_sca_length_2	Length of collector assembly	100	86	86
csp_dtr_sca_mirror_dirt_1	Dirt on mirror	0.95	0.975	0.975
csp_dtr_sca_mirror_dirt_2	Dirt on mirror	0.95	0.975	0.975
csp_dtr_sca_ncol_per_sca_1	Number of modules per assembly	12	8	8
csp_dtr_sca_ncol_per_sca_2	Number of modules per assembly	12	6	6

Variable	Label	SAM default	Stillwater Field default PB	Stillwater Field cancel PB effects
csp_dtr_sca_notify_text_1	Collector name from library	Solargenix SGX-1	SkyTrough (Manufacturer Specifications)	SkyTrough (Manufacturer Specifications)
csp_dtr_sca_notify_text_2	Collector name from library	Solargenix SGX-1	SkyTrough (Manufacturer Specifications)	SkyTrough (Manufacturer Specifications)
csp_dtr_sca_tracking_error_1	Tracking error	0.994	0.988	0.988
csp_dtr_sca_tracking_error_2	Tracking error	0.994	0.988	0.988
csp_dtr_sca_w_profile_1	Aperture width total structure	5	6	6
csp_dtr_sca_w_profile_2	Aperture width total structure	5	6	6
cycle_cutoff_frac	Min turbine operation	0.25	0.25	0.02
cycle_max_frac	Max turbine over design operation	1.05	1.05	2
dispatch_factor1	Energy Payment Factor 1	2.064	1	1
dispatch_factor2	Energy Payment Factor 2	1.2	1	1
dispatch_factor4	Energy Payment Factor 4	1.1	1	1
dispatch_factor5	Energy Payment Factor 5	0.8	1	1
dispatch_factor6	Energy Payment Factor 6	0.7	1	1
eta_ref	Rated cycle conversion efficiency	0.3774	0.3774	1
field_fl_props	User-defined HTF fluid	[0]	user-defined	user-defined
hot_tank_Thtr	Hot tank heater set point	365	190	190
m_dot_htfmax	Max single loop flow rate	12	10	10
om_capacity	Fixed cost by capacity	65	30	30
pb_rated_cap	Design gross output	111	111	16
q_sby_frac	Fraction of thermal power needed for s	0.2	0.2	0
receiver_library	Receiver Library	Schott PTR70 2008	Schott PTR80	Schott PTR80
specified_total_aperture	Field aperture	877000	24778	24778
startup_frac	Fraction of thermal power needed for s	0.2	0.2	0.01
startup_time	Power block startup time	0.5	0.5	0
store_fl_props	User-defined HTF fluid	[1]	user-defined	user-defined
tank_max_heat	Tank heater capacity	25	1	1
theta_dep	Deploy angle	10	4	4
theta_stow	Stow angle	170	175	175
tod_library		Generic Summer Peak	Uniform Dispatch	Uniform Dispatch
tshours	Full load hours of TES	6	0	0

Instructions to use the stand-alone use of SAM's Physical Trough model.

1) These Instructions assume the work is saved in a folder called *Physical_Trough_Model*
2) Use the 2015-03-12 (or the latest) versions of SAM and SDK. These can be downloaded at https://sam.nrel.gov/
3) Set up SAM simulation
   a. Open SAM and select the Physical Trough model with any financing model.
   b. Configure inputs to define the solar field you want to simulate. Most of the relevant inputs are on the Solar Field, Collector, and Receiver pages.
   c. Select "Shift + F5". This creates a text file titled 'ssc-tcstrough_physical.lk'
   d. Save this file to the *Physical_Trough_Model* folder.
4) Move 'tcsconsole.exe' from the *Physical_Trough_Model* folder to the folder containing SDK\win32. The new location should also contain 'sdktool.exe'.
5) Open 'tcsconsole.exe' from the SDK\win32 folder.
6) In the TCS Console, select the Script Editor tab at the top of the window. Select the 'Open' button and select 'Physical trough stand alone from SSC script.lk'
7) Within 'Physical trough stand alone from SSC script.lk' there are two variables pointing to file paths that need to be defined. (Note that '/' must be used when defining paths rather than '\')
   a. 'data_directory' should point to the full path for *Physical_Trough_Model* folder
   b. 'ssc_lk' should point to the file 'ssc-tcstrough_physical.lk'
   c. 'trough_csv' should point to 'input_data.csv' containing necessary input data. See input data formatting instructions below.
   d. The script is designed to extract Physical Trough inputs from 'ssc-tcstrough_physical.lk' Do not modify this .lk file. If you wish to change SAM variable values, change variables in the SAM UI and repeat the process to create a new .lk file.
   e. Save these changes.
8) Select 'Run'. Output data is available in the 'Data Tables' tab.
   a. The thermal energy produced by the solar field is given by variable *q_avail (MWt)* This is denoted in SAM time series data as *Field thermal power produced (MWt)*

Input Data File Instructions

The input data file (in .csv format) should contain input data for consecutive, evenly spaced timesteps. The following is a list and brief description of each required input. Note that typical weather files give instantaneous temperature, wind speed, and ambient pressure measurements corresponding to the hour of the day, while the irradiance values are averaged over the entire hourly timestep. SAM evaluates at the midpoint of the timestep. Therefore, the irradiance values aren't adjusted, but the other values are averaged with the previous timestep's value. This explains why SAM's temperature, wind speed, and ambient pressure hourly outputs don't exactly match the weather file values.

hr [hr, standard time]: Hour of the year at the *end* of the timestep for which data is provided. For example, if the data represent 10 minutes of measured data from 10:55 to 11:05, then the value should be 11:05 (11.083 on January 1). The simulation code uses this value and the simulation timestep (10 minutes) to calculate the midpoint at which solar position is calculated.

I_b [W/m2]: Beam irradiance.

T_db [C]: Dry bulb temperature.

V_wind [m/s]: Wind speed.

P_amb [mbar]: Ambient air pressure. If this measurement is not available, a constant value can be estimated using an equation found on Engineering Toolbox: http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html.

T_dp [C]: Dew point temperature. The performance calculations use this value to estimate the Sky Temperature that is used in radiation loss calculations. If this measurement is not available, the input value should be set to -1000 C, and the code estimates the Sky Temperature as T_db – 20 C.

T_cold_in [C]: Inlet temperature to the field.

latitude, longitude, and shift [deg]: Coordinates of the location. Shift is the difference between the site longitude and the longitude corresponding to the time zone of the location.

One can check that these inputs are properly read by displaying the variable in the Data Tables tab of TCSconsole. Select the "output" version of the variable name, which is the variable preceded by an O_ as shown in the figure below: