CSP-Plant Modeling Guidelines and Compliance of the System Advisor Model (SAM)

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Abstract. Accurately modeling risks, costs, and electricity output is essential to the financing and advancement of concentrating solar power projects. To address this need, a group of CSP experts created a guideline document, titled *SolarPACES Guideline for Bankable STE Yield Assessment* [1]. To make this information more accessible and allow stakeholders to test specific models against the recommendations, the guidelines have been condensed into a spreadsheet-based checklist. The checklist was applied to NREL's System Advisory Model (SAM) CSP modeling software, providing useful feedback to both the checklist group and the SAM development team. This study showed a strong agreement between SAM and the guidelines, demonstrated the use of the guidelines in model validation, and resulted in several recommended improvements to SAM.

INTRODUCTION

In January 2017 SolarPACES published a guideline for bankable solar thermal electric (STE) yield assessment [1]. This report, led by Tobias Hirsch of the German Aerospace Center (DLR), documents appropriate methodology and best practices for modeling the performance of concentrating solar power (CSP) systems. This work was motivated by the fact that there was no standard available to provide guidance to persons involved in energy-generation predictions of STE systems. The lack of established guidelines creates uncertainty among stakeholders, including financial institutions, regarding the veracity of project performance estimates. This uncertainty translates into higher risk for developers and financiers, which drives up project costs. In addition to improvements in technical aspects of CSP plants, wider deployment of this technology requires that prediction of the electricity generation and thus the financial revenues are made with high precision and confidence.

Later in 2017, NREL staff met with researchers from DLR, KTH Stockholm (Sweden), Fraunhofer ISE (Germany), CENER (Spain), and SolarDynamics (USA) to review these guidelines and begin the development of an associated checklist. This checklist was designed to help CSP stakeholders compare their own models and modeling methods to the recommendations outlined in the guidelines. This would allow stakeholders a higher degree of confidence in their CSP models and identify any potentially damaging model assumptions or omissions.

One well-established CSP model is the System Advisor Model (SAM, https://sam.nrel.gov/); a performance and financial model for the renewable energy industry developed at NREL. SAM has been publicly available since 2007 and has a wide array of tools for modeling a variety of renewable systems, ranging from solar to geothermal to wind. It has become an industry standard and has been downloaded by over 35,000 manufactures, project developers, academic researchers, and policy makers.

This paper documents the development of the checklist and showcases its use on SAM. Two frequently used SAM models were evaluated against the guidelines: the *CSP parabolic trough (physical)* model, and the *CSP power tower molten salt* model. This served to both refine the checklist and provide some feedback to the SAM development team regarding SAM's compliance with the SolarPACES guidelines.

The checklist layout and methodology are described in the Approach section, followed by the results of the SAM model analyses. This work is intended to both be beneficial to SAM and encourage greater use of the guidelines by the CSP community.

APPROACH

The initial checklist workshop, which met at DLR in Stuttgart, Germany reviewed the recently published guidelines and sought to develop a simplified method by which CSP stakeholders could test a specific modeling approach against the guideline recommendations. This workshop produced a draft checklist that asks a model developer a series of simple questions to compare the terminology and methods of their model(s) against the guidelines. In 2018, a joint effort was undertaken by NREL's Thermal Systems Research Group and KTH Stockholm to complete, clarify, and cross-reference the checklist back to the original guideline document. Consistent formatting was established across the checklist, descriptions and instructions were added, and the results-tabulation process was automated to streamline the user interface. Layout, rationale, and instructions for using the checklist are described below.

Checklist questions are given one of four classifications:

- **Shall** – These requirements are essential to achieve an accurate result.
- **Should** – These requirements will improve the quality of the model. Their significance is dependent on the system being modeled. These requirements also include "best practice" recommendations that do not affect model accuracy.
- **Optional** – These requirements are unlikely to have a major effect on the results but are worth considering and may be important in some situations.
- **Info** – These are suggestions for information to be reported by the model. This includes the "Reporting Variables" listed in the document. These values are updated on the sheet relating to each sub-system, and the results are summarized on the *Reporting Variables* sheet.

These classifications rank the importance of guideline requirements and affect how they are scored. Only "shall" and "should" requirements are counted in the results.

The spreadsheet-based checklist is divided into topical sections covering different aspects of the CSP plant. These sections align with the chapters of the guideline document. **TABLE 1** lists each of the checklist sheets, followed by a short description and the relevant chapter in the guidelines. The checklist returns a score in the *Overall Results* section. This score shows the percentage of "shall" and "should" requirements met for each section as well as a total of all sections, providing a quantitative measure of compliance with the guidelines.

A section of the *SF (Point Focus)* checklist sheet, with an expanded view of the first few lines, is shown in **FIGURE 1**. The leftmost "Topic" column lists a question on each line. The second column, "Page", lists the page number in the guidelines where this issue is raised. This ensures each checklist item is grounded in the guideline document and allows the user to seek further context and clarification directly in the guidelines. Each checklist question is then followed by two checkboxes. A checked box in the "yes" column signifies that the requirement is met. This should turn the cell from red to green and count this affirmative response on the *Overall Results* sheet. A checked box in the "na" (not applicable) column removes the requirement from consideration. This will turn the entire row gray, and the requirement will not be counted as either met or unmet on the *Overall Results* sheet. Checking the "na" box overrides the "yes" checkbox for that requirement. Finally, the "Category" column shows the classification of each question. Although it is not shown in the expanded portion of **FIGURE 1**, to the right of the "Category" column is a space for user comments.

For simplicity, the two types of solar field (SF) were split into separate sheets, *SF (Line Focus)* and *SF (Point Focus)*. This means that one of these sheets will not be applicable to the system being modeled. To deal with this, the topmost question in Figure 1 was added to both solar field sheets. Checking the box in this row on whichever solar field type is not relevant to the model being examined will gray out the entire sheet and the appropriate line on the *Overall Results* page.

TABLE 1. An overview of the individual sheets of the checklist spreadsheet.

Checklist Sheet	Description	Guideline Reference
Overall Results	A summary of the compliance percentages of each section	-
Reporting Variables	A summary of all the "info" (reporting question) results	Chapters 4-9
Financial Evaluation	Financial modeling requirement checklist	Chapter 2
General Modeling	Checklist for general modeling practices	Chapter 3
System Level	System level modeling checklist	Chapter 4
SF (Line Focus)	Solar field checklist for line focus (trough, linear Fresnel)	Chapter 5.2
SF (Point Focus)	Solar field checklist for point focus (tower) systems	Chapter 5.3
Power Block	Power Block modeling checklist	Chapter 6
Storage	Thermal Energy Storage modeling checklist	Chapter 7
AuxHeater	Checklist for modeling auxiliary heating (fossil, heat trace)	Chapter 8
Electrical	Electrical subsystem modeling checklist	Chapter 9
Op Strategy	Operational Strategies modeling checklist	Chapter 10
Annual Effects	Checklist for modeling annual effects	Chapter 11
Meteo	Meteorological input modeling checklist	Chapter 12
Uncertainties	Uncertainty sources, measurements, and reporting checklist	Chapter 13

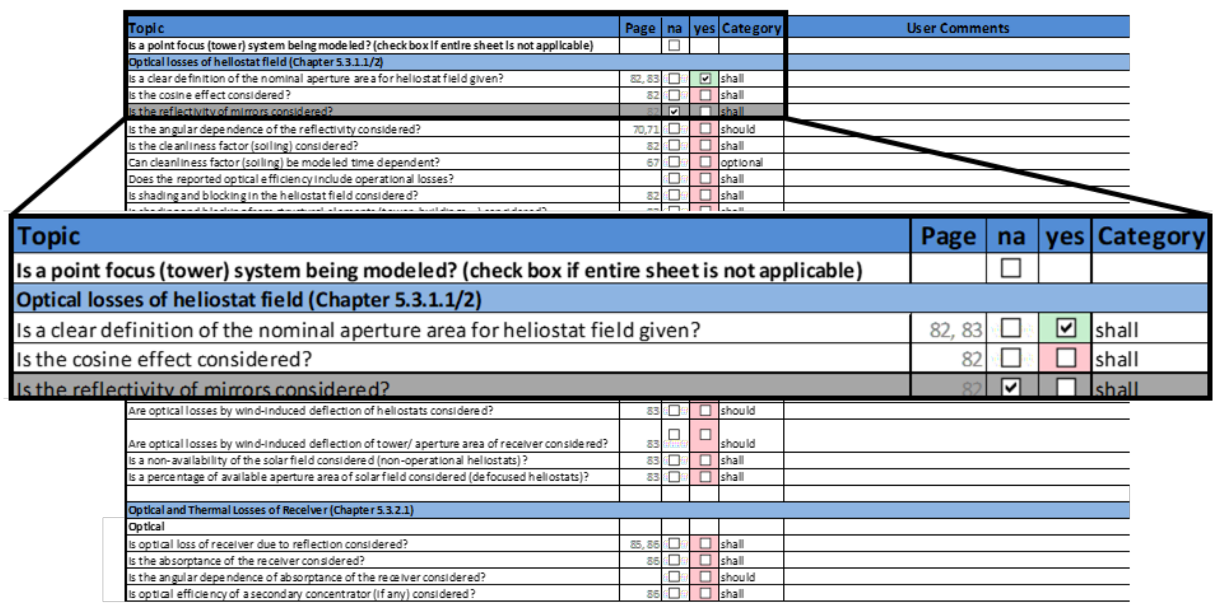

FIGURE 1. A screenshot of the "SF (Point Focus)" sheet. The User Comments column (furthest to the right) is not expanded for clarity.

The completed checklist was then used to test NREL's SAM models for molten-salt power tower and parabolic trough systems. Items and terminology found not to comply were discussed with NREL's larger SAM team to determine if changes or clarifications should be made to SAM.

RESULTS – SAM TEST CASE

The SolarPACES checklist was applied to two different test cases within SAM; the *CSP parabolic trough (physical)* and the *CSP power tower molten salt*. The goal of this was to exercise the SolarPACES checklist and while also evaluating the compliance of SAM. The summary tables below show results taken directly from the *Overall Results* tab in the checklist. They show the percentage of mandatory "shall" and recommended "should" requirements met for each sub-system. All results presented here are for SAM release 2017.9.5. Specific discrepancies between SAM and the guidelines are described in detail in the discussion subsection.

CSP Parabolic Trough (Physical) Model

SAM's CSP physical trough model is based on work by Wagner et al. and is presented in the "Technical Manual for the SAM Physical Trough Model" [2], available on the SAM website.

TABLE 2. Overall results of the checklist applied to the CSP parabolic trough (physical) model in NREL's SAM modeling system.

Category	Percentage met		Guideline Reference
	Shall	Should	
Financial Evaluation	100%	94.0%	Chapter 2
General Modeling	100%	77.8%	Chapter 3
System Level	100%	100%	Chapter 4
SF (Line Focus)	95.2%	81.3%	Chapter 5.2
Power Block	100%	66.7%	Chapter 6
Storage	81.8%	71.4%	Chapter 7
AuxHeater	66.7%	33.3%	Chapter 8
Electrical	100%	100%	Chapter 9
Op Strategy	100%	100%	Chapter 10
Annual Effects	100%	100%	Chapter 11
Meteo[1]	-	-	Chapter 12
Uncertainties	94.1%	71.4%	Chapter 13
Total	94.8%	83.0%	-

CSP Power Tower Molten Salt Model

SAM's CSP Power Tower Molten Salt model is also based on work by Wagner [3]. Simulation techniques are described in documentation available on the SAM website.

TABLE 3. Overall results of the checklist applied to the CSP power tower molten salt in NREL's SAM modeling system.

Category	Percentage met		Guideline Reference
	Shall	Should	
Financial Evaluation	100%	94.1%	Chapter 2
General Modeling	100%	83.3%	Chapter 3
System Level	100%	100%	Chapter 4
SF (Point Focus)	94.2%	41.7%	Chapter 5.2
Power Block	100%	66.7%	Chapter 6
Storage	85.7%	100%	Chapter 7
AuxHeater[2]	N/A	N/A	Chapter 8
Electrical	100%	100%	Chapter 9
Op Strategy	100%	100%	Chapter 10
Annual Effects	100%	100%	Chapter 11
Meteo	-	-	Chapter 12
Uncertainties	94.1%	71.4%	Chapter 13
Total	96.2%	83.8%	-

[1] While various meteorological data can be imported, the National Solar Radiation Data Base (NSRDB), which uses 30-min data, is built into SAM.

[2] SAM release 2017.9.5 has a new power cycle and system dispatch model for *CSP Power Tower Molten Salt* that did not retain the fossil backup (auxiliary heater) option from prior versions. It is expected that this feature will return in a future SAM release.

These results show very good agreement in almost all subsystems. Often, discrepancies are the result of the breadth of the SAM tools. Instead of including inputs for every possible source of optical, parasitic, or thermal losses, many of which would not be applicable to a given CSP system, SAM passes this responsibility on to the user. An example of this is Operations and Maintenance (O&M) costs. SAM includes spaces for different types of O&M costs to be entered (fixed annual, variable by generation, etc.), but does not list every possible source of plant O&M cost. Careful consideration on the part of the user is essential to achieve an accurate cost model. For this reason, it would be more telling to use the checklist on the SAM model for a specific CSP project, checking both SAM's calculation, and that the user included all the appropriate sources of loss and inputs.

Alternatively, someone using SAM may want to keep the checklist on hand, to make sure a generalized each SAM input (such as "Heliostat image error") includes all the relevant contributions (tracking error, mirror imperfections, motion due to wind, etc.). SAM's own Help Menu often provides a similar reminder of the types of elements that should be accounted for in a single, general input variable.

Discussion

Differences between SAM and the guidelines are examined on a section by section basis below.

Financial Evaluation

SAM's financial model is consistent across most SAM modeling systems. The user can add costs (fixed or variable) to account for all types of cost and benefit described in the checklist. However, it is often left to the user to account for various factors that compile into a single SAM input variable. For example, SAM lists *EPC and Owner Costs* as a single input and the user must account for the multiple cost elements that roll into this general category (see SAM Help Menu). An imperfect score in the "should" category is due to differences in a couple financial considerations that are not mentioned in SAM but could be added by a user. Lastly, the guidelines recommend accounting for site-specific costs that can not be included in a generic SAM model, but could be added by the user.

General Modeling and System Level

SAM defaults to hourly simulation, so it may appear that the temporal resolution requirements were not met; however, sub-hourly timesteps are acceptable within SAM as long as a full year is modeled. Although time steps are one hour by default, they can be set arbitrarily small by a user. SAM includes access to NREL's National Solar Radiation Database (NSRDB) weather data, which has a resolution of 30 minutes (for the 1998-2014 update). While these data are greater than the 10-minute resolution recommended in the guidelines; SAM can accept shorter interval data supplied by the user. The guidelines also state that one-hour resolution is adequate for pre-feasibility studies. For projects closer to construction, a user should gather high-resolution data at the specific site, which can then be imported into SAM.

Other small discrepancies are the result of differences in sub-system structure between SAM and the guidelines. These are unlikely to affect model performance, and so are classified as "should" requirements. Using the checklist on SAM also resulted in clarifications and rewording on several System Level questions.

Solar Field and Power Block

Many Solar Field efficiency factors are aggregated into single input values by SAM. Thus, meeting the requirements of the guidelines requires the user to understand and account for the individual factors. For example, all sources of optical losses must be incorporated into a single optical efficiency value. SAM specifies almost all sources of optical inefficiency that the guidelines say should be included in this value within the Help Documentation. A user can enter time-dependent losses to account for soiling and other forms of degradation as recommended by the guideline. Angle-dependent optical efficiencies and conductive thermal losses from the tower receiver are "should" requirements that are not included in SAM.

All requirements for the Power Block sub-system are met, excluding the recommendation that HTF properties be characterized by pressure. Instead, pumping power requirements for the HTF through the power block are characterized by a load-based coefficient that multiplies HTF mass flow rate. The user is free to modify this parameter as needed to match expected parasitic consumption, but the model does not predict parasitic power based on pressure considerations. This recommendation results in unchecked items across multiple sub-systems, including both Solar Field and Power Block.

Thermal Energy Storage (TES)

The thermal energy storage section received the lowest percentages in both the "shall" and "should" categories. This was due to SAM's less-rigorous modeling of thermal losses from the salt storage tanks, and of the salt-HTF heat exchanger in the indirect storage system. For thermal losses to the storage tanks, the guidelines specify that the thermal loss through the foundation (including potential active cooling effect) needs to be considered. The guidelines also state that tank thermal losses should be a function of TES state of charge. SAM's storage tank model does not meet either of these requirements. The rationale behind SAMs current model is that thermal losses through the ground are insignificant compared to losses to the atmosphere. If desired, a user would have to increase thermal losses through the walls to account for losses through the foundation. The current SAM TES model does not account for TES state-of-charge, but rather uses a single heat loss coefficient for all tank area. That is, SAM considers temperature along the inner tank surface to be constant, regardless of how full the tank is.

Lastly, in an indirect TES system, a heat exchanger is required to charge the salt in the storage tanks from the solar HTF. SAM does not consider heat losses (to ambient) or ramp-rate limits of this heat exchanger. Again, a user can account for these by increasing heat loss coefficients from other components and increasing system start-up times.

These discrepancies result in several unmet requirements. To resolve this, analysis will be conducted to look at the significance of these requirements. The SAM team will assess the relative magnitude of these terms and consider their addition in future versions of SAM.

Auxiliary Heater, Electrical, Operation Strategy, and Annual Effects

As mentioned above, the auxiliary heater model in the molten salt power tower is omitted from this version of SAM. The trough model achieves good results, the only shortcoming being that additional fuel and heating for startup is not accounted for. Once again, the user must make sure that the heater efficiency input is entered correctly, accounting for flue gas exhaust heat and heat lost to the surroundings. All requirements are met for the Electrical sub-system, as well as the Operational Strategy and Annual Effect checklists.

Meteorological Modeling and Uncertainties

Both the Meteorological Modeling, and the Uncertainty requirements are partially outside the realm of what SAM is designed for, so were difficult to analyze. SAM accepts meteorological files as inputs, and these files are responsible for meeting the meteorological requirements. These requirements consider factors such as height at which data should be taken to how often the sampling instruments are cleaned and calibrated. SAM requires one year of data to run, but can accept any weather data, at any sampling rate. Simulations with less than one year of data can be made with "dummy" values for the remainder of the year, but annual outputs will not be relevant. SAM is installed along with a number of weather files from the NSRDB, which is based on satellite-model values at 30-minutes intervals. SAM can simulate at the desired 10-minute interval of the guideline (or even shorter intervals), but this requires the user to provide the corresponding weather data.

Similarly, measuring uncertainties is largely up to the user, but SAM provides several useful tools. The built-in P50/P90 tool automatically characterizes inter-annual yield uncertainty when multiple years of weather data are available for a given site. The built-in stochastic simulation tools allow users to examine the effect of uncertainty of any (or multiple) of the input variables on an output metric. Between these two tools, most of the uncertainty requirements can be met. Other requirements are site-specific and must be examined by the user.

Checklist Difficulties and SAM Updates

A difficulty in applying the SolarPACES checklist to any model is that the relative importance or "weight" of different requirements is not assessed in the guidelines. This means that further work is required to quantify the significance of each requirement beyond "shall" or "should". This is being undertaken for some of the discrepancies between SAM and the guidelines, to assess the importance of these potential additions before making changes to SAM. For some requirements, the effect on the overall results varies from case to case, adding another level of complexity. When the checklist is applied to a model, many missed requirements can be justified with good analysis from the model user.

CONCLUSIONS

Overall the SAM CSP models show good agreement with the SolarPACES guidelines. Where discrepancies do exist, the SAM tools are flexible enough that the additional losses, considerations, and requirements can be added by the user. Many SAM inputs are aggregates with similar effects (e.g., efficiencies) and the user is instructed to account for the different factors in their input value. This flexibility allows SAM to be applied to a wide variety of STE plant designs and locations while preventing an overly cumbersome interface.

Applying the checklist to a complete SAM simulation of a specific STE system would give a more accurate evaluation of the model's capability for compliance. This would check both the equations and structure of SAM, as well as the inputs set by the user. In practice the challenge is to balance guiding the user to account for all practical factors while maintaining a clean and flexible user interface. A good compromise is ensuring the SAM help documentation lists all the potential factors that the user may need to consider.

Discrepancies were discussed with NREL's SAM CSP development team. These discussions resulted in several potential SAM improvements, which would bring SAM even more in line with the SolarPACES CSP modeling recommendations. Suggestions additions to SAM are outlined below.

- Heat gain from pressure dissipation throughout the system.
- Pressure characterization throughout the system. This will make HTF pressure drops dependent on inlet pressure to each subsystem.
- Thermal losses through TES foundation.
- More rigorous modeling of the salt-HTF heat exchanger in indirect systems (thermal losses, ramp rates, etc.).
- Operational limits for wind speed in trough systems.
- Start-up fuel consumption for auxiliary heating system.
- Difference in shading calculation for the outer rows in a parabolic trough system. (SAM treats all trough rows the same.)

SAM is a freely available and flexible tool for CSP system modeling, with users in industry and academia from around the world. NREL remains dedicated to the continual improvement of SAM and will use the SolarPACES guidelines to assess and bolster SAM's utility. The authors encourage other CSP stakeholders to test their own models and move the community toward more transparent, consistent, and accurate performance and cost modeling.

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******REFS NEED TO BE UPDATED TO TEMPLATE STYLE**