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A GENERIC CSP PERFORMANCE MODEL FOR NREL'S SYSTEM ADVISOR MODEL

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Abstract

This paper presents a new CSP performance model for the SAM tool developed by NREL and Sandia National Lab. The Generic Solar System (GSS) provides a general and flexible tool for predicting the annual performance and financial viability of concentrating solar power (CSP) systems. With the GSS, the modeler can specify the solar field optical and thermal performance using a lookup table and polynomial correlations. Performance of the power conversion system is likewise specified in terms of ambient conditions, incident solar radiation, and total load. This paper discusses the motivation and formulation for the GSS and provides model verification by comparing predicted annual results from a more detailed parabolic trough annual performance model with an equivalent implementation in the GSS.

Abbreviations

CSP	Concentrating Solar Power
GSS	Generic Solar System
DNI	Direct Normal Irradiation
DOE	Department of Energy (US)
HTF	Heat Transfer Fluid
NREL	National Renewable Energy Laboratory
PhT	Physical Trough
SAM	System Advisor Model
TES	Thermal Energy Storage

1 Introduction and Motivation

The suite of concentrating solar power (CSP) modeling tools in NREL's System Advisor Model (SAM) [1] includes technology performance models for parabolic troughs, power towers, and dish-Stirling systems.[1] Each model provides the user with unique capabilities that are catered to typical design considerations seen in each technology. Since the scope of the various models is generally limited to common plant configurations, new CSP technologies, component geometries, and subsystem combinations can be difficult to model directly in the existing SAM technology models. To overcome the limitations imposed by representative CSP technology models, NREL has developed a "Generic Solar System" (GSS) performance model for use in SAM. This paper discusses the formulation and performance considerations included in this model and verifies the model by comparing its results with more detailed models.

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The value of a generic CSP model in SAM is severalfold. First, it allows modelers to tie together the performance of various plant subsystems in a single annual-hourly model. One possible use of the GSS model is to integrate off-design performance curves that are developed using more detailed analysis tools outside of SAM. For example, a modeler may use a ray-tracing tool to characterize the optical performance of their system for a variety of sun positions and import the performance table into the generic model along with estimates for receiver thermal performance, power cycle performance, etc. Second, SAM includes detailed financial models for several common markets. The modeler may wish to take advantage of SAM's capabilities in this area without restricting their performance model to an existing technology in SAM. Finally, SAM's advanced parametric, statistical, sensitivity, and optimization tools can add value to a detailed model that would otherwise be developed outside of SAM.

2 Generic Solar System Model Description

The GSS model consists of several integrated subsystems; these include the solar field, thermal storage system, power cycle, auxiliary fossil heater, and corresponding cost models. The performance equations for each subsystem have generalized formulations that do not require specific component geometries or plant layout. For example, the user can characterize the performance of the solar field by providing optical derate factors, thermal losses as a function of solar irradiation, ambient temperature, and wind speed, and an optical efficiency table as a function of solar position.

Like the solar field, the other subsystems are characterized using general performance equations. The power generation cycle uses a part-load efficiency adjustment as well as an ambient temperature adjustment (with either wet-bulb or dry-bulb temperature as the basis) to quantify power cycle performance. Thermal storage is modeled using a simple energy balance approach that includes charging and discharging energy derates, thermal losses, and general sizing inputs. The following discussion provides details on the equations and relationships used to describe subsystem performance.

2.1 Solar Field

The solar field calculations predict the total thermal energy output by multiplying the total incident thermal energy by optical and thermal efficiency reduction terms. The total incident thermal energy is calculated by multiplying the Direct Normal Irradiation (DNI) by the total solar field aperture area, as shown in Eq.[2.1].

$$\dot{Q}_{inc} = I_{bn}\ A_{ap,tot} \tag{2.1}$$

The total aperture area is held constant throughout the simulation, and is determined using the design-point power cycle rating, field efficiency terms, and desired solar multiple[2]. The aperture area is calculated as shown in Eq.[2.2].

$$A_{ap,tot} = \frac{\dot{Q}_{inc,des}}{I_{bn,des}} \tag{2.2}$$

Where:

$$\dot{Q}_{inc,des} = \frac{\dot{Q}_{sf,des}}{\eta_{opt,peak}\ \eta_{clean}\ \eta_{gen}\ \eta_{therm,des}} \tag{2.3}$$

where the peak optical efficiency $\eta_{opt,peak}$ is the maximum efficiency value provided by the user in the efficiency table, mirror cleanliness is η_{clean}, general optical error not captured in the efficiency table is η_{gen}, and thermal efficiency at design is given by $\eta_{therm,des}$. The solar field thermal output at design

[2]The "solar multiple" indicates the ratio of the thermal output from the solar field at the design-point DNI value to the design-point thermal input to the power block

($\dot{Q}_{sf,des}$) is calculated with reference to the desired power cycle output and the solar multiple M_S.

$$\dot{Q}_{sf,des} = \frac{\dot{W}_{pb,des} \cdot M_S}{\eta_{cycle,des}} \tag{2.4}$$

During the hourly simulation runs, the solar field thermal output is calculated by adjusting the design-point thermal output value according to the actual incident solar radiation, the optical efficiency, and the thermal efficiency.

$$\dot{Q}_{sf} = \dot{Q}_{sf,des} \left(\frac{I_{bn}}{I_{bn,des}}\right) \left(\frac{\eta_{opt}}{\eta_{opt,des}}\right) \left(\frac{\eta_{therm}}{\eta_{therm,des}}\right) \tag{2.5}$$

The optical efficiency is determined by interpolating the optical efficiency table specified by the user on the Solar Field page according to the solar position[3]. Solar position calculations are handled according to equations developed in Duffie and Beckman [2] and Stine [3], and the reader is referred to these publications and documentation for other SAM models [4] for more information. Thermal efficiency is calculated using the product of three sensitivities; namely, sensitivity to (1) the irradiation value, (2) ambient dry-bulb temperature, and (3) ambient wind speed. The polynomial form for each sensitivity is given in Eq.'s[2.6-2.8].

$$f_{hl,I_{bn}} = C_0 + C_1 \frac{I_{bn}}{I_{bn,des}} + C_2 \left(\frac{I_{bn}}{I_{bn,des}}\right)^2 + C_3 \left(\frac{I_{bn}}{I_{bn,des}}\right)^3 \tag{2.6}$$

$$f_{hl,T_{db}} = C_0 + C_1 \left(T_{db} - T_{db,des}\right) + C_2 \left(T_{db} - T_{db,des}\right)^2 + C_3 \left(T_{db} - T_{db,des}\right)^3 \tag{2.7}$$

$$f_{hl,V_{wind}} = C_0 + C_1 V_{wind} + C_2 V_{wind}^2 + C_3 V_{wind}^3 \tag{2.8}$$

The product of these three heat loss factors is multiplied by the reference field thermal output and the ratio of current irradiance to design-point irradiance to determine the total solar field heat loss. The additional multiplication of the total thermal loss fraction by the irradiance ratio forces the heat loss to scale with incident irradiation and remain a fraction of the total solar field output, rather than a fraction of the design-point field output.

$$\dot{Q}_{hl} = \dot{Q}_{hl,ref} \frac{I_{bn}}{I_{bn,des}} f_{hl,I_{bn}} f_{hl,T_{db}} f_{hl,V_{wind}} \tag{2.9}$$

In addition to specifying thermal and optical performance, the user can limit solar field operation to a range of solar elevation angles using the "Stow angle" and "Deploy angle" inputs on the Solar Field page. During time steps when the solar elevation angle crosses the stow or deploy limit partway through the hour, the performance of that time step is derated to account for partial operation.

2.2 Power Cycle

The power cycle model provides a simple mechanism for modeling the conversion from thermal energy output from the solar field, thermal storage, and auxiliary backup into electrical energy. The model is not directly tied to typical power cycle processes like turbine/compressor efficiency, heat rejection pressures, etc., so the tool is not constrained to traditional electricity generation technologies. The model uses the design-point power output (gross) and reference conversion efficiency to calculate the total thermal power input requirement during each time step of the performance run, then adjusts the realized gross power production according to ambient temperature and load sensitivities.

[3]The user may alternatively elect to not interpolate the values in the table and use the nearest position instead.

The load-based efficiency adjustment factor takes the same form as the polynomial relationship presented in Eq.[2.6] above, but adds a quartic term. Efficiency is also scaled according to ambient temperature deviation (either wet-bulb or dry-bulb, selected by the user) from the design point. The temperature-based adjustment factor takes the form shown in Eq.[2.10], where the polynomial extends to the quartic term.

$$f_{pb,T} = C_0 + C_1 \ (T_{amb} - T_{amb,des}) + C_2 \ (T_{amb} - T_{amb,des})^2 ... \tag{2.10}$$

The final power output calculation is calculated as shown in Eq.[2.11].

$$\dot{W}_{cycle} = \eta_{cycle,ref} \ f_{pb,T} \ f_{pb,load} \ \dot{Q}_{pb} \tag{2.11}$$

Parasitic consumption is characterized using two categories. The first applies a fixed parasitic loss as a fraction of the total plant gross electric power output rating, and the second applies a variable parasitic loss that can vary with actual electric power production and/or ambient temperature. Two cubic polynomial equations describe how the variable parasitic responds to power production and deviation in ambient temperature from the design point. The final net power output is equal to the gross power production minus the two parasitic power losses.

$$\dot{W}_{net} = \dot{W}_{cycle} - \dot{W}_{par,fixed} - \dot{W}_{par,var} \left(T_{amb}, \frac{\dot{W}_{cycle}}{\dot{W}_{cycle,des}} \right) \tag{2.12}$$

2.3 Thermal storage and Balance of Plant

Thermal energy storage (TES) and auxiliary fossil backup systems are also included as options in the GSS model. Like the solar field, these subsystem models use a simple energy-balance approach. The state of the TES system is tracked and adjusted from time step to time step, and thermal losses can be applied as a function of charge level and ambient temperature. Aside from these TES thermal loss sensitivities, the TES, auxiliary system, and control strategy models are adopted from the SAM Empirical Trough model, and the reader is referred to the SAM documentation [1] for more information.

3 Model validation

A major goal of developing the GSS model is to facilitate hourly/annual simulation of CSP systems using a flexible set of inputs. The model is formulated on the thesis that the significant performance effects of any complex CSP system can be adequately captured in a reduced-order model. If this is true, then a modeler can use data generated by a detailed model as input into the reduced-order GSS model, and the total predicted performance results will agree (reasonably) between both models. To test this claim, we ran the SAM Physical Trough model [4] to generate performance data for a parabolic trough system, and used the data to generate input for the GSS model. One strencth of the GSS is that it is not limited to parabolic troughs or any particular CSP technology, so a successful comparison between the Physical Trough model should show equal success with any other CSP technology. This section presents the results of this validation exercise.

3.1 The SAM Physical Trough model and output data

The SAM Physical Trough tool approaches system performance modeling by using system geometry, optical properties, weather data, and thermodynamic fluid properties to calculate component performance. The model formulations generally use first-principle or semi-empirical approaches and consequently ac-

count for a wide range of possible performance effects. For example, the model calculates receiver thermal performance using absorber tube and glass envelope geometry, gas concentrations within the evacuated annulus, surface emittance properties, ambient temperature, wind speed, and other properties. In this way, the Physical Trough model accounts for primary and highly significant effects as well as secondary or even negligible effects.

This model was selected for comparison with the GSS for several reasons, namely:

- The Physical Trough model accounts for a wide range of performance effects, and it considers many effects that are not explicitly accounted for in the GSS.
- The formulation basis for the Physical Trough model differs from the GSS. For example, the Physical Trough electrical parasitic model uses piping geometry to calculate expected pressure loss and pumping power requirement, whereas the GSS expresses variable auxiliary consumption as a function of ambient temperature and power cycle load. The ability to reproduce specific performance results using a generalized formulation indicates the versatility of the generic model.
- Both models can run at hourly time steps and are easily compared within the SAM framework.

The comparison exercise makes use of the default inputs for the Physical Trough model. Table 1 highlights the major system features.

Table 1: Major system features for the parabolic trough system comparison

Description	**Value**	**Units**
Gross power output	111	MWe
Net power output	100	MWe
Power cycle gross efficiency	37.74	%
Solar field aperture area	865,352	m^2
Thermal storage capacity	6	hours
Plant location	Daggett, CA	-
Heat rejection type	Wet cooled	-
Fossil backup	None	-

GSS model design-point inputs were selected to match the Physical Trough model as closely as possible. The GSS uses a linearly interpolated lookup table to determine solar field optical efficiency, where the solar azimuth and zenith angles are the two independent variables. The optical efficiency values were calculated for each solar position of interest using the optical code from the Physical Trough model.

Inputs for off-design response of the power cycle, solar field thermal losses, and parasitic loads were created using one of two methodologies. The first and most direct method was to directly convert a lookup table programmed in the Physical Trough model into a polynomial regression fit. This method applied for the power cycle part-load and temperature efficiency adjustments. Table 2 shows the polynomial coefficients derived directly from the Physical Trough model.

Table 2: Off-design performance coefficients for the GSS model

Effect / Order	C_0	C_1	C_2	C_3	C_4
Power cycle part load adjustment	0.5628	0.8685	-0.5164	0.0844	0
Power cycle ambient temperature adjustment	1.0	-0.002	0	0	0
Parasitics part load adjustment	0.0636	0.803	-1.58	1.7134	-
Parasitics temperature adjustment	1	0.0025	0	0	-
Irradiation thermal loss adjustment	4.75	-8.0	4.5	-0.25	-
Ambient temp. thermal loss adjustment	1	0	0	0	-
Wind speed thermal loss adjustment	1	0	0	0	-

The second method for obtaining GSS input values was to run the Physical Trough model annual hourly simulation, plot the effect of interest as a function of the off-design basis variable, and generate a polynomial fit to match the data. Figure 1 shows the results of this method for the parasitic electrical consumption part-load adjustment and the solar field thermal loss irradiation adjustment. Both ambient

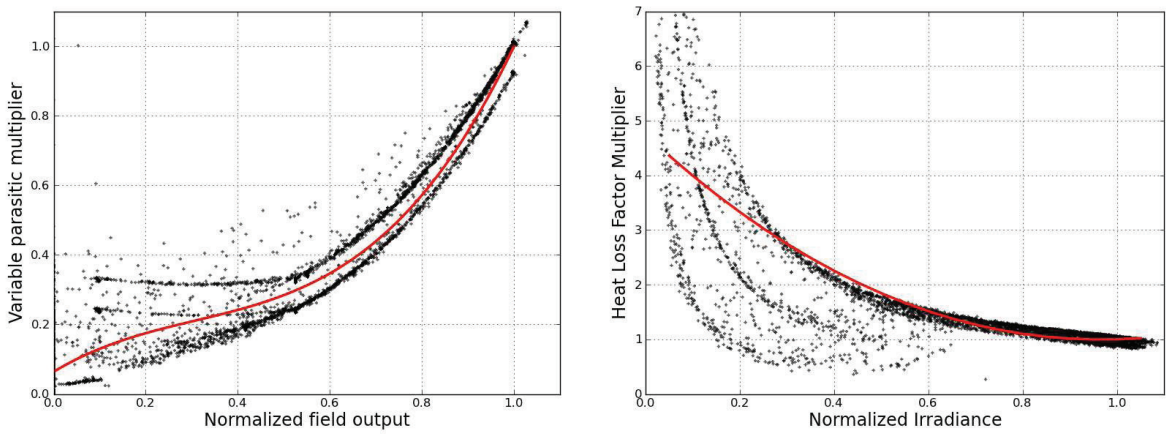

Figure 1: Parasitic electrical consumption (LEFT) and solar field heat loss (RIGHT) multiplying factors as functions of normalized solar field load and solar irradiance, respectively. Cubic polynomial fits are applied to simulated output data from the SAM Physical Trough model.

temperature and wind speed demonstrated negligible effects on solar field thermal efficiency, and they were not included in the simulation. Note also that the GSS only considers the primary performance effects, and possible interactions between effects are not modeled. All of the input coefficients are presented in Table 2 above.

3.2 Model Comparison Results

Annual simulations were performed for both the GSS and Physical Trough model with one hour time steps according to the input information specified above. The results show excellent agreement between the two models in total annual predicted electricity production. When comparing model output on shorter intervals, agreement was less precise. However, this finding is expected when considering the nature of the curve fits and generic modeling approach; the inputs to the GSS represent the best match for compiled annual data, so it stands to reason that the best match in performance prediction should be on an annual basis. Where the detailed Physical Trough model is likely more accurate over shorter intervals - when examining startup behavior of the solar field, for example - the large scale effects are captured equally well with the detailed and generic models.

Figure 2 shows a comparison between the monthly net electricity production predicted by the GSS and Physical Trough models. A comparison of monthly and annual energy flows are tabulated in Table 3.

4 Conclusions

This paper demonstrates the application of a generic model for CSP systems by comparing predicted results with a more detailed parabolic trough model. The results of the comparative exercise show good agreement between both models at several important stages in the thermal energy flow. The results also show agreement on both a monthly and annual basis, with decreasing correspondence as the length of the compared period decreases. This finding is consistent with the methodology used to formulate the model input parameters, where we compiled annual data and defined regression curves according to

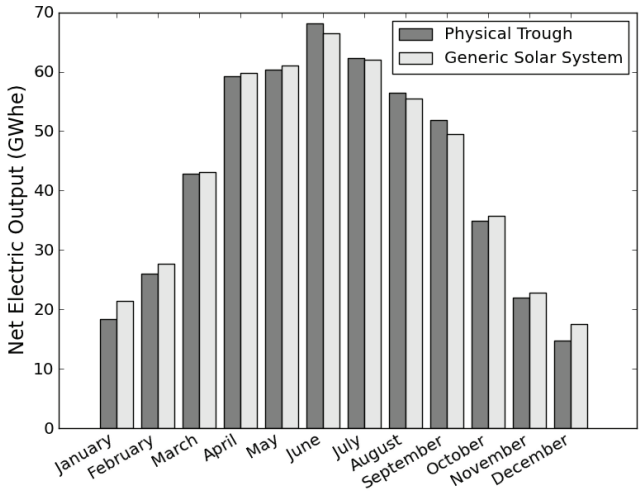

Figure 2: Monthly comparison of the net electric output of the SAM Physical Trough and GSS models.

Table 3: Comparison of results from modeling runs of the SAM Physical Trough and GSS.

	Incident power			**Power from field**			**Power to cycle**			**Gross electricity**			**Net electricity**		
	GWht		%	GWht		%	GWht		%	GWhe		%	GWhe		%
	PhT	GSS	δ	PhT	GSS	δ	PhT	GSS	δ	PhT	GSS	δ	PhT	GSS	δ
Jan	206.1	206.1	0.0	57.2	55.5	-2.9	56.7	62.8	9.7	20.0	23.9	16.3	18.4	21.4	14.3
Feb	218.6	218.6	0.0	79.4	77.2	-2.9	78.3	81.4	3.8	27.9	31.2	10.5	26.1	27.7	6.0
Mar	265.9	265.8	0.0	125.5	122.0	-2.9	124.5	125.7	1.0	45.5	48.2	5.7	42.8	43.1	0.7
Apr	327.7	327.7	0.0	172.4	177.5	2.9	170.8	174.4	2.1	63.0	66.9	5.9	59.2	59.8	1.0
May	324.0	323.9	0.0	174.6	183.5	4.8	173.3	179.2	3.3	64.4	68.3	5.7	60.3	61.0	1.1
Jun	353.8	353.8	0.0	196.3	205.9	4.7	195.0	196.8	0.9	72.8	74.7	2.6	68.1	66.5	-2.4
Jul	331.2	331.1	0.0	182.1	189.9	4.1	180.8	184.7	2.1	66.7	69.8	4.3	62.3	62.0	-0.5
Aug	309.4	309.4	0.0	166.3	168.7	1.4	164.9	164.9	0.0	60.6	62.4	2.9	56.5	55.4	-2.0
Sep	298.6	298.5	0.0	151.9	145.9	-4.1	150.6	147.0	-2.4	55.5	55.7	0.4	51.9	49.5	-4.8
Oct	257.2	257.1	0.0	103.8	98.2	-5.7	102.8	105.5	2.6	37.1	40.1	7.6	34.9	35.8	2.6
Nov	220.5	220.5	0.0	66.9	61.1	-9.6	66.6	67.2	1.0	23.4	25.5	8.0	22.0	22.8	3.3
Dec	193.8	193.8	0.0	46.5	44.3	-5.0	46.4	52.0	10.8	16.0	19.5	17.6	14.8	17.5	15.5
Tot	3307	3306	0.0	1523	1530	-0.4	1511	1542	-2.0	553	586	-6.0	517	523	-1.0

trends in the Physical Trough annual simulation. Consequently, the GSS model tends to predict system performance during any given time step that is closer to the annual average value than the Physical Trough model predicts.

Based on this observation, the most appropriate use of the GSS model is for simulations that are consistent with the dataset from which the input is derived. For example, input values derived from an annual dataset should not generally be used to examine predicted behavior on an hourly basis since errors observed at high temporal resolution may cancel out over a longer simulation.

It is also important to note that the comparison between the Physical Trough and GSS models was an example of a possible application, and the GSS is not limited to any particular CSP technology, parabolic troughs included. This framework provides advanced modelers with the option to incorporate their own external performance models into the SAM framework for sensitivity analysis, annual performance predictions, or financial modeling.

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