Solar Advisor Model Reference Manual for CSP Trough Systems

July 2009

SAM Version 3.0

Solar Advisor Model Disclaimer

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Table of Contents

1 Introduction

This reference manual describes the methodology used by the Solar Advisor Model (SAM) performance model for CSP parabolic trough systems. It applies to version 3.0 of the software. This manual does not explain cost or financial calculations. For information on costs, financial, and incentive calculations, see SAM's help system or user guide, or visit the SAM website.

Please note that the hyperlinks in this manual point to the section containing the relevant information rather than to the page containing the information.

1.1 Variable Names and Abbreviations

The following table lists the variable names used in this manual. For each variable, a letter in italics indicates the type of quantity the variable represents, and the subscript describes the quantity. For example, the letter F indicates a factor, and $F_{TempCorr}$ represents the temperature correction factor.

Table 2.1. Variable names and units

Name	Description	Units	
A	area	square meters	m2
C_p	heat capacity	joules per kilogram-cubic meter	J/kg-m3
D	length	meters	m
E	electric output	Watts-electric	We
F	multiplier factor	none	-
H	enthalpy	joules per kilogram	J/kg
h	hour	hour	h
m	mass flow rate	kilograms per second	kg/s
N	number or quantity	-	-
$[N]$	nearest integer greater than or equal to the quantity enclosed in brackets	none	-
P	power rating	Watts-electric or Watts-thermal	We or Wt
Q	thermal energy	Watt-hours	Wh
T	temperature	degrees Celsius	°C
t	time	hours	hr
v	velocity	meters per second	m/s
V	volume	gallons	gal
y	year	year	y
θ	angle (theta)	degrees or radians	°
ρ	density (rho)	kilograms per cubic meter	kg/m3

Abbreviations in variable names

Some variables use abbreviations to save space. For example, the variable F_{TempCorr} uses the abbreviation "corr" to mean "correction."

Table 2.2. Variable subscript abbreviations

Abbreviation	Description
abs	absorbed
adjust	adjustment
avg	average
BOP	balance of plant
clean	cleanliness
corr	corrected
costh	cosine theta
CT	cooling tower
D	design
DNI	direct normal irradiance, direct normal radiation incident on the collector
eff	efficiency
env	envelope
ET	electric to thermal
FP	freezing point
geom	geometric
HCE	heat collection element (receiver)
HL	heat loss
HTF	heat transfer fluid
htr	heater or boiler
IAM	incident angle modifier
len	length
LHV	lower heating value
max	maximum
min	minimum
NIP	direct normal radiation
norm	normalization
opt	optical
par	parasitic loss
parasit	parasitic loss
PB	power block
PF	performance factor
refl	reflectivity
SCA	solar collector assembly (collector)
SF	solar field
SU	start up
TC	temperature correction
TE	thermal to electric
TES	thermal energy storage
trans	transmissivity
ts	thermal energy storage
tur	turbine

1.2 Technical Support

The following resources are available to help answer your questions about SAM:

- If you have questions about the Solar Advisor Model or comments about this manual, please contact us at Solar_Advisor_Support@nrel.gov.
- For general information about SAM, links to related publications and references, and cash flow spreadsheets and cost information, please visit the the SAM website at http://www.nrel.gov/analysis/sam.
- For questions about SAM and to participate in discussions with other SAM users, please joint he SAM user group at http://groups.google.com/group/sam-user-group.

1.3 Solar Advisor Model Overview

SAM's parabolic trough performance model is a TRNSYS implementation of the Excelergy model that was developed for internal use at the National Renewable Energy Laboratory. The performance model uses the TRNSYS simulation engine to make the hourly energy flow calculations described in this manual. SAM does not require that TRNSYS be installed on your computer. The source code folder *\trnSAM\sourcecode* contains the FORTRAN code for each TRNSYS module: *TroughModel-805.f90* (solar field), *TroughPowerPlant-807.f90* (power block) and *TroughStor_dsptch-809.f90* (storage and dispatch).

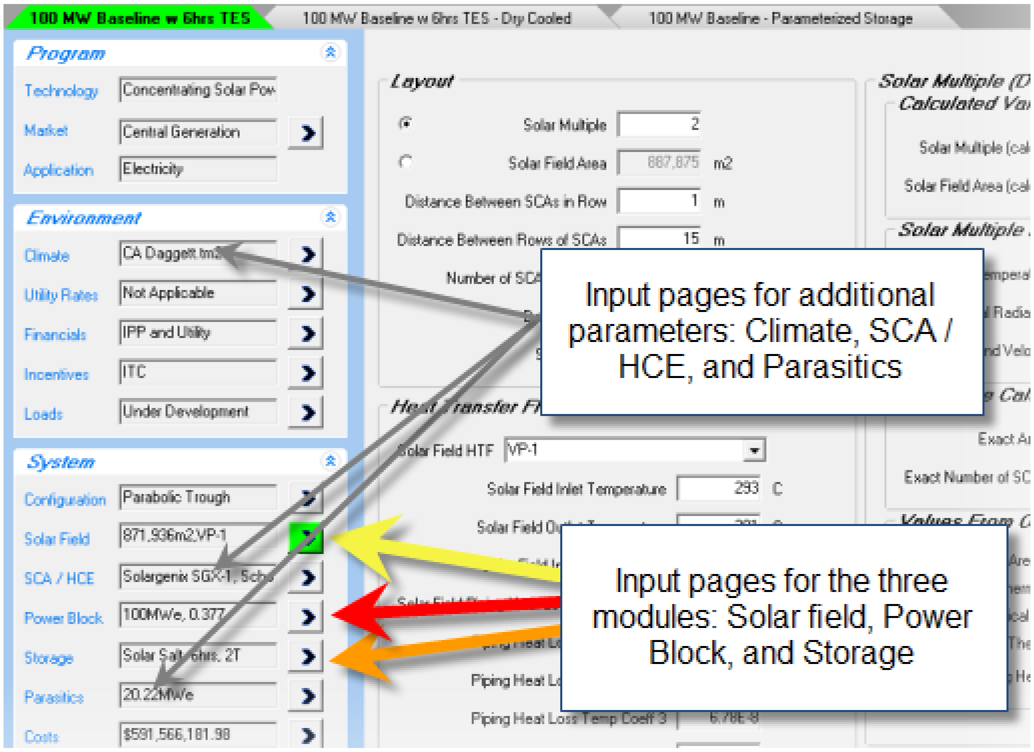
SAM calculates the system's total annual electric energy output by adding the hourly output values calculated by the performance model and passes that value to the cost, incentive, and financial modules to calculate the annual cash flows, levelized cost of energy, and other metrics reported in the results. These results are described in SAM's user guide and help system.

The trough peformance model consists of three modules. Each of the three modules is represented by an input page in SAM that provides an interface for entering input parameters.

- The solar field module calculates the solar field thermal energy output based on weather data from the weather file and solar field parameters from SAM's Solar Field and SCA / HCE pages. The solar field module also calculates thermal and optical losses, solar field warm-up energy, and freeze protection energy.
- The storage and dispatch module calculates the energy flow into and out of the thermal energy storage system and into the power block based on the solar field thermal output, thermal energy storage system parameters from SAM's Storage page. This module also calculates storage-related thermal and parasitic losses and freeze-protection energy based on the parameters on SAM's Parasitics page.
- The power block module calculates the system's electric output based on the thermal energy input from the storage and dispatch modules and parameters on the Power Block page. The power block module also calculates parasitic losses, and backup system thermal input.

SAM's Climate, SCA / HCE (solar collector assembly and heat collection element), and Parasitics input pages provide access to additional parameters.

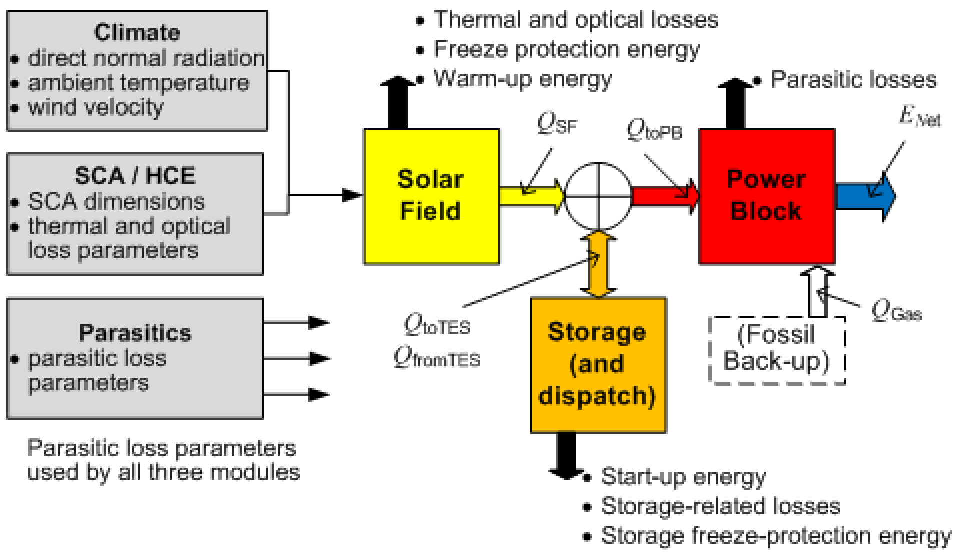
Fig 1..1. SAM trough model input pages



The parabolic trough model is an hourly energy flow model. Each module calculates an energy output value using efficiency factors calculated based on the relevant parameters.

- The solar field module calculates the solar field thermal output Q_{SF}.
- The storage and dispatch module calculates energy flow into the thermal energy storage system Q_{toTES} and out of storage $Q_{fromTES}$, and thermal energy delivered to the power block, Q_{toPB}. The storage and dispatch module also determines the timing of the storage and power block energy flows.
- The power block module calculates the system's net electric output E_{Net}.

Fig 1..2. SAM block diagram



2 Solar Field

The solar field module calculates the net thermal energy delivered by the solar field Q_{SF} and other related energy quantities for each hour of the year. The solar field module uses input variables from the Solar Field, Climate, SCA / HCE, and Parasitics input pages.

Summary

During sunny hours when the solar field is at operating temperature, the thermal energy delivered by the solar field equals the solar energy absorbed by the the solar collector assemblies (SCA) less solar field heat losses.

The absorbed energy quantity depends on the solar field size, solar position and SCA orientation, the size and number of SCAs, heat transfer fluid (HTF) type, and thermal and optical losses. The absorbed energy equations use data from the Climate, Solar Field and SCA / HCE pages.

The solar field heat losses depend on the solar field inlet and outlet temperatures, and the ambient temperature and wind speed. The heat loss equations use data from the Climate and Solar Field page. Note that SAM only uses the temperature difference across between the solar field inlet and outlet to calculate the solar field heat losses, and not to calculate the solar field's thermal energy output.

During hours when the solar field is not at operating temperature, SAM calculates the energy required for freeze protection at night and warm-up energy to bring the field up to operating temperature in the morning.

2.1 User Input Variables

The Solar Field input variables determine the size and orientation of the solar field, heat transfer fluid type, and solar field optical efficiency and heat loss parameters. The tables below list each input variable on the Solar Field page, and briefly describes each variable and where it is used in calculations. The calculations are described in more detail in the sections following these tables.

Solar Field Area and Solar Multiple

SAM provides two options for defining the size of the solar field: Solar Multiple and Solar Field Area. In Solar Multiple mode, SAM calculates the solar field area based on the solar multiple, the power block's rated thermal input capacity, reference weather conditions, and design heat loss parameters. For a solar multiple of one, SAM calculates the solar field area that, under reference weather conditions and accounting for heat losses from the field, generates a thermal energy amount equal to the design turbine thermal input value from the Power Block page.

In Solar Field Area mode, SAM uses the user-defined solar field area, and calculates the equivalent Solar Multiple.

The solar multiple mode is useful for determining the optimal solar field area for a given location. By varying the solar multiple, you can find the value that minimizes the levelized cost of energy for a given power block capacity. The levelized cost of energy metric captures the tradeoff between the benefit of higher annual electricity output and the cost of increased capital expenditures associated with increasing the solar field area.

Using the Solar Multiple mode is best for analyses involving a known or fixed power block capacity because SAM automatically calculates the solar field area based on the power block capacity. The Solar Field Area mode is best for analyses involving a known or fixed solar field area, but requires that the power block capacity be manually adjusted to match the solar field output.

Layout

The layout variables on the Solar Field page determine the dimensions of the solar field.

Table 2.1. Solar field layout variables

Name	Description	Units	Symbol
Solar Multiple and Solar Field Area	In Solar Multiple mode, SAM calculates the solar field area and displays it in "Solar Field Area (calculated)." In Solar Field Area mode, SAM calculates the solar multiple and displays it in "Solar Multiple (calculated)." Note that SAM does not use the value that appears dimmed for the inactive option.	--	--
Distance Between SCAs in Row	The end-to-end distance in meters between SCAs (solar collection elements, or collectors) in a single row, assuming that SCAs are laid out uniformly in all rows of the solar field. SAM uses this value to calculate the end loss. This value is not part of the SCA library, and should be verified manually to ensure that it is appropriate for the SCA type that appears on the SCA / HCE page.	m	D_{SCA}
Row spacing, center-to-center	The centerline-to-centerline distance in meters between rows of SCAs, assuming that rows are laid out uniformly throughout the solar field. SAM uses this value to calculate the row-to-row shadowing loss factor. This value is not part of the SCA library, and should be verified manually to ensure that it is appropriate for the SCA type that appears on the SCA / HCE page.	m	D_{SCARow}
Number of SCAs per Row	The number of SCAs in each row, assuming that each row in the solar field has the same number of SCAs. SAM uses this value in the SCA end loss calculation.	--	$N_{SCAPerRow}$
Deploy Angle	The SCA angle during the hour of deployment. A deploy angle of zero for a northern latitude is vertical facing due east. SAM uses this value along with sun angle values to determine whether the current hour of simulation is the hour of deployment, which is the hour before the first hour of operation in the morning. SAM assumes that this angle applies to all SCAs in the solar field.	degrees	θ_{Deploy}
Stow Angle	The SCA angle during the hour of stow. A stow angle of zero for a northern latitude is vertical facing east, and 180 degrees is vertical facing west. SAM uses this value along with the sun angle values to determine whether the current hour of simulation is the hour of stow, which is the hour after the final hour of operation in the evening.	degrees	θ_{Stow}

Solar Multiple (Design Point)

The design point variables describe the reference weather conditions, equipment design parameters, and thermal losses under reference conditions that SAM uses to calculate the solar field size. By definition, the exact solar field area is is the solar field area for a solar multiple of one, and is equivalent to the solar field area that, under reference conditions and accounting for heat losses, generates sufficient energy to drive the power block at the design turbine thermal input level.

SAM also uses some of the design point variables to normalize certain values to design conditions. Note that some parameters and quantities used in calculations are represented by both a design value and an simulated value. SAM calculates simulated values during the hour-by-hour simulation calculations, and uses design values (indicated throughout this text by variable symbols that include the word "Design" or letter "D") for sizing calculations and initial estimates.

Table 2.2. Solar Multiple (Design Point) input variables

Name	Description	Units	Symbol
Solar Multiple (calculated)	The solar field area expressed as a multiple of the exact area (see "Exact Area" below). SAM uses the calculated solar multiple value to calculate the design solar field thermal energy and the maximum thermal energy storage charge rate.	--	$F_{SolarMultiple}$
Solar Field Area (calculated)	The solar field area expressed in square meters. SAM uses this value in the delivered thermal energy calculations.	m^2	$A_{SolarField}$
Ambient Temperature	Reference ambient temperature in degrees Celsius. Used to calculate the design solar field pipe heat losses.	ºC	$T_{AmbientRef}$
Direct Normal Radiation	Reference direct normal radiation in Watts per square meter. Used to calculate the solar field area that would be required at this insolation level to generate enough thermal energy to drive the power block at the design turbine thermal input level. SAM also uses this value to calculate the design HCE heat losses displayed on the SCA / HCE page.	W/m^2	Q_{NIRef}
Wind Velocity	Reference wind velocity in meters per second. SAM uses this value to calculate the design HCE heat losses displayed on the SCA / HCE page.	m/s	$v_{WindRef}$
Exact Area	The solar field area required to deliver sufficient solar energy to drive the power block at the design turbine gross output level under reference weather conditions. It is equivalent to a solar multiple of one, and used to calculate the solar field area when the Layout mode is Solar Multiple.	m^2	A_{Exact}
Exact Number of SCAs	The exact area divided by the SCA aperture area. SAM uses the nearest integer greater than or equal to this value in the solar field size equations to calculate value of the Solar Field Area (calculated) variable described above. The exact number of SCAs represents the number of SCAs in a solar field for a solar multiple of one.	--	$N_{SCAExact}$
Aperture Area per SCA	SCA aperture area variable from SCA / HCE page. SAM uses this value in the solar field size equations to calculate the value of the Solar Field Area (calculated) variable described above.	m^2	$A_{Aperture}$
HCE Thermal Losses	Design HCE thermal losses based on the heat loss parameters on SCA / HCE page. SAM uses this value only in the solar field size equations. This design value is different from the hourly HCE thermal losses calculated during simulation.	W/m^2	$Q_{HCELossD}$
Optical Efficiency	Weighted optical efficiency variable from SCA / HCE page. SAM uses this design value only in the solar field size equations. This design value is different from SCA efficiency factor calculated during simulations.	--	$F_{SFOpticalEffD}$
Design Turbine Thermal Input	Design turbine thermal input variable from Power Block page. Used to calculate the exact area described above.	MWt	$Q_{PBDesign}$
Solar Field Piping Heat Losses	Design solar field piping heat losses. This value is used only in the solar field size equations. This design value different from the hourly solar field pipe heat losses calculated during simulation.	W/m^2	$Q_{SFPipeLossD}$

Solar Multiple Reference Conditions

The three reference condition variables, ambient temperature, direct normal radiation, and wind velocity, are the ambient conditions at which the solar field thermal output is equal to the power block's design thermal input multiplied by the solar multiple. In other words, under reference conditions, the system operates at the system's design capacity. Note that these reference condition variables are system design parameters, and do not describe the weather conditions at the project site. Weather conditions are determined by the data in the weather file shown on the Climate page.

The reference ambient temperature and reference wind velocity variables are used to calculate the design heat losses, and do not have a significant effect on the solar field sizing calculations. Reasonable values for those two variables are the average annual measured ambient temperature and wind velocity at the project location.

The reference direct normal radiation value, on the other hand, does have a significant impact on the solar field size calculations. For example, a system with reference conditions of 25°C, 950 W/m^2, and 5 m/s (ambient temperature, direct normal radiation, and wind speed, respectively), a solar multiple of 2, and a 100 MWe power block requires a solar field area of 871,940 m^2. The same system with reference direct normal radiation of 800 W/m^2 requires a solar field area of 1,055,350 m^2. Note that with a solar multiple of 2, both systems would produce two times the thermal energy required to drive the power block at its rated capacity during hours in which the direct normal radiation, temperature, and wind speed from the weather file are equal to the reference conditions.

For systems in the Mohave Desert of the United States, a value of 950 W/m^2 is reasonable, and for southern Spain, a value of 800 W/m^2 is reasonable.

Four factors affect the choice of a reference direct normal radiation value for a given system:

- Location
- Storage capacity
- Maximum storage charge rate
- Variability of the solar resource over the year, determined by the weather data

Using too low of a reference direct normal radiation value results in excessive dumped energy: The actual direct normal radiation from the weather data is frequently greater than the reference value so that the solar field sized for the low reference radiation value often produces more energy than required by the power block, and excess thermal energy is either dumped or put into storage. On the other hand, using too high of a reference direct normal radiation value results in an undersized solar field that produces sufficient thermal energy to drive the power block at its design point only during the few hours when the actual direct normal radiation is at or greater than the reference value.

Typically, the reference direct normal radiation value can be set to the actual direct normal radiation value that has a cumulative annual frequency value of about 95%. To find this value, on the Climate page, click View Data, and in the data viewer, click the CDF tab and choose Direct Normal Radiation in the variable list to display the "CDF of Direct Normal Radiation" graph.

Another approach to determine the best reference solar radiation value for a given location requires the following steps:

1. On the Solar Field page use the Solar Multiple option under Layout and set its value to one.
2. Enter an arbitrary value for the reference solar radiation value.
3. Run a simulation.
4. In the hourly results, examine the amount of dumped thermal energy Q_{Dump}. You can view the variable's hourly values by clicking either Spreadsheet or Time Series Graph.
5. If the amount of dumped thermal energy is excessive, try a lower value for the reference solar radiation and repeat the above steps.

Once you have chosen a value for the reference solar radiation, you can optimize the solar multiple and storage capacity to minimize the system's levelized cost of energy as illustrated in the third case of the Standard CSP Systems.sam sample file, 100 MW Baseline - Parameterized Storage.

Heat Transfer Fluid

The heat transfer fluid (HTF) parameters describe solar field properties that affect the HTF temperature calculations for the hour-by-hour simulation calculations. Note that the value of the minimum HTF temperature is stored in the HTF type library, and by default is different for heat HTF type.

Table 2.3. Heat Transfer Fluid input variables

Name	Description	Units	Symbol
Solar Field HTF	Name of the heat transfer fluid type. The Minimum HTF Temperature value depends on the HTF type. The available fluid types are limited to those described in the HTF Properties section.	--	--
Solar Field Inlet Temperature	Design temperature of the solar field inlet in degrees Celsius used to calculate design solar field average temperature, and design HTF enthalpy at the solar field inlet. SAM also limits the solar field inlet temperature to this value during operation and solar field warm up, and uses this value to calculate the actual inlet temperature when the solar field energy is insufficient for warm-up.	ºC	T_{SFinD}

Name	Description	Units	Symbol
Solar Field Outlet Temperature	Design temperature of the solar field outlet in degrees Celsius, used to calculate design solar field average temperature. It is also used to calculate the design HTF enthalpy at the solar field outlet, which SAM uses to determine whether solar field is operating or warming up. SAM also uses this value to calculate the actual inlet temperature when the solar field energy is insufficient for warm-up.	ºC	T_{SFoutD}
Solar Field Initial Temperature	Initial solar field inlet temperature. The solar field inlet temperature is set to this value for hour one of the simulation.	ºC	$T_{SFinInit}$
Solar Field Piping Losses @ Design T	Solar field piping heat loss in Watts per square meter of solar field calculated based on design variables. Used in solar field heat loss calculation.	W/m^2	Q_{PHLD}
Piping Heat Loss coefficients (3)	These three values are used with the solar field piping heat loss at design temperature to calculate solar field piping heat loss.	$-ºC^{-1}$, $-ºC^{-2}$, $-ºC^{-3}$	F_{PHL}
Minimum HTF Temperature	Minimum heat transfer fluid temperature in degrees Celsius. SAM automatically populates the value based on the properties of the solar field HTF type, i.e., changing the HTF type changes the minimum HTF temperature. The value determines when freeze protection energy is required, is used to calculate HTF enthalpies for the freeze protection energy calculation, and is the lower limit of the average solar field temperature.	ºC	T_{HTFMin}
HTF Gallons Per Area	Volume of HTF per square meter of solar field area, used to calculate the total mass of HTF in the solar field, which is used to calculate solar field temperatures and energies during hourly simulations. The volume includes fluid in the entire system including the power block and storage system if applicable. Example values are: SEGS VI: 115,000 gal VP-1 for a 188,000 m^2 solar field is 0.612 gal/m^2, SEGS VIII 340,500 gal VP-1 and 464,340 m^2 solar field is 0.733 ga/m^2.	gal/m^2	V_{HTF}

Table 2.4. Orientation

Name	Description	Units	Symbol
Collector Tilt	The SCA angle from horizontal, where zero degrees is horizontal. A positive value *tilts up* the end of the array closest to the equator (the array's south end in the northern hemisphere), a negative value tilts down the southern end. Used to calculate the solar incidence angle and SCA tracking angle. SAM assumes that the SCAs are fixed at the tilt angle.	degrees	$\theta_{ColTilt}$
Collector Azimuth	The azimuth angle of the SCAs, where zero degrees is pointing toward the equator, equivalent to a north-south axis. Used to calculate the solar incidence angle and the SCA tracking angle. SAM calculates the SCAs' tracking angle for each hour, assuming that the SCAs are oriented 90 degrees east of the azimuth angle in the morning and track the daily movement of the sun from east to west.	degrees	θ_{ColAz}

2.2 Weather Data

SAM reads data from weather files in two formats: typical meteorological year 2 ("tm2" file extension) and EnergyPlus ("epw" file extension). The location on the Climate page determines which weather file is used for the simulation. Weather files must be stored in /Data/WeatherFiles folder to appear in the location list on the Climate page. See the SAM help system for more information on using the different file formats and sources of weather data.

Table 2.5. Data elements from weather files used by SAM

Name	Description	Units	Symbol
Local standard time	Day of year, month, hour of month, day of month, and hour of day. Used to calculate hour of year.		
Direct normal radiation	Amount of solar radiation received in one hour within a limited field of view centered on the sun.	W/m^2	Q_{NIP}
Wind velocity	Average velocity of the wind for the hour. Used to calculate the HCE heat loss for hours when the wind velocity exceeds the minimum value defined on the SCA / HCE page.	m/s	v_{Wind}
Solar azimuth angle	Average solar azimuth angle for the hour. The angle between the line from the collector to the sun projected on the ground, and the line from the collector due south.	degrees	θ_{SolAz}
Ambient temperature	Average dry bulb temperature for the hour.	°C	$T_{Ambient}$
Wet bulb temperature	This value is not included in the weather file data, but is calculated by SAM based on the dry bulb temperature, dew point temperature and relative humidity data from the weather file. This value is used by the Power Block module for temperature correction calculations.	°C	T_{WetBulb}
Latitude	Degrees north or south of the equator of the project site.	degrees	$\theta_{Latitude}$
Longitude	Site longitude.	degrees	$\theta_{Longitude}$

2.3 Solar Field Size

Layout Mode: Solar Multiple

When the Layout mode is Solar Multiple, SAM calculates the solar field area $A_{\mathrm{SolarField}}$ and displays it as Solar Field Area (calculated) on the Solar Field page. The calculation is based on the value of the following Solar Field page input variables: Solar Multiple (calculated) $F_{\mathrm{SolarMultiple}}$, Aperture Area per SCA $A_{\mathrm{SCAAperture}}$, the nearest integer greater than or equal to the exact number of SCAs [N_{SCAExact}]:

$$A_{\mathrm{SolarField}} = \left[N_{\mathrm{SCA}}\right] \cdot A_{\mathrm{SCAAperture}} \cdot F_{\mathrm{SolarMultiple}} \tag{2.1}$$

Layout Mode: Solar Field Area

When the Layout mode is Solar Field Area, SAM calculates the solar multiple $F_{\mathrm{SolarMultiple}}$ and displays it as Solar Multiple (calculated) based on the value of the Solar Field page input variables Solar Field Area $A_{SolarField}$ and Exact Area A_{Exact}:

$$F_{SolarMultiple} = \frac{A_{SolarField}}{A_{Exact}} \tag{2.2}$$

Exact Area

The exact area A_{Exact} is the solar field area equivalent to a solar multiple of one, which by definition is the solar field area required to generate sufficient thermal energy under the three design point reference conditions on the Solar Field page to supply the design turbine thermal input $Q_{PBDesign}$ defined on the Power Block page, accounting for optical and thermal losses:

$$A_{Exact} = \frac{Q_{PBDesign}}{Q_{DNIRef} \cdot F_{SFOptEff} - Q_{HCELossD} - Q_{SFPipeLossD}} \tag{2.3}$$

The exact solar field area calculation uses equations that are similar to those that SAM uses for the hour-by-hour simulation, but based on design and reference values from the input pages instead of the hourly values from the weather data. SAM performs the exact area calculations as you enter values on the Solar Field page before starting the simulation.

- The reference direct normal radiation Q_{DNIRef} is an input on the Solar Field page. Sample values for Q_{DNIRef} are 950 W/m² for the Mohave Desert in the United States, and 800 W/m² for southern Spain.
- The design solar field optical efficiency factor $F_{SFOptEffD}$ from the SCA / HCE page that accounts for the SCA optical efficiency, row shadowing losses, and end losses.
- The design HCE thermal loss $Q_{HCELossD}$ from the SCA / HCE page is the HCE heat loss calculated using the same equations as the hourly simulation HCE thermal loss calculation but using design and reference variables from the Solar Field page in place of the hourly variables. The design and reference variables are: solar field inlet and outlet temperatures T_{SFinD} and T_{SFoutD}, and the reference direct normal radiation Q_{DNIRef} , reference wind velocity $v_{WindRef}$, and reference ambient temperature $T_{AmbientRef}$.
- SAM calculates the design solar field pipe loss $Q_{SFPipeLossD}$ using the three piping heat loss temperature coefficiencts $F_{PHL1...3}$, and the following design and reference variables: the solar field piping heat losses at design temperature $Q_{PHLatDsgnT}$, solar field design inlet and outlet temperatures T_{SFinD} and T_{SFoutD}, and the reference ambient temperature $T_{AmbientRef}$.

$$Q_{SFPipeLossD} = \left(F_{PHL3} \cdot \Delta T_{SFD}^{\;3} + F_{PHL2} \cdot \Delta T_{SFD}^{\;2} + F_{PHL1} \cdot \Delta T_{SFD}\right) \cdot Q_{PHLatDsgnT} \tag{2.4}$$

$$\Delta T_{SFD} = \frac{T_{SFinD} + T_{SFoutD}}{2} - T_{AmbientRef} \tag{2.5}$$

2.4 Design Variables

The solar field design variables are the solar field performance parameters under design conditions. Design variables are either user-defined variables on the Solar Field page, or values that SAM calculates during the hour-by-hour simulation.

Table 2.6. Solar Field Design Variables

Solar Field Page Input Values	Calculated Values
• Design solar field inlet and outlet temperatures, T_{SFinD} and T_{SFoutD} • HTF gallons per area, V_{HTF}	• Design solar field energy, $Q_{SFDesign}$ • Heat transfer fluid design enthalpies at the solar field inlet and outlet, H_{SFinD} and H_{SFoutD} • Design solar field HTF mass flow, $m_{SFMassFlowD}$

Design Solar Field Energy

The design solar field energy $Q_{SFDesign}$ is the thermal energy that the solar field must deliver under the design point reference conditions to supply the power block's design turbine thermal input $Q_{PBDesign}$. It is a function of $Q_{PBDesign}$ and the solar multiple $F_{SolarMultiple}$:

$$Q_{SFDesign} = Q_{PBDesign} \cdot F_{SolarMultiple} \tag{2.6}$$

SAM uses the design solar field energy to calculate the solar field load and solar field temperatures under certain conditions in the delivered thermal energy algorithm (see H and G in the delivered thermal energy diagram).

Design Heat Transfer Fluid Enthalpy

The design HTF enthalpies at the solar field inlet H_{SFinD} and outlet H_{SFoutD} depend on the type of HTF in the solar field and are a function of the design solar field inlet and outlet temperatures, T_{SFinD} and T_{SFoutD}, respectively. The HTF property tables determine the enthalpy values for given values of the inlet and outlet temperatures. SAM uses the design enthalpy values to calculate the design solar field HTF mass flow rate described below.

Design Heat Transfer Fluid Mass Flow Rate

The design solar field HTF mass flow rate is a function of the design solar field energy $Q_{SFDesign}$, and the HTF enthalpy at the solar field inlet H_{SFinD} and outlet H_{SFoutD} described above:

$$m_{SFMassFlowD} = \frac{Q_{SFDesign}}{H_{SFoutD} - H_{SFinD}} \tag{2.7}$$

SAM uses the design solar field mass flow rate, $m_{SFMassFlowD}$ to calculate solar field temperatures under certain conditions in the delivered thermal energy algorithm (see D in the delivered thermal energy diagram).

2.5 HTF Properties

The heat transfer fluid (HTF) properties and mass equations are used for several solar field energy calculations described in Delivered Energy and Losses. SAM includes property lookup tables for the seven HTF types shown in the table below. Note that the value of the minimum HTF temperature on the Solar Field page changes when you change the HTF type in the Solar Field HTF list. The current version of SAM does not allow for user-defined HTF types.

Table 2.7. Heat transfer fluids available in SAM

HTF Name	Type of Fluid	Minimum Temperature (°C)
Nitrate (solar salt)	salt	260
Caloria HT 43	hydrocarbon	-20
Hitec XL	salt	150
Therminol VP-1	synthetic	50
Hitec	salt	175
Dowtherm Q	synthetic	-30
Dowtherm RP	synthetic	-20

Mass

The HTF mass is used to calculate the following values:

- Warm-up energy Q_{Warmup}
- Freeze-protection energy $Q_{FreezeProtect}$
- Average solar field temperature when solar field energy is below the design point T_{SFAve}

SAM calculates the HTF mass M_{HTF} based on the user-defined HTF volume per area V_{HTF}, which is the volume of HTF in the entire system per solar field area (SAM converts the HTF volume input variable from gallons per square meter to metric units.):

$$V_{HTF} = V_{HTFperArea} \cdot A_{SolarField} \quad (2.8)$$

$$M_{HTF} = V_{HTF} \cdot \rho_{HTF} \quad (2.9)$$

The HTF density ρ_{HTF} is a function of the HTF temperature as show in the table below.

Table 2.8. HTF density in kilograms per cubic meter as a function of temperature in degrees Celsius

HTF	Specific Heat Equation
Nitrate salt	$\rho = -6.36\times10^{-1} \cdot T + 2.090\times10^{3}$
Caloria HT 43	$\rho = -1.265\times10^{-4} \cdot T^{2} - 6.617\times10^{-1} \cdot T + 8.85\times10^{2}$
Hitec XL	$\rho = -8.266\times10^{-1} \cdot T + 2.240\times10^{3}$
Therminol VP-1	$\rho = -7.762\times10^{-4} \cdot T^{2} - 6.367\times10^{-1} \cdot T + 1.0740\times10^{3}$
Hitec	$\rho = -7.33\times10^{-1} \cdot T + 2.080\times10^{3}$
Dowtherm Q	$\rho = -7.57332\times10^{-1} \cdot T + 9.80787\times10^{2}$
Dowtherm RP	$\rho = -1.86495\times10^{-4} \cdot T^{2} - 6.68337\times10^{-1} \cdot T + 1.04211\times10^{3}$

Enthalpy and temperature

HTF enthalpy is used to determine the thermal energy of the HTF as a function of temperature and vice versa. The equations are used to calculate:

- Average solar field temperature T_{SFAve} when the solar field energy is below the design point
- Freeze protection energy $Q_{FreezeProtect}$
- Warm-up energy Q_{Warmup}
- Design solar field mass flow rate $m_{SFMassFlowD}$

Table 2.9. HTF enthalpy in Joules per kilogram as a function of temperature in degrees Celsius

HTF	Enthalpy Equation
Nitrate salt	$H = 8.6\times10^{-2} \cdot T^{2} + 1.443\times10^{3} \cdot T$
Caloria HT 43	$H = 1.94 \cdot T^{2} + 1.6060\times10^{3} \cdot T$
Hitec XL	$H = - 3.79667\times10^{-5} \cdot T^{3} - 1.312\times10^{-1} \cdot T^{2} + 1.536\times10^{3} \cdot T$
Therminol VP-1	$H = 1.377 \cdot T^{2} + 1.498\times10^{3} \cdot T - 1.8340\times10^{4}$
Hitec	$H = 1.560\times10^{3} \cdot T$
Dowtherm Q	$H = 1.51461 \cdot T^{2} + 1.59867\times10^{3} \cdot T - 2.50596\times10^{0}$
Dowtherm RP	$H = 1.4879 \cdot T^{2} + 1.5609\times10^{3} \cdot T - 2.4798$

Table 2.10. HTF temperature in degrees Celsius as a function of enthalpy in Joules per kilogram

HTF	Temperature Equation
Nitrate salt	$T = -2.62\times10^{-11} \cdot H^{2} + 6.923\times10^{-4} \cdot H + 3.058\times10^{-2}$
Caloria HT 43	$T = 6.4394\times10^{-17} \cdot H^{3} - 2.3383\times10^{-10} \cdot H^{2} + 5.821\times10^{-4} \cdot H + 1.2744$
Hitec XL	$T = 5.111\times10^{-11} \cdot H^{2} + 6.466\times10^{-4} \cdot H + 2.151\times10^{-1}$
Therminol VP-1	$T = 7.4333\times10^{-17} \cdot H^{3} - 2.4625\times10^{-10} \cdot H^{2} + 6.3282\times10^{-4} \cdot H + 1.2403\times10^{1}$
Hitec	$T = -3.309\times10^{-24} \cdot H^{2} + 6.41\times10^{-4} \cdot H + 1.364\times10^{-12}$
Dowtherm Q	$T = 6.186\times10^{-17} \cdot H^{3} - 2.2211\times10^{-10} \cdot H^{2} + 5.9998\times10^{-4} \cdot H + 7.7742\times10^{-1}$
Dowtherm RP	$T = 6.6607\times10^{-17} \cdot H^{3} - 2.3347\times10^{-10} \cdot H^{2} + 6.1419\times10^{-4} \cdot H + 7.7419\times10^{-1}$

Specific heat

SAM uses the HTF specific heat in the delivered thermal energy equations for hours in the simulation when the solar field output is zero.

Table 2.11. HTF specific heat as a function of temperature in Joules per kilogram - degree Celsius

HTF	Heat Capacity Equation
Nitrate salt	$Cp = 1.72\times10^{-1} \cdot T + 1.443\times10^{3}$
Caloria HT 43	$Cp = 3.88 \cdot T + 1.606\times10^{3}$
Hitec XL	$Cp = -1.139\times10^{-4} \cdot T^{2} - 2.624\times10^{-1} \cdot T + 1.536\times10^{3}$
Therminol VP-1	$Cp = 7.888\times10^{-4} \cdot T^{2} + 2.496 \cdot T + 1.509\times10^{3}$
Hitec	$Cp = 1.560\times10^{3} - T$
Dowtherm Q	$Cp = -5.3943\times10^{-4} \cdot T^{2} + 3.2028 \cdot T + 1.5892\times10^{3}$
Dowtherm RP	$Cp = -3.1915\times10^{-6} \cdot T^{2} + 2.977 \cdot T + 1.5608\times10^{3}$

2.6 Collector and Sun Angles

SAM calculates the solar incidence angle, incident angle modifier, and SCA tracking angle based on location and time-of-day variables in the weather file:

- Current Julian day
- Solar declination
- Hour angle
- Time shift from standard meridian

The calculations are based on standard algorithms described in Duffie and Beckman 1991 and Stine 1985.

Solar Incidence Angle

SAM uses the solar incidence angle and incident angle modifier factor in the delivered thermal energy equations. The solar incidence angle $\theta_{SolarIncidence}$ depends on the sun's position in the sky and the orientation of the SCAs. SAM assumes that all SCAs in the solar field have the same orientation: $\theta_{ColTilt}$ and θ_{ColAz} for the SCA tilt and azimuth, respectively. SAM calculates the solar altitude θ_{SolAlt} and solar azimuth θ_{SolAz} for each hour using standard algorithms.

$$\theta_{SolarIncidence} = \arccos F_{SolarIncidence} \quad (2.10)$$

$$F_{SolarIncidence} = |1 - \cos(\theta_{SolAlt} - \theta_{ColTilt}) - \cos\theta_{ColTilt} \cdot \cos\theta_{SolAlt} \cdot [1 - \cos(\theta_{SolAz} - \theta_{ColAz})]| \quad (2.11)$$

The incident angle modifier factor F_{IAM} is an efficiency factor that accounts for collector efficiency losses due to cosine effects, and adjusts for envelope transmissivity, selective surface absorption and other losses. SAM calculates end losses separately. SAM calculates the incident angle modifier factor using an empirically derived formula based on field tests of the SEGS 2 project (Dudley 1994). The three incidence angle modifier coefficients F_{IAM1}, F_{IAM2}, F_{IAM3} are inputs on the SCA / HCE page.

$$F_{IAM} = F_{IAM1} + \frac{F_{IAM2}}{\cos(\theta_{SolarIncidence})} \cdot \theta_{SolarIncidence} + \frac{F_{IAM3}}{\cos(\theta_{SolarIncidence})} \cdot \theta_{SolarIncidence}{}^2 \quad (2.12)$$

If the value of $\cos(\theta_{SolarIncidence})$ is zero, SAM sets the value of F_{IAM} to zero.

SCA Tracking Angle

SAM calculates SCA tracking angle $\theta_{TrackAngle}$ based on the sun and collector positions, and uses the value to calculate the row shadowing factor.

$$\theta_{TrackAngle} = \arctan\left(\frac{\cos\theta_{SolarAlt} \cdot \sin(\theta_{SolarAz} - \theta_{ColAz})}{\sin(\theta_{SolarAlt} - \theta_{ColTilt}) + \sin\theta_{ColTilt} \cdot \cos\theta_{SolarAlt} \cdot [1 - \cos(\theta_{SolarAz} - \theta_{ColAz})]}\right) \quad (2.13)$$

2.7 Pipe Heat Loss

The solar field pipe heat loss $Q_{SFPipeLoss}$ in W/m² is a function of the three pipe heat loss temperature coefficients, the solar field temperature difference ΔT, and the solar field piping heat loss at design temperature factor $F_{PHLatDsgnT}$ on the Solar Field page.

$$Q_{SFPipeLoss} = \left(F_{PHL3} \cdot \Delta T^3 + F_{PHL2} \cdot \Delta T^2 + F_{PHL1} \cdot \Delta T\right) \cdot F_{PHLD} \quad (2.14)$$

The solar field temperature difference ΔT in degrees Celsius is a function of the solar field average temperature T_{SFAve}, and the ambient temperature from the weather data $T_{Ambient}$:

$$\Delta T = T_{SFAve} - T_{Ambient} \quad (2.15)$$

The solar field average temperature T_{SFAve} in degrees Celsius at is a function of the solar field inlet and outlet temperatures:

$$T_{SFAve} = \frac{T_{SFin} + T_{SFout}}{2} \quad (2.16)$$

2.8 Delivered Thermal Energy

SAM calculates the energy delivered by the solar field Q_{SF} for each hour of the simulation using an energy flow algorithm that calculates a series of adjustment and loss factors and applies them to the incident solar radiation value for the current hour. Note that SAM calculates the solar field heat losses based on coefficients derived from a combination of field tests and computer modeling.

The description below is divided into two parts. The qualitative summary describes the algorithm in general terms, and refers to the alphabetic labels in the schematic. The detailed description includes a schematic diagram of the algorithm followed by equations and descriptions.

Many of the hourly quantities described below are reported in the hourly results spreadsheet and time series graphs. The file */trnSAM/CSP/output/CSP_trough_hrly_all.out* contains a more complete set of hourly results. You can open the file with a text editor, spreadsheet program, or using SAM's time series data viewer.

Qualitative Summary

SAM first calculates initial values of the delivered solar field energy and average temperature. (A in the schematic below). These initial calculations involve the following quantities:

- Solar energy absorbed by the solar collector assemblies (SCA), which depends on the current hour's direct normal radiation value from the weather file, solar incidence angle, and optical efficiency factor.
- Solar field heat losses, which depend on the solar field inlet and outlet temperatures and are calculated based on the heat transfer fluid (HTF) properties and the current hour's ambient temperature from the weather file.

SAM uses these initial delivered solar field energy and temperature values to determine the solar field operating condition, and makes the appropriate adjustments to the initial values. There are four operating conditions:

- **Not operating.** *Initial delivered solar field energy is zero:* Delivered solar field energy is zero and the solar field temperature decreases due to heat loss (D in the schematic below).
- **Warming up.** *Delivered solar field energy is greater than zero, the average solar field temperature is less than the design point, and the solar field energy is greater than the required warm-up energy:* The delivered solar field energy is the initial value reduced by the warm-up energy and the solar field temperatures are set to the design point (F in the schematic).
- **Insufficient warm-up energy.** *Delivered solar field energy is greater than zero, the average solar field temperature is less than the design point, and the solar field energy is less than the required warm-up energy:* The delivered solar field energy is set to zero, the required warm-up energy is recalculated to account for the remaining energy in the solar field, and the solar field temperature is adjusted (H in the schematic).
- **Operating.** *Delivered solar field energy is greater than zero and the average solar field temperature is greater than or equal to the design point:* The delivered solar field energy is equal to the initial value, the solar field temperatures are set to their design points, and the required warm-up energy is set to zero (I in the schematic).

Detailed Description

The thermal energy delivered by the solar field Q_{SF} in a given hour depends on the following values:

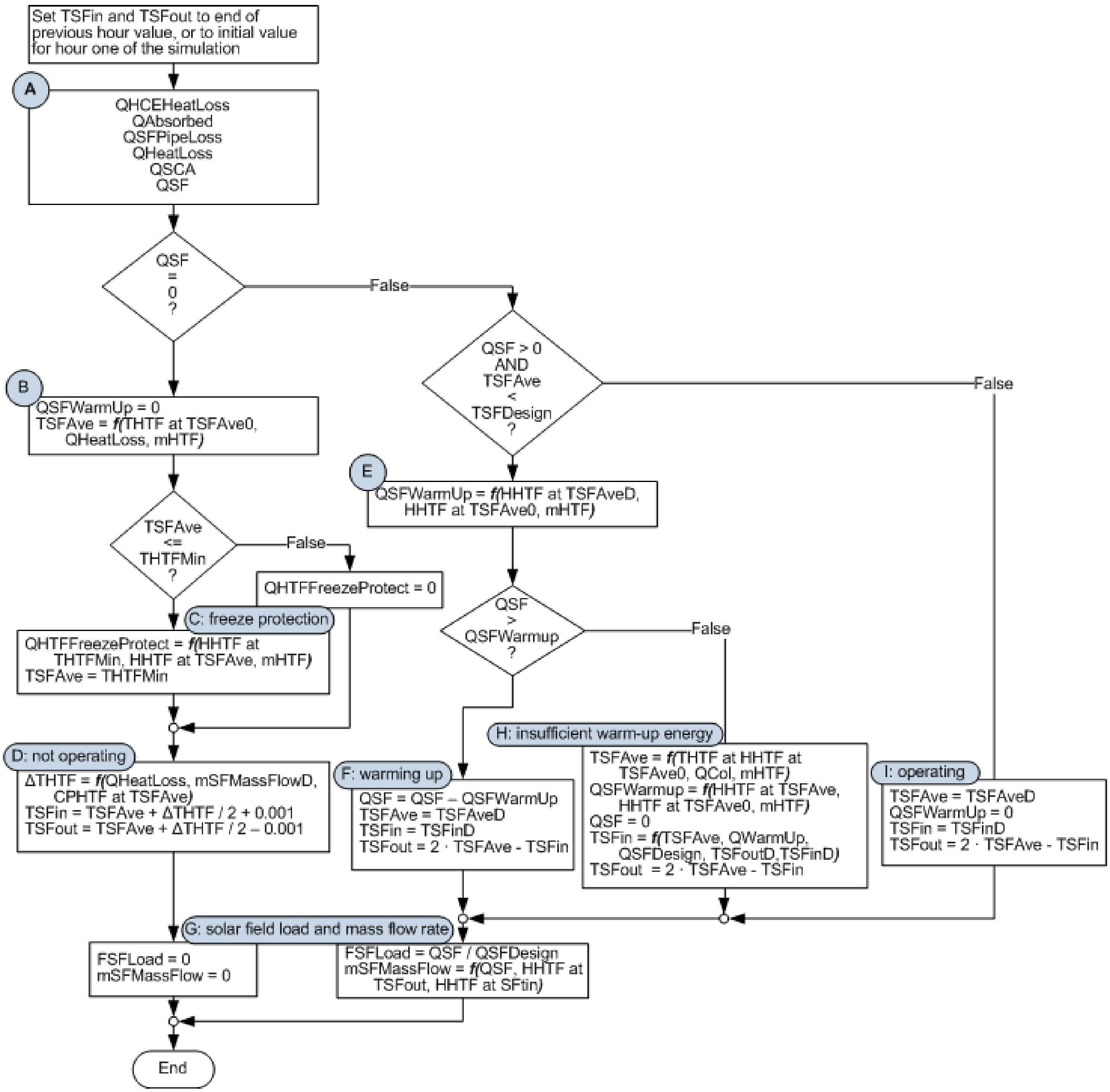
- Solar energy absorbed by the solar collector assemblies $Q_{Absorbed}$
- Solar field inlet temperature T_{SFin}, outlet temperature T_{SFout}, and average temperature T_{SFAve}
- Solar field heat losses $Q_{HeatLoss}$

SAM makes the calculations described in the schematic below for each of the 8,760 hours in a year beginning at midnight (hour one).

The algorithm calculates the next hour's solar field temperatures. The solar field inlet and outlet temperatures in the first hour are set to the solar field initial temperature on the Solar Field page.

The HCE heat loss calculation (see A in the diagram and its description below) requires the solar field outlet temperature, which is not calculated until later in the code (D, F, H, and I in the diagram). Because of this, the algorithm uses iteration to find the outlet temperature. The variable $T_{SFoutHold}$ is used to store the solar field outlet temperature value from the previous iteration.

Figure 2.1. Diagram of the solar field energy calculations. Use the letters to find explanations and equations in the text below the schematic.



(A) Initial delivered solar field energy

The delivered solar field energy Q_{SF} in thermal Watts is the energy delivered by the solar field to the power block and storage modules. SAM uses the initial value to determine the solar field operating condition in the current hour. SAM may adjust the initial value in subsequent steps of the algorithm. The solar field energy Q_{SF} is the product of the SCA energy Q_{SCA} and the solar field area $A_{SolarField}$:

$$Q_{SF} = Q_{SCA} \cdot A_{SolarField} \quad (2.17)$$

The solar field area $A_{SolarField}$ is the Solar Multiple (calculated) input variable from the Solar Field page.

SCA (collector) energy

The SCA energy Q_{SCA} in W/m² is the absorbed energy less the total solar field heat loss $Q_{HeatLoss}$:

$$Q_{SCA} = Q_{Absorbed} - Q_{HeatLoss} \quad (2.18)$$

Absorbed energy

The thermal energy absorbed by the SCAs $Q_{Absorbed}$ in thermal Watts/m² depends on the solar incidence angle $\theta_{SolarIncidence}$, incident solar radiation Q_{NIP}, solar field optical efficiency $F_{SFOpticalEfficiency}$, and the solar field availability factor $F_{Availability}$:

$$Q_{Absorbed} = \cos(\theta_{SolarIncidence}) \cdot Q_{NIP} \cdot F_{SFOpticalEfficiency} \cdot F_{Availability} \quad (2.19)$$

Heat loss

The total heat loss $Q_{HeatLoss}$ in thermal Watts is the sum of HCE thermal losses $Q_{HCELoss}$ and solar field pipe heat loss $Q_{SFPipeLoss}$:

$$Q_{HeatLoss} = Q_{HCELoss} + Q_{SFPipeLoss} \quad (2.20)$$

QSF is zero

When the delivered solar field energy Q_{SF} is zero, SAM calculates the average solar field temperature based on the HTF temperature, determines whether freeze protection energy is required, and then calculates the solar field inlet and outlet temperatures.

Note that in the following equations, the enthalpy variable name subscripts indicate the temperature at which the enthalpy is calculated. For example, the enthalpy variable $H_{HTFatTSFout}$ is the HTF enthalpy at the solar field outlet temperature T_{SFout}. The HTF properties lookup tables show the temperature-to-enthalpy equations for each HTF type. Similarly, the subscripts for temperature variables indicate the enthalpy value to use for enthalpy-to-temperature equations, which can also be found in the lookup tables.

(B) Average solar field temperature

Because no solar energy is available to heat the HTF, the solar field temperature is determined by the HTF temperature:

$$T_{SFAve} = T_{HTFatHHTF} \tag{2.21}$$

The HTF temperature $T_{HTFatHHTF}$ is calculated using the appropriate equation from the HTF enthalpy lookup table, where the HTF enthalpy is the enthalpy of the previous hour less the solar field heat losses in the current hour:

$$H_{HTF} = H_{HTFatTSFAve0} - \frac{Q_{HeatLoss} \cdot A_{SolarField}}{M_{HTF}} \tag{2.22}$$

where $H_{HTFatTSFAve0}$ is the HTF enthalpy at the solar field average temperature of the previous hour, and M_{HTF} is the mass of the HTF in kilograms. Under these conditions, the solar field warm-up energy is zero.

$$Q_{SFWarmUp} = 0 \tag{2.23}$$

(C) Freeze protection energy

When the solar field energy is zero and the average solar field temperature T_{SFAve} is above the minimum HTF temperature T_{HTFmin}, no energy for freeze protection is required. When the average solar field T_{SFAve} is below T_{HTFMin}, the system requires energy for freeze protection. Note that this energy must be supplied by either a thermal energy storage system or fossil backup system. The energy required for freeze protection for the current hour is a function of the HTF enthalpy at its freezing point T_{HTFMin}, the solar field average temperature during the hour, and the HTF mass in kilograms:

$$Q_{HTFFreezeProtect} = (H_{HTFatTHTFMin} - H_{HTFatTSFAve}) \cdot M_{HTF} \tag{2.24}$$

After the required freeze protection energy is calculated, the average solar field temperature is set to the HTF's freezing point, T_{HTFMin}:

$$T_{SFAve} = T_{HTFMin} \tag{2.25}$$

(D) Solar field inlet and outlet temperatures

When the solar field output is zero, after calculating the average solar field temperature and required freeze protection energy, SAM calculates the difference in temperature between the solar field inlet and outlet ΔT_{HTF}, which is a function of the solar field heat loss $Q_{SFHeatLoss}$, design solar field mass flow rate $m_{SFMassFlowD}$, and the HTF specific heat at the average solar field temperature $C_{pHTFatTSFAve}$:

$$\Delta T_{HTF} = \frac{Q_{SFHeatLoss}}{m_{SFMassFlowD} \cdot C_{pHTFatTSFAve}} \quad (2.26)$$

The solar field inlet and outlet temperatures are calculated as a function of ΔT_{HTF} and T_{SFAve}.

$$T_{SFin} = T_{SFAve} + \frac{\Delta T_{HTF}}{2} \quad (2.27)$$

$$T_{SFout} = T_{SFAve} - \frac{\Delta T_{HTF}}{2} \quad (2.28)$$

For this hour, because the solar field energy is zero, the solar field load factor and mass flow rate are both set to zero:

$$F_{SFLoad} = 0 \quad (2.29)$$

$$m_{SFMassFlow} = 0 \quad (2.30)$$

QSF is greater than zero and solar field temperature is below design point: Warm up energy required

When the initial delivered solar field energy (calculated in Step A in the diagram) is greater than zero, and the solar field average temperature is less than the design solar field temperature, the system must warm up to reach operating temperature. SAM calculates the required warm-up energy and determines whether the solar field can provide the required energy. For systems with thermal energy storage or fossil backup, the warm-up energy can be supplied by these sources.

(E) Required warm-up energy

Warm-up energy is thermal energy required to bring the solar field temperature to its design point in the morning to make up for heat lost during the night. The required warm-up energy is a function of the HTF enthalpies at the average solar field temperatures in the current and previous hours:

$$Q_{SFWarmup} = H_{HTFatTSFAveD} - H_{HTFatTSFAve0} \cdot M_{HTF} \quad (2.31)$$

SAM calculates the HTF enthalpies using the HTF properties tables.

F Solar energy for warm up is available

When the delivered solar field energy is greater than the required warm-up energy, the solar field can supply the warm-up energy. The delivered solar field energy is the initial solar field energy calculated in Step A minus the warm-up energy QSFWarmup, and the solar field temperatures are set to their design values.

$$Q_{SF} = Q_{SF} - Q_{SFWarmup} \quad (2.32)$$

$$T_{SFAve} = T_{SFAveD} \quad (2.33)$$

$$T_{SFin} = T_{SFinD} \quad (2.34)$$

$$T_{SFout} = 2 \cdot T_{SFAve} - T_{SFin} \quad (2.35)$$

H Solar energy for warm up is not available

When the delivered solar field energy is less than or equal to the required warm-up energy, there is some solar energy, but it is insufficient for warm-up. After calculating the average solar field energy based on the HTF enthalpy, SAM adjusts the required warm up energy for these new conditions, and sets the solar field energy to zero.

The average solar field temperature is set to the HTF temperature, which is a function of the HTF enthalpy in the previous hour:

$$T_{SFAve} = T_{HTFatHHTF0} \quad (2.36)$$

The HTF enthalpy in the previous hour H_{HTF0} is a function of the HTF enthalpy at the previous hour's average solar field temperature $H_{HTFatTSFAve0}$, the SCA energy Q_{SCA}, solar field area $A_{SolarField}$, and HTF mass M_{HTF}:

$$H_{HTF0} = H_{HTFatTSFAve0} + \frac{Q_{SCA} \cdot A_{SolarField}}{M_{HTF}} \quad (2.37)$$

The required warm-up energy $Q_{SFWarmup}$ is calculated to account for the temperature difference between the current and previous hours and is a function of the HTF enthalpy at the average solar field temperature in the current hour $H_{HTFatTSFAve}$ and in the previous hour $H_{HTFatTSFAve0}$, and the HTF mass M_{HTF}:

$$Q_{SFWarmup} = (H_{HTFatTSFAve} - H_{HTFatTSFAve0}) \cdot M_{HTF} \quad (2.38)$$

The delivered solar field energy is set to zero because no solar energy will be delivered in this hour:

$$Q_{SF} = 0 \quad (2.39)$$

The solar field inlet and outlet temperatures are calculated to account for the temperature reduction as as a function of the warm-up energy $Q_{SFWarmup}$, the design inlet and outlet temperatures T_{SFinD} and T_{SFoutD}, and the design solar field energy $Q_{SFDesign}$:

$$T_{SFin} = T_{SFAve} - \frac{Q_{SFWarmup}}{Q_{SFDesign}} \cdot (T_{SFoutD} - T_{SFinD}) \quad (2.40)$$

$$T_{SFout} = 2 \cdot T_{SFAve} - T_{SFin} \quad (2.41)$$

I QSF is greater than zero and solar field temperature is above design point: Normal operation

During normal operation, solar field temperatures are at their design points, and the solar field energy is not modified from the initial value calculated in Step A. The required warm-up energy is also set to zero.

$$T_{SFAve} = T_{SFAveD} \quad (2.42)$$

$$Q_{SFWarmUp} = 0 \quad (2.43)$$

$$T_{SFin} = T_{SFinD} \quad (2.44)$$

$$T_{SFout} = 2 \cdot T_{SFAve} - T_{SFin} \quad (2.45)$$

G Solar field load factor and mass flow rate

When the solar field is not in operation, the solar field load factor and mass flow rate are both set to zero.

Otherwise, when the solar field operates in either normal or warm-up mode, the solar field load factor is a function of the solar field energy Q_{SF} and the design solar field energy $Q_{SFDesign}$, and the solar field mass flow rate $m_{SFMassFlow}$ is a function of the solar field energy Q_{SF}, and the HTF enthalpies at the solar field outlet and inlet temperatures:

$$F_{SFLoad} = \frac{Q_{SF}}{Q_{SFDesign}} \quad (2.46)$$

$$m_{SFMassFlow} = \frac{Q_{SF}}{H_{HTFatTSFout} - H_{HTFatTSFin}} \quad (2.47)$$

2.9 Other Energy Quantities

In addition to the energy calculations described above, SAM calculates the values of several other energy quantities which are reported in the results and can be viewed in either the results spreadsheet (in Excel) or time series graphs (in DView). These quantities are not used in simulation calculations.

Note that unit conversion factors have been omitted from the following equations for clarity. (For example the Q_{DNI} value reported in the results is divided by 1,000,000 to convert from W/m^2 • m^2 to MW.)

The direct normal radiation incident on the solar field Q_{DNI} in thermal Watts is the product of the incident solar radiation Q_{NIP} and the solar field area $A_{SolarField}$.

$$Q_{DNI} = Q_{NIP} \cdot A_{SolarField} \quad (2.48)$$

The radiation in the collector plane $Q_{SFNipCosTh}$ in thermal Watts:

$$Q_{SFNIPCosTh} = Q_{NIP} \cdot \cos(\theta_{SolarIncidence}) \cdot A_{SolarField} \quad (2.49)$$

The energy absorbed by the solar field before thermal losses and including optical losses Q_{SFAbs} in thermal Watts

$$Q_{SFAbs} = Q_{Absorbed} \cdot A_{SolarField} \quad (2.50)$$

3 SCA / HCE

The solar field module uses parameters from the SCA / HCE (solar collector assembly and heat collection element) page to calculate the following values as part of the delivered thermal energy algorithm:

- Solar field optical efficiency $F_{\mathrm{SFOpticalEfficiency}}$
- Total heat loss Q_{HeatLoss}
- SCA absorbed energy Q_{SCA}

3.1 User Input Variables

The values of input variables on the SCA / HCE page are stored in two libraries. To modify the value of a variable, you must modify the library. Please contact user support at sam.user.support@nrel.gov for assistance modifying libraries.

The tables below list each input variable on the SCA / HCE page, and briefly describes each variable and where it is used in calculations. The calculations are described in more detail in the sections following these tables.

Solar Collector Assembly (SCA)

The solar collector assembly (SCA) input variables describe the dimensions and optical characteristics of the SCA or collector.

Table 3.1. SCA variables

Name	Description	Units	Symbol
Collector Type	The name of the collector in the SCA library		
SCA Length	Length of a single SCA. Used in SCA end loss calculation.	m	$D_{SCALength}$
SCA Aperture	Mirror aperture of a single SCA. Used in the row-to-row shadowing loss factor and HCE thermal loss calculations.	M	$D_{SCAAperture}$
SCA Aperture Area	Area of aperture of single SCA. Used in the solar field size calculations.	m^2	$A_{SCAAperture}$
Average Focal Length	Average trough focal length. Used in end gain and end loss factor calculations.	m	$D_{AveFocalLength}$
Incident Angle Modifier - Coeff 1...3	Incident angle modifier coefficients. Used to calculate the incident angle modifier factor, which is used to calculate the HCE absorbed energy and the solar field optical efficiency.	--	F_{IAM}
Tracking Error and Twist	Accounts for errors in the SCA's ability to track the sun. Sources of error may include poor alignment of sun sensor, tracking algorithm error, errors caused by the tracker drive update rate, and twisting of the SCA end at the sun sensor mounting location relative to the tracking unit end. A typical value is 0.985. Used to calculate SCA field error factor.	--	$F_{TrackTwist}$
Geometric Accuracy	Accounts for SCA optical errors caused by misaligned mirrors, mirror contour distortion caused by the support structure, mirror shape errors compared to an ideal parabola, and misaligned or distorted HCE. A typical range of values is between 0.97 and 0.98. Used to calculate SCA field error factor.	--	$F_{GeomAccuracy}$
Mirror Reflectivity	The solar-weighted hemispherical reflectance of the mirrors. For 4-mm low iron, pristine, second surface tempered glass mirrors, a reasonable value would be 0.95. Used to calculate SCA field error factor.	--	$F_{MirrorRefl}$
Mirror Cleanliness Factor (field avg)	Accounts for dirt and dust on the mirrors that reduce their effective reflectivity. Typically, mirrors are continuously cleaned, but a single mirror may be cleaned once each one or two weeks. The expected overall effect on the total solar field would be an average loss of between one and two percent. A typical value would be 0.985. Used to calculate SCA field error factor.	--	$F_{MirrorClean}$
Dust on Envelope (field avg)	Accounts for dust on the HCE envelope that affects light transmission. A typical value would be 0.99. Used to calculate HCE heat loss.	--	$F_{DustEnvelope}$
Concentrator Factor	A additional error factor to make it possible to adjust the SCE performance without modifying the other error factors. Useful for modeling an improved or degraded SCE. The default value is 1. Used to calculate SCA field error factor.	--	$F_{Concentrator}$
Solar Field Availability	Accounts for solar field down time for maintenance and repairs. Used to calculate absorbed energy.	--	$F_{SFAvailability}$

Mirror Reflectivity

The following information is intended to help choose a value for the mirror reflectivity factor. The solar weighted hemispherical reflectance (SWV) of mirror glass depends on the iron content, thickness, and tempering of the glass, and the thickness of the reflective coating of the mirror:

- Glass transmittance and mirror reflectivity both depend on the iron (Fe_2O_3) content of the glass. The higher the iron content, the lower the transmittance and the higher the reflectivity of the mirror. Iron contents of more than 0.02% typically result in unacceptably low mirror reflectivity values.
- Mirror reflectivity increases as glass thickness decreases. The thinner glass requires faster pulling during manufacturing and is easier to break during shipping and handling than thicker glass. A glass thickness of one millimeter mounted with a substrate is a reasonable compromise to maximize mirror reflectivity and minimize the risk of mirror breakage. Five millimeter thick, non-tempered, low-iron, self-supporting glass mirrors are typically recommended for mirrors at the periphery of the parabolic trough field that are exposed to wind. Normally, five to ten percent of a solar field is equipped with 5 mm glass.
- Glass tempering generally raises mirror reflectivity.
- Mirror coating typically uses a silver thickness between 800 - 1200Å or 0.8 -1.2 g/m2. Silver thicknesses less than 0.8 g/m2 result in unacceptably low mirror reflectivity values. Silver thicknesses greater than 1.2 g/m2 do not improve reflectivity, and have a tendency to delaminate.

Table 3.2. Suggested mirror reflectivity values for different types of commercially available glass solar mirrors using pristine second surface glass

Glass Thickness (mm)	Iron Content	Mirror Reflectivity
4	low	0.93 ±0.002
1	low	0.96 ±0.002
4	low	0.948 ±0.003
4	very low	0.946 ±0.001
3	very low	0.956 ±0.001

Receiver / Heat Collection Element (HCE)

The HCE variables describe the properties of up to four HCE types that can make up the solar field. This makes it possible to model a solar field with HCEs in different states. Each set of properties applies to one of the HCE types. The Fraction of Field variable determines what portion of the solar field is made up of a given HCE type.

Table 3.3. HCE variables

Name	Description	Units	Symbol
Receiver Type and Condition	The name of the receiver and its condition. Vacuum refers to an HCE in good condition, lost vacuum, broken glass, and hydrogen refer to different problem conditions.	--	--
Fraction of Field	Fraction of solar field using this HCE type and condition. Used to calculate HCE field error factor and HCE heat loss.	--	$F_{FractionOfField,1..4}$
Bellows Shadowing	The portion of the HCE tube that does not absorb solar thermal radiation. Used to calculate HCE field error factor.	--	$F_{Bellows}$
Envelope Transmissivity	Used to calculate HCE field error factor.	--	$F_{Transmissivity}$
Absorber Absorption	Accounts for inefficiencies in the HCE black coating. Used to calculate HCE field error factor.	--	$F_{Absorption}$
Unaccounted	Allows for adjustment of the HCE performance to explore effect of changes in performance of the HCE without changing the values of other correction factors. A typical value is 1. Used to calculate HCE field error factor.	--	$F_{Unaccounted}$
Optical Efficiency (HCE)	The design optical efficiency of each of the four receiver type and condition options. SAM uses the values to calculate the design weighted optical efficiency.	--	$F_{OptEffD,1..4}$
Optical Efficiency (Weighted)	The design weighted optical efficiency, representing the average optical efficiency of all receivers in the field (see equations below). SAM uses the value to calculate the solar field area. Note that SAM also calculates a separate HCE optical efficiency value for each hour during simulation that counts for the loss factors on the SCA / HCE page that also accounts for the incident angle modifier factor, which depends on the time of day and collector orientation.	--	$F_{OptEffD}$
Heat Loss Coefficient A0...A6	Used to calculated the HCE heat loss. The default values are based on NREL modeling and test results. (Forristall 2003)	--	$F_{HLA0...6}$
Heat Loss Factor	The design heat loss factor that applies to the active HCE type and condition. Used to calculate design HCE heat loss that is part of the solar field area equation. The heat loss factor scales the heat loss equation and can be used to fine tune the results when measured heat loss data are available. The default value of 1.25 is valid for the current version of SAM using the default heat loss coefficients.	--	$F_{HeatLoss}$
Minimum Windspeed (m/s)	Used to calculated the HCE heat loss for hours when the wind speed from the weather file is lower than the minimum wind speed.	m/s	--
Receiver Heat Losses (W/m) Thermal Losses (Weighted W/m) Thermal Losses (Weighted W/m2)	These values are provided for reference. SAM calculates the HCE heat loss for each hour during simulation based on the loss factor coefficients on the SCA / HCE page and other values from the weather data.	W/m, W/m^2	$Q_{HCELossD}$

Weighted Optical Efficiency (Design)

The design weighted optical efficiency $F_{OptEffD}$ is a design value that SAM uses to calculate the solar field area. Note that the design optical efficiency equations differ from the optical efficiency factor equations that SAM uses in the hourly simulation. It is a function of the four design optical efficiency factors $F_{OptEffD,1..4}$ and fraction of field values $F_{FractionOfField,n}$ for each receiver type and condition option.

$$F_{OptEffD} = \sum_{n=1}^{4} F_{OptEffD,n} \cdot F_{PercentOfField,n} \tag{3.51}$$

The design optical efficiency of each receiver type and condition option is a function of the efficiency and loss factors for each option.

$$F_{OptEffD,n} = F_{SCAFieldError,n} \cdot F_{DustEnvelope,n} \cdot F_{Bellows,n} \cdot F_{Transmissivity,n} \cdot F_{Absorbtion,n} \cdot F_{Unaccounted,n} \tag{3.52}$$

Weighted Thermal Losses (Design)

SAM uses the design weighted thermal losses $Q_{HCELossD}$ in watts per square meter in the solar field area equations. Note that the design HCE heat loss equations differ from the HCE heat loss equations used in the hourly simulation, which uses data from the weather file in place of the reference condition data from the Solar Field page.

The design weighted thermal losses QHCELossD in watts per square meter is the design wegithed thermal losses QHCELossD in wats per meter divided by the SCA Aperture DSCAAperture.

3.2 SCA Efficiency and Loss Factors

The SCA efficiency and loss factors account for optical losses due to reflected light at the end of each SCA, shading of SCAs by neighboring units, and mirror condition.

Solar field optical efficiency

The total solar field optical efficiency $F_{SFOptEff}$ accounts for the SCA optical efficiency, row shadowing losses, end losses, and incident angle-related losses:

$$F_{SFOptEff} = F_{SCAOptEff} \cdot F_{RowShadow} \cdot F_{EndLoss} \cdot F_{IAM} \tag{3.1}$$

It is used in the absorbed energy calculation.

SCA Optical Efficiency

The SCA (solar collector assembly) optical efficiency factor $F_{SCAOptEff}$ accounts for optical losses other than end losses and row shadowing losses.

$$F_{SCAOptEff} = F_{SCAFieldError} \cdot F_{HCEFieldError} \tag{3.2}$$

The SCA field error factor is a function of the following SCA / HCE page input variables: Tracking Error and Twist, Geometric Accuracy, Mirror Reflectivity, Mirror Cleanliness Factor and Concentrator Factor. (Note that the Dust on Envelope factor is used for the HCE field error calculation below, not here.)

$$F_{SCAFieldError} = F_{TrackTwist} \cdot F_{GeomAcc} \cdot F_{MirrRefl} \cdot F_{MirrClean} \cdot F_{Concentrator} \tag{3.3}$$

The HCE field error factor is the sum of HCE field error factors for each of the four HCE types on the SCA / HCE page. The error factor for a single HCE type is the product of the fraction of the solar field covered by a given HCE type, the Dust on Envelope factor, and the four optical parameters on the SCA / HCE page: Bellows Shadowing, Envelope Transmissivity, Absorber Absorption, and Unaccounted:

$$F_{HCEFieldError} = F_{FractionOfField} \cdot F_{Dust} \cdot F_{Bellows} \cdot F_{Transmissivity} \cdot F_{Absorption} \cdot F_{Unaccounted} \tag{3.4}$$

Row shadowing loss

The SCA row shadowing losses result from row-to-row shadowing that occurs shortly after sunrise and shortly before sunset. The row shadowing loss factor is a function of the collector angle, distance between SCAs in a row (centerline-to-centerline distance), and the SCA aperture length:

$$F_{RowShadow} = \left|\sin\left(\frac{\pi}{2} - \theta_{Track}\right)\right| \cdot \frac{D_{SCARow}}{D_{SCAAperture}} \tag{3.5}$$

SAM sets the row shadowing loss factor to zero when either of the following conditions is true:

- The calculated value of the shadowing factor $F_{RowShadow}$ is less than 0.5.
- The solar altitude angle θ_{SolAlt} is less than zero.

If the calculated shadowing loss factor is greater than one, SAM sets its value to one.

End loss

The SCA end losses result from light that reflects off the end of each row of SCAs. The end loss factor $F_{EndLoss}$ depends on the SCA average focal length $D_{AveFocalLength}$ from the SCA / HCE page input variables, the solar incidence angle $\theta_{SolarIncidence}$, and the number of SCAs per row, $N_{SCAperRow}$ from the

Solar Field page input variables.

$$F_{EndLoss} = 1 - \frac{D_{AveFocalLength} \cdot \tan(\theta_{SolarIncidence}) - \frac{(N_{SCAperRow} - 1)}{N_{SCAperRow} \cdot F_{EndGain}}}{D_{SCALength}} \quad (3.6)$$

The end gain factor $F_{EndGain}$ accounts for small gains in solar input from light reflecting off of neighboring SCA ends.

$$F_{EndGain} = D_{AveFocalLength} \cdot \tan(\theta_{SolarIncidence}) - D_{SCARow} \quad (3.7)$$

SAM sets the end gain factor to zero when its calculated value is less than zero.

3.3 HCE Heat Loss

SAM uses the HCE (heat collection element) heat loss $Q_{HCELoss}$ in the delivered thermal energy equations.

The HCE heat loss is a function of the following variables:

- The seven heat loss coefficients that are input variables on the SCA / HCE page.
- The solar field inlet and outlet temperatures calculated in the solar field delivered thermal energy equations.
- The wind speed, ambient temperature, insolation from the weather data.
- The collector angle.

The wind speed used for the heat loss calculation, v_{Wind}, is the larger of the minimum wind speed variable on the SCA / HCE page and the average hourly wind speed from the weather data file.

The adjusted HCE heat loss $Q_{HCELoss}$ in Watts per square meter of HCE aperture is the sum of heat loss for each HCE type and condition option $Q_{HCEHL,n}$ in Watts per meter adjusted by heat loss factor $F_{HeatLoss,n}$ and fraction of field $F_{FractionOfFIeld,n}$ for each receiver type and condition option, and the SCA aperture $D_{Aperture}$ and length $D_{SCALength}$.

$$Q_{HCELoss} = \sum_{n=1}^{4} \frac{Q_{HCEHL,n} \cdot F_{HeatLoss,n} \cdot F_{PercentOfField,n}}{D_{SCAAperture} \cdot D_{SCALength}} \quad (3.8)$$

The heat loss $Q_{HCEHL,n}$ for each of the four receiver type and condition options in Watts per meter of SCA length is the sum of the four HCE heat loss terms $Q_{HCEHL1..4}$ divided by the difference between the solar field outlet T_{SFout} and inlet temperatures T_{SFin}. Note that the fact that there are four receiver type and condition options and four HCE heat loss terms in the equation is a coincidence.

$$Q_{\text{HCEHL},n} = \frac{Q_{\text{HCEHL1}} + Q_{\text{HCEHL2}} + Q_{\text{HCEHL3}} + Q_{\text{HCEHL4}}}{T_{\text{TSFout}} - T_{\text{TSFin}}} \tag{3.9}$$

For each receiver type and condition option, the four HCE heat loss terms Q_{HCEHL1}, Q_{HCEHL2}, Q_{HCEHL3}, and Q_{HCEHL4} are calculated as follows:

$$Q_{\text{HCEHL1}} = \left(F_{\text{HLA0}} + F_{\text{HLA5}} \cdot \sqrt{v_{\text{Wind}}}\right) \cdot (T_{\text{SFout}} - T_{\text{SFin}}) \tag{3.10}$$

$$Q_{\text{HCEHL2}} = \frac{F_{\text{HLA1}} + F_{\text{HLA6}} \cdot \sqrt{v_{\text{Wind}}}}{2} \cdot \left[\left(T_{\text{SFout}}^2 - T_{\text{SFin}}^2\right) - T_{\text{Amb}} \cdot (T_{\text{SFout}} - T_{\text{SFin}})\right] \tag{3.11}$$

$$Q_{\text{HCEHL3}} = \frac{F_{\text{HLA2}} + F_{\text{HLA4}} \cdot Q_{\text{NIP}} \cdot \cos(\theta_{\text{SolarIncidence}}) \cdot F_{\text{IAM}}}{3} \cdot \left(T_{\text{SFTout}}^3 - T_{\text{SFTin}}^3\right) \tag{3.12}$$

$$Q_{\text{HCEHL4}} = \frac{F_{\text{HLA3}}}{4} \cdot \left(T_{\text{SFTout}}^4 - T_{\text{SFTin}}^4\right) \tag{3.13}$$

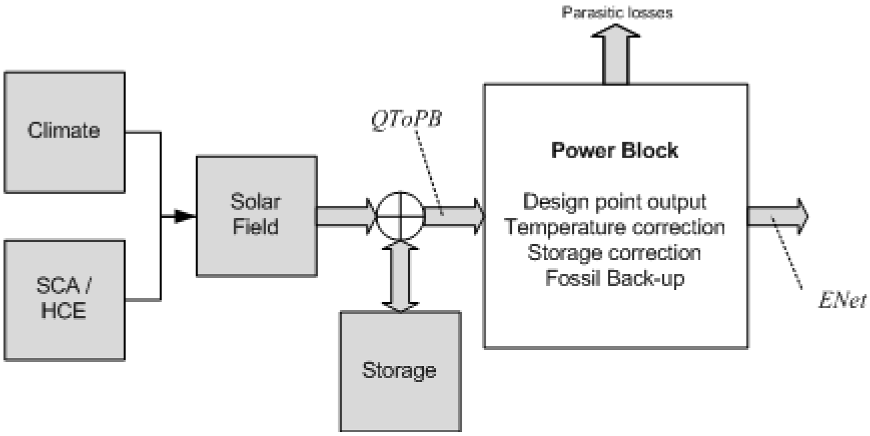
The default values of the heat loss coefficients FHLA0...6 for each receiver type and condition option are based on the results of an HCE performance model described in Forristall 2003, which were compared to the HCE heat loss test stand at the National Renewable Energy Laboratory. The coefficients were derived by running the model for a 1 meter HCE length over a range of HTF and ambient temperatures, wind speeds, and direct normal radiation values and then using statistical software to calculate the heat loss equation coefficients.The Heat Loss Factor is used to adjust the modeling results to the test stand results. The default value of 1.25 accounts for end losses at the bellows and other losses not accounted for by the model.

4 Power Block

SAM models the power block based on a reference steam turbine. The reference turbine parameters determine the steam turbine's performance characteristics. A set of turbine rating variables determine the power block's total capacity.

The power block module calculates the hourly net electric output E_{Net} based on the energy supplied to the power block Q_{ToPB} calculated by the dispatch and storage module.

Figure 4.1. Diagram of the power block module



The power block module calculates the net electric output E_{NET} by first calculating the design point gross electric output, and then applying a series correction factors and adding any energy from the fossil backup system and subtracting parasitic losses:

1. Calculate the design point gross output $E_{GrossSolarDesign}$, which is the power block electric output at the design thermal input based on the power block's thermal to electric efficiency curve. This value accounts for solar energy either directly from the solar field, or that has passed through the thermal energy storage system.
2. Calculate the corrected gross output $E_{GrossSolarCorr}$ to account for cooling tower and thermal energy storage system losses.
3. Calculate the gross solar output $E_{GrossSolar}$, ensuring that the power block output value falls within pre-defined limits.
4. Add any energy from fossil backup to calculate the design turbine gross output $E_{GrossFossil}$.
5. Subtract parasitic losses due to electric loads through the system to calculate the net electric output E_{Net}.

4.1 User Input Variables

The input variables on the Power Block page are divided into two groups. The turbine ratings group determines the capacity of the power block, and the power cycle group defines the performance parameters of the reference turbine.

The tables below list each input variable on the Power Block page, and briefly describe each variable and where it is used in calculations. The calculations are described in more detail in the sections following these tables.

Turbine ratings

The turbine ratings variables determine the steam turbine's capacity, availability, and degradation rate.

Table 4.1. Turbine rating input variables

Name	Description	Units	Symbol
Rated Turbine Net Capacity	Nameplate capacity of turbine. SAM does not use this variable in energy calculations, but does use it as the system capacity in the economic calculations. The economic calculations are described in SAM's help system and user guide.	MWe	--
Design Turbine Gross Output	Gross electric output of turbine, typically 110% of rated turbine net capacity. Used to calculate the design turbine thermal input, which is displayed in the power cycle group with a blue background. Also used to calculate the energy from the backup boiler.	MWe	E_{Design}
Power Plant Availability	Fraction of net electric energy generated by the power block that is delivered to the grid to account for plant outages. Used to calculate the net annual electric generation.	--	$F_{PBAvailability}$
Annual Degradation	Annual reduction in power block output. Used to calculate the net annual electric generation.	--	$F_{Degradation}$

Power cycle

The variables in the power cycle group describe a reference steam turbine. SAM uses the reference turbine specifications to calculate the turbine output, and then scales the actual output based on the turbine rating variables. Each set of reference turbine specifications is stored in the reference turbine library. To modify the value of a variable, you must modify the library. Please contact user support at sam.user.support@nrel.gov for assistance modifying libraries.

Table 4.2. Power cycle input variables

Name	Description	Units	Symbol
Ref System	Name of the reference turbine. Selecting a reference system determines the values of the other power cycle variables.	--	--
System Type	Brief description of the reference turbine. Does not affect calculations.	--	--
Design Turbine Thermal Input	The thermal energy required as input to the power block to generate the design turbine gross (electric) output. SAM uses the design turbine thermal input to calculate several power block capacity-related values, including the solar field size, power block design point gross output, and parasitic losses.	MWt	$Q_{PBDesign}$
Design Turbine Gross Efficiency	Total thermal to electric efficiency of the reference turbine. Used to calculate the design turbine thermal input.	--	$F_{GrossTurbineEffD}$
Max Over Design Operation	The turbine's maximum output expressed as a fraction of the design turbine thermal input. Used by the dispatch module to set the power block thermal input limits.	--	F_{PBMax}
Minimum Load	The turbine's minimum load expressed as a fraction of the design turbine thermal input. Used by the dispatch module to set the power block thermal input limits.	--	F_{PBMin}
Turbine Start-up Energy	Fraction of the design turbine thermal input required to bring the system to operating temperature after a period of non-operation. Used by the dispatch module to calculate the required start-up energy.	--	$F_{StartUp}$

Name	Description	Units	Symbol
Boiler LHV Efficiency	The back-up boiler's lower heating value efficiency. Used by the power block module to calculate the quantity of gas required by the back-up boiler.	--	F_{LHVEff}
Turb. Part Load Therm to Elec	Factors for the turbine thermal-to-electric efficiency polynomial equation. Used to calculate the design point gross output, which is the portion of the power block's electric output converted from solar energy before losses.	--	F_{TE}
Turb. Part Load Elec to Therm	Factors for turbine's part load electric-to-thermal efficiency polynomial equation. Used to calculate the energy in kilowatt-hours of natural gas equivalent required by the backup boiler. SAM dispatches the backup boiler based on the fossil-fill fraction table in the thermal storage dispatch parameters on the Storage page.	--	F_{ET}
Cooling Tower Correction	Cooling tower correction factor. Used to calculate the temperature correction factor that represents cooling tower losses. To model a system with no cooling tower, set F0 to 1, and F1 = F2 = F3 = F4 =0.	--	F_{TC}
Temperature Correction Mode	In the dry bulb mode, SAM calculates a temperature correction factor to account for cooling tower losses based on the ambient temperature from the weather data set. In wet bulb mode, SAM calculates the wet bulb temperature from the ambient temperature and relative humidity from the weather data.	--	--

4.2 Design Turbine Thermal Input

The design turbine thermal input $Q_{PBDesign}$ shown on the Power Block page is the thermal energy required as input to the power block to generate the design turbine gross output. It is a function of two other Power Block page inputs, the design turbine gross output E_{Design} and the design turbine gross efficiency $F_{GrossTurbineEffD}$:

$$Q_{PBDesign} = \frac{E_{Design}}{F_{GrossTurbineEffD}} \tag{4.1}$$

4.3 Design Point Gross Output

The design point gross electric output from solar $E_{GrossSolarDesign}$ is the gross electric output of the power block, not accounting for cooling tower or thermal energy storage losses, or for energy from a back-up boiler. SAM calculates the gross electric output value by normalizing the thermal energy delivered to the power block in the current hour Q_{ToPB} to the the power block's design turbine thermal input $Q_{PBDesign}$, and then uses the normalized value as the dependent variable in a fourth-order polynomial equation representing the power block's thermal-to-electric conversion efficiency:

$$E_{\mathrm{GrossSolarDesign}} = E_{\mathrm{Design}} \cdot \left[F_{\mathrm{TE4}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}} \right)^4 + F_{\mathrm{TE3}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}} \right)^3 + F_{\mathrm{TE2}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}} \right)^2 + F_{\mathrm{TE1}} \cdot \left(\frac{Q_{\mathrm{ToPB}}}{Q_{\mathrm{PBDesign}}} \right) + F_{\mathrm{TE0}} \right] \quad (4.2)$$

The hourly thermal energy delivered to the power block Q_{ToPB} is calculated by the Dispatch and Storage module. The turbine part load thermal to electric efficiency coefficients, F_{TE0} through F_{TE4} are input variables on the Power Block page.

4.4 Corrected Gross Output

After calculating the design point gross electric output from solar $E_{\mathrm{GrossSolarDesign}}$, SAM applies temperature and thermal energy storage (TES) correction factors to correct the value to account for losses associated with the cooling towers and TES system. The corrected gross electric output from solar $E_{\mathrm{GrossSolarCorr}}$ is a function of $E_{\mathrm{GrossSolarDesign}}$ and the two correction factors F_{CorrTemp} and F_{CorrTES}:

$$E_{\mathrm{GrossSolarCorr}} = E_{\mathrm{GrossSolarDesign}} \cdot F_{\mathrm{CorrTemp}} \cdot F_{\mathrm{CorrTES}} \quad (4.3)$$

Temperature Correction Factor

The temperature correction factor F_{TempCorr} is calculated based on whether the power block employs wet or dry cooling as defined on the Power Block page and is a function of the temperature T_{TC} and the five cooling tower correction factors F_{TC0} through F_{TC4}, also inputs on the Power Block page:

$$F_{\mathrm{TempCorr}} = F_{\mathrm{TC4}} \cdot T_{\mathrm{TC}}{}^4 + F_{\mathrm{TC3}} \cdot T_{\mathrm{TC3}}{}^3 + F_{\mathrm{TC2}} \cdot T_{\mathrm{TC2}}{}^2 + F_{\mathrm{TC1}} \cdot T_{\mathrm{TC1}} + F_{\mathrm{TC0}} \quad (4.4)$$

T_{TC} is either the wet bulb temperature or the ambient temperature for the given hour. The ambient (dry bulb) temperature is included in the weather data. SAM calculates the wet bulb temperature based on the ambient and dew point temperatures and relative humidity from the weather data. When the temperature correction mode on the Power Block page is "wetbulb basis," T_{TC} is equal to the wet bulb temperature. When the mode is "drybulb basis," T_{TC} is the dry bulb temperature.

TES Correction Factor

For systems with thermal storage (more than zero hours of thermal energy storage defined on the

Storage page), the thermal energy storage correction factor F_{CorrTES} is a function of the energy delivered by the TES Q_{fromTES} and energy delivered to the power block Q_{toPB} calculated by the dispatch and storage module, and the turbine TES adjustment efficiency $F_{\text{TESAdjustEfficiency}}$ from the Storage page:

$$F_{\text{CorrTES}} = \left(1 - \frac{Q_{\text{FromTES}}}{Q_{\text{ToPB}}}\right) + \frac{Q_{\text{FromTES}}}{Q_{\text{ToPB}}} \cdot F_{\text{TESAdjustEfficiency}} \tag{4.5}$$

Note that for a system with no TES, Q_{fromTES} is zero, and the correction factor is one.

4.5 Gross Solar Output

After calculating the corrected gross electric output from solar $E_{\text{GrossSolarCorr}}$, SAM calculates the gross solar output from solar $E_{\text{GrossSolar}}$, which is the gross electric energy converted from solar energy. SAM makes sure that the value is within the design limits defined by the minimum load $E_{\text{GrossSolarMin}}$ and the maximum over design operation $E_{\text{GrossSolarMax}}$. These design limits are based on the minimum load and design turbine gross output inputs on the Power Block page.

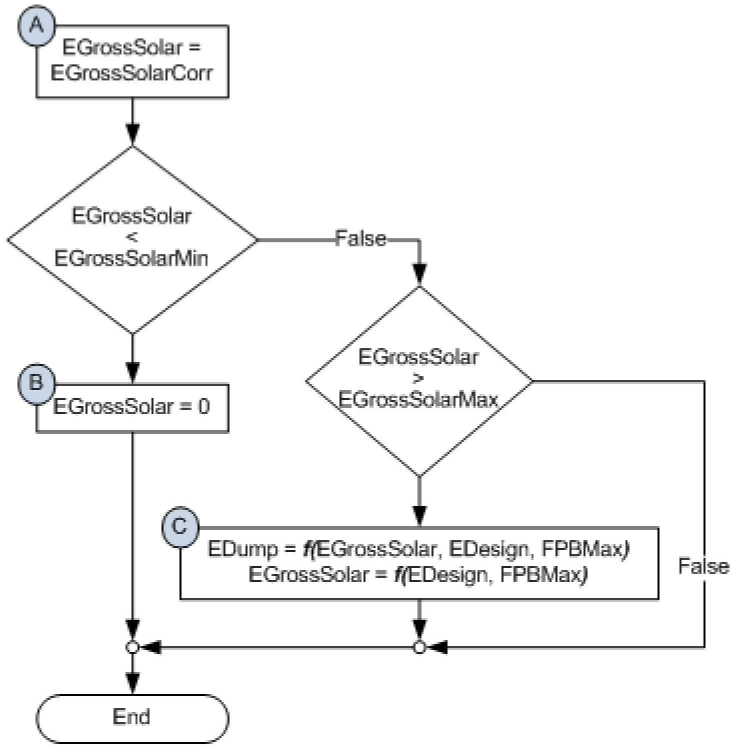
$E_{\text{GrossSolarMin}}$ is a function of the design turbine gross output E_{Design} and the minimum load factor F_{PBMin} on the Power Block page:

$$E_{\text{GrossSolarMin}} = E_{\text{Design}} \cdot F_{\text{PBMin}} \tag{4.6}$$

$E_{\text{GrossSolarMax}}$ is a function of the design turbine gross output E_{Design} and the maximum over design operation factor F_{PBMax} on the Power Block page:

$$E_{\text{GrossSolarMax}} = E_{\text{Design}} \cdot F_{\text{PBMax}} \tag{4.7}$$

Fig 4.2. Diagram of the gross solar output limits algorithm



A Initial gross solar output

The initial value of the gross electric output from solar energy $E_{\text{GrossSolar}}$ is the corrected gross solar output $E_{\text{GrossSolarCorr}}$:

$$E_{\text{GrossSolar}} = E_{\text{GrossSolarCorr}} \tag{4.8}$$

B Solar energy is energy insufficient to drive the power block

For hours when the resulting $E_{\text{GrossSolar}}$ is not sufficient to drive the power block, SAM records the value E_{Min} which is reported in the hourly results:

$$E_{\text{Min}} = E_{\text{GrossSolar}} \tag{4.9}$$

and then sets the gross solar output to zero:

$$E_{\text{GrossSolar}} = 0 \tag{4.10}$$

Solar energy exceeds maximum power block output limits

For hours when $E_{GrossSolar}$ exceeds the energy required to drive the power block at is maximum design gross output rating, the power block produces excess electricity E_{Dump}:

$$E_{Dump} = E_{GrossSolar} - E_{Design} \cdot F_{PBMax} \quad (4.11)$$

and the gross solar output is set to its maximum value:

$$E_{GrossSolar} = E_{GrossSolarMax} \quad (4.12)$$

4.6 Fossil Backup

The fossil backup module calculates the electric output from the backup boiler $E_{GrossFossil}$, and the thermal energy equivalent in fuel Q_{gas}.

SAM considers a system to have a backup boiler if one of values in the fossil-fill fraction column of the thermal storage dispatch controls table is greater than zero.

The backup electric output is based on the power block's design turbine gross output value and the fossil-fill fraction for the current hour. The dispatch schedule determines which period (1 through 6) applies to the current hour, and the fossil-fill table determines which fossil-fill fraction applies to each period.

SAM does not account for the cost of gas in the economic metrics reported in the results such as levelized cost of energy. You can roughly account for the cost of gas for the backup boiler by first simulating a system with a boiler, and then based on the total annual value of Q_{gas} reported in the hourly results and the heat content of the gas, determining an average annual cost of gas and assigning it to the annual operation and maintenance cost in dollars per kilowatt-hour of generated electricity (see the SAM user guide or help for information about entering operation and maintenance costs).

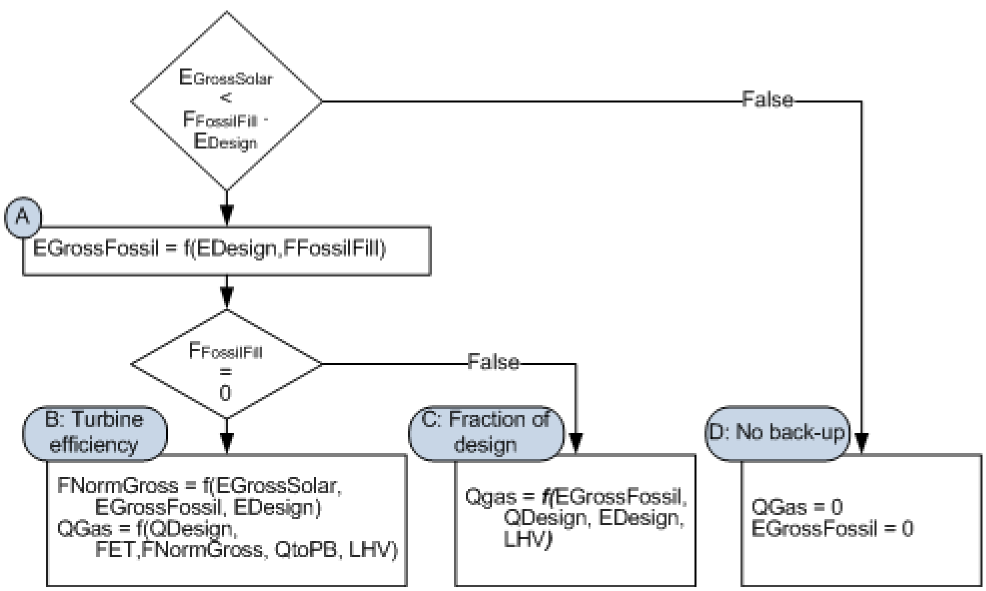
SAM calculates a fossil-fill requirement for each hour as the product of the design turbine gross output E_{Design} and the fossil-fill fraction for the current hour. The relationship between the fossil-fill requirement and the corrected gross electric output from solar $E_{GrossSolarCorr}$ determines whether the boiler supplies energy to the power block in a given hour. When the corrected gross solar output is greater than or equal to the fossil-fill requirement, there is no energy from the boiler. When the corrected gross solar output is less than the fossil-fill requirement, SAM first calculates the gross fossil electric output $E_{GrossFossil}$ as a function of the design turbine gross output and the fossil-fill fraction for the current hour, and then determines the thermal energy from fuel Q_{Gas} required to generate the electricity.

When the fossil-fill fraction is zero, Q_{Gas} is a function of the power block's efficiency curve as defined by the electric-to-thermal efficiency factors. Otherwise, it is a function of the design turbine gross output.

The fossil backup equations use the following variables:

- Gross solar output $E_{GrossSolar}$
- Fossil-fill fraction $F_{FossilFill}$ and dispatch schedule from the Storage page
- Design turbine gross output E_{Design} from the Power Block page
- Design turbine thermal input $Q_{PBesign}$
- Electric-to-thermal efficiency factors F_{ET0}, F_{ET1}, F_{ET2}, F_{ET3}, F_{ET4} from the Power Block page
- Boiler lower heating value efficiency LHV from the Power Block page

4.3. Diagram of fossil-fill algorithm



(A) Gross electric output from the boiler

The gross electric output required from the boiler $E_{GrossFossil}$ is a fraction of the design turbine gross output E_{Design} on the Power Block page, and is determined by the fossil-fill fraction for the current hour and the gross solar output:

$$E_{GrossFossil} = E_{Design} \cdot F_{FossilFill} - E_{GrossSolar} \tag{4.13}$$

(B) Fuel calculated as a function of power block's power curve

When the fossil-fill fraction for the current hour is zero, SAM calculates the fossil fuel energy required to generate the gross electric output from the boiler Q_{Gas} using the power block electric-to-thermal efficiency factors. It is a function of the normalization factor $F_{NormGross}$, the design turbine thermal input $Q_{PBDesign}$ adjusted by the five turbine electric-to-thermal efficiency factors F_{ET0} ... F_{ET4}, thermal energy delivered to the power block Q_{toPB} (calculated by the Dispatch and Storage module), and the boiler LHV efficency F_{LHVEff}:

$$Q_{Gas} = \frac{Q_{PBDesign} \cdot C - Q_{ToPB}}{F_{LHVEff}} \tag{4.14}$$

$$C = F_{ET4} \cdot F_{NormGross}{}^{4} + F_{ET3} \cdot F_{NormGross}{}^{3} + F_{ET2} \cdot F_{NormGross}{}^{2} + F_{ET1} \cdot F_{NormGross} + F_{ET0} \tag{4.15}$$

The normalization factor $F_{NormGross}$ is a function of the gross solar output $E_{GrossSolar}$, gross boiler output $E_{GrossFossil}$, and the design turbine gross output E_{Design}:

$$F_{NormGross} = \frac{E_{GrossSolar} + E_{GrossFossil}}{E_{Design}} \tag{4.16}$$

(C) Fuel calculated as a fraction of the design point

When the fossil-fill fraction is not zero, the required fossil-fill energy Q_{Gas} is a function of the unadjusted design turbine thermal input $Q_{PBDesign}$, boiler lower heating value efficiency F_{LHVEff}, the gross electric output from the boiler $E_{GrossFossil}$, and the design turbine gross output E_{Design}:

$$Q_{Gas} = \frac{E_{GrossFossil} \cdot Q_{PBDesign}}{E_{Design} \cdot F_{LHVEff}} \tag{4.17}$$

(D) No energy required from the boiler

For hours when the gross solar energy is less than the fraction of the design turbine gross output that is the fossil-fill requirement, Q_{Gas} and $E_{GrossFossil}$ are both zero.

$$Q_{Gas} = 0 \tag{4.18}$$

$$E_{\text{GrossFossil}} = 0 \tag{4.19}$$

Heater load factor

The heater (boiler) load factor is a function of the gross electric output from fossil $E_{\text{GrossFossil}}$ and the design turbine gross output E_{Design}:

$$F_{\text{HtrLoad}} = \frac{E_{\text{GrossFossil}}}{E_{\text{Design}}} \tag{4.20}$$

The heater load factor is used in the parasitic loss calculations.

4.7 Electric Output

Gross electric output

The gross electric output E_{Gross} is the total electric output from solar and fossil sources not accounting for parasitic losses:

$$E_{\text{Gross}} = E_{\text{GrossFossil}} + E_{\text{GrossSolar}} \tag{4.21}$$

SAM reports E_{gross} in the hourly results.

Power block load factor

The power block load factor is a function of the gross electric output E_{Gross} and the design turbine gross output E_{Design}:

$$F_{\text{PBLoad}} = \frac{E_{\text{Gross}}}{E_{\text{Design}}} \tag{4.22}$$

SAM uses the power block load factor to calculate the power block-related parasitic losses.

Hourly net electric output

The hourly net electric output E_{Net} is a function of the gross electric output E_{Gross} and the total parasitic losses $E_{\text{Parasitics}}$:

$$E_{\text{Net}} = E_{\text{Gross}} - E_{\text{Parasitics}} \tag{4.23}$$

Annual net electric output

SAM calculates the net electric annual output for the system's first year of production by adding the 8,760 hourly net output values, where h is the hour of the year, and $E_{Net,h}$ is the net hourly output for that hour:

$$E_{NetYearOne} = \sum_{h=1}^{8760} E_{Net,h} \tag{4.24}$$

Annual delivered electric output

The delivered annual output in year one $E_{DeliveredYearOne}$ is the net annual output multiplied by the power plant availability factor $F_{Availability}$:

$$E_{DeliveredYearOne} = E_{NetYearOne} \cdot F_{Availability} \tag{4.25}$$

To calculate the output values in year two and subsequent years used for economic calculations, SAM uses the following equation, where $F_{Degradation}$ is the annual degradation rate and y is the year:

$$E_{DeliveredAnnual,y} = E_{DeliveredYearOne} \cdot \left(1 - F_{Degradation}\right)^{y-1} \tag{4.26}$$

5 Dispatch and Storage

The dispatch and storage module performs two functions:

- Determine how energy is dispatched from the solar field, to and from thermal energy storage (TES), and to the power block.
- Model the TES system for systems with storage.

The dispatch mode depends on the power block operating mode, the amount of energy available from the solar field (and TES, if available), and the energy required by the power block. The power block has three operating modes:

- Not operating
- Starting up
- Operating

SAM assumes that the power block is not operating in the first hour of simulation, and then determines the operating mode for subsequent hours based on the operating mode of the previous hour and energy available from the solar field. For systems with storage, the operating mode also depends on the energy available from the TES and its state of charge.

For each hour of simulation, SAM calculates the energy delivered to the power block, which may come from the solar field, or from both the solar field and thermal energy storage for systems with storage. Note that energy from a backup boiler is calculated separately by the Power Block module. For hours when the solar field energy exceeds the energy required by the power block as defined by the design turbine gross output on the Power Block page, the excess solar energy is delivered to the TES. If the TES is full or the available solar energy exceeds the TES charge capacity, the remaining thermal energy is dumped.

5.1 User Input Variables

The user inputs on the Storage page are divided into two groups. The thermal energy storage (TES) group defines the thermal energy storage capacity and type along with some efficiency parameters. The thermal storage dispatch controls group determine the utilization of energy from the storage system and backup boiler as a function of the dispatch period. The dispatch and storage module also uses inputs from the Power Block page.

The tables below list each input variable on the Storage page, and briefly describes each variable and where it is used in calculations. The calculations are described in more detail in the sections following these tables.

Thermal Energy Storage (TES)

Table 5.1. Thermal energy storage (TES) input variables

Name	Description	Units	Symbol
Equiv. Full Load Hours of TES	The thermal storage capacity expressed in hours. The physical capacity is the number of hours of storage multiplied by the power block design thermal input. Used to calculate the TES maximum storage capacity.	hours	$N_{\mathrm{HoursofStorage}}$
Thermocline or Two-Tank TES	A thermocline storage system consists of a single tank with a top layer of hot storage fluid and bottom layer of cold storage fluid with sand and quartzite as filler material. A two-tank system consists of a cold storage tank and hot storage tank. The current version of SAM models only two-tank storage systems.	--	-

Name	Description	Units	Symbol
Storage Fluid Number	Storage fluid used in the TES. When the storage fluid and solar field heat transfer fluid (HTF) are different, the system is an indirect system with a heat exchanger. When the storage fluid and HTF are the same, the system is a direct system that uses the solar field HTF as the storage medium. Used to calculate the heat exchanger duty.	--	-
Maximum Energy Storage	The maximum thermal energy storage capacity of the TES. Used in the dispatch with TES calculations.	MWht	$Q_{inTESMax}$
Design Turbine Thermal Input	The thermal input requirement of the power block to operate at its design point. Used to calculate the following dispatch parameters: power block input limits, power block load requirement, TES maximum storage capacity, and the start-up requirement	MWt	$Q_{PBDesign}$
Tank Heat Losses	Storage tank thermal losses. SAM subtracts value from the total energy in storage at the end of each simulation hour.	MWt	$Q_{TankHeatLoss}$
Heat Exchanger Duty	Applies only to indirect thermal storage systems that use a different storage fluid and solar field HTF. Used to calculate the maximum TES charge rate.	None	$F_{HeatExchangerDuty}$
Turbine TES - Adj. - Efficiency	SAM applies the TES efficiency adjustment factor to the turbine efficiency for trough systems with storage to account for the lower steam temperature that results from imperfect heat exchange in the storage system. Used to calculate maximum TES discharge rate. Also used by the Power Block module for the TES correction factor.	None	$F_{TESAdjustEfficiency}$
Turbine TES Adjustment - Gross Output	Efficiency adjustment factor. Used to calculate maximum TES discharge rate.	None	$F_{TESAdjustOutput}$
Maximum Power to Storage	Maximum TES charge rate. Used in the dispatch calculation when energy from the solar field exceeds the power block load requirement.	MWt*	$Q_{toTESMax}$
Maximum Power From Storage	Maximum TES discharge rate. Used in the dispatch calculation when energy from the solar field is less or equal to than the power block load requirement.	MWt*	$Q_{fromTESMax}$
Primary bed material Secondary bed material Thermocline Temp Degradation Thermocline Efficiency Adj for TES Thermocline Output Adj for TES	These variables apply to thermocline storage systems and are not active in the current version of SAM.		

*Note that although these values are rates with units of MWh/h, they are used in equations with energy values in units of MWh because the rate values are all averaged over a one hour period, and therefore have units of MWh/h x 1 h.

Storage Dispatch Controls

The storage dispatch control variables each have six values, one for each of six possible dispatch periods. They determine how SAM calculates the energy flows between the solar field, TES, and power block. Note that although the fossil-fill fraction is included on the Storage page, it is used by the Power block module to calculate the energy from a backup boiler.

Table 5.2. Thermal energy storage (TES) input variables

Name	Description	Units	Symbol
Storage Dispatch Fraction (with Solar)	The fraction of the TES maximum storage capacity (see previous table) required for the system to start when the solar field energy is greater than zero. A value of zero will always dispatch the TES in any hour assigned to the given dispatch period; a value of one will never dispatch the TES. Used to calculate the storage dispatch levels.	--	$F_{WithSolar}$
Storage Dispatch Fraction (without Solar)	The fraction of the TES maximum storage capacity (see previous table) required for the system to start when the solar field energy is equal to zero. A value of zero will always dispatch the TES in any hour assigned to the given dispatch period; a value of one will never dispatch the TES. Used to calculate the storage dispatch levels.	--	$F_{WithoutSolar}$
Turbine Output Fraction	A fraction of the design turbine thermal input adjusted by the turbine part load electric-to-thermal efficiency factors. Used to calculate the power block load requirement.	--	F_{PBOut}
Fossil Fill Fraction	A fraction of the power block design turbine gross output from the Power Block page that can be met by the backup boiler. Used by the power block module to calculate the energy from the backup boiler.	--	$F_{FossilFill}$

5.2 Dispatch Parameters

The dispatch parameters define the limits and requirements of the power block and thermal energy storage system. They include:

- Power block input limits $Q_{toPBMin}$ and $Q_{toPBMax}$
- Power block load requirement Q_{PBLoad}
- TES maximum storage capacity $Q_{inTESMax}$
- Storage dispatch levels $Q_{WithSolar}$ and $Q_{WithoutSolar}$
- Heat exchanger duty (for indirect storage systems only) $F_{HeatExchangerDuty}$

- TES maximum charge and discharge rate limits $Q_{toTESMax}$ and $Q_{fromTESMax}$
- Start-up energy requirement $Q_{StartUpRequired}$

Power block input limits

The energy to the power block Q_{toPB} is limited by the maximum input $Q_{toPBMax}$ and minimum input $Q_{toPBMin}$, which are determined by the maximum over design operation value F_{PBMax} and minimum load value F_{PBMin} from the Power Block page. The energy to the power block is also a function of the design turbine thermal input $Q_{PBDesign}$ and the five turbine part load electric to thermal efficiency factors F_{ET0} ... F_{ET4} on the Power Block page:

$$Q_{toPBMin} = Q_{PBDesign} \cdot \left(F_{ET4} \cdot F_{PBMin}{}^4 + F_{ET3} \cdot F_{PBMin}{}^3 + F_{ET2} \cdot F_{PBMin}{}^2 + F_{ET1} \cdot F_{PBMin} + F_{ET0}\right) \tag{5.1}$$

$$Q_{toPBMax} = Q_{PBDesign} \cdot \left(F_{ET4} \cdot F_{PBMax}{}^4 + F_{ET3} \cdot F_{PBMax}{}^3 + F_{ET2} \cdot F_{PBMax}{}^2 + F_{ET1} \cdot F_{PBMax} + F_{ET0}\right) \tag{5.2}$$

Power block load requirement

The power block load requirement Q_{PBLoad} defines the desired turbine thermal load for each dispatch period and is a function of the turbine output fraction value F_{PBOut} from the dispatch schedule on the Storage page, and the design turbine thermal input $Q_{PBDesign}$ on the Power Block page. The dispatch schedule on the Storage page assigns one of the six dispatch periods to each hour of the year. The turbine output fraction column in the dispatch control table assigns a turbine output fraction to each dispatch period.

$$Q_{PBLoad} = Q_{PBDesign} \cdot \left(F_{ET4} \cdot F_{PBOut}{}^4 + F_{ET3} \cdot F_{PBOut}{}^3 + F_{ET2} \cdot F_{PBOut}{}^2 + F_{ET1} \cdot F_{PBOut} + F_{ET0}\right) \tag{5.3}$$

The power block load requirement must be within the limits defined by the minimum power block input $Q_{toPBMin}$ and the maximum power block input $Q_{toPBMax}$ (described above).

TES maximum storage capacity

SAM calculates the TES maximum energy storage $Q_{inTESMax}$ from the Storage page as a function of the equivalent full load hours of TES $N_{HoursofStorage}$ on the Storage page and the design turbine thermal input $Q_{PBDesign}$ on the Power Block page:

$$Q_{inTESMax} = N_{HoursOfStorage} \cdot Q_{PBDesign} \tag{5.4}$$

Storage dispatch levels

After a period of no operation, a system with thermal energy storage will only start in an hour when the energy in the storage system Q_{inTES} is greater than the storage dispatch level for that hour. Two storage dispatch levels apply, depending on whether the solar field energy is greater than zero, $Q_{WithSolar}$, or zero, $Q_{WithoutSolar}$. The two dispatch levels are functions of the storage dispatch fraction values $F_{WithSolar}$ and $F_{WithoutSolar}$, the maximum energy storage $Q_{inTESMax}$ described above, and the storage dispatch schedule, all from the Storage page. SAM assigns the dispatch fractions to each hour of the year based on the storage dispatch table and dispatch schedule.

$$Q_{WithSolar} = F_{WithSolar} \cdot Q_{inTESMax} \tag{5.5}$$

$$Q_{WithoutSolar} = F_{WithoutSolar} \cdot Q_{inTESMax} \tag{5.6}$$

TES maximum charge and discharge rates

The maximum thermal energy storage charge and discharge rates are the maximum power to storage $Q_{toTESMax}$ and maximum power from storage $Q_{fromTESMax}$ values on the Storage page, and depend on whether the storage system is an indirect or direct system, i.e., whether or not it has a heat exchanger. Both of these values are calculated values that appear with blue backgrounds in the SAM input pages, and their equations are shown below. Note that although these values are rates with units of MWh/h, they are used in equations with energy values in units of kWh because the rate values are all averaged over a one hour period, and therefore have units of MWh/h x 1 h.

Direct systems: No heat exchanger

When the solar field HTF on the Solar Field page and storage fluid number on the Storage page are the same, the system has no heat exchanger (direct system).

The maximum charge rate $Q_{toTESMax}$ is a function of the design turbine thermal input $Q_{PBDesign}$ and maximum over design operation fraction F_{PBMax} on the Power Block page, and the solar multiple $F_{SolarMultiple}$ on the Solar Field page:

$$Q_{toTESMax} = Q_{PBDesign} \cdot F_{PBMax} \cdot F_{SolarMultiple} \tag{5.7}$$

The maximum discharge rate from storage QfromTESMax is a function of the design turbine thermal input $Q_{PBDesign}$ and the maximum over design operation fraction F_{PBMax} on the Power Block page, the turbine TES adjustment - efficiency $F_{TESAdjustEfficiency}$ and the turbine TES adjustment - gross output $F_{TESAdjustOutput}$ on the Storage page:

$$Q_{fromTESMax} = Q_{PBDesign} \cdot F_{PBMax} \cdot \frac{F_{TESAdjustOutput}}{F_{TESAdjustEfficiency}} \quad (5.8)$$

Indirect systems: With heat exchanger

The thermal energy storage system has a heat exchanger (indirect system) only when the solar field HTF on the Power Block page and storage fluid number on the Storage page are different. When a heat exchanger is present, the maximum charge rate is a function of the design turbine thermal input $Q_{PBdesign}$ from the Power Block page and the heat exchanger duty $F_{HeatExchangerDuty}$ from the Storage page:

$$Q_{toTESMax} = F_{HeatExchangerDuty} \cdot Q_{PBDesign} \quad (5.9)$$

The heat exchanger transfers thermal energy from the solar field to the storage system, and from the storage system to the power block. The heat exchanger duty must therefore be large enough to meet the power block demand. Because by definition, a solar multiple of one is the solar field size that results in solar field energy equal to the power block input requirement, SAM uses the solar multiple to calculate the heat exchanger duty. When the solar multiple is two or less, SAM sets the heat exchanger duty value to one, which is equivalent to the power block demand . When the solar multiple is greater than two, SAM sizes the heat exchanger to handle the difference between the solar multiple and the power block design input requirement.This guarantees that the heat exchanger is large enough to transfer excess solar field energy into storage.

$$F_{HeatExchangerDuty} = F_{SolarMultiple} - 1 \quad (5.10)$$

The maximum charge and discharge rates are functions of the maximum power block thermal input $Q_{toPBMax}$ described above, and the turbine TES adjustment - efficiency $F_{TESAdjustEfficiency}$ and turbine TES adjustment - gross output $F_{TESAdjustOutput}$ on the Storage page:

$$Q_{\text{fromTESMax}} = Q_{\text{toPBMax}} \cdot \frac{F_{\text{TESAdjustOutput}}}{F_{\text{TESAdjustEfficiency}}} \tag{5.11}$$

Start-up energy requirement

The required start-up energy $Q_{\text{StartUpRequired}}$ is the thermal energy required to bring the power block to operating temperature after a period of non-operation. It is a function of the design turbine thermal input Q_{PBDesign} and the turbine start-up energy fraction F_{StartUp} on the Power Block page:

$$Q_{\text{StartUpRequired}} = F_{\text{StartUp}} \cdot Q_{\text{PBDesign}} \tag{5.12}$$

5.3 Dispatch without TES

The system is considered to not have a thermal energy storage (TES) system when the equivalent full load hours of TES value on the Storage page is zero. For systems without storage, the dispatch strategy depends on the following:

- Power block operating mode in previous hour
- Energy available from the solar field in the current hour.

There are four dispatch modes for systems without storage. Each mode (A, B, C, and D) is described qualitatively below and then shown in more detail in the figure that follow.

SAM calculates the start-up energy Q_{StartUp} for hours when system components when the power block did not operate in the previous hour, and reports the hourly values in the hourly results.

When start-up energy is required:

A When energy from the solar field exceeds the start-up energy requirement, any surplus energy not required for warm-up goes to the power block to drive the turbine. For these hours, the power block starts and both a start-up energy and energy delivered to the power block value are reported in the hourly results.

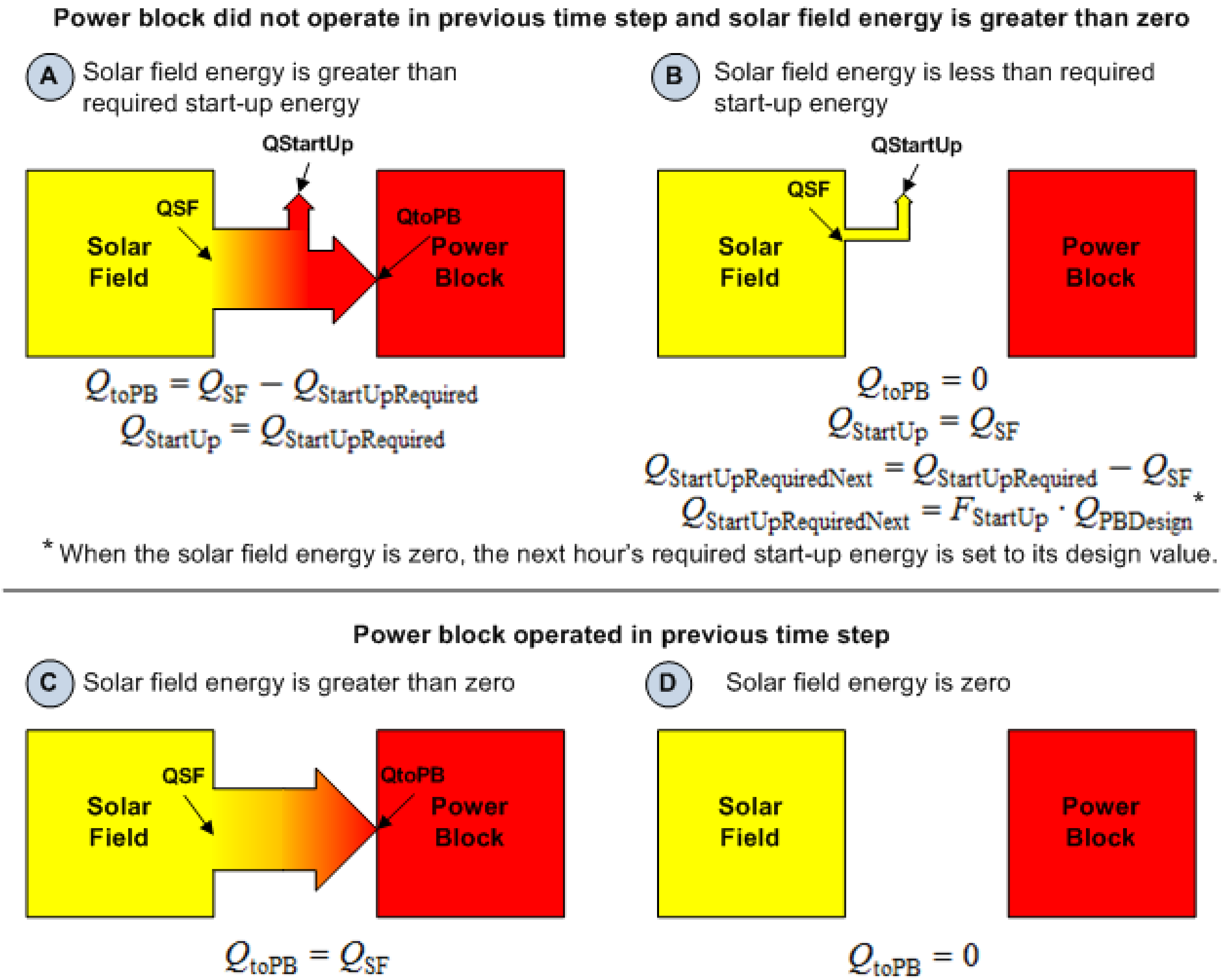
B For hours when energy from the solar field is not sufficient to start the turbine, the start-up energy is set to the solar field energy, and the power block does not start. The required start-up energy for the next hour is adjusted to account for the energy used to warm up the system in the current hour.

When the power block did operate in the previous hour, no start-up energy is required:

C When the solar field energy is greater than zero, the solar field drives the power block.

D When there is no solar field energy, the power block does not operate.

Fig 5.1. Dispatch without TES



5.4 Dispatch with TES

Systems with a non-zero equivalent full load hours of TES on the Storage page are considered to have a thermal energy storage (TES) system. For systems with storage, the energy dispatch depends on the following:

- Power block operating mode in previous hour
- Quantity of energy in storage in current hour
- Energy available from the solar field in current hour
- Time of day and storage dispatch fraction value assigned to the time of day

The following limits are set by the dispatch parameters:

- Energy in TES never exceeds the maximum energy storage value on the Storage page
- Energy to and from the TES never exceeds the maximum power to storage and minimum power from storage values on the Storage page.

- Energy to the power block is limited by the power block input limits defined by the maximum over design operation and minimum load defined on the Power Block page.

There are nine dispatch modes for systems with storage. Four modes (A, B, C, and D) apply during start-up, and five (E, F, G, H, and I) apply during operation. Each dispatch mode is described qualitatively below, and then shown in more detail in the figures that follow.

5.4.1 Start-up

Start-up energy is required to heat the power block components when the power block did not operate in the previous hour, and must be supplied by either the solar field or the thermal energy storage system. SAM reports the start-up energy $Q_{StartUp}$ in the hourly results. For systems with storage, the actual start-up energy is equal to the required start-up energy $Q_{StartUpRequired}$. SAM dispatches energy to the thermal energy storage system before using it for start-up, so start-up energy is always subtracted from the energy from storage $Q_{fromTES}$.

When the power block did not operate in the previous hour, there is sufficient energy to start it in the current hour when any of the following conditions are met:

- Solar field energy Q_{SF} is greater than zero and the energy in storage is greater than the "with solar" dispatch level $Q_{WithSolar}$.
- Solar field energy Q_{SF} is zero and the energy in storage is greater than the "without solar" dispatch level $Q_{WithoutSolar}$.
- Solar field energy Q_{SF} is greater than the maximum storage charge rate $Q_{toTESMax}$.

If the above conditions are not met, there is insufficient energy to start the system.

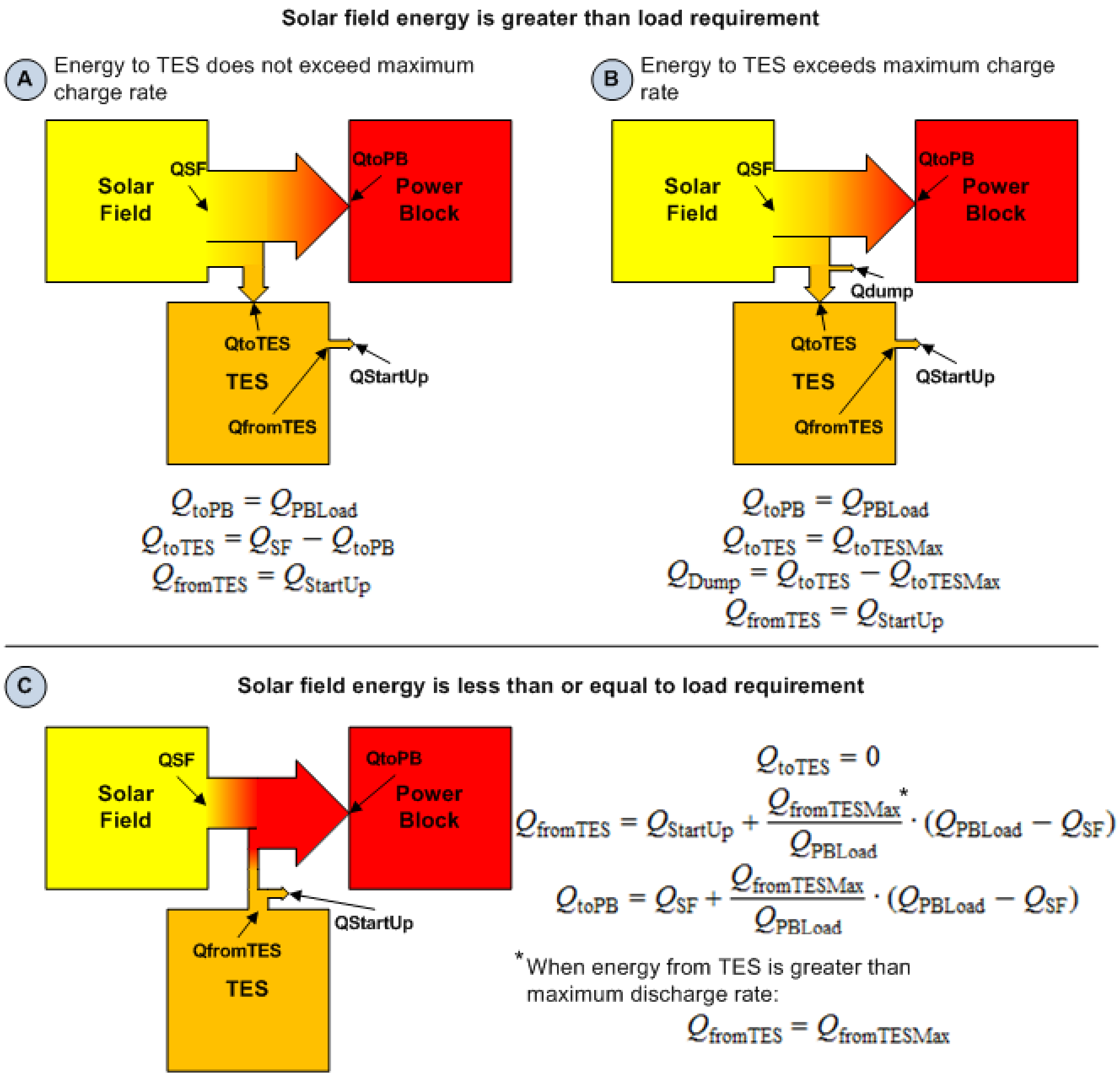
When there is sufficient energy to start the system:

(A) When the solar field energy QSF exceeds the amount required to run the power block Q_{PBLoad}, TES is charged.

(B) If the energy available to charge the TES exceeds the maximum charge rate $Q_{toTESMax}$, thermal energy is dumped.

(C) When the solar field energy cannot meet the power block load requirement, any energy in the TES is used to drive the power block.

Fig 5.2. Dispatch with TES during start-up



The ratio $Q_{FromTESMax} : Q_{PBLoad}$ is a correction factor that accounts for inefficiencies in the transfer of energy from the thermal energy storage system. Note that the maximum discharge rate is described in the Dispatch Parameters section.

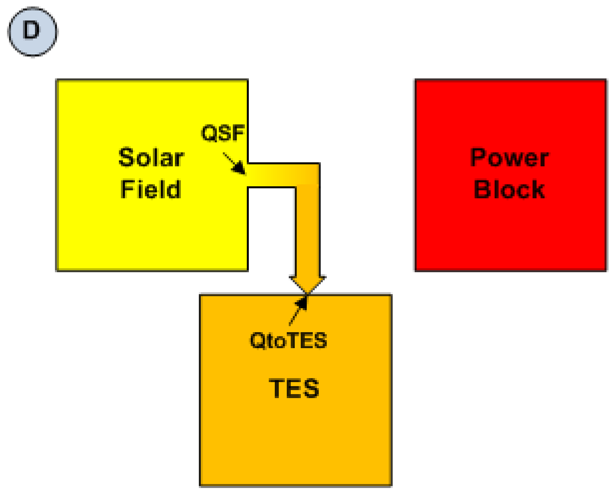
For hours when the power block starts, the energy remaining in the TES $Q_{inTESnext}$ at the beginning of the next hour is a function of the energy in the TES in the current hour Q_{inTES}, the start-up energy $Q_{StartUp}$, the solar field energy Q_{SF}, and the energy to the TES Q_{toTES}:

$$Q_{inTESNext} = Q_{inTES} - Q_{StartUp} + (Q_{SF} - Q_{toPB}) \qquad (5.13)$$

When there is insufficient energy to start the system:

(D) All solar field energy Q_{SF} charges the TES.

Fig 5.3. Dispatch with TES and insufficient start-up energy



$$Q_{toPB} = 0$$
$$Q_{fromTES} = 0$$
$$Q_{toTES} = Q_{SF}$$

For hours when there is insufficient energy to start the power block, the energy remaining in the TES $Q_{inTESnext}$ at the beginning of the next hour is a function of the energy in the TES in the current hour Q_{inTES}, and the energy to the TES Q_{toTES}:

$$Q_{inTESNext} = Q_{inTES} + Q_{toTES} \tag{5.14}$$

5.4.2 Power block operating

When the power block operated in the previous hour, energy is supplied to the power block by either the solar field, TES, or both.

When there is sufficient energy to drive power block:

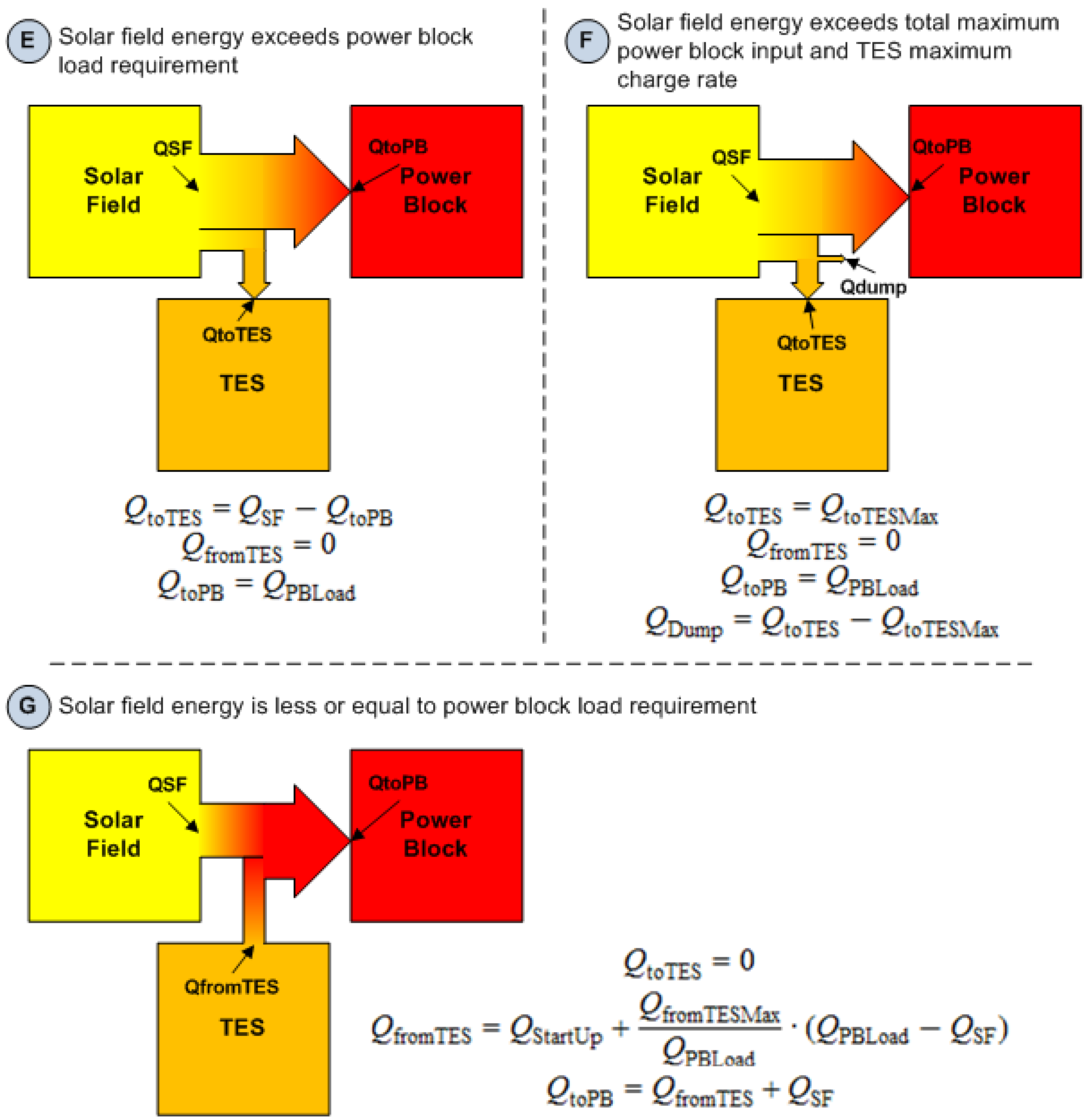
When the sum of the energy from the solar field Q_{SF} and energy in storage Q_{inTES} is greater than the power block load requirement Q_{PBLoad}, there is sufficient energy to drive the power block at its design point:

(E) When the solar field energy Q_{SF} exceeds the power block load requirement Q_{PBLoad}, the solar field drives the power block and charges the TES.

(F) If the power block load requirement Q_{PBLoad} is met and the TES is being charged at the TES maximum charge rate $Q_{toTESMax}$, then excess thermal energy is dumped.

When the solar field energy Q_{SF} is less than or equal to the power block requirement, the energy from the TES $Q_{fromTES}$ supplements the solar field energy to drive the power block until the remaining energy in the TES falls below the power block minimum input $Q_{toPBMin}$. This condition would typically occur during summer nights.

Fig 5.4. Dispatch with TES and sufficient energy to drive power block at design point



The energy remaining in the TES $Q_{inTESnext}$ at the beginning of the next hour is a function of the energy in the TES in the current hour Q_{inTES}, the solar field energy Q_{SF}, the energy to the TES Q_{toTES}, and any dumped thermal energy Q_{Dump}:

$$Q_{\mathrm{inTESNext}} = Q_{\mathrm{inTES}} + Q_{\mathrm{SF}} - Q_{\mathrm{toPB}} - Q_{\mathrm{Dump}} \tag{5.15}$$

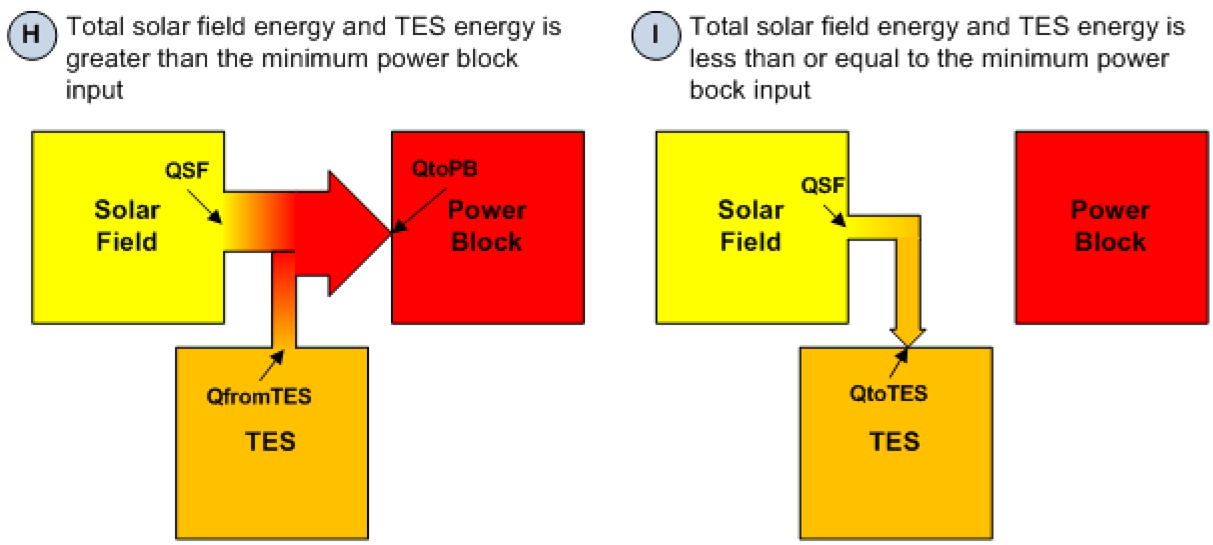
When solar field energy is insufficient to drive power block:

When the sum of the energy from the solar field Q_{SF} and energy in storage Q_{inTES} is less than or equal to the power block load requirement Q_{PBLoad}, there is insufficient energy to drive the power block at its design point. The power block either runs at part load or does not run:

(H) When the sum of the solar field energy Q_{SF} and energy in the TES Q_{inTES} is greater than the minimum power block input Q_{toPBMin}, the solar field and TES both drive the power block at part load, and the TES empties.

(I) When the sum of the solar field energy Q_{SF} and energy in the TES Q_{inTES} is less than or equal to the minimum power block input Q_{toPBMin}, all of the solar field energy is used to charge the TES.

Fig 5.5. Dispatch with TES and insufficient energy to drive power block at design point



$$Q_{\mathrm{toPB}} = Q_{\mathrm{SF}} + Q_{\mathrm{inTES}}$$
$$Q_{\mathrm{fromTES}} = Q_{\mathrm{inTES}}$$
$$Q_{\mathrm{toPB}} = 0$$
$$Q_{\mathrm{inTESNext}} = 0$$

$$Q_{\mathrm{toPB}} = 0$$
$$Q_{\mathrm{fromTES}} = 0$$
$$Q_{\mathrm{toTES}} = Q_{\mathrm{SF}}$$
$$Q_{\mathrm{inTESNext}} = Q_{\mathrm{inTES}} + Q_{\mathrm{toTES}}$$

5.5 TES losses and freeze protection

After calculating the energy in storage at the beginning of the next hour $Q_{\mathrm{inTESNext}}$, SAM adjusts the quantity to account for heat loss from the storage tank and any freeze protection energy supplied by the TES. For systems without TES, SAM assumes that freeze protection energy is supplied by an auxiliary heater.

TES HTF pump load factor

The TES HTF pump load factor is used to calculate the storage-related parasitic electric losses from the TES hot HTF pumps. For hours when the power block operates, the TES pump load factor $F_{TESPumpLoad}$ is a function of the thermal energy from the TES $Q_{fromTES}$ and the design turbine thermal input $Q_{PBDesign}$:

$$F_{TESPumpLoad} = \frac{Q_{FromTES}}{Q_{PBDesign}} \tag{5.16}$$

For hours when the power block does not operate, the TES pump load factor is set to zero.

Losses

The adjusted energy in storage at the beginning of the next hour is a function of the tank heat loss $Q_{TankHeatLoss}$ from the Storage page and the freeze protection energy supplied by the TES $Q_{FreezeProtectTES}$:

$$Q_{inTESNextAdj} = Q_{inTESNext} - (Q_{TankHeatLoss} + Q_{FreezeProtectTES}) \tag{5.17}$$

Freeze protection

Freeze protection energy prevents the heat transfer fluid temperature from dropping below its freezing point. The solar field module calculates the required freeze protection energy $Q_{HTFFreezeProtect}$, which must either be supplied by the TES $Q_{FreezeProtectTES}$ or by an an auxiliary fossil fuel-fired heater $Q_{FreezeProtectHtr}$.

For systems without TES, all freeze protection energy is supplied by the auxiliary heater:

$$Q_{FreezeProtectHtr} = Q_{HTFFreezeProtect} \tag{5.18}$$

For systems with TES, all freeze protection energy is supplied by the TES:

$$Q_{FreezeProtectTES} = Q_{HTFFreezeProtect} \tag{5.19}$$

6 Parasitic Losses

The parameters on the Parasitics page are used by the solar field, dispatch and storage, and power block simulation modules to calculate E_{ParSF}, E_{ParTES}, and E_{ParPB}, respectively. These are losses due to parasitic electric loads throughout the system. The total parasitic losses $E_{Parasitics}$ is the sum of the parasitic losses calculated by each simulation module.

$$E_{\text{Parasitics}} = E_{\text{ParSF}} + E_{\text{ParTES}} + E_{\text{ParPB}} \tag{6.1}$$

Note that the parasitic losses are shown as calculated values with blue backgrounds on the Parasitics page.

6.1 User Input Variables

The values of input variables on the Parasitics page are stored in a library of reference solar fields. To modify the value of a variable, you must modify the library. Please contact user support at sam.user.support@nrel.gov for assistance modifying libraries.

The tables below list each input variable on the Parasitics page, and briefly describes each variable and where it is used in calculations. The calculations are described in more detail in the sections following these tables.

Each parasitic loss type has a set of parameters that includes a Factor and design point value, and in some cases a PF and F0, F1, and F2 factor. These parameters are indicated by the following symbols in the equations described later in this chapter, where *Name* is an abbreviation of the type of parasitic loss:

Table 6.1. Parasitic loss parameter symbols

Parameter Name	Symbol
Factor	$F_{\text{Par}<Name>}$
PF	$F_{\text{ParPF}<Name>}$
F0	$F_{\text{Par}<Name>0}$
F1	$F_{\text{Par}<Name>1}$
F2	$F_{\text{Par}<Name>2}$
Design Point Parasitics	$F_{\text{Par}<Name>\text{D}}$

Table 6.2. Parasitics input variables used by all modules

Name	Description	Units	Symbol
Solar Field	The solar field type. SAM stores a set of parasitic parameters for six solar field types in the library of reference solar fields.	--	--
Solar Field Area	The calculated solar field area from the Solar Field page. Used to calculate parasitic losses that are based on the solar field size.	m^2	$A_{SolarField}$
Gross Turbine Output	The design turbine gross output value from the Power Block page. Used to calculate parasitic losses that are based on the power block capacity.		
Total Design Parasitics	The sum of collector drives and electronics, solar field HTF pump, night circulation pumping, power block fixed, balance of plant, heater/boiler, and cooling towers design loss values. This value represents the maximum possible value if all parasitic losses were to occur simultaneously in a given hour. SAM displays the value for reference only, and does not use it in simulation calculations.	MWe	--

Table 6.3. Parasitics input variables Calculated in the Solar Field module

Name	Description	Units	Symbol
Collector Drives and Electronics	Electrical losses from electric or hydraulic SCA drives that position the collector to track the sun and from electronic SCA tracking controllers and alarm monitoring devices. Calculated as a function of the solar field area.	MWe	E_{ParSFD}
Solar Field HTF Pump	Electrical losses from cold HTF pumping in the solar field. Calculated as a function of the solar field area. These losses are calculated only in hours when the solar field is operating, which is defined as when the solar field load is greater than zero (see condition G in the diagram of the solar field delivered thermal energy calculations).		$E_{ParHTFD}$
Antifreeze Pumping	Electrical losses from HTF pumps in the solar field. Calculated as a function of the solar field area. These losses are used only in hours when the solar field is not operating, which is defined as when the solar field load is zero (see condition G in the diagram of the solar field delivered thermal energy calculations).	MWe	$E_{ParAntiD}$

Table 6.4. Parasitics input variables calculated in the Storage module

Name	Description	Units	Symbol
Thermal Energy Storage Pumps	Electrical losses from pumps in the TES system. Calculated as a function of the design turbine gross output. Note that the F0, F1, and F2 factors are not used.		$E_{ParTESD}$

Table 6.5. Parasitics input variables calculated in the Power Block module

Name	Description	Units	Symbol
Power Block Fixed	These fixed losses apply 24 hours per day, for all of the 8,760 hours of the year.	MWe	$E_{ParPBFixedD}$
Balance of Plant	Electrical losses that apply in hours when the power block operates at part or full load, defined as when the power block load factor is greater than zero.	MWe	E_{ParBOP}
Heater/Boiler	Losses that apply only when the back-up boiler is in operation, i.e., when the electric output from the boiler is greater than zero.	MWe	E_{ParHtr}
Cooling Towers	The cooling tower parasitic losses are electrical losses that occur when the power block operates at part or full load. Calculated either as a function of power block load or at a fixed 50% or 100% of the design cooling tower parasitic losses.	MWe	E_{ParCTD}
Cooling Tower Operation Mode	Determines how cooling tower parasitic losses are calculated. For "Cooling Tower at 50% or 100%," parasitic losses are calculated as 50% of the design cooling tower parasitic losses when the power block load is 0.5 or less, and as or 100% of the design parasitic losses when the power block load is greater than 0.5. For "Cooling Tower parasitics a function of load," cooling tower parasitic losses are calculated as a function of power block load.	--	--

6.2 Power Block

The Power Block module calculates the following parasitic losses:

- Fixed power block
- Balance of plant
- Cooling towers
- Heater/boiler

The total power block parasitic losses E_{ParPB} is the sum of the four losses:

$$E_{ParPB} = E_{ParPBFixed} + E_{ParBOP} + E_{ParCT} + E_{ParHtr} \tag{6.2}$$

Fixed power block losses

The fixed power block losses are equal to the design fixed power block losses $E_{ParPBFixedD}$ from the Parasitics page:

$$E_{ParPBFixed} = E_{ParPBFixedD} \tag{6.3}$$

The design fixed power block losses are a function of the power block fixed factor $F_{ParPBFixed}$ from the

Parasitics page and the design turbine gross output E_{Design}:

$$E_{ParPBFixedD} = F_{ParPBFixed} \cdot E_{Design} \tag{6.4}$$

Balance-of-plant losses

The balance-of-plant losses depend on the design turbine gross output E_{Design}, the power block load factor F_{PBLoad}, and balance of plant parameters on the Parasitics page.

For hours when the power block load is greater than zero, the balance-of-plant losses are a function of the power block load factor F_{PBLoad}, the design balance-of-plant losses $E_{ParBOPD}$, and loss factors $F_{ParBOP0}$, $F_{ParBOP1}$,

$F_{ParBOP2}$:

$$E_{ParBOP} = E_{ParBOPD} \cdot \left(F_{PBLoad} \cdot F_{ParBOP2}{}^{2} + F_{PBLoad} \cdot F_{ParBOP1} + F_{ParBOP0}\right) \tag{6.5}$$

The design balance-of-plant losses $E_{ParBOPD}$ are a function of the design turbine gross output E_{Design} and the "Factor" and "PF" parameters F_{ParBOP} and $F_{ParPFBOP}$:

$$E_{ParBOPD} = F_{ParBOP} \cdot F_{ParPFBOP} \cdot E_{Design} \tag{6.6}$$

For hours when the power block load factor is zero, the balance-of-plant losses are zero:

$$E_{ParBOP} = 0 \tag{6.7}$$

Cooling tower losses

The cooling tower losses depend on the power block load factor F_{PBLoad}, cooling tower operating mode from the Parasitics page, and the cooling towers loss parameters on the Parasitics page.

For the cooling tower operating mode "Cooling Tower parasitics a function of load," during hours when the power block load factor is greater than zero, the cooling tower losses are a function of the power block load factor F_{PBLoad}, the design cooling tower losses E_{ParCTD}, and the loss factors F_{ParCT0}, F_{ParCT1},

F_{ParCT2}:

$$E_{ParCT} = E_{ParCTD} \cdot \left(F_{PBLoad} \cdot F_{ParCT2}{}^{2} + F_{PBLoad} \cdot F_{ParCT1} + F_{ParCT0}\right) \tag{6.8}$$

The design cooling tower losses E_{ParCTD} are a function of the design turbine gross output E_{Design} and the "Factor" and "PF" parameters F_{ParCT} and $F_{ParPFCT}$:

$$E_{\text{ParCTD}} = F_{\text{ParCT}} \cdot F_{\text{ParPFCT}} \cdot E_{\text{Design}} \quad (6.9)$$

For the cooling tower operating mode "Cooling Tower at 50% or 100%", during hours when the power block load is greater than zero, the cooling tower losses are a function of the design cooling tower parasitic losses E_{ParCTD}. When the power block load factor is less than or equal to 0.5, the cooling tower parasitic losses are set to fifty percent of the design losses:

$$E_{\text{ParCT}} = 0.5 \cdot E_{\text{ParCTD}} \quad (6.10)$$

When the power block load factor is greater than 0.5, the cooling tower parasitic losses are equal to the design losses:

$$E_{\text{ParCT}} = E_{\text{ParCTD}} \quad (6.11)$$

For hours when the power block load factor is zero, the cooling tower parasitic losses are zero:

$$E_{\text{ParCT}} = 0 \quad (6.12)$$

Heater (boiler) losses

The heater (boiler) losses are associated with the operation of the back-up boiler. The losses depend on the heater load factor and the heater loss parameters on the Parasitics page. For hours when the heater load factor is greater than zero, the heater losses are a function of the heater load factor F_{HtrLoad}, the design heater losses E_{ParHtrD}, and heater loss factors F_{ParHtr0}, F_{ParHtr1}, F_{ParHtr2}:

$$E_{\text{ParHtr}} = E_{\text{ParHtrD}} \cdot \left(F_{\text{HtrLoad}} \cdot {F_{\text{ParHtr2}}}^2 + F_{\text{HtrLoad}} \cdot F_{\text{ParHtr1}} + F_{\text{ParHtr0}}\right) \quad (6.13)$$

The design heater losses E_{ParHtrD} are a function of the design turbine gross output E_{Design} and the "Factor" and "PF" parameters F_{ParHtr} and F_{ParPFHtr}:

$$E_{\text{ParHtrD}} = F_{\text{ParHtr}} \cdot F_{\text{ParPFHtr}} \cdot E_{\text{Design}} \quad (6.14)$$

When the heater load factor is zero, the heater is not operating, and the heater losses are zero

$$E_{\text{ParHtr}} = 0 \quad (6.15)$$

6.3 Storage

The dispatch and storage module calculates one parasitic loss:

- Electric parasitic losses from the thermal energy storage (TES) hot HTF pumps

The TES parastic losses E_{ParTES} are a function of the TES HTF pump load factor $F_{\text{TESPumpLoad}}$, the design TES parasitic losses $E_{ParTESD}$, and parameters on the Parasitics page $F_{ParTES0}$, $F_{ParTES1}$, $F_{ParTES2}$:

$$E_{ParTES} = E_{ParTESD} \cdot \left(F_{ParTES2} \cdot F_{TESPumpLoad}^{2} + F_{ParTES1} \cdot F_{TESPumpLoad} + F_{ParTES0}\right) \quad (6.16)$$

The TES pump load factor $F_{TESPumpLoad}$ is calculated by the dispatch and storage module for each hour that the power block operates.

The design thermal energy storage pumps losses from Parasitics page are calculated based on the design turbine gross output E_{Design} and the "Factor" and "PF" parameters F_{ParTES} and $F_{ParPFTES}$:

$$E_{ParTESD} = F_{ParTES} \cdot F_{ParPFTES} \cdot E_{Design} \quad (6.17)$$

6.4 Solar Field

The solar field module calculates three parasitic losses:

- Collector drive and electronics losses are associated with the drive mechanisms on each SCA and with the power requirements of electronic SCA drive controllers and alarm circuitry.
- HTF pumping losses are associated with the solar field's cold HTF pumps during solar field operation.
- Antifreeze pumping losses are associated with the solar field HTF pumps during the night.

The total solar field parasitic losses E_{ParSF} is the sum of the three solar field parasitic losses:

$$E_{ParSF} = E_{ParSCADrives} + E_{ParHTFPump} + E_{ParAntiFreeze} \quad (6.18)$$

Collector (SCA) drive and electronics losses

The SCA drive and electronic losses $E_{ParSCADrives}$ depend on the solar field load F_{SFLoad} in the current hour (see condition G in the solar field energy diagram). When the solar field load is greater than zero, these losses are equal to their design value shown on the Parasitics page:

$$E_{ParSCADrives} = E_{ParSCADrivesD} \quad (6.19)$$

The design SCA drive and electronics losses $E_{ParSCADrivesD}$ is a function of the design turbine gross output E_{Design}, and the loss factors $F_{ParSCADrives}$ and $F_{ParPFSCADrives}$ in the "Factor" and "PF" columns on the Parasitics page, respectively:

$$E_{ParSCADrivesD} = F_{ParSCADrives} \cdot F_{ParPFSCADrives} \cdot E_{Design} \quad (6.20)$$

For hours when the solar field load is zero, the SCA drive and electronic losses are set to zero:

$$E_{\text{ParSCADrives}} = 0 \tag{6.21}$$

HTF pumping losses

The HTF pumping losses $E_{\text{ParHTFPump}}$ also depend on the on the solar field load F_{SFLoad} in the current hour (see condition G in the solar field energy diagram). When the solar field load is greater than zero, the pumping losses are a function of the solar field load, design HTF pumping losses $E_{\text{ParHTFPumpD}}$, and the three HTF pumping loss coefficients $F_{\text{ParHTFPump0}}$, $F_{\text{ParHTFPump1}}$, and $F_{\text{ParHTFPump2}}$:

$$E_{\text{ParHTFPump}} = E_{\text{ParHTFPumpD}} \cdot \left(F_{\text{ParHTFPump2}} \cdot F_{\text{SFLoad}}{}^2 + F_{\text{ParHTFPump1}} \cdot F_{\text{SFLoad}} + F_{\text{ParHTFPump0}}\right) \tag{6.22}$$

The design HTF pumping losses $E_{\text{ParHTFPumpD}}$ are a function of the HTF pump loss factors $F_{\text{ParHTFPump}}$ and $F_{\text{ParPFHTFPump}}$ in the "Factor" and "PF" columns of the Parasitics page and of the solar field area $A_{\text{SolarField}}$:

$$E_{\text{ParHTFPumpD}} = F_{\text{ParHTFPump}} \cdot F_{\text{ParPFHTFPump}} \cdot A_{\text{SolarField}} \tag{6.23}$$

For hours when the solar field load is zero, the HTF pumping losses are set to zero:

$$E_{\text{ParHTFPump}} = 0 \tag{6.24}$$

Antifreeze pumping losses

The antifreeze pumping losses occur when the solar field load F_{SFLoad} is zero (see condition G in the solar field energy diagram). When the solar field load is greater than zero, the antifreeze pumping losses are zero:

$$E_{\text{ParAntiFreeze}} = 0 \tag{6.25}$$

For hours when the solar field load is zero, the antifreeze pumping losses $E_{\text{ParAntifreeze}}$ are equal to the design antifreeze pumping losses:

$$E_{\text{ParAntifreeze}} = E_{\text{ParAntifreezeD}} \tag{6.26}$$

The design antifreeze pumping losses $E_{\text{ParAntifreezeD}}$ are a function of the design turbine gross output E_{Design} and the antifreeze pumping loss factor $F_{\text{ParAntifreeze}}$:

$$E_{\text{ParAntifreezeD}} = F_{\text{ParAntifreeze}} \cdot E_{\text{Design}} \tag{6.27}$$

7 Results

SAM displays a summary of results on the Results page, and detailed results, including hour-by-hour values for a selection of the variables discussed in this manual, in the results spreadsheet or in DView. These results are described in SAM's help system and user guide.

Each time you run SAM, it creates files containing the hourly results. The data displayed in the results spreadsheet and DView are from files stored in *trnSAM\CSP\output* in the SAM folder, which is *c:\SAM* by default. Note that each time you run SAM, the files are overwritten. If you want to save hourly results for a given run, you must move a copy of the file to a different location on your computer.

The file */trnSAM/CSP/output/CSP_trough_hrly_all.out* contains a more complete set of hourly results that shows the value of many of the variables discussed in this manual. You can open the file with a text editor, spreadsheet program, or DView.

7.1 Hourly Output Variables

The data described in the following tables is from the hourly data displayed in the results spreadsheet and in DView when you click one of the Results buttons in SAM. The data can be viewed directly by opening the file in a text editor, or in an Excel spreadsheet by clicking Spreadsheet at the bottom on SAM's navigation menu. They can also be viewed graphically in the data viewer DView by clicking Time Series Graph.

Table 8.1. Hourly output variables calculated by the Solar Field module

Name	Name in Hourly Results	Description	Units	Symbol
Direct normal radiation	Q_nip	Direct normal radiation value read from the weather file.	W/m^2	Q_{NIP}
Incident normal radiation	QSF_nipCosTh	Radiation in the solar field collector plane in thermal Watts. This value is reported in hourly results for reference, but not used in calculations. (This value can be used to manually calculate the value of the solar incidence angle $\theta_{SolarIncidence}$ in each hour: $\theta_{SolarIncidence} = Q_{SFNIPCosTh} \div Q_{DNI}$.)	MWt	$Q_{SFNIPCosTh}$
Direct normal insolation	Q_dni	The direct normal radiation incident on the solar field in thermal Watts, which is the product of Q_{NIP} and the solar field area. This value is reported in hourly results for reference, but not used in calculations.	MWt	Q_{DNI}
Absorbed solar energy	Q_abs	Thermal energy absorbed by the collectors.	W/m^2	Q_{Abs}
Solar field absorbed energy	QSF_abs	The energy absorbed by the solar field before thermal losses and including optical losses. This value is reported in hourly results for reference, but not used in calculations.	MWt	Q_{SFAbs}
Solar field delivered energy	Q_SF(MW)	Thermal energy delivered by the solar field	MWt	$Q_{SolarField}$
Solar field pipe heat loss	QSF_Pipe_HL	Energy lost by header piping in the solar field.	MWt	$Q_{SFPipeLoss}$
Solar field HCE heat loss	QSF_HCE_HL	Energy lost by HCEs (receivers) in the solar field.	MWt	$Q_{HCELoss}$

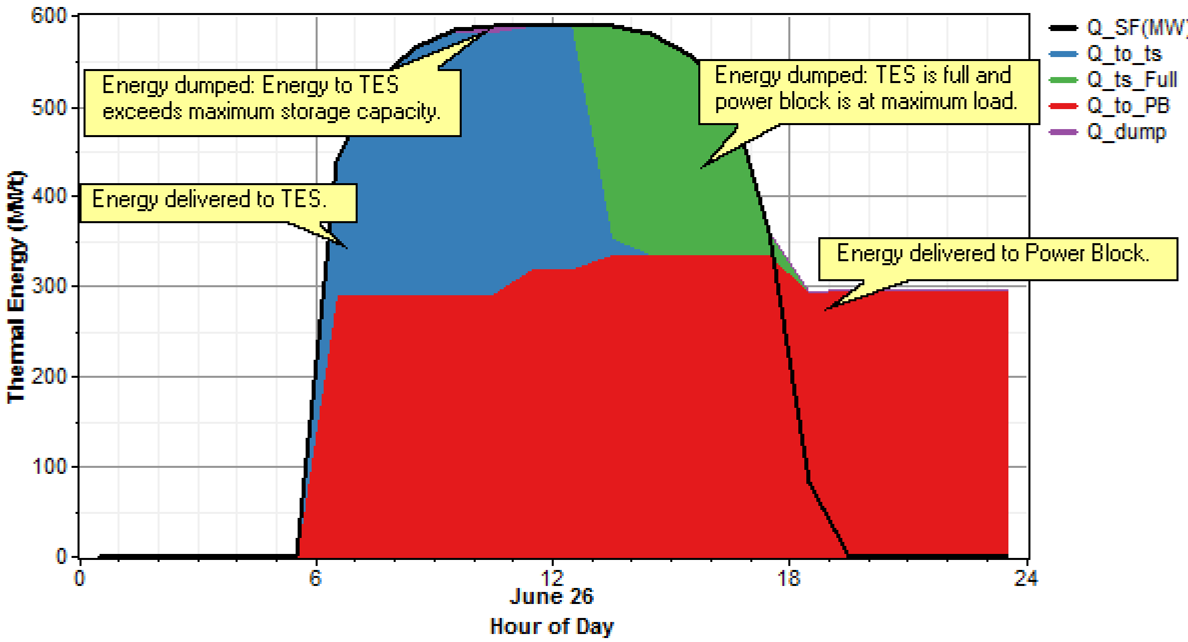
Table 8.2. Hourly output variables calculated by the Power Block module

Name	Name in Hourly Results	Description	Units	Symbol
Gross turbine output	E_gross	Hourly turbine electric output from both solar and fossil sources, but not accounting for parasitic losses or availability.	MWe	E_{Gross}
Net electric output	E_net	Net hourly turbine electric output from both solar and fossil sources accounting for parasitic losses, but not for availability.	MWe	E_{Net}
Parasitic losses	E_parasit	Total electric energy losses due to parasitic electrical loads in the system (pumps, control electronics, etc.)	MWe	$E_{Parasitics}$
Minimum turbine output	E_min	The calculated gross solar output during hours when the solar energy is insufficient to drive the turbine. This value is reported in the hourly results, but does not contribute to the power output.	MWe	E_{Min}
Excess electricity	E_dump	For hours when the gross solar output exceeds the maximum over design output, the difference between the two is reported as excess electricity. This value does not contribute to power output.	MWe	E_{Dump}
Fossil backup energy	Q_gas	The thermal energy equivalent of the electric energy generated by the fossil fuel-fired backup boiler.	MWt	Q_{Gas}

Table 8.3. Hourly output variables calculated by the Dispatch and Storage module

Name	Name in Hourly Results	Description	Units	Symbol
Energy to thermal storage	Q_to_ts	Thermal energy delivered to TES	MWt	Q_{toTES}
Energy from thermal storage	Q_from_ts	Thermal energy from the TES	MWt	$Q_{fromTES}$
Energy to the power block	Q_to_PB	Thermal energy delivered to the power block. May include energy from the solar field, or energy from both the solar field and thermal storage.	MWt	Q_{toPB}
Dumped TES energy	Q_ts_Full	Thermal energy dumped when the TES is full. This happens in hours when the calculated energy in TES exceeds the maximum TES capacity $Q_{inTESMax}$, described in Dispatch Parameters.	MWt	$Q_{TESDump}$
Dumped energy	Q_dump	Thermal energy dumped when either the energy delivered to either the power block or TES exceeds the maximum allowed.	MWt	Q_{Dump}
Start up energy	Q_tur_SU	Energy required to start power block. This happens in hours when energy is available from the solar field or thermal storage and the power block did not operate in the previous hour.	MWt	$Q_{PBStartup}$
Freeze protection energy from TES	Q_htfFPTES	Energy supplied by the TES when the heat transfer fluid temperature falls below its freezing point (defined by the minimum HTF temperature on the Solar Field page).	MWt	$Q_{TESFreezeProtect}$
Freeze protection energy from auxiliary heater	Q_hftFpHtr	Energy supplied by the auxiliary heater when the heat transfer fluid temperature falls below its freezing point (defined by the minimum HTF temperature on the Solar Field page).	MWt	$Q_{HTRFreezeProtect}$
Thermal storage heat loss	QTS_HL	Heat loss from the storage tank, equal to the tank heat losses on the Storage page.	MWt	$Q_{TankHeatLoss}$

SAM reports dumped thermal energy that result from two different conditions:



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Note: The page numbers in this index refer to the first page of the section containing the keyword.

Index

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