

A Generalized Model to Estimate Field Size for Solar-Only Parabolic Trough Plant

Channiwala S.A.* and Ekbote A.

*Author for correspondence

Department of Mechanical Engineering,
Sardar Vallabhbhai National Institute of Technology,
Surat, Gujarat,
India,

E-mail: sac@med.svnit.ac.in

ABSTRACT

A number of computer performance simulations have been developed for modelling the performance of parabolic trough plants, most of which are proprietary or require very detailed inputs. Hence, there is a need to develop a generalized model that allows the designer to quickly estimate the solar field size for a parabolic trough plant at a given location.

In order to cater to this need, a generalized model has been developed using the equations, correlations and typical values of certain parameters available in the open literature. The paper presents the complete details of various equations, correlations, loss models and the general data to be used by designer and outlines a systematic procedure coded in Matlab™ to evaluate solar field size for solar-only parabolic trough plant. Finally, to demonstrate this procedure, the model has been used to estimate the solar field size for a small 25 kWe solar-only trough plant at SVNIT, Surat, India. The results of the model indicate the solar field size of 245m² for a 25 kWe plant to be installed at SVNIT, Surat.

INTRODUCTION

Parabolic trough technology is currently the most proven solar thermal electric technology. This is primarily due to nine large commercial-scale SEGS (Solar Energy Generating System) plants, the first of which has been operating in the California Mojave Desert since 1984. [1] These plants, which continue to operate on a daily basis, range in size from 14 to 80 MW and represent a total of 354 MW of installed electric generating capacity.

A parabolic trough power plant generates electricity using concentrated sunlight as the heat source for its power cycle. Rows of single-axis-tracking, linear parabolic mirrors comprise a solar field that concentrates beam radiation onto tubular

receivers (also known as heat-collection elements [HCEs]) located along the focal line of each parabolic trough. Heat-transfer fluid (HTF) pumped through the receivers is heated by convection from the sun-heated receiver walls. After being heated by the solar field, the HTF travels to a power block where it generates steam in a series of heat exchangers. The energy in the steam is converted to electricity in a Rankine steam-turbine power cycle. After heating the steam, the HTF returns to the solar field.

Simulation models

Because solar plants rely on an intermittent fuel supply (the sun), it is necessary to model the plant's performance on an hourly (or finer resolution) basis to understand what the annual performance will be.

A number of proprietary computer performance simulations have been developed for modeling the performance of parabolic trough plants. Luz International Limited developed an hourly simulation model that was used to help design the SEGS plants. Flabeg Solar International (FSI, known as Pilkington Solar International and Flagsol before 1995) developed a performance simulation model to market parabolic trough plants and conduct design studies for clients [1]. KJC Operating Company (KJCOC), the operator of SEGS III.VII, has developed an hourly simulation model for assessing the performance of its plants. This model is very specific to the 30-MWe plants at Kramer Junction and the needs of the operating company. As a result, it has limited capability for modeling different plant configurations. The German research laboratory Deutsches Zentrum für Luft- und Raumfahrt (DLR) has also developed a performance model for parabolic trough plants. All of these models are proprietary and are not generally available to the general public.

DLR and Sandia National Laboratories (SNL) have developed a special library for use with the TRNSYS thermal simulation software, to model parabolic trough solar power

plants [2]. TRNSYS is a commercially available software package and is very suited for modeling complex systems, such as parabolic trough power plants. Unfortunately, TRNSYS requires very detailed input data to get results that accurately reflect expected plant performance. In addition, TRNSYS only calculates plant performance, thus economic trade-off studies must be iterated between TRNSYS and a separate economics model.

The System Advisor Model (SAM) is a comprehensive solar technology systems analysis model developed by staff at National Renewable Energy Laboratory and Sandia National Laboratory and is available to the general public. It is able to model the costs, finances, and performance of solar plants.

However there is a need to develop a model that allows the designer to quickly estimate the solar field size for a parabolic trough plant at a given location.

NOMENCLATURE

θ	[deg]	angle of incidence
δ	[deg]	declination angle
ω	[deg]	hour angle
θ_z	[deg]	zenith angle
f	[m]	focal length
η_{field}	[-]	field efficiency
η_{HCE}	[-]	HCE efficiency
T	[°C]	temperature
V	[m/s]	wind velocity

Abbreviations

SEGS	Solar Energy Generating System
CSP	Concentrated Solar Power
HCE	Heat Collection Element
HTF	Heat Transfer Fluid
FSI	Flabeg Solar International
DLR	Deutsches Zentrum für Luft-und Raumfahrt
KJCO	KJC Operating Company
DNI	Direct Normal Insolation
SAM	System Advisor Model
IAM	Incidence Angle Modifier
SCA	Solar Collector Assembly

DESCRIPTION OF THE MODEL

The model has been developed using the equations, correlations, loss models and typical values of certain parameters available in the open literature[3][4][5]. The model is coded in MatlabTM and provides several options for the designer to select from such as type of collector and receiver as well as suggests the typical values of certain parameters.

The model first calculates the parameters required for subsequently calculating the net energy collected over the solar field and finally the solar field aperture area as follows:

Direct normal insolation

Extraterrestrial solar radiation follows a direct line from the sun to the Earth. Upon entering the earth's atmosphere, some solar radiation is diffused by air, water molecules, and dust within the atmosphere [5]. The direct normal insolation represents that portion of solar radiation reaching the surface of

the Earth that has not been scattered or absorbed by the atmosphere. The adjective "normal" refers to the direct radiation as measured on a plane normal to its direction.

For DNI, the model provides the user three methods to select from:

Method 1: The selection of the first method requires the user to specify the DNI directly

Method 2: The selection of the second method requires the user to specify the global and diffuse radiation. In case of the second method, the model calculates the DNI from global and diffuse radiation and the zenith angle.

$$DNI = \frac{Global - Diffuse}{\cos \theta_z} \quad (1)$$

Method 3: The third method calculates the DNI based on the ASHRAE model (modified by Iqbal). However, the user can specify the day of the year as either June 21 (n=172; summer solstice) or December 21(n=355; winter solstice) only. [6] [7]

Incidence angle

Over the course of an entire year, the north-south oriented single-axis tracking receives slightly more energy than an east-west single-axis tracking aperture in the same location [8]. Also, the north-south oriented tracking aperture receives more energy in the summertime, when electricity demand is highest and the solar collectors are designed for their peak performance.

The incidence angle for a plane rotated about a horizontal north-south axis with continuous east-west tracking to minimize the angle of incidence is given by [5]:

$$\cos \theta = \sqrt{\cos^2 \theta_z + \cos^2 \delta \cdot \sin^2 \omega} \quad (2)$$

The calculation of the incidence angle thus involves the calculation of the declination angle, hour angle and zenith angle.

The expression for the declination angle as given in [5] is as follows:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (3)$$

Where n = the day number of the year, from 1 (corresponding to January 1) to 365 (corresponding to December 31).

As given in [3], the hour angle comes as a result of the rotation on the earth, which spins on its axis at a rate of 15° per hour:

$$\omega = (SolarTime - 12) \cdot 15^\circ / hr \quad (4)$$

where ω is the hour angle [deg] and SolarTime is the solar time [hr].

The relationship between solar time and standard time, in hours, is:

$$SolarTime = StandardTime + \frac{(L_{st} - L_{loc})}{15} + E \cdot \frac{1h}{60 \text{ min}} \quad (5)$$

The equation of time used here, in minutes, comes from Spencer as cited in [7]:

where

$$B = \frac{360}{365}(n-1) \quad (6)$$

n = day number of the year (1 for January 1, 365 for December 31)

The zenith angle is related to both the declination angle and the hour angle by the following relationship [5]:

$$\cos \theta_z = \cos(\delta) \cdot \cos(\phi) \cdot \cos(\omega) + \sin(\delta) \cdot \sin(\phi) \quad (7)$$

where

= declination angle [deg]

= hour angle [deg]

= latitude location of the plant [deg]

Incidence angle modifier

In addition to losses due to the angle of incidence, there are other losses from the collectors that can be correlated to the angle of incidence. These losses occur due to additional reflection and absorption by the glass envelope when the angle of incidence increases. The incidence angle modifier (IAM) corrects for these additional reflection and absorption losses.

The equation for the incidence angle modifier is:

$$IAM = 1 + 0.000884 \cdot \frac{\theta}{\cos \theta} - 0.00005369 \cdot \frac{\theta^2}{\cos \theta} \quad (8)$$

The model has been developed in such a way so as to allow the designer (user) to select any combination of SCA and HCE. Euro Trough ET150, Luz LS-2, Luz LS-3 and Solargenix SGX-1 are the types of the SCAs (collectors) to select from. Luz Cermet, Solel UVAC2, Solel UVAC3, Schott PTR70 and 2008 Schott PTR70 are the types of the HCEs (receivers) to select from.

Row shadowing and end losses

The positioning and geometry of the collector troughs and HCEs can introduce further losses, due to shading of parallel rows in the morning and evening as well as end losses from the HCE.

Row shading decreases collector performance by decreasing the amount of radiation incident on the collectors. The width of the mirror aperture which receives incident radiation (that is, the width of the aperture that is not shaded) is defined as the "effective mirror width." The row shadow factor is the ratio of the effective mirror width to the actual mirror width. This ratio can be derived from the geometry of the solar zenith angle, the incidence angle, and the layout of the collectors in a field [9]:

$$RowShadow = \min \left[\max \left(0, \frac{Lspacing}{W} \cdot \frac{\cos \theta_z}{\cos \theta} \right); 1.0 \right] \quad (9)$$

where

$RowShadow$ = row shadow factor [-]

$Lspacing$ = length of spacing between troughs [m]

W = collector aperture width [m]

θ_z = zenith angle

θ = angle of incidence

where $RowShadow \in [0;1]$. A value of 0 for $RowShadow$ means complete shading whereas a value of 1 for $RowShadow$ means no shading of the collector.

End losses occur at the ends of the HCEs, where, for a nonzero incidence angle, some length of the absorber tube is not illuminated by solar radiation reflected from the mirrors.

The end losses are a function of the focal length of the collector, the length of the collector, and the incident angle [10]:

$$EndLoss = 1 - \frac{f \tan(\theta)}{L_{SCA}} \quad (10)$$

where

f = focal length of the collectors [m]

θ = incident angle

L_{SCA} = length of a single solar collector assembly [m]

	Euro Trough ET 150	Luz LS-2	Luz LS-3	Solargenix SGX-1	Albisa Trough AT 150
SCA length (L_{SCA}) [m]	150	49	100	100	150
SCA Aperture (W) [m]	5.75	5	5.75	5	5.774
Average Focal Length (f) [m]	2.11	1.8	2.11	1.8	2.11
SCA Aperture Area [m ²]	817.5	235	545	470.3	817.5

Table 1 Parameters for SCA [4]

Field efficiency and HCE efficiency

The final category of solar radiation losses lies in the surface properties and inaccuracies of the solar collector trough mirrors, glass envelope, and receiver tube materials. Insolation may be absorbed or scattered by dirt on the mirrors, or mis-reflected due to small mirror inaccuracies or tracking error. The transmissivity of the glass envelope, the absorptivity of the receiver tube selective coating, and other surface properties will also contribute to the final solar radiation absorption.

Over time, as older malfunctioning collectors are gradually replaced with the next generation of HCEs and mirrors, the makeup of the field may include two or three or more types of solar collector assemblies and receiver tubes. Surface properties and correction factors may vary from one type or generation of equipment to the next. The resultant efficiency for the field as a whole is assumed in the model to be the weighted average of the performance of each type of component found in the field.

However, since our objective is to design a new plant, we have considered that the solar field is composed of a single type of solar collector assembly. The sum effect of surface and correction parameters for the collector assembly and mirrors is accounted for in the field efficiency term, η_{field} :

$$\eta_{field} = TrkTwstErr \cdot GeoAcc \cdot MirRef \cdot MirCln$$

where

$TrkTwstErr$ = twisting and tracking error associated with the collector type

$GeoAcc$ = geometric accuracy of the collector mirrors

$MirRef$ = mirror reflectivity
 $MirCln$ = mirror cleanliness

Typical values:
 $TrkTwstErr$ = 0.99
 $GeoAcc$ = 0.98
 $MirRef$ = 0.935
 $MirCln$ = 0.95

The sum effect of surface and correction parameters for the heat collection element is accounted for in the HCE efficiency term, η_{HCE} :

$\eta_{HCE} = HCEdust \cdot BelShad \cdot EnvTrans \cdot HCEabs$
 where
 $HCEdust$ = losses due to shading of HCE by dust on the envelope
 $BelShad$ = losses from shading of ends of HCEs due to bellows
 $EnvTrans$ = transmissivity of the glass envelope
 $HCEabs$ = absorbtivity of the HCE selective coating

Table shows the typical surface properties and correction parameters for the HCE.

	Schott PTR70	Luz Cermet	Solel UVAC2	Solel UVAC3	2008 Schott PTR70
$HCEdust$	0.98	0.98	0.98	0.98	0.98
$BelShad$	0.963	0.971	0.971	0.971	0.963
$EnvTrans$	0.963	0.935	0.96	0.96	0.963
$HCEabs$	0.96	0.925	0.96	0.96	0.96

Table 2 Optical parameters for the HCE [4]

Receiver heat loss

As the heat transfer fluid in the receiver tubes absorbs energy, its temperature will increase. This temperature increase creates a temperature difference between the bulk temperature of the fluid and the temperature of the surrounding ambient air. Heat losses from the receiver tube to the glass envelope, as well as from the glass envelope to the ambient air, are driven by this temperature difference.

The heat loss in W/m^2 is calculated as below:

$$RecHL = \frac{F_{HL}}{W} \cdot \frac{(Q_{HL1} + Q_{HL2} + Q_{HL3} + Q_{HL4})}{T_{SFout} - T_{SFIn}}$$

where

The heat loss terms Q_{HL1} , Q_{HL2} , Q_{HL3} and Q_{HL4} are calculated as follows:

$$Q_{HL1} = (A0 + A5 \cdot \sqrt{V}) \cdot (T_{SFout} - T_{SFIn})$$

$$Q_{HL2} = \frac{A1 + A6 \cdot \sqrt{V}}{2} \cdot [(T_{SFout}^2 - T_{SFIn}^2) - T_{amb} \cdot (T_{SFout} - T_{SFIn})]$$

$$Q_{HL3} = \frac{A2 + A4 \cdot DNI}{3} \cdot (T_{SFout}^3 - T_{SFIn}^3)$$

$$Q_{HL4} = \frac{A3}{4} \cdot (T_{SFout}^4 - T_{SFIn}^4)$$

The default values of the heat loss coefficients A0, A1, A2, A3, A4, A5 and A6 for each receiver type 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 coefficients for each receiver type are shown in the Table 3. F_{HL} (in the main Heat Loss Eqn.) is the Heat Loss Factor which 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.

	Schott PTR70	Luz Cermet	Solel UVAC2	Solel UVAC3	2008 Schott PTR70
A0	1.8615	2.4237	1.8615	0.6364	4.0500
A1	0.18741	0.21369	0.18741	0.11360	0.24700
A2	-1.15940E-3	-0.47461E-3	-1.1594E-3	-0.8E-3	-1.46E-3
A3	6.6026E-6	6.8836E-6	6.6026E-6	4.9860E-6	5.65E-6
A4	8.803E-8	9.6216E-8	8.803E-8	6.588E-8	7.62E-8
A5	-0.91215	-2.24230	-0.91215	-0.51620	-1.70000
A6	0.011763	0.032325	0.011763	0.006500	0.012500

Table 3 Heat loss coefficients for the HCEs

Solar Field Piping Heat Losses

Thermal losses from the piping leading to and from the loops in the solar field are accounted for by the following empirical equation:

$$SfPipeHL = 0.01693 \Delta T - 0.0001683 \Delta T^2 + 6.78 \cdot 10^{-7} \Delta T^3$$

Where $SfPipeHL$ is expressed per unit area of solar field aperture [W/m^2], and ΔT [$^{\circ}C$] is the difference between the average field temperature and the ambient air temperature:

$$\Delta T = \frac{T_{SFout} + T_{SFIn}}{2} - T_{amb}$$

Thermal losses due to piping to and from the solar field are generally small, on the order of 10 [W/m^2] or less during solar field operation.

The net energy collected by the heat transfer fluid over the field, per unit aperture area [W/m^2], is the difference between the heat absorbed into the fluid by the absorber tubes ($\dot{Q}_{absorbed}$) and the sum of heat loss from the receivers ($RecHL$) and heat loss from the piping to and from the solar field ($SfPipeHL$):

$$\dot{Q}_{collected} = \dot{Q}_{absorbed} - (RecHL + SfPipeHL)$$

The thermal rating of the solar field (\dot{Q}_{rating}) is calculated from the design turbine gross output and power cycle efficiency as follows:

$$\dot{Q}_{rating} = \frac{\text{Design Turbine Gross Output}}{\text{Power cycle efficiency}}$$

The required solar field aperture area ($SF_{\text{aperture area}}$) is calculated as below:

$$SF_{\text{aperture area}} = \frac{\dot{Q}_{\text{rating}}}{\dot{Q}_{\text{collected}}}$$

where \dot{Q}_{rating} = thermal rating of the solar field [W]

$\dot{Q}_{\text{collected}}$ = net energy collected by the heat transfer fluid over the field [W/m^2]

$SF_{\text{aperture area}}$ = required solar field area [m^2]

Land area and capital cost

Additionally, the model enables the determination of the total land area and the capital cost.

Solar field land area is calculated as follows:

$$\text{Solar field land area} = SF_{\text{aperture area}} \cdot \frac{L_{\text{spacing}}}{W} \cdot 0.000247$$

where

Solar field land area = Land area required for the solar collectors including the space between the collectors [acres]
0.000247 is the sq. m. to acre conversion factor.

Total land area is calculated as follows:

Total land area = Non Solar field area multiplier . Solar field land area

where Non Solar field area multiplier is a multiplier which accounts for the land area other than the solar field i.e the land occupied by power block, etc. Usually, the value of Non Solar field area multiplier is around 1.4.

Total land area = Land area required for the entire system including the solar field land area [acres]

Cost of entire power plant is calculated as follows:

Cost = Cost per MW . Turbine Gross Output

According to CERC's Tariff Order, the cost per MW of solar thermal power plant is 120 million INR. [13]

ILLUSTRATION

For a 25 kWe parabolic trough plant at Surat, the solar field aperture area (i.e. no. of SCAs/collectors) is required to be estimated.

Solar resource assessment

Solar radiation and meteorological data for Surat was obtained from different sources and analysed. The radiation data for Surat was obtained from NREL's RRED [33]. The SUNY model produces estimates of global and direct irradiance at hourly intervals on the 10-km grid for all of India, as shown on the India solar maps. The data are produced using visible images from a Meteosat satellite. The radiation data from December of 2001 to December of 2008 was available. Complete data was available only for the years 2003, 2004, 2005 and 2006. Hence only these years were chosen for analysis. The results of the analysis are shown in Table 4.

	2003	2004	2005	2006
Max. DNI	902	915	895	882
95% cum. freq.	823	841	832	829

Table 4 DNI analysis for Surat [11]

The meteorological data required for the analysis such as the average wind speed and the average dry bulb temperature was taken from the ISHRAE weather file (downloaded from EnergyPlus website). [12] From the above analysis of DNI values, a value of 800 W/m^2 is appropriate to be selected as design value for Surat. Generally, the solar thermal power plants are designed for solar noon of 21st June (summer solstice). Luz LS-2 was chosen as the collector type and Luz Cermet as the receiver type. The values for ambient temperature and the wind speed were chosen as the average ambient temperature and average wind speed for Surat. Capital cost per MW was chosen in line with the cost assumption of Central Electricity Regulatory Commission (CERC).

Determination of power cycle efficiency

The value of power cycle efficiency for the plant was determined as follows:

Turbine rated output (gross) = 25 kWe

Condenser pressure = saturation pressure corresponding to summer condition

Summer condition: 50°C DBT (Max.); 44°C WBT

Design condition temperature, $T_m = 46^\circ\text{C} = T_1$

Therefore, condenser pressure = P_{sat} at $46^\circ\text{C} = 0.1 \text{ bar}$

The steam conditions at inlet to the turbine was assumed to be 20 bar and 320°C based on the survey of the turbines of similar capacity used in sugar factories.

Enthalpy of the steam at the inlet of the turbine, h_1 (at 20 bar, $320^\circ\text{C} = 3070 \text{ kJ/kg}$)

Enthalpy of the steam at the outlet of the turbine, h_2' (at 0.1 bar) = 2175 kJ/kg

$$\eta_{\text{isen}} = \frac{h_1 - h_2}{h_1 - h_2'}$$

Isentropic efficiency of turbine,

Isentropic efficiency of turbine was assumed to be 70% considering that its capacity is 25 kWe.

$$0.7 = \frac{3070 - h_2}{3070 - 2175}$$

Hence, $h_2 = 2443.5 \text{ kJ/kg}$

Now, turbine work

$$\dot{W}_t = \dot{m}_s (h_1 - h_2)$$

$$\dot{m}_s = \frac{\dot{W}_t}{(h_1 - h_2)} = \frac{25}{(3070 - 2443.5)} = 0.0399 \text{ kg/s}$$

$$h_3 = h_f \text{ at } 46^\circ\text{C} = 192.5 \text{ kJ/kg}$$

$$\text{Heat supplied} = \dot{m}_s (h_1 - h_3) = 0.0399(3070 - 192.5) = 114.8244$$

Hence, Heat supplied = 114.8244 kW

$$\text{Overall efficiency, } \eta_{\text{overall}} = \frac{\text{Net Work}}{\text{Heat supplied}} = \frac{25}{114.8244} = 0.2177$$

RESULTS

The inputs that are to be given to the model for estimating the solar field aperture area are shown in Table 5

Sr. No.	Input parameters	Values
1	Standard Meridian [deg]	82.5 (for India)
2	Latitude [deg]	21.17 (for Surat)
3	Longitude [deg]	72.83 (for Surat)
4	Day number of the year [-]	172 (21 st June, summer solstice)
5	Solar Noon [-]	1 (Yes)
6	Method for DNI [-]	1 (to directly specify)
7	DNI [W/m ²]	800 (for Surat)
8	Type of collector [-]	Luz LS-2
9	Row spacing, center-to-center [m]	15
10	Type of receiver [-]	Luz Cermet, Vacuum
11	Design solar field outlet temperature [°C]	393
12	Design solar field inlet temperature [°C]	293
13	Ambient temperature [°C]	27.2 (for Surat)
14	Wind speed [m/s]	3.7 (for Surat)
15	Turbine gross output [MWe]	0.025
16	Power cycle efficiency (%)	21.77
17	Cost of 1 MW [million INR]	120
18	Non_SF_area_Multiplier [-]	1.4

Table 5 Inputs to the model

The outputs obtained from the model are shown in Table 6.

Sr. No.	Output parameters	Values
1	Solar field aperture area [m ²]	244.2597
2	No. of SCAs [-]	2
3	Solar field land area [acres]	0.1810
4	Total land area [acres]	0.2534
5	Cost [million INR]	3

Table 6 Outputs from the model

For a 25 kWe parabolic trough plant at Surat, the solar field aperture area was estimated to be 245 m². Hence two Luz LS-2 collectors would be required. The required total land area and capital cost was estimated to be 0.25 acres and 3 million INR respectively.

CONCLUSION

The model allows the designer quickly estimate the solar field size for a solar-only parabolic trough plant under a given set of conditions and technical configuration of a parabolic trough power plant. The model can be modified to include the values of the parameters of newer collectors and receivers. The model can also be modified to enable the designer to provide inputs for calculating the power cycle efficiency instead of directly specifying the power cycle efficiency as an input. After carrying out rigorous resource assessment, detailed design and

simulations a small scale parabolic trough solar thermal power plant of around 25 kWe is planned to be setup at SVNIT, Surat. For this proposed plant, the model was used to estimate the solar field area. The results indicate that the required solar field area would be 245 m² and the total land area would be 0.25 acres. The capital cost of the plant would be 3 million INR.

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