Preliminary Design of Heliostat Field and Performance Analysis of Solar Tower Plants with Thermal Storage and Hybridisation

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Abstract

Solar tower technology has gained considerable momentum over the past decade. In a solar tower plant, a single receiver is used and the power collected by the heliostat field is strongly coupled to the tower height and its location with respect to the field. The literature available focuses largely on the component-level details of the heliostat field, ray-tracing mechanisms, receiver heat transfer analyses, etc. However, there is no systematic method to determine the preliminary optimum tower height and solar field together with an estimation of a solar tower plant's technical performance. The present paper provides a methodology to estimate the design performance of a tower plant (with storage and hybridisation) using an external cylindrical receiver. The methodology is validated with the Gemasolar plant in Spain and the Crescent Dunes plant in the United States of America. The optimum efficiency is 16% for the Gemasolar plant (20 MW and 15 hours of storage) and 18.3% for the Crescent Dunes plant (110 MW and 10 hours of storage). Further, the methodology is applied to hypothetical plants in Jodhpur as a case study and the results are analysed. The trends seen are similar to that observed for parabolic trough plants.

Keywords: Solar Tower; Thermal Storage; Hybridization; Tower Height; Concentrated Solar Power

Nomenclature

Symbol	Variable Name	Units
DNI_i	Hourly Direct Normal Irradiance at the location for the i^{th} hour	W/m^2
LA	Total land area	m^2
MA	Total mirror area	m^2
N_f	Number of points under boundary chosen by user	
PD	Packing density at point p of the field	
$P_{cap,d}$	Design plant capacity	MW
$P_{htf,i}$	Thermal power input to the heat exchanger from solar field for the i^{th} hour	W
P_i	Solar power impinging on receiver for hour i	W
P_{imax}	Maximum of the P_i values (over 8760 hours)	W
$P_{s,d}$	Design solar power required from the field	W
SM	Solar Multiple	
$S_{n,j}$	Slant distance from point j of the solar field to the receiver (this is effectively $S_{n,nd,j} \times h$)	km
$\frac{d_x}{h}$ and $\frac{d_y}{h}$	Non-dimensional length/width of elemental area	
e_g	Gross electrical energy that would be generated during the hour without considering energy needed for start-up	Wh
e_{ga}	Gross hourly electrical energy available after accounting for start-up	Wh
$e_{ga,t}$	Total annual gross electrical energy available	Wh
$e_{grid,t}$	Total annual gross electrical energy supplied to the grid	Wh
$e_{hb,t}$	Total annual gross electrical energy apportioned to hybridisation	Wh
e_l	Annual reflected energy per unit land area of the solar field (taking into account cosine effect and packing density)	Wh/m^2
$e_{s,t}$	Total annual gross electrical energy apportioned to solar input	Wh

f_{hb}	Fraction of hybridisation power	
f_p	Fraction of the design gross electrical power generated ignoring thermal losses during shutdown	
f_{pa}	Ratio of electrical power generated to the rated capacity	
f_{th}	Fraction of design thermal power delivered to power block	
h	Height of the tower	m
$h[1]_i$	Initial height of tower at $SM = 1$	
$h[1]$	Final height of tower at $SM = 1$	m
$h[SM]$	Height of tower for a given SM	m
$h_{new}[1]$	Height variable used during iteration	m
i	Number of hours (varies from 1 to 8760)	
j	Set of all points under boundary (varies from 1 to N_f)	
p	Each point in the field	
r	Radial distance from the base of the tower to a point in the field	m
r/h	Non-dimensionalised radial distance of point $(x/h, y/h)$ from the tower	
$\left(\frac{r}{h}\right)_{min}$	Minimum non-dimensional distance of the solar field from the tower	
t_s	Number of hours of thermal storage	Hours
x/h	Non-dimensionalised x coordinate of a point in the field	
y/h	Non-dimensionalised y coordinate of a point in the field	
Δh	Height increment	m
$\eta_{att,j}$	Attenuation efficiency of point j	fraction
η_{he}	Heat exchanger efficiency	fraction
η_m	Mirror efficiency	fraction
η_{pb}	Power block efficiency	fraction
$\eta_{receiver}$	Receiver efficiency	fraction
η_{s-e}	Annual solar-to-electric conversion efficiency	in %

η_{st}	Thermal storage efficiency	fraction
ϕ	Latitude of the location	Degrees
$\theta_{i,p}$	Angle of incidence of sunrays for hour i and at point p	Degrees

1. Introduction

A Solar Tower (ST) makes use of a large number of heliostats or mirrors (which have a dual-axis control system to track the sun's rays throughout the day) to reflect the solar energy impinging on them onto a receiver that is located at the top of a tower. Concentrated solar energy that falls on the receiver is transferred to a Heat Transfer Fluid (HTF), which passes through the receiver. The thermal energy of the HTF is then transferred to a working fluid in the power block, by means of a heat exchanger, thereby generating electricity. ST systems generally have a storage component that allows for a part of the solar energy that is collected to be stored for later use. A schematic illustration of an ST plant is shown in Fig. 1.

The available literature on ST covers component-level analyses, specifically on heliostats and their tracking mechanisms [1-4], shadowing and blocking effect algorithms [5], receiver performance and heat transfer analyses [6-7], and heliostat layout optimisation studies [8-9]. Reviews of the many components in this technology as well as existing plants that are in operation and under construction have also been performed [10-11]. Empirical guidance on the preliminary sizing and specification of a heliostat field is provided in [12]. However, the present literature lacks an overall methodology to model a complete ST plant from scratch (with given inputs such as hourly Direct Normal Irradiation (*DNI*) data at the plant location, capacity, thermal storage hours, gross efficiencies, etc.) as was done for the Parabolic Trough (PT) technology [13].

In recent times, the use of ST technology has increased considerably and it is comparable to PT technology. Traditional PV arrays and wind turbine are subjected enormously to the vagaries of nature and are not easily available for large capacity energy storage. Consequently, they are not suitable for large scale dispatchable power. On the other hand, ST technology with thermal storage and hybridisation offers an alternative means of using renewable energy for large scale dispatchable power.

The primary objective of this study is to develop a methodology to carry out a technical analysis of a ST, similar to the one carried out for a PT plant in CSTEP's Solar Techno-Economic Model (CSTEM). The working of the PT tool model is described in detail in [13-14]. While attempting to do this, it was realised that due to fundamental differences between the PT and ST technologies, a straightforward extension of the methodology could not be used for an ST. On studying these differences, it was observed that the crux of the issue is that in the case of PT, the solar energy that can be collected by the receiver is directly proportional to the land area of the solar field. However, in the case of an ST, the solar energy that can be collected by the solar field is a complex function of the solar field layout relative to the tower. Therefore, the first pre-requisite for developing a methodology analogous to that developed for PT [13], was to obtain a rational method for fixing the boundary of the solar field around the tower in terms of the variation of the non-dimensional quantity, r/h , with respect to the azimuth angle, where r is the radial distance from the tower and h is the height of the tower. This method is explained in detail in [15] but an outline is discussed in Section 2. Once the coupling between tower height and the heliostat solar field is established, it has been possible to extend the methodology used for PT, with some modifications, to an ST to determine the optimum tower height and the corresponding solar field for a given capacity of steam Rankine power cycle with specified hours of storage and limited hybridisation.

This paper describes the methodology to determine the optimum solar field, associated tower height and plant performance of an ST that uses an external cylindrical receiver and molten salt as both the HTF and storage medium, operating with a steam Rankine power cycle, by utilising this coupling between tower height and solar field through a non-dimensional solar field.

The inputs to the model and the details of the methodology are explained in Section 3. Section 4 describes the validation of the model. Section 5 describes a case study on a hypothetical ST plants

located at Jodhpur (India), for various capacities, with different hybridisation and thermal storage capacities, followed by the concluding remarks in Section 6.

2. Determination of Non-Dimensional Solar Field Boundary

A rational method for fixing this non-dimensional boundary is explained in detail in [15]. This method is applicable to a solar field with radially staggered heliostats and using an external cylindrical receiver. An outline of this method is briefly covered in this section.

This non-dimensional boundary depends on the following:

- 1) Location of the plant (latitude)
- 2) Hourly DNI data for the plant
- 3) Variation of the Packing Density (PD) of heliostats (ratio of local heliostat area and land area) with r/h .

Considering the variation of the PD of a few existing ST plants, a nominal variation of PD with r/h as given in Eq. (1), Eq. (2) and Eq. (3) has been assumed for this analysis.

$$PD = 0 \quad \text{for} \quad \frac{r}{h} < \left(\frac{r}{h}\right)_{min} \quad (1)$$

$$PD = 0.492 - 0.0939 \frac{r}{h} \quad \text{for} \quad \left(\frac{r}{h}\right)_{min} \leq \frac{r}{h} \leq 2.8 \quad (2)$$

$$PD = \frac{0.6}{\sqrt{\left(\frac{r}{h}\right)^2 - 1}} \quad \text{for} \quad \frac{r}{h} > 2.8. \quad (3)$$

The variation of PD with r/h is shown in Fig. 2.

The steps involved in the method for fixing the non-dimensional solar field boundary are as follows:

- 1) A non-dimensional solar field of extent $-10 \leq x/h \leq +10$ and $-10 \leq y/h \leq +10$ is considered (Y axis being along the north-south direction) and field points in this region, spaced d_x/h and d_y/h from the X and Y coordinate axes, are chosen.
- 2) Knowing the non-dimensionalised coordinates (x/h and y/h) of any field point p , r/h can be determined by Eq. (4).

$$\frac{r}{h} = \sqrt{\left(\frac{x}{h}\right)^2 + \left(\frac{y}{h}\right)^2}. \quad (4)$$

The corresponding PD of point p can be determined.

- 3) For a given location (latitude), for any given hour i of the 8760 hours of a year, the declination, hour, zenith, altitude and azimuth angles can be calculated. Then $\theta_{i,p}$, the angle between the incident ray and the normal to the heliostat located at field point p , can be calculated [16]. This allows us to determine the cosine effect ($\cos\theta_{i,p}$).
- 4) The annual solar energy per unit land area, e_l (taking into account the PD), in MWh/m^2 that can be collected from point p of the solar field and reflected onto the receiver is computed using Eq. (5).

$$e_l = (PD) \sum_{i=0}^{8760} DNI_i \times \cos\theta_{i,p} / 10^6, \quad (5)$$

where DNI_i is the DNI in W/m^2 for the hour i .

- 5) Since all existing plants are generally symmetric w.r.t. the north-south direction, the e_l values are made symmetric at each y/h by using Eq. (6).

$$e_{l(x/h)} = e_{l(-x/h)} = \frac{e_{l(x/h)} + e_{l(-x/h)}}{2}. \quad (6)$$

- 6) A particular value for e_l equal to $e_{lchosen}$ is chosen for fixing the outer solar field boundary. This value is chosen based on the fact that if the energy collected per unit area of the solar field is lesser than a particular value, then it is economically undesirable to use it as a solar field. This value has to be determined from many practical economic considerations, but taking a cue from existing plants (Gemasolar, PS10 and PS20, and Crescent Dunes) the default value chosen is 0.16 MWh annually per unit solar field area.
- 7) For ST plants, the solar field starts beyond a certain minimum value of r/h , given as $(r/h)_{min}$. All points ranging from $j = 1$ to N_f , which have e_l values greater than or equal to $e_{lchosen}$ and r/h values greater than $(r/h)_{min}$, are identified as solar field points for the plant. It may be noted that these non-dimensional field points for an ST depend only on the hourly DNI data at the location of the plant and the variation of PD with r/h , and are independent of the plant capacity ($P_{cap,d}$) or the number of hours of thermal storage (t_s).
- 8) For all solar field points $j = 1$ to N_f , $\cos\theta_{i,p}$ corresponding to each hour i for all 8760 hours in the year is stored and these are utilised in the methodology for determining the physical field boundary for a given $P_{cap,d}$, t_s and fraction of hybridisation (f_{hb}), and the corresponding technical performance of the ST plant. Details are provided in the next section.

3. Methodology for Determination of Tower Height and Technical Assessment of ST Plants

The methodology is similar to that, which was followed for PT plants [13]. However, the adaptation of the methodology for an ST is different from that for PT as is highlighted in this section.

3.1. Overview of the Methodology

In the present paper, the scope of the methodology is limited to the use of molten salt both as heat transfer fluid and thermal storage medium. Further, a steam Rankine cycle is considered for the power block. The inputs needed for applying this methodology are given below.

- i. Location of the ST plant (latitude)
- ii. Hourly DNI data
- iii. Minimum r/h and e_l values for the boundary
- iv. Design plant capacity (MW)
- v. Full load plant efficiency as a function of plant capacity
- vi. Effect of part load on efficiency
- vii. Empirical model to consider thermal losses during plant shutdown
- viii. Efficiencies of various systems: Receiver, mirror and heat exchanger
- ix. Number of hours of thermal storage
- x. Extent of hybridisation for augmentation as a fraction of design thermal power

The outline of the methodology is presented in the flowchart provided in Fig. 3.

3.2. Determination of tower height for $SM=1$ and the Reference Solar Field Area

The inputs are the location of the plant; DNI data for a Typical Meteorological Year (TMY); latitude (ϕ); plant capacity ($P_{cap,d}$); and the efficiencies of the mirrors (η_m), receiver ($\eta_{receiver}$) and heat exchanger (η_{he}). Apart from these, non-dimensional lengths d_x/h and d_y/h , and coordinate points x/h and y/h for all points N_f falling in the non-dimensional solar field (as discussed in Section 2) are also used. For considering attenuation, one of two models can be considered: Clear or Hazy day, depending on atmospheric visibility conditions.

In the present paper, we limit the scope to a steam Rankine cycle to run the power block. The power block efficiency (η_{pb}) depends on many factors, for example, the inlet pressure and temperature of steam, condenser pressure, capacity of turbine and mass flow rate of steam. The variation of gross maximum power block efficiency with turbine inlet temperature for different turbine outlet temperatures is given in [14]. Based on the variation of gross maximum efficiency with turbine inlet temperature, the final power block efficiency conditions (which have been used in this model) are given in Eq. (7) and Eq. (8). The turbine inlet and outlet temperatures have been taken as $\sim 560^\circ\text{C}$ and 70°C , respectively.

$$\eta_{pb} = 0.441 - 0.262 \times e^{-0.06 \times P_{cap,d}} \quad \text{for } 0 \leq P_{cap,d} < 50 \quad (7)$$

$$\eta_{pb} = 0.44 \quad \text{for } P_{cap,d} \geq 50. \quad (8)$$

Using these inputs, the reference solar field area is determined using the following procedure:

- 1) The design solar power, $P_{s,d}$, that needs to impinge on the central receiver to generate the electric power corresponding to $P_{cap,d}$, taking into account η_{pb} , η_{he} and $\eta_{receiver}$, is computed as given in Eq. (9).

$$P_{s,d} = \frac{P_{cap,d} \times 10^6}{\eta_{receiver} \times \eta_{he} \times \eta_{pb}}. \quad (9)$$

- 2) The minimum physical solar field area, corresponding to $SM = 1$, which is needed to provide the power $P_{s,d}$ to the receiver (at the peak $DNI \times \cos\theta$ out of 8760 hours of the year) needs to be determined. In the case of PT, $P_{s,d}$ is directly proportional to the solar field area, and, hence, it is straightforward to determine the physical solar field corresponding to $SM=1$. But for an ST, $P_{s,d}$ is dependent on both the solar field and its relation to the tower location and height. Since the solar field is now coupled to the tower through the non-dimensional field described in the previous section, the determination of the solar field corresponding to $SM=1$ is equivalent to the determination of tower height at $SM=1$.

It may also be noted that P_i (in W), the solar power impinging on the receiver for hour i , is dependent on the tower height in a complex manner as given in Eq. (10).

$$P_i = \left(\left(\frac{d_x}{h} \times \frac{d_y}{h} \right) \times \eta_m \times \sum_{j=1}^{N_f} DNI_i \times \cos\theta_{i,j} \times PD \times \eta_{att,j} \right) \times (h)^2, \quad (10)$$

where $\eta_{att,j}$ is the attenuation efficiency at point j . It depends on whether a clear-day model [Eq. (11)] or a hazy-day model [Eq. (12)] is used [16].

$$\eta_{att,j} = 0.99326 - 0.1046S_{n,j} + 0.017S_{n,j}^2 - 0.002845S_{n,j}^3 \quad (11)$$

or

$$\eta_{att,j} = 0.98707 - 0.2748S_{n,j} + 0.03394S_{n,j}^2, \quad (12)$$

where $S_{n,j}$ is the slant height of point j from the receiver at the top of the tower in kilometres and is given by Eq. (13).

$$S_{n,j} = \left(\sqrt{(x)^2 + (y)^2 + (h)^2} \right) / 1000. \quad (13)$$

As can be seen, $\eta_{att,j}$ is a function of the height of the tower. The task is to find the value of h such that the maximum of all 8760 P_i values, P_{imax} , is equal to $P_{s,d}$.

Since it is an implicit equation, h is determined by iteration.

First, the initial value of h at $SM=1$, $h[1]_i$, is determined by taking $\eta_{att,j} = 1$ (zero-attenuation condition). Then, $h[1]_i$ is calculated using Eq. (14).

$$h[1]_i = \sqrt{\frac{P_{s,d}}{\left(\frac{dx}{h} \times \frac{dy}{h} \right) \times \eta_m \sum_{j=1}^{N_f} DNI_i \times \cos \theta_{i,j} \times PD \times 1}}. \quad (14)$$

If P_{imax} is calculated with this value of h , considering attenuation, it will naturally be lesser than $P_{s,d}$.

Therefore, a numerical iterative procedure is used for determining $h_{new}[1]$ by incrementing h in steps of Δh such that for a particular value of $h_{new}[1]$, P_{imax} is lesser than or equal to $P_{s,d}$ and for $(h_{new}[1] + \Delta h)$, P_{imax} is greater than $P_{s,d}$.

The value of Δh is initially taken to be 5 m and subsequently reduced in steps of 0.1 m, such that, $h_{new}[1]$ is determined to an accuracy of 0.1 m. This converged value of h is taken as the final height $h[1]$ of the tower corresponding to $SM=1$.

- 3) With the solar field corresponding to $SM=1$, the power generated will be less than $P_{cap,d}$ at all hours other than the peak hour. Therefore, the solar field design involves choosing an optimum solar field with SM greater than 1, after taking into account the storage and hybridisation constraints. The consideration for determining the optimum SM can be based on the coincide state of η_{s-e} vs. SM and Levelised Cost of Electricity (LCOE) vs. SM , if cost inputs are available. In the present study, optimisation is based on maximum η_{s-e} .

3.3. Solar Power Input to the Heat Exchanger at a Chosen SM

The height corresponding to $SM=1$ once found is then used to determine the height at higher SM s, using Eq. (15).

$$h[SM] = h[1] \times \sqrt{SM}. \quad (15)$$

This relation is chosen since the physical solar field area is roughly proportional to h^2 .

It may be noted that $h[1]$ is based only on the capacity of the plant. Other parameters like hours of thermal storage and extent of hybridisation do not play any part in this calculation. Once $h[SM]$ is calculated, the actual power input to the heat exchanger is computed for each hour of the year, using Eq. (16).

$$P_{htf,i} = \left(\left(\frac{dx}{h} \times \frac{dy}{h} \right) \eta_m \times \eta_{receiver} \sum_{j=1}^{N_f} DNI_i \times \cos \theta_{i,j} \times PD \times \eta_{att,j} \right) \times (h[SM])^2, \quad (16)$$

where $\eta_{att,j}$ is a function of $h[SM]$.

3.4. Annual Electrical Energy Generated

The annual electrical energy generated by the plant taking into account the thermal storage and hybridisation constraints is computed. The optimum SM that gives the highest η_{s-e} is chosen for fixing the optimum tower height and the corresponding solar field. Except for the fact that the solar power generated is proportional to the SM in the case of PT, the methodology to account for thermal storage and hybridisation, and for arriving at the optimum SM , is identical to that employed for PT. For every hour, the fraction of thermal power delivered to the power block (f_{th}), the fraction of gross electrical power generated ignoring thermal losses during shutdown (f_p) and the ratio of electrical power generated to the rated capacity (f_{pa}) are computed. The electrical energy generated without accounting for start-up losses (e_g), the electrical energy generated after accounting for start-up losses (e_{ga}), the total annual electrical energy generated after accounting for start-up losses ($e_{ga,t}$) and the annual electricity to the grid ($e_{grid,t}$) are computed. The total electrical energy apportioned to hybridisation ($e_{hb,t}$) and that apportioned to solar ($e_{s,t}$), the Capacity Utilisation Factor (CUF) and η_{s-e} are all computed using the methodology identical to that in [13].

The total Mirror Area (MA) and the total Land Area (LA) are computed using Eq. (17) and Eq. (18), respectively.

$$MA = \left(\sum_{j=1}^{N_f} PD \right) \times \left(\frac{d_x}{h} \times \frac{d_y}{h} \right) \times (h[SM])^2 \quad (17)$$

$$LA = \left\{ \left(N_f \times \left[\frac{d_x}{h} \times \frac{d_y}{h} \right] \right) + \left(\pi \times \left(\left(\frac{r}{h} \right)_{field\ min} \right)^2 \right) \right\} \times (h[SM])^2. \quad (18)$$

The solar energy input is considered as (Annual $DNI \times MA$). Thereby, the value of η_{s-e} is defined as the ratio of the annual electrical energy generated to the solar energy input.

3.5. Determination of the Preliminary Design of Tower Height, Solar Field and Performance of ST

For the specified capacity, storage hours and extent of hybridisation, the variation of η_{s-e} with SM is considered. The SM , for which η_{s-e} is maximum, is used for the preliminary design of tower height and solar field. Subsequently, the performance of the plant is estimated. In this paper, the economic aspects are not considered. However, if information regarding cost and other financial aspects is known, one can go further and determine the variation of LCOE with SM and choose the SM that corresponds to the least LCOE, for the design. Once SM is known, the height, physical solar field and technical performance of the designed ST can be easily estimated.

4. Validation of Model

Based on the methodology discussed, a Java-based Graphical User Interface (GUI) tool called CSTEM – CSTEP's Solar Techno-Economic Model – has been developed. This tool helps to perform hourly simulation of Concentrated Solar Power (CSP) plants using the PT as well as ST technology for various capacities taking into account thermal storage and hybridisation as well.

The default values of various parameters used in this model are shown in Table 1.

To confirm the validity of this model, ST Plant data of Gemasolar (20 MW with 15 hours of storage and 0.15 factor of hybridisation) and Crescent Dunes (110 MW with 10 hours of storage)

were taken and this model was applied to see how the preliminary design obtained by this model compared with the actual values of the plant regarding tower height, land and mirror area, as well as the annual electrical energy generated. The comparison is shown in Table 2. Considering there are many parameters, like the efficiencies of various components, the PD variation assumed and the e_l boundary chosen, whose values used in the model may be different from those of the plant, it can be concluded that as a first-order approximation, the results obtained from the model are quite satisfactory.

It is found that the optimum SM occurs at $SM=2.75$ for Gemasolar ($\eta_{s-e} = 16\%$) and $SM=2.5$ for Crescent Dunes ($\eta_{s-e} = 18.3\%$).

Apart from the efficiencies of various components, the parameters that are important for the model are the PD variation assumed and the e_l boundary value. In fact, these are coupled. The PD variation assumed lies roughly along the mean of the data available up to $r/h = 6.0$. Beyond that, extrapolation is done to obtain the PD for higher r/h values. The solar field of Crescent Dunes extends beyond an r/h of 6, up to about 8. Therefore, if our extrapolated values are different from those used by them, error is likely to be more.

It may also be pointed out that the actual PD variation used in the plants is not smooth and there are kinks when extra heliostats are added to the ring whenever permitted by the circumferential distance. Therefore, if the heliostat pattern for a plant is finalised, the exact PD variation and boundary can be fixed for the chosen e_l value. The important thing to note is that with proper inputs, the model is capable of generating a reasonable first-cut preliminary design for the ST plant, which can be refined in the more detailed design.

5. Application of the Model to Jodhpur as a Case Study: Results and Discussion

In this section, the results of applying the engineering model developed for hypothetical ST plant located in Jodhpur are discussed. Jodhpur ($\phi = 26.26^\circ$) is chosen because it is one of the locations in India that receive high annual DNI . The DNI data for this analysis are taken from CSTEP report [17]. The parameters chosen for the study are shown in Table 3.

For various combinations of these parameters, η_{s-e} , CUF and the annual electricity generated have been computed for various SM values between one and four in suitable steps.

The results are presented and discussed below.

5.1. Case 1: No Thermal Storage and No Hybridisation

This section analyses the effect of various plant parameters when no thermal storage or hybridisation is used. The variation of the CUF with SM for all capacities is shown in Fig. 4. It can be seen that the CUF tends to saturate beyond $SM=4$. With increased SM , the excess power generated beyond the capacity of the plant cannot be utilised and the heliostats have to be defocussed. Hence, the CUF gets saturated with increased SM .

The variation of η_{s-e} with SM for various capacities is plotted in Fig. 5. From this figure, it can be seen that the maximum efficiency occurs at an SM value of about 1.4 for all capacities and the efficiency increases with capacity, reaching a value of about 18% for a 50-MW plant.

5.2. Case 2: Thermal Storage without Hybridisation

In this section, thermal storage for 3, 6 and 15 hours of storage has been considered for plants of capacities 1, 5, 10, 20, 35 and 50 MW. The effect of SM and storage hours on η_{s-e} has been discussed.

5.2.1. Effect of SM

The variation of annual energy generated per MW with SM , for thermal storage of 0, 6 and 15 hours (for various capacities) and with no hybridisation, is shown in Fig. 6. Since the variation in annual energy generated is proportional to the capacity, in this case, the variation of the CUF with SM is similar to the case when no storage hours are used. From Fig. 6, one can also see that as the number of hours of thermal storage increases, the SM should also increase (otherwise the system is not efficient). The requirement of higher thermal storage hours implies the need for a higher SM .

The variation of η_{s-e} with SM for various capacities for 6 hours of thermal storage is shown in Fig. 7. It is observed that in this case, the highest efficiency occurs at $SM=2.1$ and it is independent of plant capacity. It can also be seen that the overall efficiency increases as the capacity of the plant increases. This is mainly due to higher efficiencies offered by the power block at higher plant capacities.

5.2.2. Variation of Optimum SM with Storage Hours ($f_{hb}=0$)

The SM corresponding to the maximum η_{s-e} is considered as the optimum SM (which is independent of plant capacity). Fig. 8 shows the variation of the optimum SM with number of hours of storage (with no hybridisation). A linear trend is observed with number of hours of thermal storage. As mentioned earlier, this optimum SM is independent of the capacity of the plant.

5.3. Case 3: Hybridisation without Thermal Storage

In this section, the effect of hybridisation (without thermal storage) on different parameters of the plant is discussed. Hybridization is mainly used to augment the thermal power from the heliostat field. In the present case, this is restricted to the extent of 0.2 times the rated thermal power.

5.3.1. Effect of Hybridisation on the hourly variation of fractional thermal power and fractional electrical power

In this section, the hourly variation of fractional solar power, $f_{th,s}(P_{htf}/P_{htf,d})$, and fractional electrical power, f_{pa} (electrical power generated/rated capacity), for a typical day (January 21) for $SM=1$ and $SM=1.5$ is shown.

Note that $f_{pa} = e_{ga}/(P_{cap,d} \times 10^6)$ and $f_p = e_g/(P_{cap,d} \times 10^6)$. The advantage of representing $f_{th,s}$ and f_{pa} is that they are independent of the capacity of the plant.

Fig. 9 shows the variation of f_{pa} over a typical day for $f_{hb}=0, 0.1$ and 0.2 along with $f_{th,s}$ for $SM=1$. Note that for the day chosen, $f_{th,s}$ is of the order of 1.0 even during mid-day.

With no hybridisation ($f_{hb} = 0$), there is a lag in power generation, since $f_{th,s}$ is initially used up for compensating thermal losses over-night. Beyond 9 hours, f_{pa} nearly follows $f_{th,s}$.

For $f_{hb} = 0.1$, there is a lag for f_{pa} relative to $f_{th,s}$ but it is lesser. f_{pa} is higher than $f_{th,s}$ beyond 8 hours. However, the upper limit of $f_{pa}=1.1$ has not been reached even during mid-day.

For $f_{hb} = 0.2$, the lag gets further reduced. Between 10 to 14 hours, f_{pa} reaches a limit of 1.1 and the available f_{hb} is only partly used.

These aspects are made clear in Fig. 10 where f_{hb} utilised during the day is shown. It can be seen when $f_{hb} = 0.1$, it is utilised throughout whereas when $f_{hb} = 0.2$, it is utilised only partly between 10 to 14 hours.

Fig. 11 shows the variation of f_{pa} over a typical day for $f_{hb}=0, 0.1$ and 0.2 along with $f_{th,s}$ for $SM=1.5$. With $SM=1.5$, $f_{th,s}$ itself is beyond 1.1 between 9 to 16 hours. Therefore, there is no need for augmentation from hybridisation during these hours. The amount of hybridisation utilised during the day is shown in Fig.12. It may be seen that between 7 to 8 hours and 16 to 17 hours, the extent of hybridisation of 0.1 or 0.2 is utilised. Between 8 to 9 hours, f_{hb} of approximately 0.02 only is utilised.

From the above, it is obvious, as the SM increases, solar power $f_{th,s}$ increases. Even at $SM=1.5$, for the day considered, augmentation needed through hybridisation is very small. Therefore, $SM>1.5$ has not been used for the analysis.

Fig. 12 gives the value of $f_{hb,used}$ during the day. It can be seen that the amount of energy from the field ($f_{th,s}$) is sufficient to run the plant at 1.1 times the full capacity for most of the day, and, hence, there is no necessity of hybridisation for most of this period. It can be observed that for the first hour, $f_{th,s}$ and hybridisation contribute towards compensating for the thermal losses that have occurred overnight. So the amount of energy generated for this hour, f_{pa} , is small. This can be contrasted with the last hour where f_{pa} is not as less as it is for the first hour.

Since at SM values greater than 1.5, the solar field itself might be sufficient to cater the needs of the power block, higher SM s have not been considered in this analysis.

5.3.2. *Effect of Hybridisation on the Annual Efficiency Attributed to the Solar Field*

Fig. 13 shows the variation of η_{s-e} with SM for $f_{hb}=0, 0.1$ and 0.2 for capacities of 1 MW and 50 MW (with no thermal storage). It can be seen that the higher the hybridisation factor, the higher is the overall efficiency. However, the benefit of hybridisation decreases as the SM increases.

5.4. *Case 4: Thermal Storage and Hybridisation*

CUF is independent of the rated capacity of the plant. Fig. 14 and Fig. 15 show the variation of the CUF with SM for 0 and 6 hours of storage, respectively. In both these figures, hybridisation values of 0, 0.1 and 0.2 are considered. It can be seen that the CUF increases with SM , but the benefit of hybridisation is maximum for $SM=1$ and decreases as SM increases as shown in the previous section. It may also be noted that benefit of thermal storage is felt for higher SM s beyond 1.5.

5.5. *Height of Tower at Optimum SM ($f_{hb}=0$)*

From section 2, it is seen that the optimum SM depends only on the number of hours of thermal storage (t_s) and not on the capacity of the plant. However, the optimum physical height of the tower and the corresponding physical solar field for the optimum SM is a function of the capacity of the plant. Fig. 16 shows the variation of tower height with capacity for thermal storage of 0, 6 and 15 hours (and no hybridisation) at the respective optimum SM s. This case was taken just to give an idea of the variation of tower height with capacity at optimum SM .

5.6. *Comparison of Results for Clear- vs. Hazy-Day Attenuation Models*

Attenuation, as explained earlier, depends on the actual slant distance from a heliostat to the top of the receiver. At any instant, the attenuation is an integrated effect of all the heliostats in field.. The effect of attenuation on the performance of 1 MW and 50 MW ST plant with 6 hours of storage and no hybridisation (optimum $SM=2.1$) is shown in Table 4.

This case has been taken as an example to illustrate the degree by which the annual electrical energy generated and η_{s-e} reduce when the hazy-day model (<23 km visibility) is used. It can be

seen that the reduction is quite substantial when the capacity is higher: the annual electrical energy reduces by 3.3%, while η_{s-e} reduces by about 10.4% (for a 50-MW plant). This is expected because for larger capacities, the field is bigger and, consequently, the slant distances are larger. The effect of the haziness of the atmosphere is negligible for plants with smaller capacities.

Therefore, in actual practice, for analysing higher-capacity plants, the hourly variation of atmospheric effects needs to be taken into consideration.

6. Conclusion

A rational method has been developed for the preliminary design of a solar tower plant with a given capacity, thermal storage and hybridisation similar to the one that had been developed for a parabolic trough plant [13]. It was possible to develop such a methodology by utilising the method for defining a non-dimensional solar field boundary in terms of tower height [15]. The methodology has been validated by comparing the results obtained by this method with those used in the Gemasolar and Crescent Dunes plants with regard to tower height and solar field area.

Based on this study, a Java-based tool – CSTEM for Solar Tower – has been developed. This tool was used to generate data on hypothetical plants in Jodhpur, of various capacities, thermal storage hours and hybridisation. It was found that the optimum SM s for plants using 0, 6 and 15 hours of storage are 1.4, 2.1 and 3.2, respectively. These are found to be independent of the capacity of the plant. Since cost data are still not comprehensively available for this technology, the annual solar-to-electrical efficiency (η_{s-e}) was taken as the criterion for choosing the optimum SM . It is found that the annual efficiency increases with increase in the capacity of the plant. It is observed that hybridisation is more effective at lower SM s. Hybridisation also improves the plant efficiency by allowing the power block to operate at better part load conditions. For a plant of 20 MW and with 6 hours of storage, the optimum height of the tower is found to be about 105 m. It is found that atmospheric attenuation does not play a significant role when the capacities are low.

In the case of a cavity receiver, the field is also intimately coupled with the design of the cavity receiver (the angle subtended by the opening of the receiver, etc.). The angle subtended by the field is a function of the type of cavity and is not very amenable for generalisation. If the cavity angle is known, the present study can be extended to cavity receivers as well.

It is recommended, that just as in the case of the CSTEM tool for Parabolic Trough, the CSTEM tool for Solar Tower can be used to analyse plant performance. The tool can be used by designers, developers and policymakers to facilitate an initiatory design to estimate the optimum height of the tower and, thereby, the size and performance of the solar field for a plant of a given capacity (using thermal storage and hybridisation).

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Fig. 3: Flowchart Outlining the Methodology to Determine the Preliminary Design for ST plant

Fig. 4. Variation of CUF with SM for all Capacities ($t_s=0$ and $f_{hb}=0$)

Fig. 5. Variation of η_{s-e} with SM for Various Capacities ($t_s=0$ and $f_{hb}=0$)

Fig. 6. Variation of Annual Electrical Energy/MW with SM for $t_s=0, 6$ and 15 hours ($f_{hb}=0$)

Fig. 7. Variation of Solar-to-Electric Conversion Efficiency with SM for Various Capacities and $t_s=6$ hours ($f_{hb}=0$)

Fig. 8. Variation of Optimum SM with Thermal Storage Hours ($f_{hb}=0$)

Fig. 9. Effect of Hybridisation ($f_{hb}=0.1$ and 0.2) on the Electrical Power Generated during a Typical Day for $SM=1$ ($t_s=0$)

Fig. 10. Fraction of Hybridisation Used During a Typical Day for $SM=1$ ($t_s=0$)

Fig. 11. Effect of Hybridisation ($f_{hb}=0.1$ and 0.2) on the Electrical Power Generated during a Typical Day for $SM=1.5$ ($t_s=0$)

Fig. 12. Fraction of Hybridisation Used During a Typical Day for $SM=1.5$ ($t_s=0$)

Fig. 13. Variation of η_{s-e} with SM for $f_{hb}=0, 0.1$ and 0.2 ($t_s=0$)

Fig. 14. Variation of CUF with SM for $t_s=0$ hours and $f_{hb}=0, 0.1$ and 0.2

Fig. 15. Variation of CUF with SM for $t_s=6$ hours and $f_{hb}=0, 0.1$ and 0.2

Fig. 16. Tower Height vs. Capacity for $t_s=0, 6$ and 15 at Optimum SM ($f_{hb}=0$)

Table 1: Input Parameters to the Model

Input Parameter	Value
Minimum non-dimensional distance from the tower $(r/h)_{field\ min}$	0.5
e_l contour value (MWh/m ²)	0.16
Non-dimensional length/width of elemental area, d_x/h or d_y/h	0.25
Heliostat (mirror) efficiency (η_m)	0.95
Attenuation model considered	Clear sky
Receiver efficiency ($\eta_{receiver}$)	0.8
Heat exchanger efficiency (η_{he})	0.95
Thermal storage efficiency (η_{st})	0.97

Table 2: Output Data and Validation (Using Default e_l Value = 0.16)

Parameter	Gemasolar			Crescent Dunes		
	Actual	From Model	Error (%)	Actual	From Model	Error (%)
Tower height (m)	140	124	-11.8%	195	213	14.8%
Mirror area (m ²)	304750	285737	-6.2%	1197148	1102803	-8.4%
Land area (m ²)	1550396	1565123	0.9%	6474970	7341265	4.4%
Annual electrical energy generated (MWh/year)	110000	105487	-4.1%	500000	542952	8.6%

Table 3: Parameters Considered for Analysis

Parameter	Value Range
Design capacity (MW)	1, 5, 10, 20, 35, 50
Hours of thermal storage (t_s)	0, 6, 15
Fraction of hybridisation (f_{hb})	0, 0.1, 0.2

Table 4: Effect of Attenuation for $SM=2.1$ (optimum) and $t_s=6$ hours ($f_{hb}=0$)

Clear Day			Hazy Day	
Capacity (MW)	Annual Electrical Energy Generated (MWh)	η_{s-e} (%)	Annual Electrical Energy Generated (MWh)	η_{s-e} (%)
1	4059	8.77	4029	8.55
50	200343	19.11	193666	17.13