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HELIOSTAT DESIGN FOR LOW WIND TERRAIN

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ABSTRACT: Concentrated solar thermal power tower plants (PT) have a great potential for generating electricity on a large scale for places with high DNI. They are highly relevant due to their ability to store energy in an inexpensive manner by way of high temperature thermal storage. However they are quite capital intensive. The largest capital outlay in a PT plant is on account of heliostats. Heliostats constitute 45-50% of the total cost of a PT plant and their design is highly influenced by wind loads. This paper looks at a few locations in India where the DNI is high but the wind speed is quite moderate. The analysis shows that significant cost reduction is possible by sizing and suitably redesigning the heliostats.

KEYWORDS

Heliostats, Design wind speed, Wind loads, Heliostat costs

Introduction

The demand for electricity continues to grow in developing countries like India. To keep pace with the demand, more and more thermal power plants fired by coal are being added. At the same time for environmental reasons as well as under pressure from global community for its growing greenhouse gas emissions, the renewable energy capacity is also being added. Indian government has targeted to install 100000 MW of solar capacity by the year 2022 (Ross, 2016). However solar power in India is virtually synonymous with solar photovoltaic (PV). The reason for this is the rapid reduction in the price of electricity from PV. But due to its intermittent nature, solar from PV cannot address the peak electricity demand which in any case peaks in the evenings when solar is not available. This necessitates the setting up of fossil fuel thermal plants. This means that peak demand in the grid is met almost entirely by fossil fuel plants except for some hydro and wind and solar PV only forces the fossil fuel plants to back down and thus reduce their capacity factor which in turn increases their cost per unit of electricity generated. Appropriate strategy would be to make renewable energy like solar to be available as and when demand is there, so that coal based plants can be phased out completely. As per current strategy, setting up more and more coal based plants is a necessity to meet the growing energy needs of the country. This issue can only be overcome if solar energy could be stored and supplied as per demand. This stored energy will then be put into the grid as per demand and dependence on coal plants will come down. The storage can be created in Solar PV plants too by using batteries, but this is a very expensive proposition and also the batteries need to be replaced at regular intervals ("Battery Storage for Renewables : Market Status and Technology Outlook" 2015). This makes Solar PV with storage a very expensive solution. It is in this context that the concentrated solar thermal power with storage becomes a potential alternative. Concentrated solar thermal power plants utilize a eutectic mixture of salts for storage of solar energy in the form of heat. This salt mixture is environmentally benign unlike batteries, whose disposal creates electronic waste (Way Julie, 2008). Concentrated solar thermal power plants are of two types, namely, Parabolic Trough and Power Tower (PT). Both of these can store solar energy in the form of heat and convert it to electrical energy using steam turbines.

Parabolic trough plants without storage have been widely used and capacity to produce several thousand MW is in place worldwide (Sargent & Lundy LLC Consulting Group Chicago Illinois 2003). PT is a relatively new entrant but it is also now booming with several new projects at a commercial scale in the operational and construction phase (Solar Paces 2016). However where the PT plants score immensely over the parabolic trough plants is in their ability to store thermal energy (Turchi et al. 2010). By storing thermal energy using molten salts, PT plants can be designed to operate 24 hours a day and thus be operated like a base load plant similar to a coal fired thermal power plant. PT plants could also be designed to operate for peaking power requirement and thus save capital expenditure for coal fired plants being planned. Parabolic trough plants too can store energy but because of their design involving several kilometers of horizontal pipelines, it is extremely cumbersome and unviable to use them with molten salt. Experts predict that the future belongs to PT (Turchi et al. 2010). Latest 110 MW solar tower plant at Crescent Dunes in USA, built by Solar Reserve is an excellent testimony to above prediction. It is now fully integrated into the grid and running successfully (Solar Reserve 2016). It produces power to meet demand with storage capacity of 10 hours of full rated output. This plant is already supplying power to the grid at 13.5 cents/ kWh, which is at a significant discount to earlier tower plants with typical prices of 22-25 cents/kWh. PT plants obviate the need for back up fossil fuel plants, which is a prerequisite for solar PV. However to make the PT plants a mainstay of electricity production, it is very important to further reduce the levelized cost of energy from such plants. In fact SunShot Initiative from Department of energy of USA is a well planned effort to bring the levelized cost of electricity from PT plants down to 6 cents/kWh by year 2020 and it appears that this target may actually be exceeded (Sun Shot Vision Study 2012). One of the key goals of this initiative is to bring down the cost of heliostats used in a PT plant very aggressively. This paper is an attempt in that direction. It suggests a way to reduce LCOE by bringing down heliostat field cost, which is a very large component of PT plant cost. (kolb etal., 2011). It focuses on locations in India, but is applicable at other similar locations too.

The heliostat field consists of thousands of heliostats around a high tower. They all direct the solar radiation falling on them to the tower. A heliostat is essentially a mirror which is tracked in two axes continuously to ensure that the solar radiation falling on it is directed towards the receiver located at the top of the tower. The cost of the heliostat field could be up to 40-50% of the total project cost of a tower project (Blackmon 2012).

During the literature survey, it became increasingly clear that the design of the heliostat is highly dependent on the wind loads (Murphy 1980). In fact the wind loads are the decisive factors for dimensioning of heliostats (Pfahl, Buselmeier, and Zaschke 2011). A heliostat is designed to track the sun and accurately reflect the radiation onto the receiver on a high tower. Due to the long distance between the tower and a heliostat, the accuracy of reflection has to be very high and hence, the loads on heliostat play a very important role. Among the early heliostats, 148 m2 ATS heliostat developed in late 80s was considered a good safe design as it had been used for several years and withstood extreme weather and wind loads too (Strachan and Houser 1993). Also at that time, it was felt that bigger the heliostat, lower would be the cost of heliostat field as lesser numbers of heliostats would be required for the same area (Kolb et al. 2007). But this view was challenged later by Blackmon (Blackmon 2012) who did a detailed cost analysis of the ATS heliostat. Blackmon developed algorithm to parametrically determine the heliostat cost as a function of its mirror area and determined that smaller heliostats in the range of 40-50m^2 would be much more economical.

While Blackmon looked at the area of a heliostat as an attribute to be optimized, he did not consider wind speed of a location as an equally important variable. So Blackmon found an optimum value of heliostat reflector area for standard design wind condition.

However the wind speed and its turbulence vary a great deal from place to place and since wind loads are proportional to square of wind velocity, the wind speed should be considered as another attribute while designing a heliostat.

In this paper, an attempt has been made to first identify the prevailing wind speeds at a few locations in India, where direct normal irradiation DNI is high and then apply the optimization procedure to obtain the optimum area and optimum cost per unit area of such heliostats.

Content

Methods

Input data

PT plants can only use direct normal irradiance and diffused radiation cannot be used in this technology. It is thus necessary to locate these plants in places where DNI is around 2000 kWh/year or higher (Emes, Arjomandi, and Nathan 2015). DNI data can vary significantly from place to place and before a plant is planned to be setup, at least a year's data is collected using accurate instruments like Pyrheliometer. However for our purpose of heliostat size determination, exact data is not necessary. For this research, satellite data was instead used for analysis.

National renewable energy laboratory of USA in collaboration with Ministry of Renewable Resources of India had commissioned an exercise to collect solar and other data over Indian peninsula through the use of Meteosat satellite over several years. This data is available up to year 2014 and can be freely downloaded. This satellite data for the year 2014 was used as an input to identify areas with highest DNI potential (Maps India Solar Resource 2016). The satellite data also provides hourly wind speed data and this was used to calculate the estimated wind loads in the respective locations. For a real project, it is necessary to do a detailed onsite investigation of solar radiation and atmospheric conditions over a long period of time, however the satellite data is accurate enough for our investigation of cost assessment of heliostats. Hourly data of DNI and wind speed for five locations with DNI > 2000 KWH/year was downloaded for these locations for year 2014. The Weibull probability distribution function is used to fit a frequency curve to the range of recorded data (Belhamadia, Mansor, and Younis 2013). Weibull distribution is universally used for the purpose of wind data analysis (Blackmon 2014).

Site identification

After looking at the DNI map of India, the areas of high DNI marked in deep red colour were clearly identified. Locations in Ladakh region were not considered due to inhospitable terrain there. Five locations in Karnataka, Gujarat and Rajasthan, having DNI around 2000 KWH/year are chosen and hourly wind data and DNI data are downloaded from NREL website for this analysis ("India Solar Resource Maps and Data" 2018).

Meteosat satellite data from NREL has been used for site identification. This satellite data provides hourly readings of DNI as well as wind speed for a grid of 0.10 Latitude x 0.10 Longitude viz. approximately an area of 10 km x 10 km for India. Based on the highest DNI data, a few locations with good DNI in the states of Karnataka, Gujarat and Rajasthan were selected. Satellite data for year 2014 is used for the analysis.

Wind data analysis

Wind speed plays a very important role in load on the heliostat. The load is directly proportional to square of the wind velocity. Also the load on a heliostat is dependent on its orientation. It is important to note that the heliostat need not be designed for the maximum wind speed prevalent at a location. The wind load is a function of wind load coefficient too and this coefficient varies with heliostat orientation.

During the day, the heliostat can be in any orientation due to operational requirement based upon sun position, but at night the heliostats are parked flat with their reflectors parallel to the ground. This minimizes the wind loads on heliostats as wind load coefficients are much lower in the flat position.

This ability of heliostat to go into parking position rapidly is effectively utilized to put them in parked position in case the wind speed goes above the maximum safe operating speed of the heliostats. This will cause a loss of energy in case the high wind event occurs during the day when solar radiation is available but since its probability is very low, the loss is offset by the reduction in capital cost due to lower design wind speed of heliostats. However for this analysis, only maximum wind speed has been considered as design wind speed. By choosing a design wind speed lower than maximum, further optimization is possible (Emes, Arjomandi, and Nathan 2015).

The probability of occurrence of a wind speed is determined using the Weibull probability distribution curve. Weibull probability distribution is the most appropriate statistical method for wind data where typically the probability of maximum values is much lower than mean and minimum values. The Weibull function is used to fit a frequency curve to the range of recorded data. The Weibull distribution requires computation of two parameters namely shape factor and the scale factor (Odo, Offiah, and Ugwuoke 2012) .

Weibull probability distribution function was calculated using equation 1.

Weibull probability distribution function was calculated using equation 1.

$$f(U)=\left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{1}$$

Where, shape factor (k) and scale factor (c) are as per equations 2 and 3 respectively.

$$k=\left(\frac{\sigma_U}{\overline{U}}\right)^{-1.086} \tag{2}$$

$$c=\frac{\overline{U}}{\left(\Gamma\left(1+\frac{1}{k}\right)\right)} \tag{3}$$

The purpose of determining Weibull probability curves is to establish the range of desihn wind speed (DWS) for which analysis is to be carried out.

Optimum area of square heliostat

Blackmon has shown that the optimum azimuth-elevation heliostat cost can be determined by analyzing cost relationships in terms of heliostat area parametrically, distributed among three distinct categories. Advance Thermal System's ATS 148 m^2 heliostat is considered to be very well designed, proven heliostat by National Renewable Energy Labs. Of USA. Using the detailed cost break up of ATS 148 m^2 heliostat as a benchmark, he divided the cost/m^2 (CSM) into three categories. The three categories are described as below.

Category (C1): These costs are constant costs per unit area and are independent of heliostat size for a given heliostat field mirror area (e.g. mirrors).

Category (C2): These costs are size-dependent and are determined by the wind loads imposed which increase the cost/m^2 (CSM) as the area increases. (E.g. structure, pylon, foundation, elevation and azimuth drives). Size dependent costs follow the so called three halves power law suitably amended for non-uniform wind speed.

Category 3 (C3): These costs are fixed costs for components used on each individual heliostat, irrespective of its size; for a given field size. This fixed cost/m^2 increases linearly with the number of heliostats, and thus the cost per unit area increases as the size decreases, and vice versa. (E.g. Controllers, position sensors, limit switches etc.). Given below is flow chart for area optimization process.

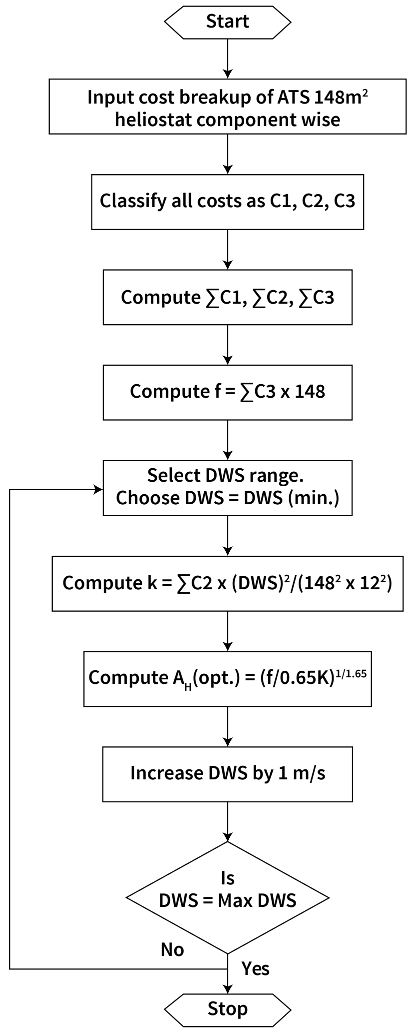

FIGURE 1. Flow chart to calculate optimum area of the heliostat

C2 category components costs (like structure, pylon, foundation, drives) have been demonstrated to be proportional to their weights, which in turn are proportional to the bending moment on the respective components in this category. Since, bending moments are also directly proportional to the square of wind speed, the maximum bending moments on each element have been determined as a function of DWS. While, Blackmon had restricted himself to a single DWS and thus, found an optimum heliostat area, DWS has been added as a variable in this paper and the optimum area (least cost/m2) has been calculated as a function of DWS using above mentioned algorithm.

Cost of heliostat field per sq. meter, CSM was calculated by using following equation from (Blackmon 2013).

$$CSM = C_1 + kA_H^{0.65} + \frac{f}{A_H} \tag{4}$$

CSM is cost/m^2 for a heliostat for a non-uniform wind speed (Wind speed varying with height). AH is the area of heliostat, k is a constant for each DWS and f is the fixed total cost per heliostat. The constants were computed using Advanced Thermal Systems (ATS) 148 m^2 heliostat data as benchmark. ATS 148 m^2 heliostat is a very well accepted benchmark, which has been subjected to expensive durability test by Sandia National Laboratory. The detailed cost breakup of ATS heliostat cost of individual parts is freely available. ATS heliostat has been projected to have a CSM of $129 for a volume production of 50,000 units per year. Based upon the ATS 148 m^2 cost breakup by Blackmon, the constants C1, C2 and C3 are calculated. (Important to note that these costs are inclusive of installation costs).

C1 =$34.44 / m.^{2}

(C1 is taken as fixed cost/m2 irrespective of its size).

$$k = \frac{86.26 * DWS^2}{12^2} \qquad (5)$$

Basis for k is the C2 cost of $86.26 for ATS 148 m^2 heliostat for DWS of 12m/s.

$$f = \$1332 \qquad (6)$$

f is fixed cost per heliostat, irrespective of its size.

By differentiating the equation (4) with respect to A_H and setting the derivative to zero, we obtain the optimum area (least cost per sq. m.) of a square heliostat (Blackmon 2013). This is a function of DWS as 'k' is a function of DWS.

$$A_{H/OPTIMUM} = \left(\frac{f}{0.65}k\right)^{1/1.65} \qquad (7)$$

Using the above derived optimum area, the optimum cost/m^2 for a sq. heliostat was computed. A range of optimum values for varying DWS was calculated. The value of constant k increases as DWS increases and thus the optimum value of A_H decreases. So the optimum area (Least cost/m^2) reduces as DWS increases.

Results & Discussion

Analysis of wind speed data

Fig.1 shows the probabilistic distribution of wind speed throughout the year for five different sites chosen for this study. It is apparent that maximum possible mean DWS is 8 m/s whereas typically heliostats like ATS heliostat is designed for 12 m/s operational wind speed (Murphy 1980). This shows that heliostats could be designed for much lower wind speeds to reduce costs. There are places where speeds are even lower than 8 m/s, but it may not be economically prudent to design for each specific wind speed as high volumes mean better economy of scale.

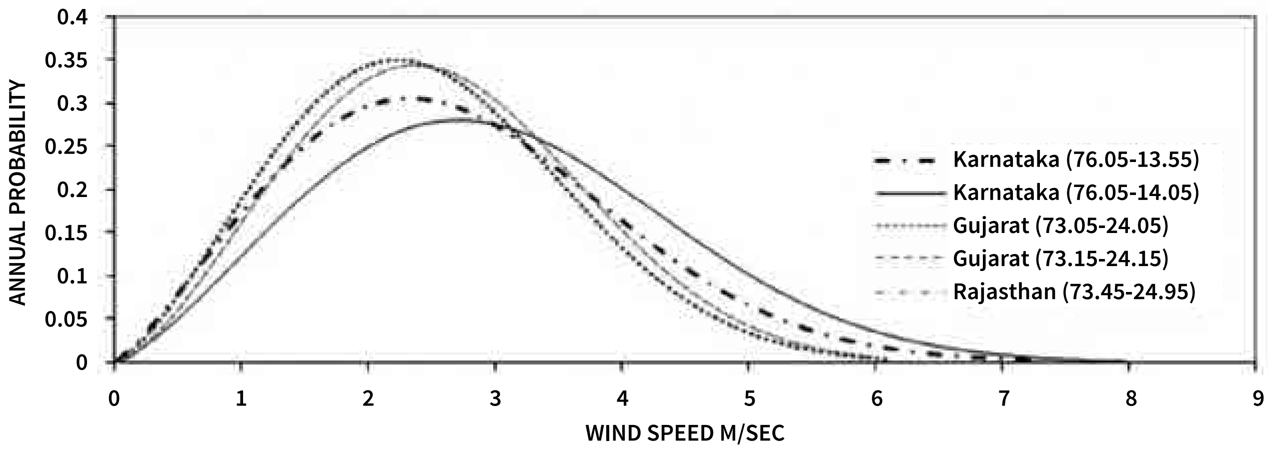

FIGURE 2. Mean wind speed probability distribution at six sites for year 2014

2.2.2 Optimum area & cost/m2 of a heliostat

Fig. 2 shows the cost/m^2 (CSM) and optimum area as a function of DWS from 6 m/s to 12 m/s. At 12 m/s wind speed, the CSM is US$103.7 if area is kept at 49 m^2 compared to US$129.7 for the ATS heliostat with area of 148 m^2 (Blackmon 2012). At the maximum speed of 8 m/s observed at the six locations, CSM is US$77 and the corresponding area is 80 m^2. This shows a reduction of nearly 40% compared to ATS heliostat.

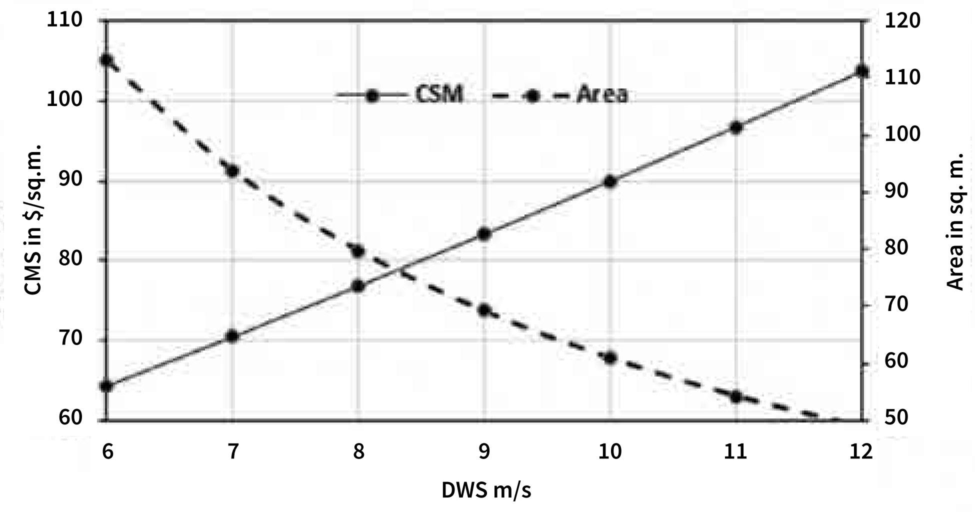

FIGURE 3. Optimum cost/m² and reflector area of heliostat vis-à-vis design wind speed

Conclusions

Heliostats designed for low wind areas can be significantly cheaper than current standards. The heliostat design should be based upon the wind speed data of the location. The optimum area of a heliostat and sizing of its components are both determined by the wind data. This will play a vital role in improving the viability of PT plants viable in these location. While this paper has focused on Indian locations only, the methodology is applicable for any other part of the world.

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