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Effect of heliostat design wind speed on the levelised cost of electricity from concentrating solar thermal power tower plants

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Abstract

This paper assesses the influence on the levelised cost of electricity (LCOE) of the design wind speed at which heliostats in concentrating solar thermal (CST) power tower (PT) plants are stowed. Lowering the design wind speed for parking heliostats in the stow position reduces the cost of the heliostat field at the expense of a reduction in the energy harvested. However, both influences are highly nonlinear and also vary from site to site, so that new understanding is needed to guide the optimisation of this parameter. The capacity factor and the power output for a PT plant without thermal storage are calculated for six locations by mapping hourly solar irradiance data to the Weibull probability distribution of mean wind speed. The cost of materials for the heliostat components and their sensitivity to heliostat size are estimated as a function of the design (stow) wind speed based on the specification of the structural design for quasi-static wind loads. The sensitivity of the LCOE to the design is assessed statistically. The results show that the materials cost of structural components in larger heliostats are most sensitive to the design wind speed, so that a 34% reduction in cost can be achieved by lowering the design wind speed from 15 m/s to 10 m/s. In contrast, the optimum design wind speed for smaller heliostats between 20 m^2 and 50 m^2 is typically above 10 m/s. The LCOE can be reduced by as much as 18% by lowering the design wind speed from the maximum recorded wind speeds at the three Australian sites. Hence there is significant economic benefit from optimising the minimum design at sites with high wind speeds.

Keywords: Levelised cost of electricity; Concentrating solar thermal; Power tower; Heliostat

1. Introduction

Current energy systems based on the consumption of fossil fuels are unsustainable in the long term, so that a transition to an environmentally sustainable energy system with the integration of renewable energy sources is necessary (Hernández-Moro and Martínez-Duart, 2013). Concentrating solar thermal (CST) power tower (PT) is one of the most promising renewable technologies capable of large scale electricity production (Hinkley et al., 2013). It offers both thermal energy storage and relative ease of integration with existing fossil fuel power plants and hybridisation for a base line power supply (Kolb et al., 2011). Government funded initiatives that are supporting the research and development of CST systems to make them competitive with base load energy rates include the US Department of Energy's SunShot Initiative, with a goal of $0.06/kW h by 2020 (Kolb et al., 2011), and the more conservative Australian Solar Thermal Research Institute (ASTRI) program targeting $0.12/kW h by 2020. To achieve these targets there is a need to lower the capital cost of a PT plant, of which the largest cost is the heliostat field.

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One opportunity to lower the heliostat cost is through careful selection of the design wind speed. Here this is demonstrated by the assumption of quasi-static wind loads with a peak-load coefficient derived from wind tunnel data, although the use of site-specific data, if available, would make the estimates more accurate.

The opportunities identified to reduce heliostat costs through technical advances in a recent Sandia workshop (Kolb et al., 2011) are through improved materials, and through improved structural performance of stowed heliostats during survival high wind conditions. Optimisation of the heliostat structure is predicted by Kolb et al. (2011) to enable a 10% reduction in heliostat cost per unit area ($/m^2) of PT plants by 2020, which would help achieve the DOE goal of $75/m^2 heliostat total installed costs. The scaling relationships of Kolb et al. (2007) were used to estimate that the heliostat costs scale with the mirror area to the power of 1.5, which is consistent with the quasi-static wind load approach by Lovegrove and Stein (2012) and by Blackmon (2013) applied to the three cost categories of a heliostat. There is also currently no consensus on the optimum size of a heliostat. Hence an aim of this investigation is to develop cost-load relationships that can be used to estimate the cost of a single heliostat as a function of the design (stow) wind speed and the heliostat mirror area.

The current practice in the operation of heliostat fields is to move each heliostat to a parked (or stowed) position during periods of high wind speeds, which reduces loads by greatly reducing the cross projected area to the wind. Peak wind loads associated with gusts and dynamic amplification on stowed heliostats have been measured to be more than 10 times larger in magnitude than the mean loads on heliostats in the stow position (Peterka et al., 1989). Currently the design wind speed for stowing heliostats is 22 m/s, according to specifications for Department of Energy (DOE) second generation heliostats (Murphy, 1980). Stowing the heliostats lowers the effective capacity factor of the plant if the periods of high wind speed occur during periods of good solar irradiance. However, the probability distribution of wind speed typically follows a Weibull distribution so that the most extreme wind speeds are highly improbable. Furthermore, the probability that the periods of extreme wind coincide with a period of high solar irradiance is even lower. Hence there is an opportunity to lower costs by optimising the trade-off between losses in capacity factor and lowering the cost of the heliostat array through lowering the design wind speed at which the heliostats are parked. A systematic study of the trade-off between capacity factor and design wind speed has not been reported before. Hence the present investigation aims to meet this need.

The economic feasibility of renewable energy technologies such as CST relative to fossil fuel plants is often assessed by levelised cost of electricity (LCOE) (IEA, 2010). The current LCOE of CST PT systems is estimated to be $0.223/kW h in Australia (Hinkley et al., 2013) and $0.137/kW h in USA (Turchi et al., 2010), so that significant reductions are needed to reach the ASTRI and SunShot targets of $0.12/kW h and $0.06/kW h respectively by 2020. The LCOE is influenced by the capital cost of the plant, of which the field of heliostats is estimated to constitute 39% (Hinkley et al., 2011), and by the capacity factor. Both of these are dependent on the design wind speed for stowing the heliostat. A recent sensitivity analysis about a $0.25/kW h baseline cost of CST in Australia (Lovegrove et al., 2012) showed that a 10% reduction in the capital cost of a PT plant results in a 9% reduction in LCOE. However, while the influence of the local variation in solar irradiation on LCOE has been reported to decrease by 4.5% for each 100 kW h/m^2-year between 2000 kW h/m^2-year and 2800 kW h/m^2-year (IEA-ETSAP and IRENA, 2013), the effect of wind speed has not been reported before. The aim of the present paper is therefore to address the economic viability of CST PT technology on the basis of selection of the design wind speed for stowing heliostats.

The overall aim of this paper is to determine the trade-off between lowering the design wind speed for stowing heliostats, which reduces the capital cost of heliostats, and the losses in capacity factor and power output of a PT plant. The first aim is to estimate the relationship between wind load and the material costs of manufacturing heliostat fields as a function of the design wind speed. The second aim is to calculate the reduction to capacity factor associated with lowering heliostat cost through lowering the design wind stow-speed for heliostats. The third aim is to calculate the relative influences of the design stow speed on the LCOE of a PT plant through its impact on heliostat cost and the capacity factor.

2. Methodology

Six sites were selected for assessment based on the joint criteria of a good solar resource with an annual average DNI greater than 2000 kW h/m^2-year and the availability of good quality records of both wind speed and solar DNI. Here the value of 2000 kW h/m^2-year, which corresponds to an annually averaged flux of 228 W/m^2, has been estimated to be the minimum threshold needed for a solar thermal plant to be economically viable (IEA-ETSAP and IRENA, 2013). The solar energy input was calculated from historical time series of direct normal irradiance (DNI) measured using a pyrheliometer, which can achieve an accuracy of 15 W/m^2 on a regional scale (Arvizu et al., 2011). This is more reliable than satellite measurements. Similarly, wind speed data must also be based on local measurements, since it is too difficult to predict the effects of topography and weather from other data. Hence the six sites in Table 1 were identified with good quality data of hourly average DNI and hourly average wind speed (Bureau of Meteorology, 2014; National Climatic Data Center, 2014; NREL, 2010).

2.1. Variation of mean wind speed with height

The log law was used to estimate the vertical profile of the wind speed under the assumption of asymptotic