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Methodology for sizing the solar field for parabolic trough technology with thermal storage and hybridization

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Abstract

A detailed methodology to design the size of solar field for a parabolic trough plant is not explicitly available in open literature, particularly if thermal storage and hybridization are also considered, as most of the papers present a gross overview. This paper gives a procedure to determine the annual electricity generated for a parabolic trough based solar plant of a given rated capacity (1–50 MWe), at a chosen location & given hourly annual solar input, specified hours of thermal energy storage using a two-tank molten salt system and specified fraction of hybridization using natural gas. In this methodology losses due to shut down or cloud cover are also covered. The size of the solar field is optimized for the maximum annual solar to electric conversion efficiency using the concept of solar multiple (ratio of actual aperture area to the reference aperture area needed to get rated power output at maximum solar input). This procedure is validated with the existing parabolic trough plants (Solar Energy Generating Systems VI and Solana Generating Station) and it was found that the annual electrical energy generated by the plant matches reasonably well.

Jodhpur, in India, was considered as a location for the case study and the results are presented to understand the influence of thermal storage and hybridization for a given capacity of the plant. The results for various combinations of thermal storage hours and fraction of hybridization used with respect to plant capacity, solar multiple, annual plant efficiency etc. have been discussed in detail. It is observed from the results that, under design conditions, the reference aperture area per MW decreases as plant capacity increases and reaches a limiting value asymptotically at a capacity of 50 MW. The optimized size of the solar field, with respect to annual efficiency, is found to be 1.4 and 2.3 times the size under design conditions for zero and six hours thermal storage respectively. The benefit of hybridization is high for lower solar multiples.

Keywords: Parabolic trough; Thermal storage; Hybridization; Concentrated Solar Power; Solar multiple

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1. Introduction

Among the Concentrated Solar Power (CSP) technologies, Parabolic Trough (PT) technology is the most commercially proven technology (Hachicha et al., 2013; Zaaraoui et al., 2012; Reddy and Ravi Kumar, 2012). A PT power plant can be segregated into two major segments: solar field and power block. The schematic representation of the parabolic trough plant with thermal storage and

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Nomenclature

A_a	actual mirror aperture area
A_r	reference mirror aperture area
C	chord of the mirror
E_{tea}	thermal energy available from storage
$E_{tes,max}$	maximum amount of thermal energy that can be stored
L_f	loss factor
P_g	actual gross power generated
$P_{g,d}$	rated gross power
P_s	solar power impinging on the absorber tube per unit length
P_{abs}	thermal power impinging on the absorber tube
$P_{abs,d}$	thermal power impinging on the absorber tube at design conditions
P_{hb}	maximum thermal power input to HTF from hybridization
P_{htf}	thermal power input from HTF to heat exchanger
$P_{htf,d}$	thermal power input from HTF to heat exchanger at design conditions
$P_{htf,s}$	thermal power input from solar field to HTF
$P_{th,d}$	thermal power of working fluid at design conditions
$P_{th,s,d}$	solar power input to mirrors at design conditions
SM	solar multiple
e_g	gross electrical energy generated without considering energy needed for start-up
$e_{g,a}$	gross electrical energy generated accounting for start-up
$e_{g,t}$	$\sum e_{g,a}$
e_{grid}	electrical energy supplied to grid
$e_{grid,t}$	$\sum e_{grid}$
e_{hb}	electrical energy apportioned to hybridization
$e_{hb,t}$	$\sum E_{hb}$
e_s	electrical energy apportioned to solar input
$e_{s,t}$	$\sum e_s$
e_{start}	equivalent electrical energy required for start-up accounting for thermal losses during shut down period
f_{hb}	maximum fraction of hybridization power permitted
$f_{hb,used}$	actual hybridization fraction used
f_{th}	fraction of thermal power delivered to power block
f_p	fraction of the gross electrical power generated ignoring thermal losses during shutdown
f_{pa}	fraction of gross electrical power generated taking into account thermal losses during shutdown
$f_{th,s}$	solar thermal power as a fraction of the design thermal power
$f_{th,st}$	Fraction of thermal power used from storage
$f_{th,sta}$	fraction of thermal power available from storage
t_s	number of hours of thermal storage
β	angle of tilt of parabolic trough
γ	intercept factor
δ	declination of the day
η_{abs}	absorber efficiency
$\eta_{abs,d}$	efficiency of absorber tube at design conditions
η_c	efficiency of solar collection
η_{he}	efficiency of power block heat exchanger
η_m	optical efficiency of the mirror system
$\eta_{p,d}$	power block efficiency at design conditions
η_{pl}	part load efficiency of power block
η_r	relative efficiency $= \eta_{pl}/\eta_{p,d}$
$\eta_{s\text{-}e}$	annual efficiency attributed to the solar
η_{st}	efficiency of storage heat exchanger
θ	angle between the normal to the mirror aperture and sun's rays
ρ	specular reflectivity of the mirror
ϕ	latitude of the location
ω	solar hour angle

hybridization is shown in Fig 1. In Fig. 1, T-1 to T-4 represents stages of turbines and other components are self explanatory in the figure itself. The solar field consists of highly reflective mirrors mounted on a support structure, which can be tilted about an axis (normally aligned in the North–South direction) to track the sun as it moves from East to West. At the focal line of the parabolic mirrors, a receiver is mounted. Receiver composed of absorber tube and glass envelope. Absorber tube in the receiver is encapsulated in a glass envelope and the annular space between the glass cover inner surface and the absorber is evacuated. The absorber tube is given a special coating which along with the evacuation leads to better absorption and transfer of heat to the Heat Transfer Fluid (HTF) flowing inside the receiver (Ravi Kumar and Reddy, 2009; Thomas and Guven, 1993). The HTF flows in and out from the absorber tubes through header pipes. The power block is almost similar to that used in the conventional power plants. In the power block, the thermal energy acquired by the HTF is used to operate a conventional steam turbine to generate electricity. Generally, the thermal energy of the HTF is transferred to the feed water through a series of heat exchangers (pre-heating, vaporizing and super-heating) to produce superheated steam, which drives the steam turbine coupled to a generator (Antonio et al., 2013; Montes et al., 2009). The steam exiting the turbine is condensed using wet or dry cooling condenser and the condensed water goes to the feed water pumps to pump it to the heat exchanger.

Thermal storage is necessary to provide full-load, steady state electrical generation during time of cloud cover,