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Deformation and optics based structural design and cost optimization of cylindrical reflector system

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ABSTRACT

It is a stated goal of renewable energy research to make solar power reach price parity with power from fossil fuel based power plants. Solar-thermal plants are capital intensive and do not benefit strongly from economies of scale. Hence, reducing unit costs is the most effective path to an economically attractive technology. Conventional parabolic trough systems have numerous limitations not least of which are the expensive mirror and support requirements required to maintain high precision in the optics. Further, the flexible hosing necessary to enable a moving receiver leads to excessively high pressure drops and pumping costs. While linear Fresnel systems address much of these shortcomings, they require accurate field alignment of a large number of independent reflecting elements leading to complex maintenance issues. Here we propose a relatively simple design with a small number of reflecting elements with a stationary receiver which is facile to fabricate, transport and install while also be far most cost effective. We also present a structural cost optimization together with optical ray tracer analysis using *in-house* ray tracer code. The concept has been validated with experiments. The proposed optimum design can be considered as a step toward achieving the economically attractive line concentrator technology.

1. Introduction

Solar thermal technology (or Concentrating Solar Power CSP) can be considered a bridge between fossil fuels and renewables (Dalvi et al., 2015) since it employs the same heat engines as conventional power plants and its heat can be stored cost-effectively. Of the four major CSP technologies, the parabolic trough technology is, by far, the most widely deployed. The installed plants have a cumulative capacity more than 4 GWe which are currently under operation (Concentrating Solar Power Projects). Since 1984 many utility scale parabolic trough based power plants like SEGS, were built in the Californian desert of US and also in Spain (Concentrating solar power SEGS plants): yielding tremendous insight into operation and maintenance, materials, performance constraints and fossil fuel based integration. One of the stark limitation of conventional parabolic trough systems is that the flexible hoses necessitated by the moving receiver impose a pressure drop 50% in excess of that with a straight pipe. The moving receiver also poses a risk of breakage of its (discontinuous) glass tube and the operations and maintenance costs that entail. In an attempt to address these shortcomings researchers at ANU came up with the concept of the Linear Fresnel concentration (Mills, 2004; Mills and Morrison, 2000) which tracks the sun by rotating a large number of narrow reflecting elements that can be rotated independently. This leads to its own problems of maintenance due to the sheer number of elements involved.

In an attempt to address these shortcomings, we have explored an alternate design/concept which involves a stationary receiver but only a small number of reflecting elements. Further, this device can be fabricated using relatively simple tools and processes that are available in any moderately industrialized region of the world.

According to the latest NREL report (Kurup and Turchi, 2015) which includes bottom-up build and cost estimates performed for two state-of-the-art parabolic trough designs, namely SkyTrough (SkyFuel, USA) and Ultimate trough (FLABEG, Germany) have specific costs 170 and 178 $/m^2 respectively. The cost breakup assuming 100 MWe plant installation, the solar field installed cost contributions are: a support structure (37%), receiver (16–18%) and reflectors (15–25%). According

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Nomenclature

C	C_{target}, C_{device} collector system specific costs (\$/m^2), targeted and device respectively
CF_{CSP}	annual capacity factor of solar power plant
CR	concentration ratio of the system
d	percent discount rate
J_{CG}	polar moment of inertia, m^4
T	torque, N m
G	modulus of rigidity, Pa
Ls	length of tracking shaft, m
P	nameplate capacity of solar power plant
n	exponent dependent on the local terrain roughness and other effects such as buildings or trees (n = 7 for open terrain)
t	plant useful life, year
T	torque in tracking shaft, N m
ΔT	average deviation from ambient temperature $= \left(\frac{T_{Out}+T_{In}}{2} - T_a\right)$, K
$u(z_0)$	basic wind speed, m/s
z_0	reference height at which the data is weather data is collected
β, β_{max}	trough elevation, max. trough elevation (degree)
ϕ	latitude of location on earth, degree
δ	declination of earth, degree
ρ_{mirror}	reflectivity of mirror
τ_{glass}	transmitivity of cover glass of secondary reflector
$\alpha_{receiver}$	absorptivity of receiver tube surface
η_{cc}	thermal to electric efficiency
η_{cos}	cosine loss efficiency of E-W mounted trough
η_{DNI}	fraction of global radiation incident normally which can be concentrated
$\eta_{Optical}$	optical efficiency of the system
η_{OI}	optical intercept factor of the system
η_{Th}	thermal efficiency of the collector system
ε	annual repair and maintenance cost
ψ	rim angle

to the cost data from the four sources mentioned in the IRENA report (Mouchout and Shuman, 2010), the solar field cost contribution in the installed project cost is in the range of 35–49% depending on the solar multiple and hours of thermal energy storage (TES). The cost of the solar field and thermal storage are directly related to plant capacity; hence, significant cost reductions cannot be realized by economies of scale. Support structures and mirrors are the key components to focus on cost savings. The optical performance of the trough depends on its design and structural rigidity which demands high material requirements. Therefore, efforts are underway to explore different designs to reduce the material requirements while maintaining/improving rigidity (Mouchout and Shuman, 2010). Different commercial trough designs such as LS-1, LS-2, LS-3, New IST, Dukesolar, and Eurotrough are deployed in utility-scale power plants like SEGS-I – IX. Specific weight (kg/m^2) of these designs and plants are mentioned in Table 1 (Price et al., 2002). Also, some cost projections for the trough type system are shown in Table 2.

Table 1
Specific weights and optical efficiencies of commercial designs (Price et al., 2002).

Collector	Mirror Type	Module weight per m^2 (kg/m^2)	Peak optical efficiency (%)	References
LS-1	Silvered low iron float glass	–	71	SEGS I + II
LS-2	Silvered low iron float glass	29	76	SEGS II-VII
LS-3	Silvered low iron float glass	33	80	SEGS V–IX
New IST	Silvered thin glass	24	78	IST
Euro-Trough	Silvered low iron float glass	29	80	PSA
Duke Solar	Silvered low iron float glass	24	80 (projected)	Duke DS1

In this paper, we describe line concentrator system of a *cylindrical* cross section which can be considered a hybrid between the conventional parabolic trough reflectors and the linear Fresnel systems. The Fig. 1 shows a field-implementation of the system. It is a line concentrating system like parabolic trough or linear Fresnel collectors. Like linear Fresnel systems, the receiver pipe is fixed and each receiver pipe is illuminated by rays concentrated by three independently tracked cylindrical reflectors which pivot about their axes and are low on the ground. Like parabolic troughs, the number of reflectors are few (three or five at most) hence easier to clean and maintain. The cylindrical shape is easy to fabricate using simple glass-bending machines. Further, the concentration ratios are considerable (as high as 30). Hence, this system promises to combine the benefits of high concentration ratio of parabolic trough with the facility of operation of linear Fresnel systems.

Levelized cost of electricity (LCOE) is an effective metric to compare the economics of different CSP systems and also with the other types of power plants. LCOE changes with solar resource, plant capacity factor, plant performance, capital investment, discount rate or cost of capital etc. LCOE in 2010 was in the range of 0.2–0.36 \$/kWh assuming 10% discount rate (Mouchout and Shuman, 2010). As LCOE is affected by capacity factor and solar resource intensity, we can back calculate the target total capital cost of Andasol-1 like power plant to be economically feasible. Thus, for CSP to compete with the coal-based power, its LCOE should be below 0.077 \$/kWh. With this LCOE target, the plant capital cost per m^2 aperture area for various capacity factors in the range of 20–60% and direct normal insolation (DNI) in the range of 800–2500 kWh/m^2-y are calculated according to the procedure described in reference Purohit and Purohit (2010).[1] Further, area requirements are calculated for 50 MW plant using solar to electric efficiency of 15%. Hence, specific plant costs (\$/m^2) are obtained for a wide range of capacity factors and solar intensities at various plant locations in the world using common parameters mentioned in Table 3. Such values are also obtained for various Indian locations. Average value of specific plant cost for CSP plant locations in the world and for India are 309 \$/m^2 and 220 \$/m^2 respectively, for Andasol-1 like power plant to be economically feasible (see Annexure). Now, excluding labour cost which varies country wise, the collective contribution by mirror, steel structure and receiver is around 29–39% of the total plant cost as per cost breakup given in the reference Mouchout and Shuman (2010) and Sargent and Lundy (2003) which also include components like pylons, foundation, tracker, swivel joint, thermal storage system, power block etc.

The target cost is a function of available solar resource and the ability to efficiently convert it to electricity. The Table in the Annexure shows calculations for target cost (C_{target}) for solar to electric efficiency of 15% averaged over various locations in India. Hence, the following relation between target cost in USD and solar to electric efficiency is obtained as,

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[1] Annual electricity generation (AEG) $=(365 \times 24) CF_{CSP} P$ where CF_{CSP} is the capacity factor and P the nameplate power capacity. The capital recover factor $CRF = \frac{d(1+d)^t}{(1+d)^t - 1}$ where d is the discount rate and t the life of the plant in years. Hence plant cost is $C = \frac{LCOE \times AEG}{(CRF + \varepsilon)}$ where ϵ is the operation and maintenance cost factor.