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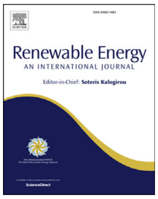

Assessing the impact of optical errors in a novel 2-stage dish concentrator using Monte-Carlo ray-tracing simulation

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ABSTRACT

Optical errors decrease the performance of solar concentrators. Here we assess the sensitivity of a novel 2-stage dish concentrator against optical errors. We use Monte Carlo ray-tracing, probability statistics, and optical geometrical principles in the analyses. The key finding is that the novel concentrator can reach a high radial distribution of flux concentration and high optical efficiency over a range of optical errors. Compared to a traditional 2-dish concentrator, the performance was clearly better. The results are in good agreement with results from the TracePro® tool. The results also imply improved tracking stability with the novel 2-stage dish concentrator.

1. Introduction

Compared to photovoltaics, concentrating solar power (CSP) possesses several advantages such as hybridization and dispatchability through coupling with thermal energy storage [1,2]. CSP technologies are usually categorized into 4 different classes: parabolic trough collector (PTC), linear Fresnel reflector (LFR), solar power tower (SPT), and parabolic dish system (PDS) technologies [3]. The PTC, LFR, and SPT technologies have successfully been commercially deployed in the USA, Spain, Australia, China, and in some other regions. The PDS technology coupled with an efficient thermodynamic cycle can reach a high conversion efficiency (>30%) due to the good optical efficiency [4,5]. But its technical and commercial potential has not yet been fully utilized and the size of dish systems with Stirling or Brayton cycles typically remains below 50 kWe per engine unit [6].

The concentrator is the key component of a solar dish system. It uses a large reflector or multiple facets arranged in a certain combined pattern approximating a paraboloid of revolution to concentrate sunlight into the focus. Conventional reflector schemes mainly employ 1-stage structures with several drawbacks, which could be overcome with a 2-stage dish concentrator providing more flexibility and stable structures. Different types of 2-stage concentrators have been proposed [7–19], but they have problems in reaching a high flux concentration (β) and a good intercept factor (γ) at the same time, because of the shadowing of the secondary mirror when the concentration ratio increases, which leads to a decreasing intercept factor. To overcome this problem, a novel 2-stage dish concentrator (Fig. 1) has been proposed with a unique hollow structure which enables the mirrors to overlap, but avoids excess shading [20]. This novel concentrator, which is also the basis of this paper, is superior to the conventional 2-stage dish in terms of optical performance.

Different optical errors encountered in practical applications may adversely influence the optical performance of the concentrator. The main aim of this paper is to analyze how such errors would influence the performance of the novel 2-stage dish concentrator compared to a conventional 2-stage dish system.

The literature on optical errors is ample. State-of-the-art glass mirrors have a low specularity error less than 0.2 mrad over a large range of incident angles (0°–70°) and wavelengths relevant for CSP [21,22]. Low slope errors around 0.5 mrad can also be reached, but this needs often to be balanced with the manufacturing costs [23]. Tracking errors can be kept down to some mrads, but it is also subject to trade-off with cost factors. Thus for glass mirrors, error values from 0.5 to >3 mrad could be typical [24]. However, the

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Nomenclature

Symbols

D	Diameter of the paraboloid dish
d	Diameter of the hyperboloid dish
e	Distance from the vertex of paraboloid mirrors to the left focal point of hyperboloid mirrors ($e \cdot (f_{para} - f_{hyper}) \geq 0$)
E	Distribution of radial flux density
$\overline{E}$	Average radial flux density absorbed on receiver
f	Focal length
E_0	Incident radial flux density
L	Deviation distance
NA	Sine of the rim angle from the centre ray
Q	Radiant flux
R^2	Correlation coefficient
r	Radius of concentrated spot
θ	Rim angle of the dish
β	Radial distribution of flux concentration
λ	Wavelength of sunlight
γ	Intercept factor
η	Efficiency
δ	Rim angle of the sun disc
δ_{off}	Random variables indicating off-axis angle deviating from on-axis position
δ_{sun}	Random variables indicating radial angles deviating from the sun's centre
δ_{slope}	Random variables indicating zenith angle deviations of local surface normal
ϕ	Random variables indicating azimuth angle
σ	Standard deviation
ξ	Absolute error
ζ	Sample standard deviation
Δ	Outer rim angle of aureole regions
Γ_0	Performance ratio as ratio of β_{novel} to β_{cov} (or γ_{novel} to γ_{cov})
Φ	Normalized radiation distribution of source (the sun)

Subscripts

1	Primary mirror
2	Secondary hyperboloid mirror
3	Secondary paraboloid mirror
4	Tertiary mirror
Cov	Conventional 2-stage dish concentrator
Local	Local value
N	Normalized value
Novel	Novel 2-stage dish concentrator
Off	Off-axis
Optic	Optical
Peak	Peak value
Sun	Sun
Slope	Slope or Effective slope
Tracking	Tracking

Abbreviations

APU	Auxiliary power unitCR Centre region
CSP	Concentrating solar power
CSR	Circumsolar ratio
LFR	Linear Fresnel reflector
MCRT	Monte Carlo ray-tracing
OCR	Off-centre region
PCU	Power conversion unit
PDS	Parabolic dish system
PTC	Parabolic trough collector
PM	Primary mirror (Mirror 1)
SM	Secondary mirror (Mirror 2)
SM1	Secondary hyperboloid mirror
SM2	Secondary paraboloid mirror
SPT	Solar power tower
TM	Tertiary mirror

literature on the shape error is limited and is often handled together with the slope error [25]. Here we analyze the slope and tracking error in particular.

2. Novel 2-stage dish concentrator

The 2-stage novel (Fig. A2) and reference (Fig. A1) dish concentrators are described in the Appendix. Assumptions and definitions used in the analysis are as follows:

- The incident radial flux density (E_0) is 996 W/m^2. All incident sunlight is assumed with a rim angle (δ) of 4.65 mrad [26];
- The reflectivity of reflectors is 0.949 independent of the angle of incidence;
- The receiver plate is a black body;
- Only effects of the sun shape and the effective slope error are considered here;
- The intercept factor of the dish concentrator (γ) is defined as the fraction (from 0 to 1) of rays incident upon the dish section that reach the receiver [27];
- The optical efficiency (η_{optic}) is the percentage of the radiant flux (Q) received on the gross receiver area;

The external diameter of the primary mirror (PM) was set to 20 m. To obtain an optimized design, we fix mirror PM and vary the shape of mirror SM in Fig. A1 and A2. Ray-trace analyses (with Tracepro® ray-tracing tool [28,29]) were performed to estimate β and η_{optic} for different geometries.

Table 1 summarizes the key parameters for the optimal designs of the two concentrator configurations [20]. With these values, the best optical performance of the conventional system (Fig. A1) correspond to $\beta = 11{,}792$ and $\eta_{optic} = 0.663$. The optical losses are mostly due to shadows from the secondary mirror (SM). Because high values of β correspond to those SMs with large size of opening areas, a high β and η_{optic} cannot be achieved simultaneously through the traditional 2-stage dish concentrator. For the novel design employing the focusing overlap method, the optimal design gives $\beta = 15{,}498$ and $\eta_{optic} = 0.781$, which is much better than with the conventional design.