Technical Analysis and Optimization of a High Concentrating Photovoltaic Power Tower

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Abstract. Based on the results of previous research, a technical study on a 1 MW prototype photovoltaic power tower is presented in this contribution. Some options to optimize the heliostat field were assessed to improve the optical efficiency and yearly energy output. Aiming strategies to create a highly homogeneous radiant flux distribution on the PV receiver and additional optimization options were analyzed. A significant improvement compared to earlier results and an annual mean optical efficiency of 54.7 % was achieved. The cost calculation for the improved system resulted in levelized cost of electricity (LCOE) of 0.19 €/kWh for the exemplary location Seville, Spain. Assumptions for further improvements and heliostat field cost reduction showed an additional cost reduction potential to 0.08 €/kWh.

Keywords: photovoltaic power tower, high concentration PV, optical simulations, ray tracing, solar concentrator, central receiver system, homogeneous illumination distribution

INTRODUCTION

Highly concentrating photovoltaic power towers combine the advantages of concentrated solar power (CSP) towers and high efficiency concentrator photovoltaics (CPV) modules. Heliostats are used to track the sun and reflect the sunlight onto a central receiver. In this study, the PV receiver consists of Compact Concentrator Modules (CCM) developed at Fraunhofer Institute for Solar Energy Systems (ISE) for highly concentrated radiation of up to 1000 suns [1].

A previous feasibility study at Fraunhofer ISE about a photovoltaic power tower prototype indicated a relatively high levelized cost of electricity (LCOE) [2]. In this contribution, a more detailed technical study on the collector system and some options to improve the system efficiency are presented. In particular, options will be discussed to optimize the optical field efficiency and to create a homogeneous flux distribution with a high mean intensity on the receiver without increasing the cost. The homogeneous flux distribution is necessary due to the restriction of a maximum irradiance on the modules, the high cell cost and the electrical characteristics of the series connected PV cells. The main goal is to decrease the LCOE through the optimization of the collector system.

SIMULATION MODELS

Optical simulations were performed using the Fraunhofer ISE in-house ray tracing software Raytrace3D, a Monte Carlo based ray tracing software suite. Suitable models for the PV receiver and the optical analysis of the collector system (heliostat field) were designed and implemented. A simplified PV receiver model will be described in this paper. A more detailed description of both the heliostat field design and the PV receiver model will be published later.

The photovoltaic receiver is an assembly of compact concentrator modules (CCMs). These CCMs consist of multi-junction solar cells electrically interconnected and mounted on an actively cooled heat spreader. They currently achieve electrical efficiencies of 30.1 % [3]. In our analysis, we modeled a receiver consisting of 25 x 25 CCMs and 8 x 8 solar cells per CCM. All the cells inside a CCM are connected in series. The current of each CCM is limited by the cell with the lowest current. We therefore assume that the usable radiant flux for electrical conversion, Φ_{CCM}, is limited by the cell with the lowest irradiance within the CCM; the electrical output of the CCM is determined by this cell. The wavelength dependence of the electrical output is not considered in our analysis.

A binned flux map on the receiver is generated from optical simulations. To determine inhomogeneity losses, the model searches for the bin with the lowest intensity inside each CCM and calculates the radiant flux Φ_{CCM} usable for electrical conversion, multiplying the lowest intensity with the module area and the irradiance G_B. The electrical output $P_{el,CCM}$ is obtained by multiplying Φ_{CCM} with the electrical receiver efficiency η_{rec}. The electrical output of the entire receiver is the sum of the electrical output of all CCMs. A graphical representation of the receiver model is given in Fig. 1.

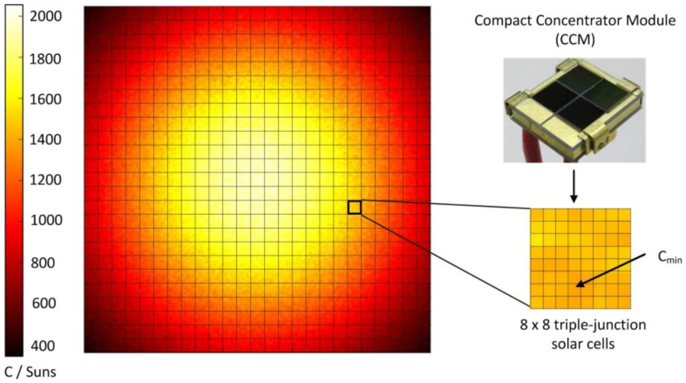

FIGURE 1. Graphical representation of the PV receiver model used to calculate the electrical output from a distribution of concentration ratios. Left: binned flux map, entire receiver aperture with grid of CCMs; lower right: representation of one CCM with 8 x 8 triple-junction solar cells; upper right: photograph of CCM prototype with 2 x 2 cell units [3].

In the electrical receiver efficiency η_{rec}, further losses are considered, including the angle dependent reflection of the incoming irradiance, surface losses due to gaps between the modules, temperature dependent cell efficiency, inverter losses, system availability and auxiliary power. This results in an overall receiver efficiency of 20 %.

The heliostat field was designed following the no-blocking algorithm described in [4] and optimized to achieve a high optical efficiency when aiming the reflected sun light to the center of the receiver. The field layout is shown in Fig. 2.

OPTICAL DESIGN STUDY

Optical simulations were performed at one design point, which was chosen to be the 21st of June 2010, 12 pm in Seville, Spain. Different aiming strategies were assessed and developed to limit the irradiance on the PV modules to no more than 1000 suns and to achieve a highly homogeneous distribution of irradiance across the receiver while maintaining a high optical efficiency (low spillage).

In a second step, the receiver area was increased to minimize intercept losses. Consequently the receiver accepts a lower mean intensity, additional losses due to inhomogeneous illumination on the outer modules are introduced and additional costs for the larger receiver arise. All parameters for the simulations are listed in Table 1.

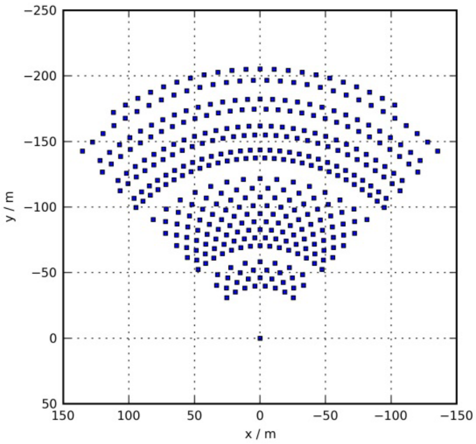

FIGURE 2. Optimized field layout for a power tower system with photovoltaic receiver.

TABLE 1. Design and simulation parameters for the optical analysis:

Number of heliostats	390
Heliostat aperture area	25 m²
Total reflective aperture area	9750 m²
Mirror reflectance	90 %
Beam error	3 mrad
Receiver aperture area	6.25 m²
Receiver tilt angle (to vertical)	25 °
Radiative power incident on the receiver	5 MW
Mean concentration on the receiver	800 suns
Direct normal irradiance G_B	1000 W/m²

RESULTS

With an adapted aiming strategy, we were able to create a fairly homogeneous flux distribution on the receiver. However, it was not possible to maintain a mean concentration ratio of 800 suns over the entire surface. By moving the target point away from the receiver center, a significant part of the reflected radiation is not concentrated on the receiver, but falls just outside the receiver area. These spillage losses lead to a significantly reduced optical efficiency. Furthermore, the later completed annual simulation pointed out a strong dependency of the flux distribution on the sun position, causing additionally increased spillage losses.

In Fig. 3 the distribution of concentration ratios is shown for three receiver sizes (6.25 m², 9 m², 12.25 m²), resulting from the same aiming strategy. To calculate this distribution, the receiver area is divided into segments, each segment consisting of 5% of the area and the concentration inside each segment is averaged. The homogeneity obviously decreases when the receiver area is increased if the aiming point strategy is not adapted.

The optical efficiency with a 9 m² receiver was increased by 23 % compared to the original setup (6.25 m²) and by 36 % with a 12.25 m² receiver. The homogeneity decreased slightly in both cases due to the less homogeneous irradiance distribution in the outer regions of the receiver. In case of a receiver with 12.25 m² receiver area more than 20 % of the modules are illuminated with an irradiance of less than 300 suns.

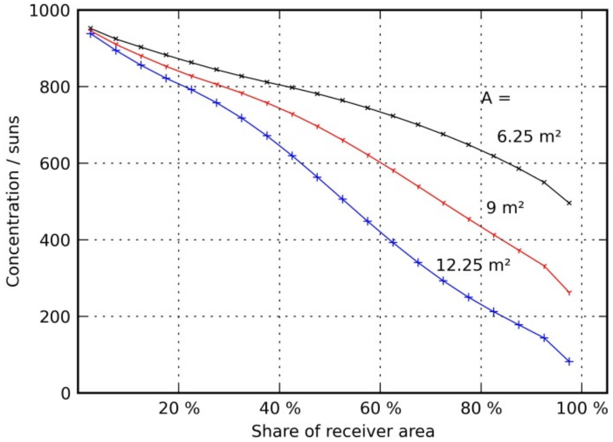

FIGURE 3. Distribution of concentration ratios averaged inside 5 % shares of the receiver area, from regions with highest to regions with lowest concentration ratios. The results for three receiver sizes are shown: 6.25 m², 9 m² and 12.25 m².

ANNUAL SIMULATION AND TECHNO-ECONOMIC ANALYSIS

After an initial optimization of the aiming strategies and receiver geometry, an annual simulation was completed using the collector configuration that was found to give the best results at the design point. Weather data for a typical meteorological year in Seville from Meteonorm [5] was used.

The annual simulation showed an annual mean solar field optical efficiency of 54.7 % which is a significant improvement from 40.1 % calculated in [2]. The total annual electrical output is 2370 MWh.

To calculate the LCOE, assumptions were made for the investment costs (heliostat field, receiver, inverter, tower, infrastructure and engineering). Operating and maintenance (O&M) costs, including cleaning of mirrors [6], are assumed to be 2.5 % of the initial investment costs and 1 ct/kWh for variable operating costs. All assumptions and the calculation method are the same as in [2].

The resulting LCOE is 0.196 €/kWh and was reduced by 32 % compared to the results from [2]. To show the potential of further cost reduction, the LCOE was calculated for two additional cases. First, minimum investment costs for heliostats and receiver are assumed. Secondly, we presume that further improvement of both optical efficiency and receiver efficiency can be achieved through additional optimization studies. Optical losses for instance could be further reduced by optimized aiming strategies and variation of heliostat field parameters such as the heliostat size, shape and position.

Assuming heliostat costs of 100 €/m² (target costs are in range of 75-120 USD/m² according to [7]) and 78000 €/m² for the PV receiver and cooler unit, LCOE of 0.11 €/kWh can be achieved. For the second case we assumed an improvement in the optical efficiency of 10 %. Furthermore, an efficiency of 36 % for the concentrator modules should be achievable in the future, leading to a possible receiver efficiency of up to 27 %. With these improvements, the LCOE could be even further reduced to 0.08 €/kWh, demonstrating the general potential of this technology to achieve low LCOE.

Some results are given in the following Table 2, where detailed numbers are given for the original simulation results (second column), under the assumption of reduced investment cost (third column) and additionally assuming further improvement in efficiency of collector system and PV receiver (fourth column).

TABLE 2. Simulation results from an annual simulation and evaluation of a PV power tower with weather data from Seville, Spain. Levelized cost of electricity (LCOE) for our simulation results, assuming reduced investment cost and assuming further improvement in efficiency of collector system and PV receiver.

	Simulation Results	**Reduced Investment Costs**	**Efficiency Improvement**
Power output	2 370 MWh	2 370 MWh	3 519 MWh
Optical efficiency η_{opt}	54.7 %	54.7 %	60.1 %
Receiver efficiency η_{rec}	20 %	20 %	27 %
Heliostat cost	250 €/m²	100 €/m²	100 €/m²
Receiver cost	108 000 €/m²	78 000 €/m²	78 000 €/m²
LCOE	**19.6 ct/kWh**	**11.3 ct/kWh**	**8 ct/kWh**

DISCUSSION

The presented technical analysis of a PV power tower shows a high potential of technical improvement. The optimization of the collector system resulted in a significant increase in the annual mean optical efficiency compared to earlier analyses. It was shown that PV power towers can reach similar cost potential ranges as those forecast for other solar technologies [8].

Nevertheless, there is still potential for further improvements. An optimization of the aiming strategy not only for one sun position, but continuously over the whole operating time could further reduce spillage losses. A higher PV cell and module efficiency could significantly increase the energy output of the receiver. Additionally, to significantly lower the LCOE, the investment cost for the heliostat field has to be reduced. More details on the simulations, aiming strategies, results and a location study will be part of a future publication.

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