Feasibility Study on High Concentrating Photovoltaic Power Towers

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Abstract: This paper presents an analysis on the concept of high concentrating PV power towers. A feasibility study is conducted in order to evaluate the future potential of this technology. Objective of the analysis is to provide an improved basis for establishing research and development priorities for the PV power tower concept. Performance assessments and cost calculations for a 1 MW prototype PV tower power are derived. Based on the assumption of a highly homogeneously illuminated receiver, levelized costs of electricity of 0.29 €/kWh have been calculated for a prototype PV tower power.

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INTRODUCTION & MOTIVATION

Concentrated solar power (CSP) towers utilize heliostats to track the sun on two axes with the objective of focusing and concentrating solar radiation onto a central thermal receiver. The receiver is situated on top of a tower to absorb the solar radiation and convert it to thermal energy, which is then converted to electricity by conventional power cycles [1]. This technology has demonstrated commercial availability and is recognized as an option for large scale renewable electricity production [2].

The technology of a PV power tower is quite similar to the concept of a CSP tower as presented e.g. in 1992 by R.M. Swanson [3]. However, sole difference is that the thermal receiver and conventional power cycle turbines are replaced by a PV receiver.

When compared with competing solar electricity generating technologies, PV power towers provide considerable advantages:

- Compared to CSP, the direct conversion of sunlight into electricity allows for the omission of turbines and mechanic-electric generators.
- Compared to CSP, PV tower power plants have a greater flexibility with respect to the size of the power plant, as the thermodynamic disadvantages of small turbines do not apply to PV power towers.
- Complexity of electricity and cooling liquid transmission is reduced by centralizing the electrical conversion onto a central PV receiver.
- Economic deployment of high-efficiency multi-junction III-V-concentrator cells and reduction of semiconductor material becomes possible due to the use of highly concentrated sunlight.

The combination of the power tower technology with PV appears promising and may improve the cost-effectiveness of solar power plants. However, as of today, no power tower system employing a PV-receiver has successfully broken the market barriers.

During the EU-funded project HICONPV, the Fraunhofer Institute of Solar Energy Systems (ISE), in cooperation with its partners, has developed a water-cooled dense array PV-receiver employing III-V concentrator cells, the so called compact concentrator module (CCM). To avoid the problem of excessively high currents, monolithic interconnected modules (MIMs) are well suited to be used in CCMs (figure 1) [4,5].

MIMs reaching efficiencies of 20.0 % have been successfully tested in CCM based outdoor concentrator systems up to 1 000 suns, where overall operational electrical efficiencies of 15.9 % have been confirmed [4].

Receivers based on the MIM technology have been chosen as the basis of the technical and economic evaluation in this paper. This analysis is performed for a power tower system with a nominal electric power output of 1 MW.

FIGURE 1. Photograph of a CCM. Gallium Arsenide concentrator cells (MIMs) mounted on an actively cooled heat sink for efficient conversion of 1 000x solar radiation into electricity.

TECHNICAL ANALYSIS

The calculations for the heliostat layout and flux profiles at the receiver are carried out with an advanced ray tracing software called OPTIMTSA [6]. OPTIMTSA calculates the solar radiation transferred by each heliostat into the given square of the PV receiver 50 m above the heliostat field taking into account blocking, shading, cosine loss, and spillage.

The PV receiver for concentrated radiation requires an uniform illumination over the whole surface to achieve the best performance. One approach to achieve this homogeneity could be the use of a secondary optic [7], which can distribute the reflected solar radiation more homogeneously over the receiver.

However, a secondary concentrator also adds more complexity to the overall system. It needs to be actively cooled, absorbs a fraction of the potential useful solar radiation, and increases the initial investment costs.

Due to these drawbacks, a secondary optic was not considered in this study and the heliostat field was designed to generate a comparatively homogenous flux distribution over the PV receiver surface (figure 2).

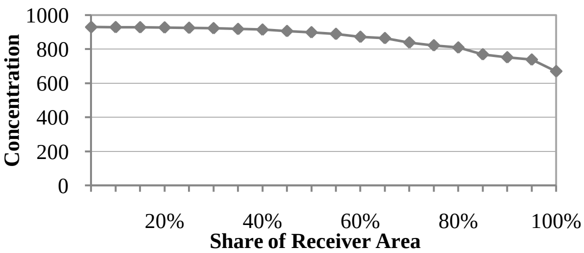

FIGURE 2. Flux distribution over the PV receiver surface at the design point (June 21st, 12:00 pm).

Table 1 summarizes the assumptions for the optical part.

TABLE 1. Summary of assumptions for the plant layout and design of optical part

Number of Heliostats	[#]	1 386
Size of Heliostats:	[m^2]	7.22
Total Heliostat Field Size	[m^2]	10 010
Reflectivity of Heliostats	[%]	92.5
Beam Error of Heliostats:	[mrad]	3
Tower Height:	[m]	50
Receiver Size:	[m^2]	6
Total DNI on Heliostats	[kWh/m^{2}a]	1 904
Location	[-]	Seville, Spain

The annual sum of the radiative power transferred from the heliostat field onto the receiver surface is 7 648 MWh/a, resulting in an annual reflector area efficiency of 40.1 %.

An assumed MIM conversion efficiency of 25.0 % leads to an overall operational electrical efficiency of 18.7 % according to the estimated losses in table 2.

TABLE 2. Parasitic losses.

Inactive CCM area:	[%$_{abs}$]	1.8
Inhomogeneous flux distribution:	[%$_{abs}$]	1.4
Increased temperature :	[%$_{abs}$]	0.8
DC-AC-Inverter:	[%$_{abs}$]	0.4
Availability:	[%$_{abs}$]	0.4
Cooling:	[%$_{abs}$]	1.5

The electrical output generated from the 1 MW PV power tower, as the product of the power transferred onto the receiver surface multiplied by the overall operational electrical efficiency, accumulates to 1 433 MWh/a.

ECONOMIC ANALYSIS

For the economic analysis, market prices for building a prototype 1 MW PV power tower according to table 3 are assumed.

TABLE 3. Assumed market prices for the PV power tower.

Heliostat Field	[€/m^2]	250
PV Receiver and Cooler Unit	[€/m^2]	108 000
Tower	[€]	115 000
Inverter	[€/kW]	250
Real Estate and Infrastructure	[€]	50 000
Engineering	[€]	168 000

In consideration of the listed specific cost data in table 3, the expected investment costs amount to 3 537 800 € or 3 540 €/kW. The share of the total investment costs are presented in figure 3.

Figure 3 reveals that a significant portion of the investment costs are associated with non-photovoltaic components. The heliostat field claims the biggest share with more than 70 % of the total investment costs. The PV receiver and cooler unit accounts for 13 %. Annual operating and maintenance (O&M) costs are assumed to be 3.5 % of the initial investment costs, resulting in approximately 120 000 €/a.

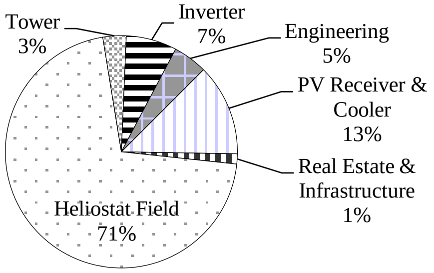

FIGURE 3. Share of the total investment costs.

The levelized cost of electricity (LCOE), are calculated as the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life (Eq. 1).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (1)$$

I_t = Investment expenditures in the year t
M_t = O&M expenditures in the year t
E_t = Electricity generation in the year t
r = Discount rate
n = System life time

For the calculation of the LCOE a set of technical and economic boundary conditions are needed. The conditions used in our calculations are listed in table 4.

TABLE 4. Technical and economic assumptions.

System life time	[a]	25
Debt-equity ratio:	[-]	65:35
Debt interest rate	[%]	6.5
Equity interest rate	[%]	14.0
General inflation rate:	[%]	2.5
Discount rate	[%]	6.6
Debt payback time	[a]	15
System residual value	[€]	0

The LCOE for a PV power tower as detailed in the technical analysis above was calculated using Eq. 1 and the boundary conditions as listed in table 4. The LCOE for a prototype PV power tower amounts to 0.29 €/kWh.

SENSITIVITY ANALYSIS

The results of the LCOE calculation presented depend on many assumptions that were necessarily taken. This includes the investment costs and economic boundary conditions, as well as assumptions on solar radiation and yearly average energy yields. It is critical to consider the sensitivities of these values to variations in the input data of the analysis and to carefully assess the effects of the important factors.

The sensitivity of the LCOE is plotted in figure 4 in dependence of the variation of several parameters with respect to their assumed values. The cell efficiency affects the LCOE the most, followed by the DNI at the site and the heliostat costs. For example, increasing the sum of the annual DNI from 1904 kWh/m^{2}a (Seville, Spain) to 2400 kWh/m^{2}a (e.g. North Africa) would result in the LCOE decreasing by 21 % to 0.23 €/kWh. Furthermore, reduced heliostat costs of 125 €/m^2 would result in LCOE of less than 0.19 €/kWh.

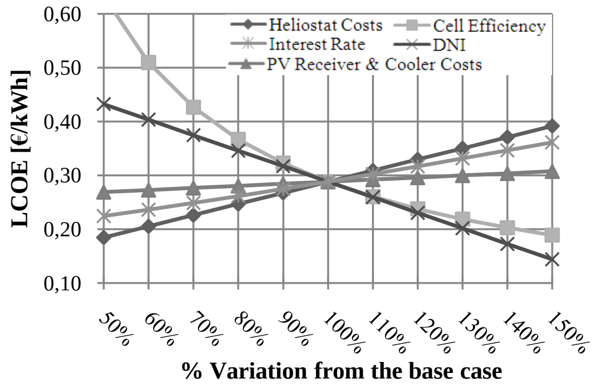

FIGURE 4. Sensitivity of the LCOE to the variation of several parameters.

DISCUSSION

The economic analysis shows total investment costs of 3540 €/kW, resulting in a LCOE of 0.29 €/kWh. This compares to 0.22 €/kWh from conventional photovoltaic systems with an assumed market price of 3100 €/kW and energy yield of 1500 kWh/kW$_p$ at adequate locations with identical economic and technical boundary conditions. With a prototype 1 MW PV power tower, the LCOE of conventional PV cannot be reached.

Effort must be taken to substantially reduce the costs. As commercialization of this technology progresses, two major factors will influence such a cost reduction. One is the economics of scale which leads to diminishing costs as the annual installed capacity increases beyond the 1 MW prototype power tower. The other factor is technological progress, e.g. through an increase in receiver efficiency. The comparison of the assumed cell efficiency of 25.0 % compared to the best concentrator cell efficiency of > 41 % [8,9] indicates the potential that could be achieved by an optimization of the system.

Since the heliostat field constitutes the largest single investment cost in a photovoltaic power tower, it is important to lower heliostat costs on a €/m^2 basis to improve the economic performance. A recent study suggests that heliostat costs can be as low as 90 US$/m^2 (≈ 66 €/m^2), if heliostat R&D continues and production rates are adequate [10]. In 2015, III-V concentrator cell costs are also expected to decline to approximately 22 000 - 37 000 €/m^2 [11]. Taking these values into consideration, 0.12 - 0.13 €/kWh may be achieved in the medium term.

Currently, a vast majority of the solar radiation, concentrated at high cost in the heliostat field, is transformed to *free* heat as a byproduct, but not energetically used. A possible approach to accomplish higher energy conversion rates of the absorbed solar radiation is the co-generation of electrical and thermal energy. The simultaneous generation, as proposed in the literature [12,13], is feasible using photovoltaic/ thermal (PV/T) collectors. Such collectors capture the heat with a heat exchanger behind the PV receiver. The relatively low temperature heat produced in the PV power tower might be suitable for thermal applications ranging from solar cooling to desalination, but need to be further examined if they are to be applied to PV power towers.

An alternative method of achieving better electrical conversion efficiencies in solar power towers might be to employ a spectrally selective filter [14]. Such filters split the collected and focused solar radiation from the heliostat field into components, which are optimized and suitable for multiple separate receivers, e.g. thermal receiver and PV receiver. Unfortunately, the practical design and manufacturing of such filters face several challenges and have yet to be commercially realized.

SUMMARY

A techno-economic evaluation for a 1 MW PV power tower prototype concept has been made in this study. The technical analysis defines a heliostat configuration and a flux profile for a 1 MW power tower with 1 386 heliostats, aperture size of 7.22 m^2, and PV receiver area of 6 m^2. The economic analysis shows total investment costs of 3 540 €/kW, resulting in a LCOE of 0.29 €/kWh at the exemplary location of Seville, Spain. These costs must be reduced significantly in the future to achieve the goal of grid parity with conventional electricity production.

To identify the largest cost reduction potentials, a sensitivity analysis has been conducted. This analysis ranks an increase in cell efficiency and DNI at the site, as well as a reduction in heliostat costs among the factors with the highest impact on LCOE reduction. The advancement in these topics is therefore the focus of current R&D activities for PV power towers.

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