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# Investigating the impact of weather variables on the energy yield and cost of energy of grid-connected solar concentrator systems

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ABSTRACT

This work connects the electrical performance and economics of High Concentrator Photovoltaic technology beyond the cell and module levels. It analyses the impact of fundamental variables on the calculated energy output and economics of a typical system for real-world solar power plants in five locations with diverse climatic conditions. It was found that there exists a nearly linear relationship between the Final Energy Yield and the average direct normal irradiance, while the cell temperature and spectral AC energy losses ranged from 4.6% to 1.8% and 5.0%–2.4%. The LCOE (Levelised Cost of Electricity) calculations used these insights, together with the specific economic values for each location. The results show that the locations with the higher annual energy yield tend to have the lower LCOE values. In particular, the LCOE ranged from 5.5 c€/kWh to 22.2 c€/kWh for a conservative scenario. However, the sites with the highest final yield do not necessarily present the lowest values of LCOE. The results emphasize the interrelationship between the instantaneous effects of cell temperature and spectrum on the performance of the system, as well as the importance of considering the specific economic parameters to estimate the LCOE at each location.

## 1. Introduction

HCPV (High Concentrator Photovoltaic) technology represents a promising energy source to produce more cost-effective electricity compared to conventional PV (Photovoltaic) technology by reducing the amount of expensive semiconductor material used for the cell by using less expensive optical elements [1]. Currently, this technology is largely based on the use of high efficiency III-V concentrator MJ (multi-junction) solar cells consisting of several p-n junctions, usually three, to increase the absorption of the incident solar spectrum, and thus maximize the efficiency of the solar conversion device [2,3]. The most widely used optical configuration consists of a POE (primary optical element), usually Fresnel lenses, and a SOE (secondary optical element). The aim of the POE is to collect and concentrate the direct rays, while the aim of the SOE is to receive the light from the POE to homogenize the luminous power on the solar cell surface and improve the acceptance angle of the overall concentrator system [4,5]. An HCPV module is the fundamental unit of an HCPV system used to convert the direct sunlight into electricity. It consists of a particular number of MJ solar cells and concentrator optical units, and other peripheral components necessary to generate electricity and dissipate the heat produced by the high energy flux of concentrated sunlight [6]. Passive cooling mechanisms are mainly used because of their simplicity and reliability [7–9]. Finally, a typical grid-connected system consists of several modules interconnected in series and parallel mounted on a high-precision pedestal. This two-axis solar tracker is connected to a high efficiency DC/AC inverter and the rest of BOS (balance of system components) [10–12]. The tracker allows for the optical axis of the concentrator optics to be within <1° of the solar disk. The efficiency of MJ concentrator cells, HCPV modules and systems is increasing over time, and is expected to reach values up to 50%, 45% and 40%, respectively, within the next few years [13,14]. Moreover, the costs of electricity for this technology has shown decreasing trends and has already shown promising results at locations with a high solar resource [15,16]. The comments above show the great potential of this technology, as an alternative

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## Nomenclature

| | |
|---|---|
| $A_{module}$ | Area of the modules, $m^2$ |
| $b_0$, $b_1$ and $b_2$ | Coefficients for the inverter, dimensionless |
| d | Nominal discount rate, % |
| $DEP_y$ | Annual tax depreciation, €/kWp |
| DNI | Direct Normal Irradiance, $W/m^2$ |
| $DNI_{heat}$ | Portion of the direct normal irradiance transformed into heat, $W/m^2$ |
| $d_s$ | Annual dividend of the equity capital, % |
| E | Energy output, kWh |
| *f* | Instantaneous power correction function, W or dimensionless |
| $HCPV_{AOM}$ | Annual operation and maintenance cost, €/kWp |
| $HCPV_I$ | Initial investment cost, €/kWp |
| $HCPV_l$ | Amount equal to the portion of the initial investment financed with the loan, % |
| $HCPV_s$ | Amount equal to the portion of the initial investment financed with equity, % |
| i | Annual inflation rate, % |
| $i_l$ | Annual loan interest rate, % |
| L | Power conversion losses, dimensionless |
| LCC | Life cycle cost of the system, €/kWp |
| LCOE | Levelised Cost of Electricity, €/kWh |
| N | Life cycle (useful lifespan) of the system, years |
| $N_d$ | Tax life for depreciation, years |
| $N_l$ | Loan duration, years |
| $N_S$ | Number of modules in series, dimensionless |
| $N_P$ | Number of modules in parallel, dimensionless |
| P | Power, W |
| $p_{in}$ | Normalized inverter input power, dimensionless |
| PR | Performance Ratio of the system ($PR = Y_F/\Sigma DNI$), % |
| PW [DEP($N_d$)] | Present worth of the tax depreciation, €/kWp |
| PW[$HCPV_{OM}$ (N)] | Present worth of operation and maintenance cost, €/kWp |
| $r_d$ | Annual degradation rate of the efficiency of the system, % |
| $r_{O\&M}$ | Operation and maintenance cost of the system, €/kWp |
| $R_{total}$ | Thermal resistance of the modules, °C/$Wm^{-2}$ |
| T | Income tax rate, % |
| $T_{air}$ | Air temperature, °C |
| $T_C$ | Cell temperature, °C |
| WACC | Weighted average cost of capital, % |
| $Y_F$ | Final energy yield, kWh/kWp |

*Greek letters*

| | |
|---|---|
| $\delta$ | Temperature coefficient of maximum power, %/°C |
| $\varepsilon$ | Air mass coefficient of maximum power, % |
| $\varphi$ | Aerosol optical depth coefficient of maximum power, % |
| $\eta_{inverter}$ | Efficiency of the inverter, % |

*Subscripts and superscripts*

| | |
|---|---|
| * | Values at reference conditions |
| 550 | 550 nm (AOD) |
| AC | Alternating current electricity |
| DC | Direct current electricity |
| DNI | Direct Normal Irradiance |
| inverter | Inverter of the system |
| module | Module of the system |
| nominal | Nominal power (inverter) |
| o | Peak power (system) |
| $S_b$ | Spectral direct normal irradiance |
| $T_c$ | Cell temperature |
| U | Umbral value |

*Abbreviations*

| | |
|---|---|
| AERONET | Aerosol Robotic Network |
| AM | Air Mass |
| AOD | Aerosol Optical Depth |
| BOS | Balance of System |
| CDM | Clean Development Mechanism |
| CEAEMA | Centro de Estudios Avanzados en Energía y Medio Ambiente |
| CSTC | Concentrator Standard Test Conditions |
| EQE | External Quantum Efficiency |
| HCPV | High Concentrator Photovoltaics |
| MJ | Multi-junction (solar cell) |
| PMMA | Poly(methylmethacrylate) (Fresnel lens) |
| POE | Primary optical element |
| PV | Photovoltaics |
| SMARTS | Simple Model of the Atmospherics Radiative Transfer of Sunshine |
| SOE | Secondary optical element |

renewable power source, to play an important role in the global energy market [17].

Despite such excellent potential, different barriers must still be eliminated to increase the confidence of investors, and thus to promote the market expansion of concentrator technology as a real alternative to traditional PV. Among all of them, the following two main concerns can be cited [18]: on the one hand, the understanding of the performance of HCPV systems when operating in real world conditions is clearly lower than conventional PV systems [19,20]; on the other hand, the cost of electricity and bankability of HCPV technology needs to be more thoroughly studied [15,21].

The electrical modelling of HCPV devices is inherently different and more complex than conventional PV devices. As in other types of PV technology, the energy output of HCPV is mainly determined by the irradiance, temperature and spectrum [19]. However, for instance, HCPV only collects the direct component of the irradiance due to the use of optical devices and the thermodynamic connections between concentration ratio and acceptance angle. Moreover, this aspect has demonstrated to be, by far, the most relevant variable to determine the performance of HCPV systems in the outdoors [20]. At the same time, the energy output of MJ solar cells is strongly affected by the spectral changes produced by the time-varying atmospheric parameters [22,23], due to the series connection of several subcells with different energy gaps [24]. Therefore, the input spectrum also plays a crucial role in determining the energy output of HCPV modules or systems [25,26]. The current–voltage characteristics of MJ solar cells are also affected by temperature [27,28]. Under real-world working conditions, the operating cell temperature of HCPV systems is also affected by the weather variables [29]. So, the performance of HCPV modules or outdoor systems is also going to be determined by their cell operating temperature [30]. However, the measurement and/or estimation of the cell temperature is a complex task due to the fact that the MJ cells mounted on HCPV modules are surrounded by several peripheral elements [31]. During recent years, the HCPV community has devoted large efforts to develop tools tailored to the