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A bankable method of assessing the performance of a CPV plant

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HIGHLIGHTS

- This methodology allows estimating the long-term energy production of a CPV project with $\sigma = 5\%$.
- The long-term trend of DNI is determined from satellite and its bias is corrected through a measurement campaign.
- The Yield Assessment is carried out using a physical model that simulates the energetic yield of a reference CPV system.
- The Certificate of Provisional Acceptance is delivered through on-site measurements achievable within one or two weeks.
- The Certificate of Final Acceptance is awarded on the basis of a continuous monitoring campaign during 1 or 2 years.

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ABSTRACT

Concentrating Photovoltaics (CPV) is an alternative to flat-plate module photovoltaic (PV) technology. The bankability of CPV projects is an important issue to pave the way toward a swift and sustained growth in this technology. The bankability of a PV plant is generally addressed through the modeling of its energy yield under a baseline loss scenario, followed by an on-site measurement campaign aimed at verifying its energy performance. This paper proposes a procedure for assessing the performance of a CPV project, articulated around four main successive steps: Solar Resource Assessment, Yield Assessment, Certificate of Provisional Acceptance, and Certificate of Final Acceptance. This methodology allows the long-term energy production of a CPV project to be estimated with an associated uncertainty of ≈5%. To our knowledge, no such method has been proposed to the CPV industry yet, and this critical situation has hindered or made impossible the completion of several important CPV projects undertaken in the world. The main motive for this proposed method is to bring a practical solution to this urgent problem. This procedure can be operated under a wide range of climatic conditions, and makes it possible to assess the bankability of a CPV plant whose design uses any of the technologies currently available on the market. The method is also compliant with both international standards and local regulations. In consequence, its applicability is both general and international.

1. Introduction

Concentrating Photovoltaics (CPV) is an alternative to the more classic photovoltaic (PV) technology based on flat-plate modules. From 2008 to 2013, the price of conventional crystalline silicon (xSi) PV modules has decreased sharply from €3.5/W to €0.5/W, a sevenfold decrease [1]. The challenge for CPV being to compete mainly with PV has therefore grown in similar proportions. Economies of scale represent the key factor that has been chiefly responsible for driving down the prices of xSi modules, which benefitted from a learning curve that allowed costs to be reduced by 20% for each doubling of the manufacturing capacities [2]. CPV technologies will have to follow a steeper learning curve [3] to have a chance of becoming commercially viable in the long term. Still, to date, very few CPV installations have been commissioned worldwide relative to conventional PV, and the initiatives are being taken by a reduced number of technology leaders [4]. The sector thus needs a quick and consequent kick-start if it is ever to validate this steeper learning curve and become part of the future energy scenario [5–7]. The bankability of CPV installations is an important issue in paving the way to a swift and sustained growth in this technology [8], but several significant obstacles still remain. Little detailed operational data relevant to CPV installations has been published to date [9–12]. A first International Electrotechnical Commission (IEC) standard for CPV modules has been under way for several years [13–19], but it is unlikely that a broader standard will be developed soon to provide guidance on evaluating the bankability of CPV plants. Therefore a robust methodology is

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rapidly needed to accelerate the financing of new CPV plants, a methodology that is both sufficiently accurate to be accepted by the CPV industry as well as by financial entities, and sufficiently simple and versatile to be of a practical application during the whole project assessment process, while using as little technical information as possible. At this point it is important to emphasize the current absence of any established procedure that could be used to assess the financial viability of a CPV project.

The bankability of a conventional PV plant is generally addressed through the modeling of its energetic yield under a baseline loss scenario, followed by an on-site measurement campaign. These two steps are compulsory when project finance is requested from a financial entity, for which it is critical to make sure that the energetic yield will be high enough to ensure the expected financial return. The assessment procedure must therefore be defined in a way that must be rigorous from a scientific point of view, and at the same time discriminant enough to result in clear PV plant acceptance/rejection decisions. In the case of conventional PV plants, the solution is relatively straightforward, because the DC power output of the PV generator is properly described by [25]:

$$P_{DC} = P^* \frac{G}{G^*} \left[1 + \gamma (T_c - T_C^*)\right] \cdot \left[1 + C \ln \frac{G}{G^*}\right] f_{DC} \tag{1}$$

where the symbol * refers to Standard Test Conditions (STC), P_{DC} is the DC power output of the PV generator, P^* is the nameplate DC power of the PV generator, G is the global (plane-of-array) solar irradiance received by the PV generator, G^* is the global solar irradiance under STC, γ is the coefficient of power variation due to cell temperature, T_c and T_c^* are respectively the cell temperatures under operating and STC conditions, C is the variation coefficient of current with solar irradiance, and f_{DC} is a coefficient that lumps together all the additional system losses in DC, e.g., technology-related issues, soiling and shading.

The corresponding AC power output is then given by:

$$P_{AC} = P_{DC} \eta_{INV} f_{AC} \tag{2}$$

where P_{AC} is the AC power output of the PV generator, η_{INV} is the yield of the inverter (which can be estimated from several coefficients characteristic of its load curve), and f_{AC} is a coefficient that lumps together all the technology-related additional AC system losses.

The energy produced during a period of time T is finally given by:

$$E_{AC} = \int_T P_{AC} dt \tag{3}$$

As a matter of fact, these procedures are already being implemented in the current PV market for large PV plants (say, larger than 1 MW), and rely on available and trustworthy solar engineering simulation software, solar radiation databases, and widely accepted performance figures, such as the Performance Ratio (PR). All this solid information is a guarantee of relatively low uncertainties along the process.

The main difference between PV and CPV resides in the CPV modules themselves, in particular in the inclusion of optical elements and III-V multijunction cells that are much more sensitive to the variations of the spectral direct solar irradiance than xSi cells [20], while the rest of the system behaves in a way that possesses many common points with xSi technology. The modeling of the DC power output of a CPV system thus requires several important second-order parameters to be considered, mainly related to optics, spectral direct irradiance, wind speed, tracker accuracy and heat dissipation of cells. The relation between DC power output and operational conditions thus takes the general form:

$$P_{DC} = P^* \frac{DNI}{DNI^*} f_{SHAD} f_{SOIL} f_{\lambda} f_{TEMP} f_{DC} \tag{4}$$

where DNI stands for Direct Normal Irradiance, and the power losses coefficients f_{SHAD}, f_{SOIL}, f_{λ}, f_{TEMP} and f_{DC} are related, respectively to shading, soiling, spectral distribution of DNI, cell temperature and technology-related issues, i.e., differences between real and nominal characteristics of the PV system.

Apart from the potential complexity of the physical models involved behind each one of these losses parameters, the practical use of this equation is made difficult by the necessity of their experimental verification during an on-field campaign [21]. For example, during on-site measurement campaigns of conventional PV plants, the second-order effects of temperature, solar spectrum and soiling are offset by the measurement of the solar irradiance and cell temperature by means of reference PV modules of a technology that is similar to the one of the modules installed (similar spectral response, similar power temperature coefficient) and of a similar degree of soiling. However, when CPV is concerned, these second-order effects are much more significant, and additional sources of power losses, such as the tracker accuracy, make the use of calibrated CPV modules virtually impossible. As a consequence, the CPV industry now necessitates quality control procedures that are adapted to the CPV technological specificities: spectral direct beam irradiance (instead of broadband global irradiance), high spectral sensitivity of solar cells and optics, high dependence of power output to tracking accuracy, etc. Improper consideration of these peculiarities typically translates into important uncertainties that are unacceptable from the investor's point of view, and which indeed have recently hindered or made impossible the completion of several important world CPV projects [22,23]. The practical experience is still too scarce to model the losses related to field conditions or technology-related issues with a sufficient degree of accuracy for bankability. Meanwhile, some early CPV projects of importance have revealed productivities well below expectations, indicating that too optimistic assumptions can lead to unpleasant situations. An illustrative example is the case of the then largest CPV plant in the world, installed in 2007 in Spain, in which the energy productivity from 2009 to 2012 was 30% below expectations [24]. At the beginning of 2013, the owners of the plant finally took the decision to replace all the CPV modules with xSi modules at their own cost, because it still made more economical sense to them. The CPV industry cannot afford to multiply these harmful experiences, which would wipe out its credit among investors.

During the last five years, the Universidad Politécnica de Madrid (UPM) and Universidad Politécnica de Jaén (UJAEN) have offered both indoor and outdoor control quality services to the PV and CPV industry, and have carried out on-site quality control campaigns for more than 60 PV plants totaling more than 300 MW, in close relation with Engineering, Procurement and Construction Contractors (EPCC) and financial entities. The experience thus gained has been published elsewhere [25–32]. Both universities have also been taking extensive meteorological measurements at their facilities in Madrid [33] and Jaén [34].

A growing number of models are now published in the literature to deal with specific parts of a CPV system, but these publications belong to a wide variety of disciplines, and are usually understood by completely different categories of experts. The present contribution presents a selection of applicable modeling methods with the aim of reaching a compromise between accuracy and simplicity, in a language as understandable as possible by the industry [35]. It summarizes the authors' previous experiences with assessing the performance of conventional PV plants in commercial frameworks and testing industrial CPV prototypes. To the best of our knowledge, the proper consideration of such peculiarities (a