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Photovoltaic performance and LCoE comparison at the coastal zone of the Atacama Desert, Chile

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ABSTRACT

Two photovoltaic technologies are compared with regard to the energy yield, performance ratio and their levelized cost of energy. Plants based on amorphous/microcrystalline silicon tandem thin films and multicrystalline silicon solar cells installed at the coastal zone of the Atacama Desert, Chile, were monitored for 21 months. This region can be one of the most suitable places for the use of solar energy due to the high solar radiation levels. However, the coastal desert climate may influence the performance of photovoltaic systems. The global tilted solar irradiation reached mean values of 8.6 kW h/m^2 day in summer and 6 kW h/m^2 day in winter demonstrating the high irradiation available. It came out that the performance ratio is influenced by the dust accumulation and the temperature associated to this place. The performance ratio of thin films decreased due to the dust accumulation at a rate from −4.2 to −3.7%/month for decreasing temperature and from −4.8 to −4.4%/month for increasing temperature. For multicrystalline silicon modules, the degradation rates were −2.4 to −1.8%/month for decreasing temperature, and −6.2 to −3.7%/month for increasing temperature. It was concluded that the electricity costs were 14.48 cents€/kW h and 15.65 cents€/kW h for thin film and mc-Si, respectively. Thus, the thin films had more benefit after cleaning than multicrystalline modules.

1. Introduction

The performance of a photovoltaic (PV) system does not only depend on the selected technology but also on the environment. External factors such as ultra violet solar radiation, corrosive surroundings, temperature, humidity, ventilation and dust can strongly affect the energy, which PV modules can produce. In order to predict the energy yield of a PV system, field measurements are needed to create models, such as shown in [1,2]. A summary of different approaches is found in [3]. The use of a mathematical expression is another way to predict the energy production [4].

One important reason for the performance decrease of a PV system is the dust or dirt accumulation (soiling). It was pointed out that the performance degradation was −0.2%/day in California, where limited rainfall in summer months was reported [5]. Recommendations to prevent the soiling effects have been given in [6]. The environmental conditions can strongly vary even within the same region. Consequently, energy predictions for PV systems, which consider the impact of the environment, must be accompanied by studies of the specific place, such as those performed by [7]. An example is the Atacama Desert.

The Atacama Desert is a large land area in South America extending across 1000 km from 30°S to 20°S along the Pacific coast. Its surface is approximately 105,000 km^2 occupying Chile, Peru, Bolivia and north of Argentina. Though, it is a temperate desert with mean temperatures between 10 and 20 °C for cold months and 20–30 °C for warm months, it is extremely arid with scarce rainfall. The maximum air temperature keeps below 38 °C (contrasting with the 50 °C found in the Death Valley, California) and the minimum is −5.7 °C [8].

The most used indicator to study and evaluate PV systems is the performance ratio (*PR*). The *PR* determines how effectively a PV system converts sunlight collected by the PV modules into electricity considering the availability of solar resource and relating to the name plate power [9,10]. According to [11], *PR* is defined as the ratio of the energy yield (Y_f) to the reference yield (Y_r). The Y_f is the normalized energy produced by the modules (E_{DC} in kW h) to the size of a PV system (power at standard testing conditions, P_{STC} in kWp). The Y_r is the quotient between the total in-plane irradiation H in kW h/m^2 and the irradiance at STC (G_{STC}), i.e. 1 kW/m^2.

$$PR = \frac{\frac{E_{DC}}{P_{STC}}}{\frac{H_{POA}}{G_{STC}}} = \frac{Y_f}{Y_r}\ (\%) \qquad (1)$$

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Using the *PR*, PV systems installed in different locations can be compared [12] and the degradation of a specific PV technology from year to year can be studied [13]. An investigation about the comparison of different PV technologies under same environmental and radiation conditions installed in northern India found that *PR* of Heterostructure with Intrinsic Thin Layer (HIT) and *PR* of amorphous silicon (a-Si) were 7% higher than that of multicrystalline silicon (mc-Si) [14]. Another study specified that *PR* ranged from 57% to 93% for mc-Si and from 54% to 88% for a-Si based PV plants in western India [15]. The performance of four technologies from which three of them were thin films and one was mc-Si resulted to be dependent on the season due to the change in the solar radiation available and operating temperature [16]. In Italy, the variability of *PR* was analyzed to compare several technologies resulting also in a seasonal dependence [17,18]. In Singapore, PV systems of 10 different technologies were evaluated. Among them, a-Si and mc-Si modules exhibited an annual degradation of −2%/year and 1%/year, respectively [19].

Regarding uncertainties, main sources of errors come out due to the measurement of solar irradiance as well as the DC electrical power, current and voltage. A study reports that the error in the tilted radiation and *PR* is estimated to be 6–7% [20] in which uncertainties associated to azimuth and elevation angles are also considered in the error propagation. In order to reduce uncertainties, a number of practices are required, such as the determination of the solar resource, considering the effects of micro-climates and improving the reliability, accurate module ratings [21], and inclusion of the effects of soiling, among others [22].

According to Eq. (1) the performance ratio is independent of local radiation conditions and module orientation, quantifying the overall effect of losses and external environmental factors [23]. Two external factors will be considered in this work: (i) dust accumulation on the module surface and (ii) temperature. External factors will be primarily studied by evaluating the performance ratio. This is a first step within a larger investigation which will involve the study and impact of environment on the performance of PV systems installed in northern Chile. A further step will be the specific analysis of the optical degradation due to dust and the chemical as well as physical characterization of dust.

For (i) it has been pointed out that the presence of dust on the module surface can have detrimental effects on the available radiation which a PV device can use. Due to light absorption and reflection by fine accumulated particles, attenuation of solar radiation intensity is produced according to the mass surface concentration of pollutants, expressed in g/cm^2, its size distribution and chemical composition [24]. In other words, the module glass transmittance (T), defined as the capacity of the glass to transmit radiation, is affected by dust. In this way, the available irradiance, $I(\lambda)$, for the PV devices is calculated as:

$$I(\lambda) = I_o(\lambda) \cdot T(\lambda) \ (\mathrm{W/m^2\ nm}) \quad (2)$$

where $I_0(\lambda)$ is the incident spectral irradiance onto the PV module in W/m^2 nm, λ the wavelength in nm and $T(\lambda)$ is the spectral transmittance, which includes the glass spectral transmittance $T_G(\lambda)$ and the spectral transmittance of the deposited dust layer, $T_D(\lambda)$, as follows:

$$T(\lambda) = T_G(\lambda) \cdot T_D(\lambda) \quad (3)$$

The accumulated dust on the glass decreases T regarding clean conditions and thus the available I is reduced. It is difficult to determine the spectral dependence of the transmittance due the dust deposition because it depends strongly on the particle size, the thickness of the accumulated dust layer, and chemical composition, among other local parameters. On one hand, some authors have been reported that these transmittance losses are higher in the range 300–570 nm than at longer λ [25]. On the other hand, a previous study showed that for dust concentration higher than 19 g/cm, T does not depend on λ [26]. A fundamental study on dust effects on PV showed a reduction in the overall plane glass transmittance of 20% for 45 days exposure [27]. In that work, anti-reflective coated glass resulted in a lower degradation of the transmittance than non-coated plane glass. Another study [28] performed in Malaga (Spain) reported that for a year the mean value of the daily irradiation losses due to the soiling can be 4%, and up to 20% for summer. Knowing the spectral response (*SR*) in A/W of the PV device, it is possible to determine the maximal theoretical value of the generated current density J which a PV module can generate as:

$$J = \int_{\lambda_1}^{\lambda_2} SR(\lambda) \cdot I_o(\lambda) \cdot T_D(\lambda) d\lambda \ (\mathrm{mA/cm^2}) \quad (4)$$

The value of J is not strongly dependent on temperature but, as expressed in Eq. (4), on *SR*, the irradiance $I_0(\lambda)$ and $T_D(\lambda)$. For accurate simulations, it must be considered that J slightly increases with temperature [29]. It has been shown that c-Si modules usually exhibit a better *SR* than thin films (both clean and dusty) [25]. Whether the dust associated to a location attenuates the incoming irradiance in a certain wavelength range or the attenuation is nearly equal at all wavelengths, it is expected that c-Si technology achieves a higher current density than thin films due to Eq. (4).

For (ii), when weather conditions strongly vary, a temperature correction for *PR* can be made [30]. According to their work, the solar cell temperature depends not only on ambient temperature (T_{amb}) but also on the incoming solar radiation. As a consequence of the strong dependence of voltage and power on solar cell temperature (T_{cell}) [29], it is expected to obtain a higher *PR* in winter than in summer. An evaluation has showed that the energy performance is strongly dependent on the operation module temperature [31].

In order to quantify the relation between the dust accumulation on PV modules and the cost that this effect implies, an economical study was made. The Levelized Cost of Energy (LCoE) it is an indicator used for the comparison between different sources of energy and is equal to the sum of all the cost incurring during the lifetime of the project divided by the units of energy produced during its lifetime [32,33]. According to recent studies, the LCoE for PV technology reaches values between 7.8 and 14.2 cents€/kW h by the third quarter of 2013 [34]. One of the aims of this research is to calculate the LCoE for two cases: first, the two PV plants with dust accumulation and second, the two PV plants with clean surfaces, placed in the coastal zone of the Atacama Desert.

Among the known studies, so far, on the effects of dust on solar energy technology [35] and particularly on photovoltaics [3], none of them reports any experimental results from PV plants in the Atacama Desert, Chile, and their interaction with the local environment of this region. Regarding the evaluation and measurements of the solar resource in Chile, advances in this matter can be found in [36].

2. Experimental

2.1. The study

This investigation was performed with PV systems located at the coastal zone of the Atacama Desert, Chile, at a latitude 23°41′39.23″S and longitude 70°24′59.08″W. The goal was to compare the performance of two different PV technologies working under similar environmental conditions such as solar irradiance, ambient temperature, and dust accumulation.

2.2. PV systems

The PV systems, plant 1 and 2, are based on modules of amorphous/microcrystalline silicon (a-Si/μc-Si) tandem thin films and