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Performance of CdTe Solar Cells under Diffuse Solar Irradiance

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Abstract: This study investigates how CdTe thin film solar cells perform under varying diffuse solar spectrum due to the changes of environmental parameters. These parameters are, generally, the air mass, the atmospheric water vapour content, the turbidity and the albedo. The solar irradiance striking the solar cell is simulated using the spectral irradiance model SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) for clear skies. The results show the short circuit current increases with increasing turbidity and albedo and it decreases with increasing air mass and atmospheric water vapour content but with different proportions. The performance of the cells is notably reduced, both in terms of efficiency and open circuit voltage, with increasing air mass but the cell performs better with increasing water vapour content, albedo and turbidity.

Key words: Solar cells, CdTe, thin film, environmental parameters, diffuse irradiance

INTRODUCTION

In recent years new thin film technologies have entered the Photovoltaic (PV) marketplace and are now available commercially, namely cadmium telluride (CdTe), Copper-Indium-Gallium-Diselenide (CIGS) and amorphous silicon (a-Si). These technologies exhibit a steadily improving efficiency and are potentially cheap to produce. Today, CdTe is one of the leading thin film photovoltaic materials due to the optimum band gap of 1.5 eV for the efficient photo conversion and high optical absorption coefficient. A thin film of CdTe with thickness of approximately 2 μm will absorb nearly 100% of the incident solar radiation (Ferekides *et al*., 2004). This leads to a successful development of high efficiency solar cells and modules. Amongst several attractive features, high chemical robustness and a simple phase diagram are the most important ones for large area production of CdTe solar modules at industrial scale.

When elaborating the photovoltaic cells, they are tested under standard reporting conditions of illumination and temperature (SRC: illumination = 1000 W m^{-2}, temperature = 25°C and AM 1.5 reference spectrum). However, these conditions practically never occur during normal outdoor operation as they do not take into consideration the actual geographical and environmental conditions at the installation site (Gottschalg *et al*., 2001). The performance of solar cells is influenced by the solar radiation at ground level that is not only place and time dependent but also varies in intensity and spectrum due to varying environmental parameters as turbidity, atmospheric water vapor content, air mass and albedo.

Before striking the solar cell, the solar rays are submitted to different transformations through the atmosphere. It acts as a continuously variable filter affecting the solar radiation propagating to the ground. Atmospheric gases, aerosols and particles, water vapor and droplets and various pollutants modify the distribution of solar energy with respect to wavelength. The result is a wide range of variation in the spectral distribution of natural sunlight. There are a wide variety of PV material combinations and systems with varying spectral distributions functions. The combination of the variability in natural spectral distributions and spectral response functions make designing, evaluating and predicting the performance of PV devices in the real world challenging (Zanesco and Krenzingeur, 1993; Gottschalg *et al*., 2005).

The composition of sunlight is further complicated by the fact that atmosphere scattering gives rise to a significant indirect or diffuse component. Even in clear, cloudless skies, the diffuse component can account for large amount of the total radiation received by a given surface during the day. The integration of the solar cells into one or more of the exterior surfaces of the building envelope represents a growing photovoltaic application. Building integrated photovoltaic modules with orientation and tilted angles different from the optimum, which may cause partial shading as well as indoor photovoltaic applications, operate often under diffuse solar irradiance. Therefore, accurate predictive and performance analysis are then of vital importance.

In this study the variation in the diffuse solar irradiance due to the variation of the environmental

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parameters namely; air mass, turbidity, albedo and atmospheric water vapor content can produce significant variation on the overall performance of the CdTe cells. The variation of the common performance indicators such as short circuit current, open circuit voltage, fill factor and efficiency are also discussed.

Calculation procedure: Many biological, chemical and physical processes are activated more powerfully at some wavelengths than at others. This is especially true and important in the field of solar energy engineering, where spectrally-selective systems such as PV devices play an increasing role. For such systems, spectral radiation data are more appropriate than the more common broadband irradiance data. Unfortunately, spectral irradiance is not measured routinely, but only sporadically at a few experimental sites in the world. Consequently, the only way to accurately simulate the instantaneous energy production or overall performance of a spectrally-selective system is to rely on appropriate modelling.

A large range of atmospheric radiation models has been elaborated by different authors for calculating the spectral solar irradiation. The majority has been developed by various climate research centers and are highly complex numerical models utilizing the data from aircraft and satellite observations as inputs (Ellingson and Fourquart, 1991). An upgraded spectral model, elaborated by (Gueymard, 1995), called SMARTS2 (Spectral Model for Atmospheric Transmission of Sunshine) is introduced here to determine the spectral values of diffuse horizontal irradiance for clear skies. This model can advantageously be used to predict clear-sky irradiance spectra on surfaces of any tilt and orientation. The SMARTS spectral model is attractive and has gained acceptance in both the atmospheric and engineering fields due to its low number of inputs, ease of use, to its versatility, execution speed and various refinements (Gueymard *et al.*, 2002; Gueymard, 2001, 2004, 2005). It can calculate punctual estimations of spectral irradiances using as input parameters; local geographic coordinates, atmospheric water vapor content, atmospheric pressure and aerosol optical thickness. Provided that the most important inputs are known with sufficient accuracy, it is concluded that the model performance is very high when compared to reference model (Gueymard, 2006).

The cell conversion efficiency is determined as:

$$\eta = FF\frac{V_{co}I_{sc}}{P_i S} \tag{1}$$

With: Isc is the short circuit current, S is the solar cell area and Pi is the total irradiance and is given by:

$$P_i = \int_0^{\infty} E(\lambda)\, d\lambda \tag{2}$$

Where E(λ) is the calculated diffuse spectral irradiance.

The fill factor FF can be expressed as (Green, 1982):

$$FF = \frac{v_{co} - Ln\left(v_{co} + 0.72\right)}{v_{co} + 1} \tag{3}$$

Where:

$$v_{co} = \frac{V_{co}}{n\left(\frac{kT}{q}\right)} \tag{4}$$

The open circuit voltage is calculated as:

$$V_{co} = n\frac{kT}{q}Ln\left(\frac{I_{ph}}{I_s} + 1\right) \tag{5}$$

The ideality factor, n and the saturation current, I_s, are calculated from the I-V characteristics using a method based on an auxiliary function and a computer routine (Cheqaar *et al.*, 2006).

The value of the photocurrent density ($J_{sc} = I_{sc}.S$) of a device is directly linked to the solar irradiance and can be calculated using the following expression:

$$J_{sc} = \int E(\lambda)\, SR(\lambda)\, d\lambda \tag{6}$$

Here E (λ) is the energy of the incident light and SR(λ) is the measured spectral response at a given wavelength.

RESULTS AND DISCUSSION

The diffuse solar irradiance is calculated at Setif (36.11°N, 5.25°E, 1081 m) on a horizontal surface by varying one environmental parameter and maintaining the others fixed, using SMARTS2. Then for each value of the environmental parameter in the study, we calculated the short circuit current, the open circuit voltage, the fill factor and the conversion efficiency of the CdTe solar cell.

Air mass effect: The air mass is defined as the relative path length of the direct solar beam irradiance through the atmosphere. It may be expressed as a multiple of the path traversed to a point at sea level with the sun at zenith. When the sun is directly above a sea-level location the path length is defined as air mass 1 (AM 1.0). Air mass 0 is intended the solar spectral distribution outside the atmosphere. Air mass 1.5 corresponds to a solar elevation of about 42°. When the angle of the sun from zenith increases, the air mass increases.

The diffuse spectral irradiance as a function of wavelength for different values of air mass is shown in (Fig. 1). In this figure an increase in air mass reduces the diffuse irradiance.

The variation of the short current, open circuit voltage and fill factor as function of the air mass are illustrated in (Table 1). The short circuit current decreases with increasing air mass, this reduction is 56.09%, when the air mass increases from AM = 1.031 to AM = 4.431. The efficiency decreases with increasing air mass. This is illustrated in (Fig. 2).

Turbidity effect: Atmospheric turbidity is a convenient parameter frequently used to estimate the aerosol optical characteristics. These later are important to monitor closely because of their daily, seasonal and long-term variability, as well as their link to global climate change, atmospheric pollution, visibility degradation and solar radiation extinction. Turbidity is a measure of the opacity of the atmosphere. A perfectly clear sky has a turbidity of 0 (the sky has no dust) and a perfectly opaque sky has a turbidity of 1. Typical values of turbidity vary between 0 and 0.4. Turbidity is affected by air molecules and aerosols. It is used to quantify the attenuation by aerosols that is responsible for increasing diffuse solar radiation as well as responsible for changing the spectral composition.

Figure 3 shows the diffuse spectral irradiance as a function of wavelength for different values of turbidity. Increasing turbidity increases the solar spectrum at wavelengths with high photon energy. So the output current is dramatically increased. Naturally greater turbidity results in higher amount of diffuse radiation.

Table 2 shows the influence of the turbidity on the short current, open circuit voltage and fill factor. The variation of the efficiency as function of turbidity is shown in (Fig. 4). It can be see that the efficiency increases with increasing turbidity. The increase in the short circuit current due to increasing turbidity is 67.27% when the turbidity increases from 0.1 to 0.4.

Table 1: Effect of air mass on the CdTe solar cell parameters

Air mass	Jsc (mA cm^{-2})	Voc (V)	FF
1.031	4.2549	0.7384	0.7277
1.327	3.8234	0.7318	0.7261
2.370	2.8219	0.7131	0.7214
4.159	1.8683	0.6878	0.7148

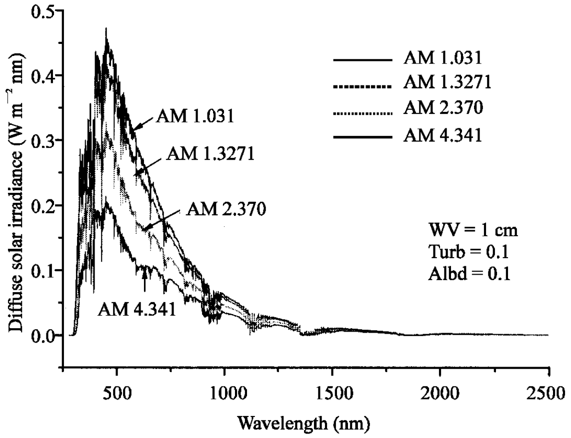

Fig. 1: Diffuse solar irradiance vs. wavelength for different values of air mass

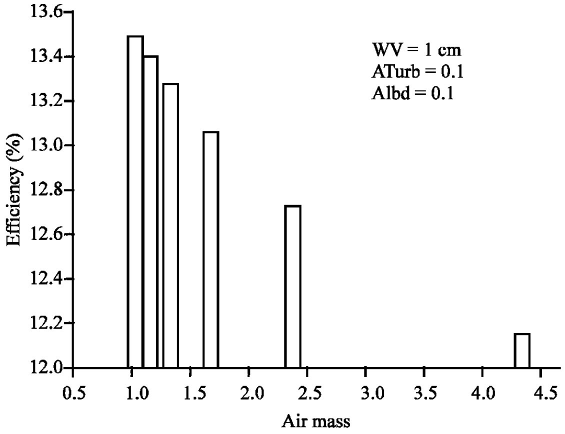

Fig. 2: Conversion efficiency of the CdTe solar cell vs. air mass

Water vapor effect: Precipitable water is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending from the surface to the top of the atmosphere. Precipitable water is commonly expressed in terms of the height to which that water substance would stand if completely condensed and collected in a vessel of the same unit cross section. It plays a crucial role in atmospheric dynamics through the release of huge amounts of latent heat associated with condensation, since water vapor is one of the primary contributors to the opacity at radio wavelengths, the opacity is expected to correlate very well with the amount of precipitable water. The concentration of water vapor in the atmosphere reflects the number of molecules of water compared with the total number of air molecules (mainly nitrogen and oxygen). It can vary, from nearly 3% at the surface to almost nothing high up, depending on weather, altitude and season. An extremely dry atmosphere may contain as a little as 1mm of precipitable water and

Table 2: Effect of turbidity on the CdTe solar cell parameters

Turbidity	Jsc (mA cm^{-2})	Voc (V)	FF
0.1	4.2549	0.7384	0.7277
0.2	7.0708	0.7696	0.7350
0.3	8.7233	0.7825	0.7380
0.4	9.1687	0.7855	0.7386

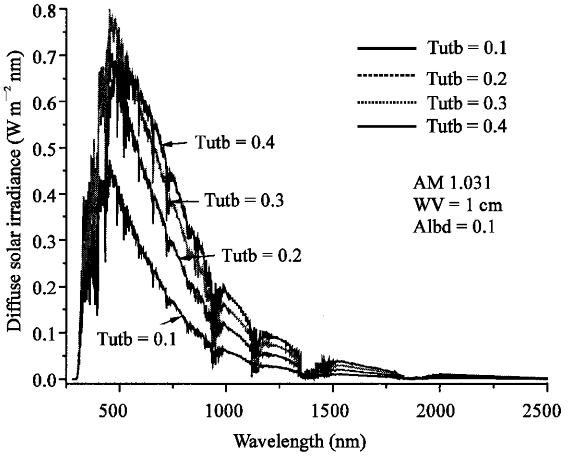

Fig. 3: Diffuse solar irradiance vs. wavelength for different values of turbidity

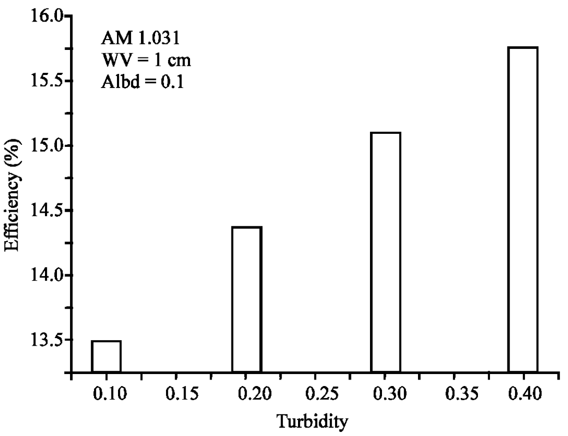

Fig. 4: Conversion efficiency of the CdTe solar cell vs. turbidity

humid atmosphere may contain more that 40 mm. As a consequence of its properties and its abundance in the troposphere, water vapor concentration is one of the most important considerations in understanding meteorology and climate.

The variations of the diffuse spectral irradiance as a function of wavelength under the influence of precipitable water amount are presented in (Fig. 5). The main water vapour absorption bands of solar radiation can be seen at 0.72, 0.82, 0.94, 1.1, 1.38, 1.87, 2.7 and 3.2 μm.

Figure 6 illustrates the effects atmospheric water vapor content variations on the efficiency of the cell. The efficiency increases with increasing water vapor content in the atmosphere. Increasing water vapor in the atmosphere reduces the available irradiance and consequently the short circuit current. The reduction in short circuit current is 2.78% when the water vapor amount increases from 0.5 to 4 cm. A general summary of the variations of the short current, open circuit voltage, fill factor and efficiency as function of the water vapor are presented in (Table 3).

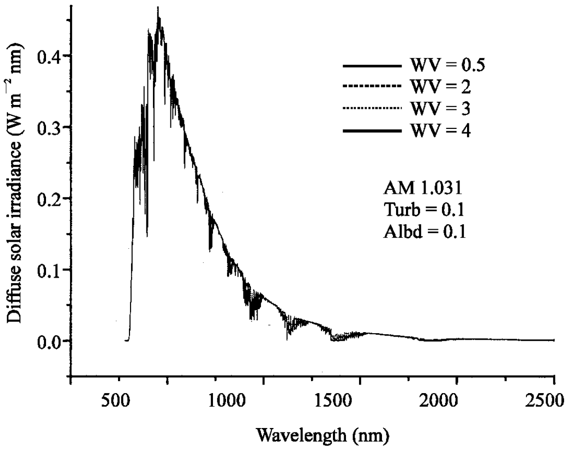

Fig. 5: Diffuse solar irradiance vs. wavelength for different values of water vapor

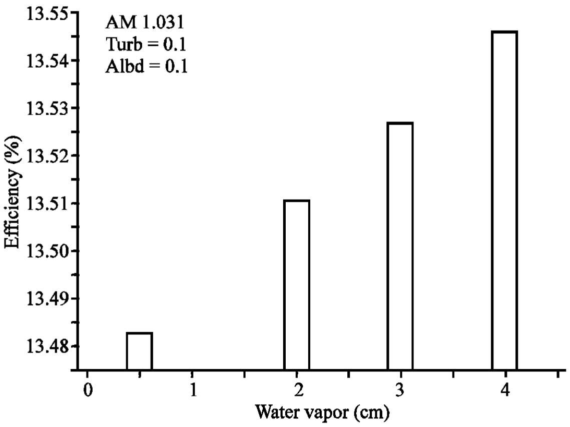

Fig. 6: Conversion efficiency of the CdTe solar cell vs. atmospheric water vapour content

Albedo effect: When radiant energy is incident on a surface, it may be partly absorbed, partly reflected and partly transmitted. The reflectance of solar radiation depends on the nature of the reflecting surface. The fraction of the solar irradiation that is reflected from the surface of the earth is called the albedo of the surface. Typical values of albedo are: 0.1 for dark soil, 0.2 for vegetation, 0.3 for pale soil and 0.6-0.85 for snow.

Table 3: Effect of atmospheric water vapour content on the CdTe solar cell parameters

Water vapor	Jsc (mA cm^{-2})	Voc (V)	FF
0.5	4.2726	0.7386	0.7278
2	4.2240	0.7379	0.7276
3	4.1979	0.7375	0.7275
4	4.1741	0.7372	0.7274

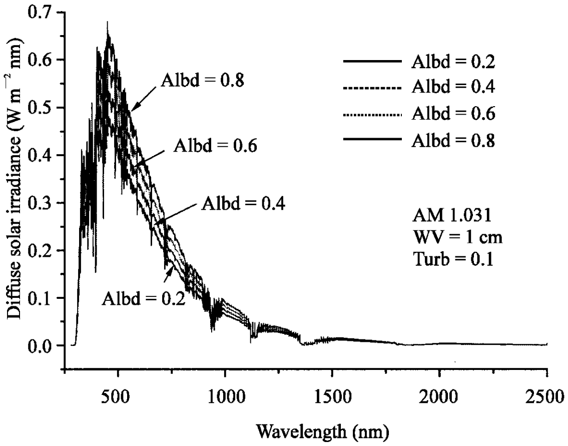

Fig. 7: Diffuse solar irradiance vs. wavelength for different values of albedo

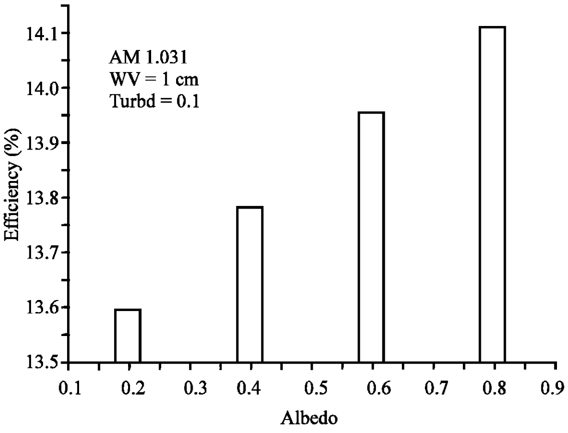

Fig. 8: Conversion efficiency of the CdTe solar cell vs. albedo

Figure 7 shows the diffuse spectral irradiance as a function of wavelength for different values of albedo at Setif. When the reflectance of the surroundings changes from bare soil to snow, the diffuse spectral irradiance changes consequently. The characteristics of the reflected irradiance favor the higher energy wavelengths.

Table 4 shows the influence of the albedo on the short circuit current, open circuit voltage and fill factor. As can be seen in (Fig. 8) the efficiency increases with increasing albedo. The short circuit current increases with increasing albedo, this reduction is 31.68%, when the albedo increases from 0.2 to 0.8.

Table 4: Effect of albedo on the CdTe solar cell parameters

Albedo	Jsc (mA cm^{-2})	Voc (V)	FF
0.2	4.5121	0.7420	0.7286
0.4	5.0457	0.7488	0.7302
0.6	5.6028	0.7553	0.7317
0.8	6.1853	0.7614	0.7332

CONCLUSION

The aim of this study was to assess the effect of changes in diffuse solar spectral distribution due to the variation of environmental parameters, using the spectral irradiance model SMARTS2, on the different parameters characterising the performance of a CdTe solar cell. The results show an increase in the short circuit current due to increasing turbidity and albedo. The short circuit current decreases with increasing air mass and water vapour content in the atmosphere. The performance of the cells is notably reduced, both in terms of efficiency and open circuit voltage, with increasing air mass but the cell performs better with increasing water vapour content, albedo and turbidity. We conclude from this analysis that the variation of air mass, turbidity, ground albedo and water vapor content can have an important impact on the overall performance of the solar cells and should be taken into consideration when analyzing the photovoltaic devices performance under outdoor conditions.

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