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Effects of diffuse spectral illumination on microcrystalline solar cells

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Abstract

The main objective of this work lies on the fundamental need of knowledge of the effect of variations in diffuse spectral distribution due to the variation of atmospheric parameters on the performance of a micro crystalline solar cell using the spectral irradiance model for clear skies SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) on the site of Tlemcen. The results show that the efficiency is a function of atmospheric conditions and is not constant. it increases with increasing turbidity, water vapour content and albedo but it decreases with increasing air mass.
The short circuit current increases with increasing turbidity and albedo, and it decreases with increasing air mass and atmospheric water vapor content for diffuse solar irradiance.

1. Introduction

Thin film solar cells promise lower photovoltaic costs for the future. The only thin film technology which has a significant market penetration to date is microcrystalline silicon. This technology varies in its performance from the commonly used crystalline silicon technology in that microcrystalline exhibits a lower efficiency. Compared to other thin-film technologies currently under development and being presently industrialized (CIGS, CdTe), silicon thin-films have the key advantage of using silicon as raw material, a raw material that is non-toxic and widely available in the earth's crust.
The microcrystalline silicon material is reported to be a quite complex material consisting of an amorphous matrix with embedded crystallites plus grain boundaries. Although this material has a complex microstructure, its optical properties have a marked crystalline characteristic: an optical gap at 1.12 eV [1]. This implies the spectral absorption of microcrystalline silicon covers a much larger range. Microcrystalline silicon absorbs light coming from a wider spectral range, extending to 1000 nm [2]. Furthermore, the μc-Si:H solar cell is reported to be largely stable against light induced degradation [3].
Another advantage of the (μc-Si) technology is the flexibility with regards to the method of manufacture. Thin films of hydrogenated microcrystalline silicon (μc-Si:H) are deposited by the Plasma Enhanced Chemical Vapour Deposition method onto substrates with the aim to fabricate solar cell devices [4].
Manufacturers report photovoltaic module power output at standard testing conditions (STC), which correspond to 1000 W/m2, 25C°, air mass 1.5 and normal incidence. In real operating conditions however, the module output is strongly affected by various environmental conditions such as irradiance, temperature, spectral effects. Furthermore the impact of each climatic factor on the energy production varies according to the module technology in use [5].
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 atmospheric parameters as turbidity, water vapour, air mass, and albedo. The effect of the variations of the solar spectrum on the performance of the different photovoltaic devices is not yet quantified on a large scale and few works have been published [6]. This is mainly due to the difficulty to obtain spectral measurements especially

for developing countries for not being able to afford the necessary equipment.
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 aim of this study is to evaluate the effect of changes in spectral distribution of diffuse irradiation due to the variation of atmospheric parameters such as air mass, turbidity, ground albedo and water vapor content on the performance of micro crystalline solar cells. The diffuse solar irradiance striking a micro crystalline solar cells is estimated using the spectral irradiance model for clear skies SMARTS2. The variation of the common performance namely short circuit current, fill factor, open circuit voltage, and efficiency are shown and discussed.

2. Calculation procedure

When solar radiation enters the earth's atmosphere it is attenuated by scattering and absorption processes, which, in many instances, change abruptly with wavelength and therefore modify the incident solar spectrum in both quantity and quality. The knowledge of these spectral processes and more particularly of spectral irradiance (direct and diffuse) is important for many scientific disciplines as well as engineering and biological applications.
A large range of spectral irradiance models has been published [7]. Several of these models have been developed by various climate research centres and are highly complex numerical models based on many interacting energy streams in the atmosphere and utilizing data from aircraft and satellite observations as inputs [8]. The model adopted here is based on their widely used SMARTS2 model for clear skies developed by Gueymard [9]. In the last few years, the more recent and sophisticated SMARTS model [10-13] has gained acceptance in both the atmospheric and engineering fields, due to its versatility, execution speed, low number of inputs, ease of use. This model can advantageously be used to predict clear-sky irradiance spectra on surfaces of any tilt and orientation. It can calculate punctual estimations of spectral irradiances using as input parameters local geographic coordinates, atmospheric pressure, atmospheric water vapor content, 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 [14]. SMARTS2 is used here to generate the diffuse component solar spectra for the site of Tlemcen (34.56°N, 1.19°E) under different conditions.

The fill factor and the conversion efficiency of the solar cell are linked through:

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

Where S is the area of the device, Isc is the short circuit current, and Pi is the incident irradiation in W/m^2 and is given by:

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

With E (λ) is the spectral irradiance.
The fill factor FF is defined as [15]:

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \tag{3}$$

Where:

$$v_{oc} = \frac{\beta V_{oc}}{n} \tag{4}$$

$\beta \, (= \frac{q}{kT})$ is the usual inverse thermal voltage.

The open circuit voltage is calculated using:

$$V_{oc} = \frac{n}{\beta} \ln\left(\frac{I_{sc}}{I_s} + 1\right) \tag{5}$$

The ideality factor, n, and the saturation current, Is, are calculated from the I-V characteristics using the modified analytical five-point method [16].
The short circuit density Jsc of device, which is the value of the photocurrent density, is directly linked to the spectral irradiance E(λ) and can be calculated as:

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

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

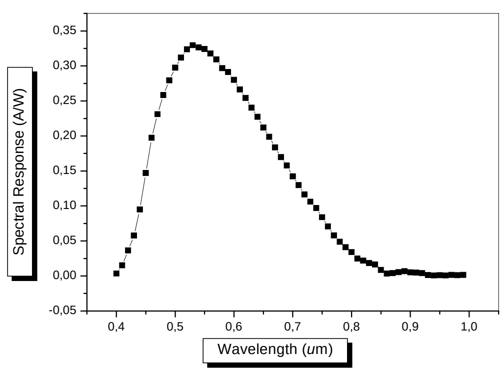

Figure 1: Spectral response of microcrystalline solar cell.

3. Resutls and discussion

3.1. Air mass effect

The air mass is the ratio of the mass of the atmosphere through which beam radiation passes to the mass it would pass through if the sun were at the zenith. It may be expressed as a multiple of the path traversed to a point at sea level with the sun at zenith. By air mass 0 is intended the solar spectral distribution outside the atmosphere. When the sun is directly above a sea-level location the path length is defined as air mass 1. 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 approximately by the secant of the zenith angle.

the diffuse spectral irradiance as a function of wavelength for different values of air mass at Tlemcen (34.56°N, 1.19°E, 810m) is shown in Fig. 2. In this figure an increase in air mass reduces diffuse solar irradiance.

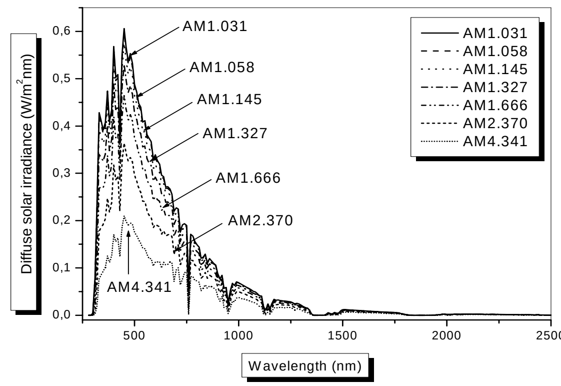

Figure 2: Diffuse spectral irradiance vs. wavelength for different values of air mass at Tlemcen.

The variation of the short current, open circuit voltage, fill factor and efficiency as function of the air mass are illustrated in Table 1. The short circuit current decreases with increasing air mass, this reduction is 64.41% when the air mass increases from AM= 1.031 to AM = 4.431. The efficiency decreases with increasing air mass.

Air Mass	Jsc (mA/cm²)	Voc (V)	FF	Efficiency
1.031	2.8323	0.2155	0.3668	1.0799
1.058	2.7949	0.2144	0.3657	1.0717
1.148	2.6825	0.2110	0.3623	1.0463
1.327	2.4735	0.2044	0.3555	0.9963
1.666	2.1577	0.1933	0.3439	0.9133
2.370	1.6921	0.1740	0.3229	0.7717
4.159	1.0078	0.1354	0.2786	0.5104

Table 1: Effect of the air mass on the micro crystalline solar cell parameters.

3.2. Water vapor effect

Precipitable water is the total amount of water vapour in the zenith direction, between the surface of the earth and the top of the atmosphere. It is often described as the thickness of the liquid water that would be formed if all the vapour in the zenith direction were condensed at the surface of a unit area. Water vapour absorbs strongly in bands in the infrared part of the solar spectrum, which absorption bands centred at 0.72, 0.82, 0.94, 1.1, 1.38, 1.87, 2.7 and 3.2 μm. beyond 2.5μm, the transmission of the

atmosphere is very low due to absorption by water vapour.
Water vapour is one of the most important of all constituents of the atmosphere. Its amount varies widely with season, in time and space due to the great variety of both sources of evaporation and sinks of condensation that provide active motivation to the hydrologic cycle. An extremely dry atmosphere may contain as a little as 1mm of precipitable water and humid atmosphere may contain more that 40mm. About half of precipitable water is concentrated in the first 2 km of the atmosphere. The concentration of water vapour in the atmosphere reflects the number of molecules of water compared with the total number of air molecules (mainly nitrogen and oxygen). Near the surface, water vapour can be as high as 2-3% of the gaseous portion of the atmosphere in a warm ground fog. In the stratosphere, the layer of atmosphere where a temperatures increase with height and vertical motions are weak, water vapour is typically a few parts water per million molecules of air by volume. Water vapour is important not only as the raw material for cloud and rain and snow, but also as a vehicle for the transport of energy and as a regulator of planetary temperatures through absorption and emission of radiation, most significantly in the thermal infrared.
Fig. 3 shows the diffuse spectral irradiance as a function of wavelength for different values of water vapour at Tlemcen.

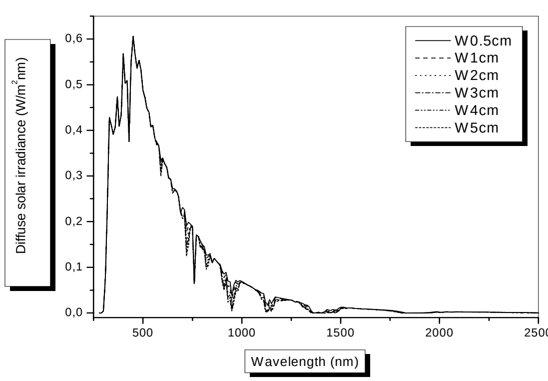

Figure 3: Diffuse spectral irradiance vs. wavelength for different values of water vapour at Tlemcen.

As it can be seen in Table 2 the efficiency increases with increasing water vapour content in the atmosphere. Increasing water vapour in the atmosphere reduces the available irradiance and consequently the short circuit current. This reduction is 1.23% when the water vapour amount increases from 0.5 cm to 4 cm. A general summary of the variation of the short current , open circuit voltage and fill factor as function of the water vapour are illustrated in Table 2.

Water vapor	**Jsc (mA/cm²)**	**Voc (V)**	**FF**	**Efficiency**
0.5	2.8386	0.2157	0.3670	1.0729
1	2.8323	0.2155	0.3668	1.0799
2	2.8215	0.2152	0.3665	1.0874
3	2.8121	0.2149	0.3662	1.0916
4	2.8037	0.2147	0.3660	1.0943

Table 2: Effect of the water vapour on the micro crystalline solar cell parameters

3.3. Turbidity Effect

Atmospheric turbidity is a convenient parameter frequently used to estimate the aerosol optical characteristics. It is a measure of the opacity of the atmosphere, and is defined as the effect of aerosols, through their total optical depth, in reducing the transmission of direct solar radiation to the surface below that through a purely molecular atmosphere. Typical value of turbidity can vary between 0 for an ideally dust free atmosphere, to about 0.4 for extremely turbid climates. Turbidity affects longer wavelengths more than Rayleigh scattering, 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. It is a difficult process to quantify as the particles can vary in size, in number, and in other subtle ways.
Fig. 4 shows the diffuse spectral irradiance as a function of wavelength for different values of turbidity at Tlemcen. Increasing turbidity increases the diffuse solar spectrum at wavelengths with high photon energy. Naturally greater turbidity results in higher amount of diffuse radiation.

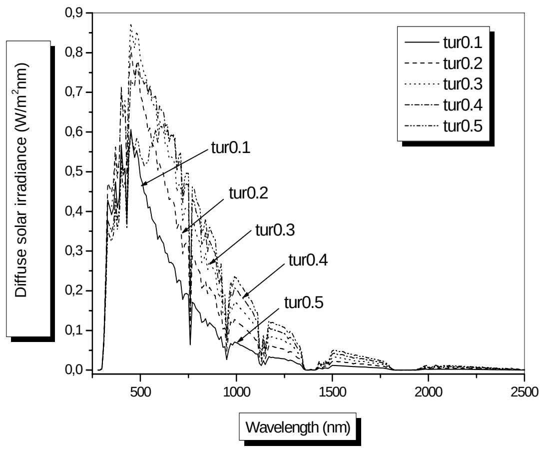

Figure 4: Diffuse spectral irradiance vs. wavelength for different values of the turbidity at Tlemcen.

Table 3 shows the influence of the atmospheric turbidity on the efficiency of the cell under diffuse solar irradiance. The efficiency increases with increasing turbidity, so that the output current is increased. The increase in the short circuit current due to increasing turbidity is 43.51% when the turbidity increases from 0.1 to 0.40.

Turbidity	Jsc (mA/cm²)	Voc (V)	FF	Efficiency
0.1	2.8323	0.2155	0.3668	1.0799
0.2	4.1937	0.2486	0.3985	1.3572
0.3	4.9162	0.2623	0.4107	1.4687
0.4	4.9325	0.2626	0.4109	1.5498

Table 3: Effect of the turbidity on the micro-crystalline solar cells parameters.

3.4. Albedo effect

Albedo is the ratio of the amount of radiation reflected from an object's surface compared to the amount that strikes it. This varies according to the texture, color, and expanse of the object's surface and is reported in percentage. The solar energy community defines albedo as the fraction of solar radiation that is reflected from the ground, ground cover, and bodies of water on the surface of the earth. Astronomers and meteorologists include reflectance by clouds and air. To reduce confusion, some solar researchers use the term ground reflectance.

When the sun is low in the sky (with large zenith angle) the albedo of a water surface is much greater than 0.1. The albedo of clouds depends on how thick they are. Surfaces with high albedo include sand and snow, while low albedo rates include forests and freshly turned earth.
The variations of the spectral irradiance as a function of wavelength under the influence of albedo at Tlemcen are presented in Fig 5. When the reflectance of the surroundings changes from bare soil to snow, the diffuse spectral irradiance changes consequently. The characteristic of the reflected irradiance favor the higher energy wavelengths.

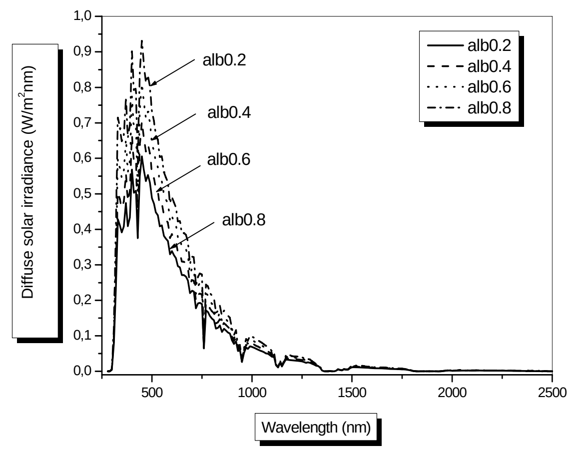

Figure 5: Diffuse spectral irradiance vs. wavelength for different values of albedo at Tlemcen.

Table 4 shows the influence of the albedo on the microcrystalline solar cells parameters such as the short current, open circuit voltage, fill factor and efficiency at Tlemcen. As can be seen the efficiency increases with increasing albedo. The short circuit current increases with increasing albedo, this increase is 47.46% when the albedo increases from 0.2 to 0.8.

Albedo	Jsc (A/cm²)	Voc (V)	FF	Efficiency
0.2	2.8323	0.2155	0.3668	1.0799
0.4	3.2465	0.2269	0.3780	1.1705
0.6	3.6921	0.2378	0.3884	1.2558
0.8	4.1767	0.2483	0.3981	1.3376

Table 4: Effect of the albedo on the micro crystalline solar cell parameters

4. Conclusion

The purpose of this work was to know how micro crystalline solar cells perform under possible diffuse solar spectrum variations due to the variation of the air mass, water vapour, albedo and turbidity using the spectral irradiance model SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) for clear skies on the site of Tlemcen (Algeria).

The results show that the short circuit current increases with increasing turbidity and albedo and it decreases with increasing air mass and atmospheric water vapour content. The efficiency decreases with increasing air mass but it increases with increasing water vapour content, albedo and turbidity. From this analysis, we conclude that the air mass, water vapour amount and the turbidity and ground albedo have a significant influence on the overall performance of the examined solar cells.

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