Spectral Irradiance Effects on the Outdoor Performance of Photovoltaic Modules

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Abstract

The outdoor performance of photovoltaic modules is influenced by spectrum. Even if the irradiance level and the operating temperature is the same, performance difference of photovoltaic modules between the seasons can be increase up to 15% depending on the photovoltaic module type. In this paper, seasonal spectral irradiance effects on the outdoor photovoltaic module performance and previous studies has been summarised thoroughly. The spectrum indicators which are used for spectra characteristics, Useful Fraction and Average Photon Energy are described in detail. This study also indicates spectrum effects on PV performance and outlines the present studies investigating this effect.

Keywords: spectral effect, photovoltaic module, outdoor performance, useful fraction, average photon energy

Contents

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Nomenclature

$G(\lambda)$	Spectral irradiance	R_s	Series resistance (Ω)
$b(\lambda)$	Flux density per unit wavelength	R_{sh}	Shunt resistance (Ω)
$f(\lambda)$	Incident photon flux	a	Modified ideality factor
$SR(\lambda)$	Spectral response	N_s	Number of series-connected cell/module
ϵ_λ	Energy of a photon (J)	n_I	Diode ideality factor
E_g	Band gap (eV)	k_B	Boltzmann constant (J/K)
$\emptyset(\lambda)$	Spectral photon flux density	q_e	Electronic charge (C)
λ_a	Lower absorption wavelength limit	P_{in}	Power of incident light (W)
λ_b	Higher absorption wavelength limit	PV	Photovoltaic
h	Planck constant (Js)	STC	Standard Test Conditions
c	Velocity of light in the vacuum (m/s)	G	Total (broadband) irradiance (W/m^2)
SR	Spectral Response	ASTM	American Society for Testing and Materials
I	Current (A)	IEC	International Electrotechnical Commission
V	Voltage (V)	AoI	Angle of Incidence
K_T	Clearness index (daily)	AM	Air mass
k_T	Clearness index (hourly)	α	Solar altitude angle (°)
H	Measured daily Total Solar Radiation	γ_s	Solar azimuthal angle (°)
H_0	Extra-terrestrial daily Total Solar Radiation	$E_{AM1.5}(\lambda)$	Spectral irradiance distribution of the AM1.5
I	Measured hourly Total Solar Radiation	$SR_{DUT}(\lambda)$	SR of the device under test
I_0	Extra-terrestrial hourly Total Solar Radiation	$SR_{ref}(\lambda)$	SR of the reference cell
I_{ph}	Photocurrent (A)	AM0	Air Mass zero, Spectral representation outside the atmosphere
I_L	Light-generated current (A)	AM1.5	Air Mass at solar zenith angle 48.2°
I_{sc}	Short circuit current (A)	UF	Useful Fraction
V_{oc}	Open circuit voltage (V)	APE	Average Photon Energy (eV)
P_{mpp}	Power at mpp (Wp)	a-Si	Amorphous Silicon
I_{mpp}	Current at mpp (A)	CIS	Copper Indium (di)Selenide
V_{mpp}	Voltage at mpp (V)	CdTe	Cadmium Telluride
A	Module area (m^2)	SPCTRL2	Spectral model developed by NREL
T_c	Operating cell temperature (K)	FF	Fill Factor

1 Introduction

PV modules are rated by their power output under standard test conditions (STC) which are a set of reference PV device measurement conditions consisting of irradiance of 1000 W/m^2, AM1.5G spectrum, and a module temperature of 25ºC. However, STC are not representatives of actual outdoor conditions in most regions of the world. Therefore, it is suspected that the score of a PV module by power rating method under STC is different from the actual performance in outdoor conditions [1-5]. The performance of photovoltaic (PV) modules installed outdoor is greatly influenced by various ambient environmental factors such as incident irradiance, the module temperature and the spectral irradiance distribution.

In this study, solar spectrum, the spectral effects on PV performance is discussed. There are a lot papers presented in different organizations outlines the effect on the installed PV systems. More than 200 studies are reviewed and some of them are published in journals or conference proceedings, the rest are unpublished or contains only local data.

1.1 Solar Spectrum and Additional Spectral Irradiance Descriptors

Emission of radiation from the sun contributes to the solar spectrum as observed from Earth. Just above the Earth's atmosphere, the radiation intensity, or Solar Constant, is about 1.353 kW/m^2 [6,7] and the spectral distribution is referred to as an air mass zero (AM0) radiation spectrum. The Air Mass is a measure of how absorption in the atmosphere affects the spectral content and intensity of the solar radiation reaching the Earth's surface. The Air Mass number is given by

$$Air\ Mass, AM = \frac{1}{cos\theta} \tag{1}$$

where θ is the angle of incidence ($\theta = 0$ when the sun is directly overhead). Moreover, the outdoor solar spectrum distribution changes during a day because of the aerosol and water vapour. Hence, it is rare to fit the standard solar spectrum (Fig.1) AM1.5G defined in ASTM GE173-03 and standard IEC 60904-3 [8,9]. Measured spectral irradiance data does not lend itself well to use in simple analysis or modelling approaches as it consists of an ensemble of measurements. Ideally, a spectral distribution would be summarised as a single parameter, which could then be used in much the same way as broadband irradiance and device temperature to isolate and quantify the different environmental effects acting on the PV device. The colour temperature associated with a blackbody radiator is an option that can reasonably represent the solar spectrum outside the Earth's atmosphere, but is unsuitable for terrestrial application because the various gas absorption bands and wavelength dependent scattering prove too distorting [10]. A few terrestrial spectral descriptors can be found in the existing literature, although not as many as might appear since often the same measure is used under different names by various groups [10].

The sun's location in the sky relative to a location on the surface of the earth can be specified by two angles. They are: (1) the solar altitude angle (α) and the solar azimuthal angle (β). The angle α is the angle between the sun's position and the horizontal plane of the earth's surface, while the angle β specifies the angle between a vertical plane containing the solar disk and a line running due north [11]. Therefore, a new parameter, angle of incidence (AoI) is defined to explain the position of solar rays on the plane [10]. AoI is a measure of deviation of something from "straight on". A surface directly facing the sun has an AoI of zero, and a surface parallel to the sun (such as a sunrise striking a horizontal plane) has an AoI of 90°. Sunlight with an incident angle of 90° tends to be absorbed, while lower angles tend to be reflected.

Another important parameter effecting the solar radiation on a plane is the clearness index (K_T), which is defined as the value of a particular day's radiation to the extra-terrestrial radiation for that day, or an hourly clearness index (k_T) can be defined in equation forms:

$$K_T = \frac{H}{H_0}\ (daily)\ \ and\ \ k_T = \frac{I}{I_0}\ (hourly) \qquad (2)$$

Where H and I are measured values of total solar radiation and H_0 and I_0 are the extra-terrestrial values which can be calculated using several methods [6,11]. This value depends on atmospheric conditions; usually the value lies between zero and unity. Under clear weather conditions clearness index is high and if the atmosphere is turbid or cloudy it is generally low (e.g. $K_T \leq 0.4$ heavily overcast)

The outdoor performance and the energy yield of PV modules depend on a large number of factors. The most important factor is the amount of irradiation that arrives on the plane of the PV modules, which in turn depends on the local environmental conditions such as rain, ambient temperature, and wind. To enable more wide spread deployment of PV modules, it is important to analyse the influences of environmental factors on outdoor performance of PV modules [12-21].

Decreases refer absorption by chemical elements in the atmosphere. The intensity of light in the frequency of incident photons is absorbed. There are some computational models developed by several laboratories which compute clear sky spectral direct beam, hemispherical diffuse, and hemispherical total irradiances on a plane (tilted or horizontal) at a defined location in time [22-24].

1.1.1 Spectral Mismatch Factor (MMF)

One of the discrepancies between indoor and outdoor measurements is Spectral Mismatch errors. Spectral mismatch errors may influence the estimation of the short-circuit current and arise when using a reference cell with a spectral response (SR) different from that of the device under test. The amount of the spectral mismatch depends strongly on the difference of the spectral irradiance distribution of the solar simulator with respect to the reference spectrum AM 1.5G. The procedure for correcting the error introduced in the testing of a PV device, caused by the mismatch between the test spectrum and the reference spectrum and by the mismatch between the SRs of the reference cell and of the device under test. According to IEC 60904-7 [25], the mismatch MMF is defined as:

$$MMF = \frac{\int E_{A.M\ 1.5}(\lambda)SR_{ref}(\lambda)d\lambda \int E_{\lambda}(\lambda)SR_{DUT}(\lambda)d\lambda}{\int E_{\lambda}(\lambda)SR_{ref}(\lambda)d\lambda \int E_{AM1.5}(\lambda)SR_{DUT}(\lambda)d\lambda} \tag{3}$$

where $E_{AM1.5}(\lambda)$ is the spectral irradiance distribution of the AM1.5 spectrum according to IEC 60904-3 ,$E_{\lambda}(\lambda)$ is the spectral irradiance distribution of the incoming light at the time of measurement, $SR_{ref}(\lambda)$ is the SR of the reference cell, and $SR_{DUT}(\lambda)$ is the SR of the device under test [4].

1.1.2 Useful F*raction* (UF)

To illustrate the effect of the solar spectral variations, it is useful to define a parameter that can represent a spectral shift towards higher energies (which will result in a larger proportion of blue or ultraviolet light) than a spectral shift towards lower energies. Different authors use different indices to evaluate this behaviour [10,26]. The most used parameters are the Useful Fraction (UF) that is dependent from the PV technology under investigation and the Average Photon Energy (APE) [27-31].

If the spectral irradiance encountered by a given device/cell (electrically series or parallel connected cells form PV modules) is $G(\lambda)$; the total irradiance, G; is defined as [28],

$$G \equiv \int_0^{\infty} G(\lambda)\, d\lambda = \int_0^{\infty} \varepsilon_{\lambda} b(\lambda)\, d\lambda \tag{4}$$

where $b(\lambda)$ is the flux density (number per unit area and unit time) per unit wavelength of photons of energy ε_{λ} and wavelength λ. UF is the ratio of the solar irradiance within the usable wavelength range of a PV device to the total solar irradiance and defined as

$$UF \equiv \frac{1}{G}\int_0^{\lambda(E_g)} G(\lambda)\, d\lambda \tag{5}$$

Here, E_g is the band-gap of the solar device/cell which equates to a long wavelength cut-off of wavelength λ. For example, for amorphous silicon cells the cut-off wavelength is $\sim 780\ nm$ and for the standard AM1.5 spectrum, $UF \cong 0.604$. A value of UF>0.604 therefore indicates a spectral shift towards the blue, relative to this standard. This will tend to occur when the incident light is mainly diffuse (and thus has a low total irradiance G) or when the light is incident with a very low air mass (and thus has a high total irradiance G). Conversely, a value of UF<0.604 indicates a spectral shift towards the red [28].

1.1.3 Average Photon Energy (APE)

The other unique value to characterize the spectrum shape is APE. The APE is an instantaneous value defined as the ratio of the total irradiance of the spectrum over the photon flux density. Consequently, the definition of APE is usually referred to as a finite integration interval APE, expressed in the unit of electronvolt (eV),

$$APE = \frac{\int_{\lambda_a}^{\lambda_b} G(\lambda)d\lambda}{q_e \int_{\lambda_a}^{\lambda_b} \Phi(\lambda)d\lambda} \quad (6)$$

where q_e is the electron charge, $\Phi(\lambda)$ is the spectral photon flux density , $\lambda_a$and λ_b are the lower and the higher absorption wavelength limits of the device. It should be noted that the calculated APE value depends on the integration limits in Eq.(6). This wavelength interval effect is shown in Table 1 for the AM1.5G standard spectrum.

The spectral photon flux density at a specific value of wavelength λ can be determined by dividing the spectral irradiance evaluated at λ between the energy of a photon (ε_λ) with that wavelength (in joules):

$$\Phi(\lambda) = \frac{G(\lambda)}{\varepsilon_\lambda} = \frac{G(\lambda)}{\frac{hc}{\lambda}} \quad (7)$$

where h is the Planck constant $h = 6.62606877 \times 10^{-34}\, Js$ and c is the velocity of light in the vacuum $c = 2.99792458 \times 10^8$ m/s . With the use of these values, the final result of APE will be expressed in J, but it is usually expressed in $electron\,Volt, eV$ taking into account that $1\,eV = 1.602176463 \times 10^{-19}\ J$. APE value can be expressed in eV as usual.

There are several studies reporting the performance of widely used different PV materials (crystalline silicon technologies, amorphous silicon, Cupper Indium (di) selenide CIS, Cadmium Telluride CdTe, third generation PV and other thin film technologies) in real installations at different locations with thermal and spectral effects [1,2,4,5,10-16,18-21,24,26-60].

1.2 Natural solar spectral variation

When solar radiation enters the Earth's atmosphere, not only the irradiance but also the spectral content is affected. The standard solar spectrum used for testing PV devices is given in Fig.1 but in general, the shape of spectrum is variable during a day. Increasing air mass displaces the solar spectrum towards the red [60]. The solar radiation that fills the sky can be direct, diffuse and reflected irradiance. Total or global solar radiation measured on a surface is the sum of beam and diffuse radiations. Beam or direct radiation is the solar radiation received from the sun without having been scattered by the atmosphere. Therefore, the solar radiation received from the sun after its direction has been changed by scattering in the atmosphere is defined as the diffuse component of the total solar radiation. The effect in the spectral distribution is shown in Fig.2. The global solar irradiance is composed of the direct irradiance and diffused irradiance and the solar spectral irradiance distribution has the significant influence on the output of a PV device. When the sky is clear and the sun is very high in the sky, direct radiation is around 85% of the total insolation striking the ground and diffuse radiation is about 15%. As the sun goes lower in the sky, the percent of diffuse radiation keeps going up until it reaches 40% when the sun is 10° above the horizon. Atmospheric conditions like clouds and pollution also increase the percentage of diffuse radiation. On an extremely overcast day, pretty much 100% of the solar radiation is diffuse radiation. This means the larger the percentage of diffuse radiation, the less the total incident solar radiation. So overall spectrum depends on ratio of beam/diffuse [10].

However, since diffuse radiation is generally pretty equally distributed throughout the sky, the most diffuse radiation is gathered when PV modules are lying down horizontally. PV modules are generally settled with tilted angles to maximise the total irradiance and this also increases the amount of direct irradiance that reaches on the array plane. The steeper PV modules are tilted, the less of the sky they are facing and the more of the sky's diffuse radiation they miss out on. Reflected radiation describes sunlight that has been reflected off of non-atmospheric things such as the ground. Asphalt reflects about 4% of the light that strikes it and a lawn about 25%. However, PV modules tend to be tilted away from where the reflected light is going and reflected radiation rarely accounts for a significant part of the sunlight striking their surface. Besides this, both crystalline silicon and thin film based PV modules need glass and commercial glass has a solar transmission of 83.7%, i.e 16.3% of the sun's energy do not even get to the PV material. And reflection off PV front glass affects spectrum incident on active layers.

To show the seasonal variation of UF and APE values during a day, first, two representative days in July and January are selected for a 37ºN latitude location. Then UF and APE values from sunrise to sunset are calculated with the help of SPCTRAL2 [18]. 15º and 35º seasonal tilt is accepted for summer and winter, respectively. Both UF and APE values are almost constant during the day time except in the early and late hours of the day. In summer both UF and APE values are increases in these hours because of the rising diffuse component of the global irradiation when the sun is behind the array plane. But in winter the values are decreases in these time intervals.

2 PV performance and effect of spectrum

The electrical power available from a PV device/cell can be modelled with the well-known equivalent circuit which includes a series resistance and a diode in parallel with a shunt resistance [41]. This circuit can be used either for an individual cell, for a module consisting of several cells, or for an array consisting of several modules. The current–voltage relationship is expressed in Eq. (6) at a fixed cell/module temperature and solar radiation. Five parameters must be known in order to determine the current and voltage, and thus the power delivered to the load. These are: the photocurrent I_{ph} (also known as I_L light generated current), I_0 the diode reverse saturation current, R_s the series resistance, R_{sh} the shunt resistance, and $a \equiv N_s n_I k_B T_c / q_e$ the modified ideality factor defined in Eq. (8).

$$I = I_{ph} - I_0 \left[e^{\frac{V+IR_S}{a}} - 1 \right] - \frac{V+IR_S}{R_{sh}} \tag{8}$$

Where, N_s is the series connected cell/module, n_I is the diode ideality factor of a cell, k_B is the Boltzmann constant, $k_B = 1.3806504 \times 10^{-23}\, J/K$ and q_e is the electronic charge $q_e = 1.602176463 \times 10^{-19}\, C$. The power produced by the PV device/cell or module is the product of the current and voltage. At small applied voltages, the diode current is negligible and the current is just the short circuit current, I_{sc}, which is so close to I_{ph} as can be seen when *V* is set to zero in Eq. (8). At open circuit $I = 0$, all the photocurrent, $I_{ph} \approx I_{sc}$, is flowing through diode, for ideal case $(R_s = 0, R_{sh} = \infty\ and\ n_I = 1)$ the open-circuit voltage can be written as

$$V_{oc} \approx \frac{k_B T_c}{q_e} ln\left(\frac{I_{sc}+I_o}{I_o}\right) \tag{9}$$

The rectangle-defined V_{oc} and I_{sc} provides a convenient means for characterizing the maximum power point [45]. The fill factor, *FF*, is a measure of the squareness of the *I* –*V* characteristic and is always less than one. It is the ratio of the areas of the two rectangles and defined as

$$FF = \frac{P_{mpp}}{I_{sc}V_{oc}} = \frac{I_{mpp}V_{mpp}}{I_{sc}V_{oc}} \tag{10}$$

Where $P_{mpp}$is the power of the device/cell or module at the maximum power point, I_{mpp} and V_{mpp} are the current and the voltage values at this point, respectively. And the most important figure of merit for a PV device/cell or module is its power conversion efficiency, η, which is defined as

$$\eta = \frac{P_{mpp}}{P_{in}} = \frac{FF \times I_{sc} \times V_{oc}}{P_{in}} \tag{11}$$

where, P_{in}, is the power of the light determined by the properties of the light spectrum incident upon the device/cell or module. And, can be defined as in Eq. (12) spectrum dependent with the help of Eq. (4), where A is the surface area.

$$P_{in} = G \times A = A \int_0^\infty \epsilon_\lambda b(\lambda)\, d\lambda \tag{12}$$

2.1 Spectral response

There are large differences in the sensitivity of different PV materials to spectral variation. This is determined in the first instance by the band gap of the material, which sets the upper wavelength limit of the spectral response.

The sensitivity of different PV device/module electrical parameters to the various environmental influences of these conditions depends on the technology (device material and structure) and the performance is directly proportional to spectral response where spectral response is the ratio of the current generated by the PV device to the solar power incident on its surface. Spectral response of a PV device is given by the probability that the absorbed photon will yield a carrier to the I_{ph}photogenerated current of the cell and the spectral response is determined by the band gap, cell thickness and transport in the material. The spectral response is defined as the short-circuit current, $I_{SC}(\lambda)$, resulting from a single wavelength of light normalized by the maximum possible current [20-23, 41-44]

$$SR(\lambda) = \frac{I_{SC}(\lambda)}{qAf(\lambda)} \tag{13}$$

Where, q is the electronic charge 1.6×10^{-19}C, A is the surface area of the PV device and $f(\lambda)$ is the incident photon flux (number of photons incident per unit area per second per wavelength).The degree to which the spectral response and the incident irradiance spectrum coincide varies as the spectrum changes and gives rise to a spectral effect on the device current and efficiency. Spectral responses of some module types and AM1.5G spectrum (up to 1300nm) is shown in Fig.2 to show the response differences of different technologies [42].

To quantify matters, some effective measure of spectral distribution is required, one that encapsulates the idea that a spectral shift towards higher energies will result in a larger proportion of blue or ultraviolet light than a spectral shift towards lower energies. Since a-Si devices absorb more strongly in the blue than in the red, and not at all in the infra-red, such shifts will inevitably have an impact on the device parameters, even if all other factors (e.g. total irradiance, incident angle, temperature) remain constant [23,40].

PV device operating temperature may affect the photocurrent in two ways: Through a change in absorption efficiency represented by an instantaneous temperature coefficient, or via material changes caused by annealing recovery of light-induced degradation. Temperature coefficients of $I_{sc}, V_{oc} and\ P_{mpp}$ are generally given in manufacturer data sheets, measured under STC irradiance and spectrum. Hence, the operating temperature results variation in I_{sc} at the same irradiation levels with an enhancement of up to 2% and a winter reduction up to 1% [20, 43, 44]. This effect is severe for thin film devices, yet the parametric sensitivity of these devices to variations in the incident spectrum is still not fully understood but several studies were evaluated to define the main reason of variation for different materials, especially for a-Si based solar cells [8, 20, 23, 35, 42-45, 60].

I_{sc} is spectrum dependent as given in Eq. (11) so the other PV device performance parameters namely $FF, \eta\ and\ V_{oc}$ are also affected by the spectrum variations [44,62]. Numerous performance analysis studies have been carried out to assess the magnitudes of these effects on different technology based PV devices [65-78]. Hence, for a 1000W/m^2 irradiation level, the operating temperature of the PV devices is transposed to the value at STC which process is known as temperature correction. There are several analytical and numerical translation methods of the measured values to desired conditions in the literature [79-83]. Temperature corrected short circuit current over irradiation (I_{sc}/G) variation of the cell/module with respect to the irradiation will give knowledge about the spectral dependence eliminated from the thermal effects.

3 Conclusions

The influence of spectrum on the performance of PV modules is summarised in this paper. Performance variation is strongly dependent to module type. Based on this, the ratio of available to global solar radiation had a seasonal variation of 5%. For clear sky days, spectrum has little influence for low band gap material based PV modules (efficiency varies only 4% or 5% between seasons for e.g. crystalline silicon solar cells), but for large band gap materials like a-Si this effect is severe (efficiency varies -10% to +15% between seasons). Temperature corrected (I_{sc}/G) variation with respect to the irradiation will give knowledge about the spectral dependence of the PV device/cell or module eliminated from the thermal effects. Numerous performance analysis studies investigating the spectrum effects on different technology based PV devices are addressed.

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Figure 1-revised

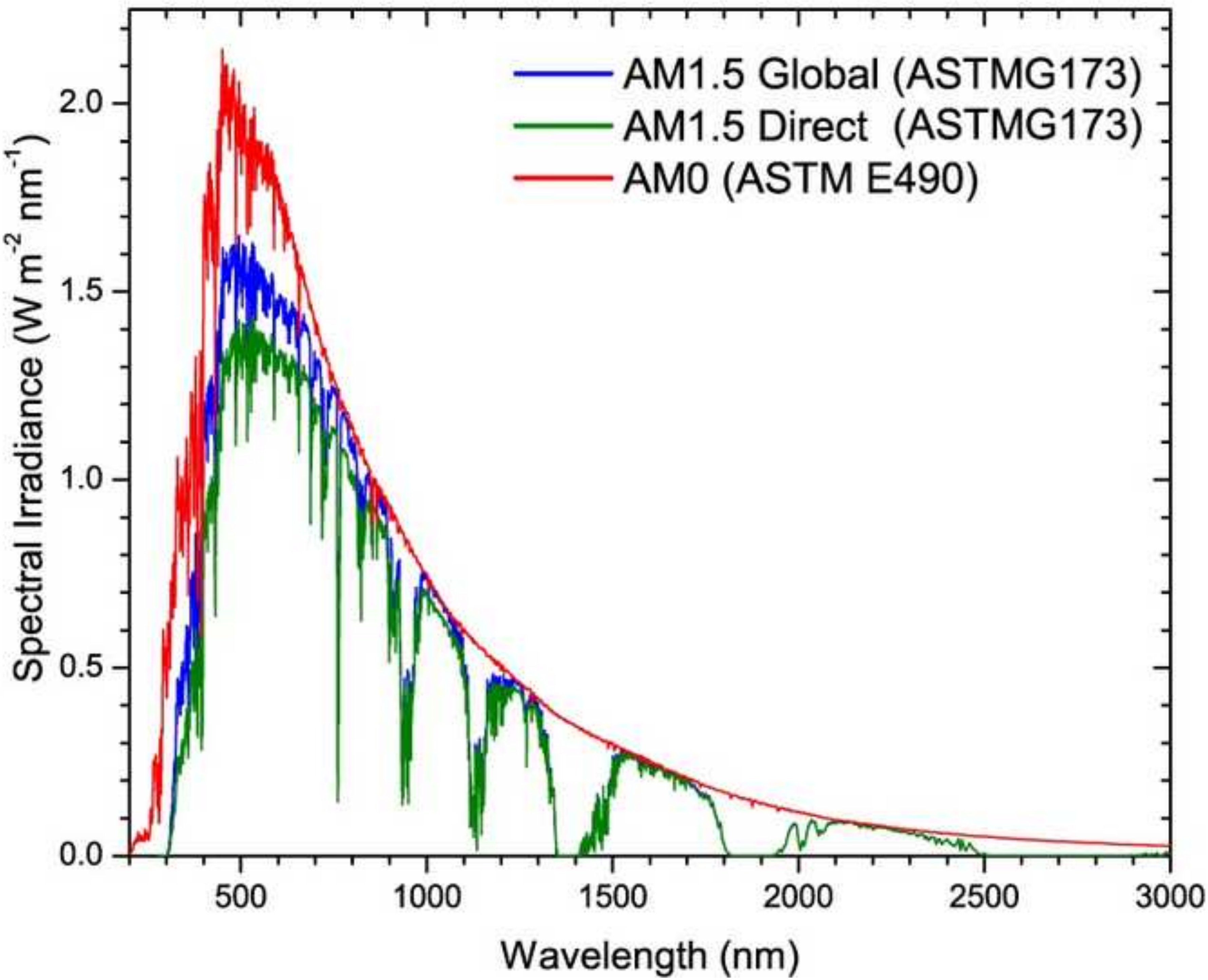

Figure2

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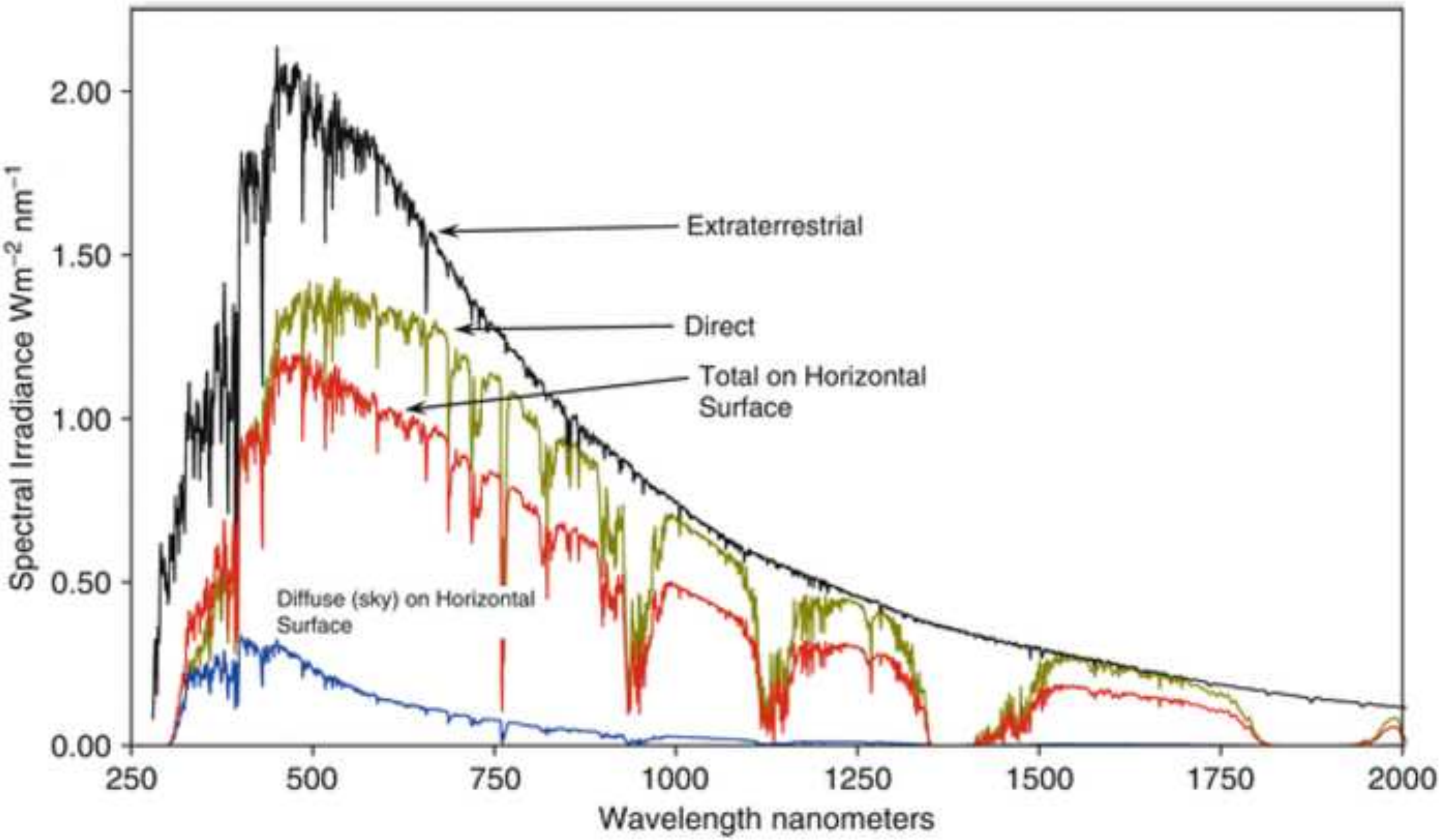

Figure 3-revised
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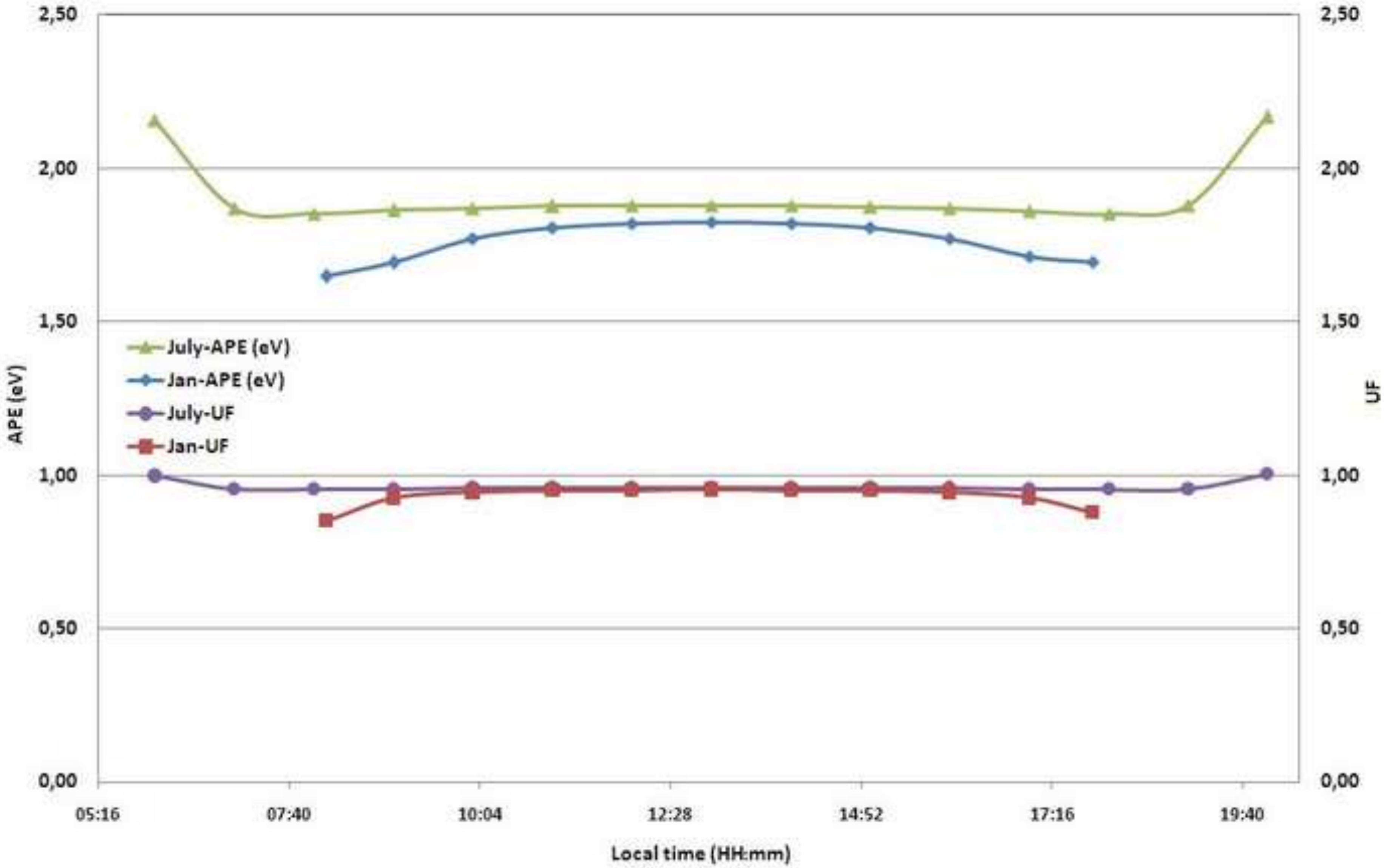

Figure4

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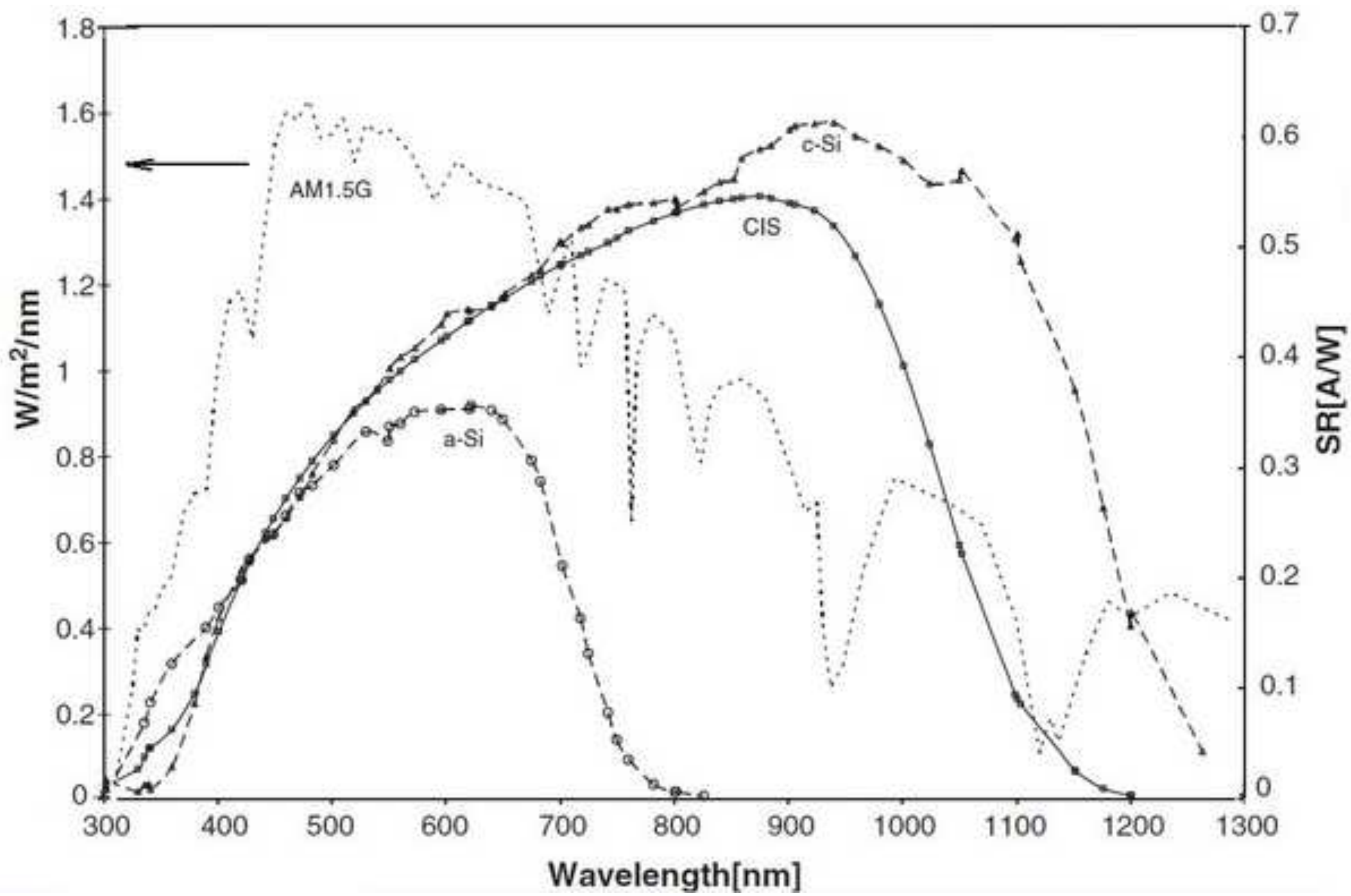

Table 1-revised

Table 1: APE of the standard spectrum evaluated from different spectral integration limits [19].

Wavelength range (nm)	APE, Average Photon Energy (eV)
300-4000	1.43
300-2500	1.48
300-1700	1.62
300-1100	1.86

Figure and Table Captions

Figure 1: Standard reference solar spectra.

Figure 2: Solar spectral distribution with its components.

Figure 3: Calculated APE and UF values for clear sky days for a location of 37ºN latitude (15º and 35º seasonal tilt is taken for summer and winter, respectively)

Figure 4: Spectral responses of some module types and the AM1.5G spectrum (up to 1300 nm) [39].

Table 1: APE of the standard spectrum evaluated from different spectral integration limits [20].