# COMPARISON OF ATACAMA DESERT SOLAR SPECTRA vs. ASTM G173-03 REFERENCE SPECTRA FOR SOLAR ENERGY APPLICATION

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## Abstract

Knowledge of the solar spectrum is essential for the design and study of numerous technologies based on the use of the solar resource. In spite of the fact that the Atacama Desert is in the spotlight of solar industry, there is not enough information about the spectral irradiance present on it. This fact and the special atmospheric conditions of Atacama cause an increasing interest of solar industry to know the spectral differences with other places of the world. Using a standard spectrum may represent very different results from the true. In this paper, direct and global tilted Atacama Desert Solar Spectra are derived from mean values of available satellite and model retrievals databases. Results are compared against the ASTM G173-03 Reference Spectra in order to know if the information provided by the standard is useful for solar energy applications. For that, solar spectra derived from SMARTS atmospheric transfer model in combination with the atmospheric information from the available databases are previously compared with several spectral irradiance measurements from the first spectral measurement campaign in Chile, developed on 2015. Later, the average of the atmospheric parameters for the whole Atacama Desert area is calculated from these data bases and is used to obtain the mean Global tilted Irradiance and Direct plus Circumsolar Irradiance solar spectrum.

Keywords: *Spectral Irradiance, Atacama Desert, Atmospheric Radiative Transfer Model, Solar Energy*

## 1. Introduction

Chile has experienced a rapid grow regarding the implementation of solar energy technologies. According to the Centre for Innovation and Promotion of Sustainable Energy (CIFES), the cumulative installed photovoltaic (PV) capacity in the country surpassed 1.5 GWp in June 2016, where 0.78 GWp will be added next. Concentrated Solar Power (CSP) is also reported with a 110 MW plant currently under construction (CIFES, 2016). Many of these solar projects are located in the Atacama Desert.

The Atacama Desert is located along the Pacific coast in South America. It has a hyper arid climate with annual precipitations lower than 50 mm (Larraín and Escobar, 2012). Characteristic mean temperatures range from 10ºC to 20ºC in winter and 20ºC to 30ºC in summer, whereas the air temperature keeps below 38ºC (McKay et al., 2003). In terms of chemical composition, nitrates represent 28% of the soil and water-soluble salts such as perchlorates and iodides. These salts rarely exist anywhere else (Navarro-González et al., 2003).

Under clear sky conditions, the spectral distribution of solar radiation strongly varies during the day, mainly due to the distance that light must travel through the atmosphere, or air mass (M). It also depends on the climate conditions, which are responsible for the variation of the spectrum from one day to another and throughout the year. The most important parameters affecting the solar spectrum are the Solar Zenith Angle (SZA) related to M, cloudiness, the Total Ozone Column (TOC), the Precipitable Water (PW), the Aerosol Optical Depth (AOD), and the reflectance from the ground or albedo.

The Atacama Desert Solar Spectrum and environmental conditions can differ from what is usually found in northern hemisphere. The key factors responsible for these spectral differences are the high mean altitude, a large number of days with clear skies and low absorption ozone and water vapour columns (Cordero et al., 2016). Thus, this location receives highest surface irradiation. It was determined that the Global horizontal irradiation (GHI) can reach more than 8 kWh/m² per day resulting in more than 2500 kWh/m² per year (Escobar et al., 2014).

Knowledge of the solar spectrum at the earth surface can be important for the application of any solar energy technology but also for other disciplines. A spectral treatment of solar radiation can provide more accuracy since it incorporates more physical phenomena. The spectral irradiance can be essential for spectral, narrow-band and broadband applications. Among the spectral applications, the precise determination of the solar spectrum can be used for quantifying atmospheric parameters, for testing the performance of spectroradiometers, for defining a reference spectrum to certify PV technology, and for obtaining accurate spectra in the UV part of the spectrum. Narrow-band and broadband applications include UV radiation, illuminance and luminous, photosynthetically active radiation, filter radiometry as well as circumsolar radiation for pyrheliometers, assessment of broadband radiation models, turbidity determination from irradiance data and mapping and predictions of radiation fluxes (Gueymard, 2005).

Reference spectra were first generated as independent norms as E-891-82 and E-892-82, for the direct normal and global tilted irradiance, respectively. From June 1999 on, the subcommittee G3.09 of the American Society for Testing and Materials (ASTM) combines these two documents in the "Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37 Degree Tilted Surface". This norm is based only on E891 and E892 standards and has the ISO 9845-1 certification. In January 2003, the G159 norm was reviewed and replaced by the G173-03. The current G173-03 was created by the North American PV industry together with ASTM (http://www.astm.org/) and research centers of the US government. They developed and defined two standard distributions of the ground solar spectrum. These spectra are the standards for direct normal and global tilted (at 37º) spectral irradiances (Myers, D. R.; Emery, K.; Gueymard, 2004).
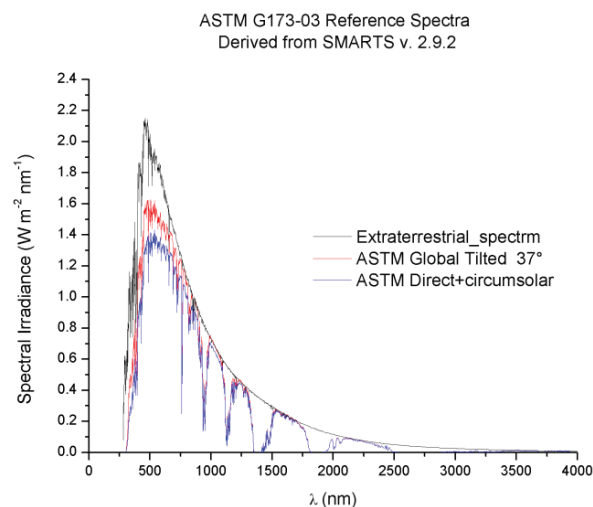


**Fig. 1: ASTM G173-03 Reference Spectra Derived from SMARTS v.2.9.2, available in (American Society for Testing and Materials, 2012; Gueymard, 2004; Gueymard et al., 2002; NREL, 2015)**

The calculation of the standard spectral irradiances was performed by means of the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) (Gueymard, 2001, 1995). SMARTS is a spectral model based in the Fortran programming language which can determine solar spectral irradiances under clear sky conditions for a set of given atmospheric parameters.

The ASTM G173 spectra, available in (NREL, 2015), represents the solar spectral irradiance at the earth surface which falls on a plane with specific orientation and specific atmospheric parameters. This spectrum provides the only reference for the evaluation of PV materials studied under natural and artificial light with different spectral distributions. However, the chosen atmospheric conditions were thought for the US during one year. Therefore, the tilt angle as well as the atmospheric conditions correspond to the national average values (Berman et al., 1999).

As the actual sunlight and environments, where PV systems operate, can be very different to those defined by standard testing conditions (STC), PV modules may not produce the maximum power output, as they should. The spectral effects need to be considered (Simon and Meyer, 2011; Topi et al., 2007). As reported in (Bücher, 1997) the efficiency of PV devices can differ up to 35% with respect to what is rated under STC due to the spectral differences. In order to demonstrate the relevance of the spectra, the photovoltaically active fraction (PAF) was defined (Berman et al., 1999). The effect of the solar spectrum was observed when using semiconductors with different bandgap energy. In order to quantify that impact on the absorbing materials, another parameter was defined, namely the useful fraction (UF) (Gottschalg et al., 2003). According these results, the need for a representative spectrum for Atacama Desert becomes clear.

In order to ensure optimal performance of PV technologies under specific conditions such as those of the Atacama Desert, PV module materials, solar cells and modules can be adapted and designed. Advances in this matter have been reported in (Cabrera et al., 2016, 2015; Ferrada et al., 2017) where different module materials were combined with several solar cell configurations and considering a preliminary calculated Atacama Solar Spectrum.

In order to achieve the aim of this paper, the Simple Model of the Atmospheric Radiative Transfer of Sunshine, or SMARTS (Gueymard, 2001, 1995), was chosen to estimate mean direct an global spectral irradiances for the Atacama Desert. Firstly, SMARTS model and the selected data bases were validated by comparison against global horizontal spectral irradiance measurements in north of Chile. Subsequently, the astronomic factors and long-term atmospheric parameters, available in satellite databases, were averaged for Atacama Desert area. Then, results were used to calculate mean solar spectra. Finally, the estimated Atacama spectra were compared with the ASTM G173-03 Reference Spectra.

## 2. Comparison with ground measurements

The SMARTS code is used for many applications in the solar industry and previously it has been widely validated by researchers. Some examples are (Eltbaakh et al., 2013; Gueymard, 2008, 2005, 2004, 1995; Kocifaj and Gueymard, 2011; Myers, D. R.; Emery, K.; Gueymard, 2004). However, estimated spectra derived from SMARTS and the available databases were compared against ground spectral measurements in order to know if it is reliable the use of SMARTS and the selected databases in this work.

A first campaign of solar spectral measurements supported by CIFES (CIFES, 2016) was performed in February 2015. The campaign focused on the spectral global horizontal measurement of solar irradiance at several places from Antofagasta and Iquique Regions, in north of Chile. The resulting information from the measuring campaign was not enough to obtain mean solar spectral irradiances for the Atacama Desert, because of the short time period of measurement at each place, around three days per each location, and the short covered area. However, the spectral measurements play an important role to validate the performance of atmospheric radiative transfer models and satellite databases..

The measurement campaign were carried out with a Bentham DTMS300 double monochromator spectroradiometer and a probe to measure the solar spectral global horizontal irradiance ($G_\lambda$), as described in (Cordero et al., 2016). The spectroradiometer measured the spectral irradiance between 290 and 1800 nm wavelengths, and took nearly 10 minutes to measure in this range. Consequently, only measurements taken under clear and stable sky conditions were considered. The measurement uncertainty was estimated around ±10% for the UV-B spectral range [290, 315] nm and ±4% for upper wavelengths, obtained from the comparison of the integral values for each spectral range, as reported by authors. Authors also point out that higher uncertainties may be found in atmospheric absorption bands but they did not quantity them.

To compare the estimation of solar spectral irradiances with the measurements, three places where chosen according to the availability of ground and satellite databases. Antofagasta, Calama and Caldera were the selected locations; and Era Interim (ECAD, 2016), Giovanni (NASA and Kempler, 2016) and the ground database of the National Air Quality Information System, SINCA (SINCA, 2015), were the consulted databases.
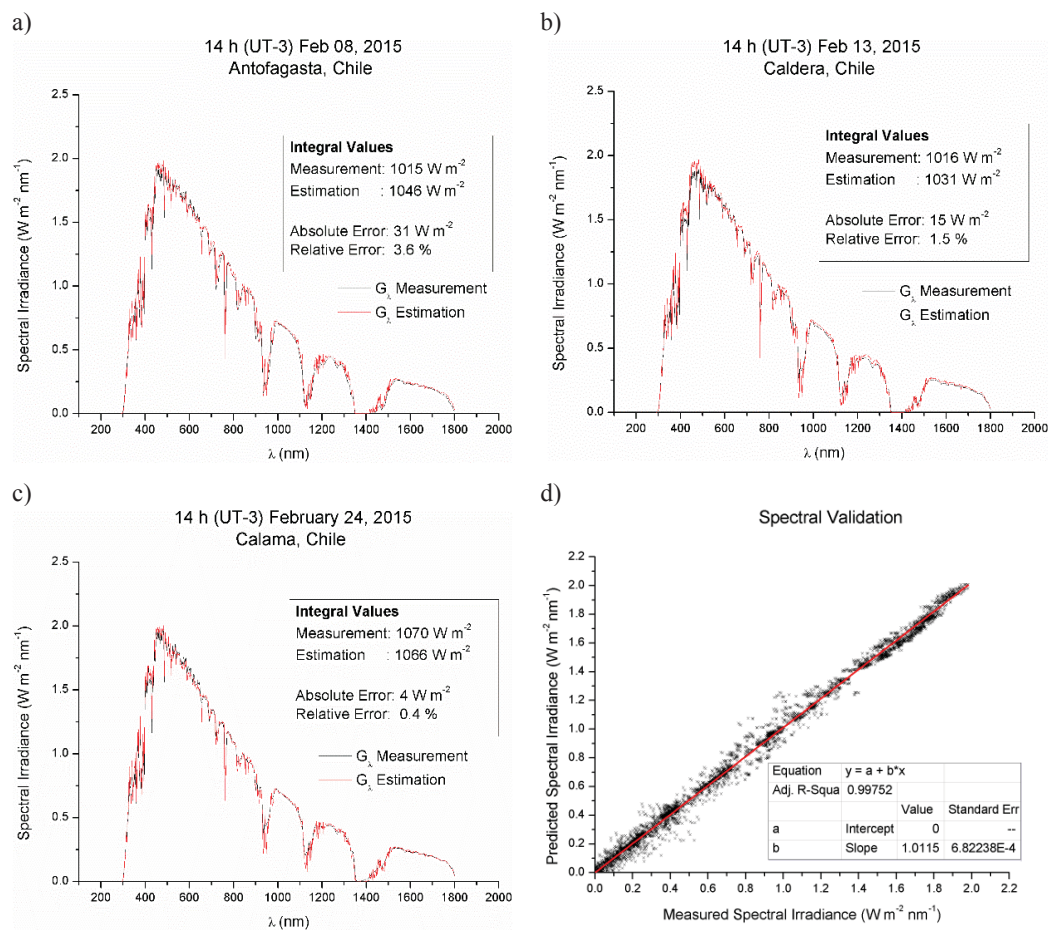


**Fig. 2: Spectral global horizontal measurements (black) and spectral irradiance calculations using SMARTS (red) for Antofagasta (a), Caldera (b) and Calama (c). (d) Linear fit of the measured spectral irradiances against the calculations obtained with SMARTS model.**

An example of the validation test for each place is shown in Fig. 2, as well as the fit of predictions and measurements for the spectral irradiance values (Fig. 2-d).

As shown in Fig. 2, some differences are presented in the bands relating to the water vapour and ozone absorption. This fact is in agreement with ground measurement reported by authors. A slight deviation can be

observed also at short wavelengths, where predictions overestimate the measurements. These differences may be due to the radiative transfer model or, aerosols or instrument uncertainty. An in-depth investigation will be developed in future works in order to improve the estimations. However, if the instrument uncertainty is taken into account, the results of the SMARTS predictions are in agreement with the measurements shown in Fig. 2 d, and Tab. 1.

**Tab. 1: Averaged relative errors for the validation test according to the integration spectral range.**

| *Spectral Range* | **Comparison Relative error** | ***Instrumental Relative Error*** |
|:---:|:---:|:---:|
| *[290, 316]* | ±3% | ±10% |
| *[316, 400]* | ±3% | ±4% |
| *[400, 700]* | ±1% | ±4% |
| *[700, 1800]* | ±3% | ±4% |
| *[290, 1800]* | ±2% | ±4% |

## 3.    The Atacama Desert Solar Spectra

On one hand, several inputs, most of them characterized with a high temporal and spatial variability, are needed to predict or calculate a solar spectrum. On the other hand, different criteria can be considered to estimate the average values to calculate a representative spectrum for the area of interest. For these reasons, it is difficult to affirm that an average solar spectral irradiance is the representative mean spectra for a specific place, mainly for the direct normal component of the solar irradiance. However, this work intends to highlight the importance of considering local atmospheric parameters in spectral studies related to solar energy technologies instead of the global reference spectra.

The inputs considered to calculate an average of the Atacama Desert Solar Spectrum were: temperature, relative humidity, precipitable water, ozone, pressure, altitude at ground, carbon dioxide, turbidity (AOD at 550 nm), albedo, and surface tilt angle. Each one of the mentioned inputs was changed individually with respect the ASTM G173-03 Reference Spectra. The remaining inputs were left as the default values: Air Mass (M) and Shettle & Fenn aerosol model (rural). All atmospheric parameters were averaged for the area of interest before to be introduced as inputs in SMARTS to estimate mean solar spectral irradiances for Atacama Desert.

The surface tilt angle, $\beta$, for PV panels was calculated according to the following expression (Gallegos and R. Righini, 2012):

$$\beta = 3.7 + 0.69\,\phi \qquad\qquad\qquad \text{(eq. 1)}$$

where β results 18º when the ϕ value is 20.7º.

The average elevation of the area of interest for solar technologies in Atacama Desert is approximately 2 km. This value is derived considering that the elevated places, over 3.5 km, are not suitable for the installation of solar power plants due to their complex orography with steep slopes, difficult access, long distances to the distribution network and villages, and the disadvantages of working at height: altitude sickness, low atmospheric density and strict national safety regulations for these places. The atmospheric pressure value, 804.3 hPa, corresponds to the value of pressure at 2 km altitude for a sub-tropical reference atmosphere considering a pressure of 1013.25 hPa at sea level (Gueymard, 1995).
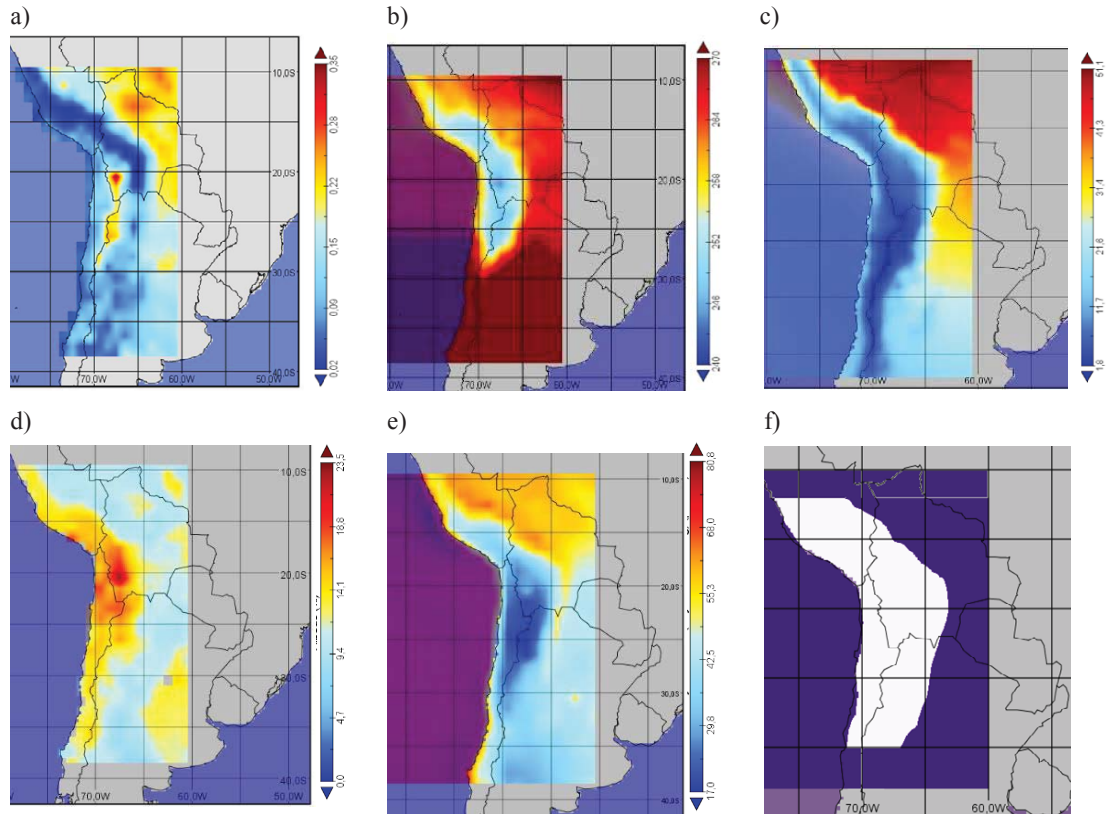
**Fig. 3: a) Aerosol Optical Depth at 550 nm [no units]; b) Ozone Total Column [DU]; c) Precipitable Water Vapor [cm]; d) Albedo [no units]; e) Relative Humidity [%]; all parameters were averaged for a time-period of 10 years. f) The white region represents the area where parameters were averaged.**

Other atmospheric parameters derived from long-term satellite databases were averaged for Atacama Desert area (Fig. 3), which is represented as a white region in figure 4 f. All parameters plotted in Figure 4 are available in (NASA and Kempler, 2016). Figure 4a and 4c show the MODIS retrievals for Atacama Desert Aerosol Optical Depth (AOD) at 550 nm and Precipitable Water (PW) values averaged from January 2006 to January 2016 (Bellouin et al., 2013; Kato et al., 2011; Remer et al., 2005). Figure 4b shows the Ozone Total Column (TOC) values over the Atacama Desert and figure 4e the Relative Humidity (RH), both from AIRS/Aqua L3 Daily Standard Physical Retrieval (Wang et al., 2012). Albedo (Figure 4d) was obtained from Global Land Data Assimilation System Version 2, bases on temporal averaging of the 3-hourly reprocessed data. It contains a set of land surface parameters simulated from the Noah Model 3.3 (Rodell and Beaudoing, 2015). Albedo values were calculated as an average for dates from January 1999 to January 2010.

Results of the average and the remaining inputs are shown in the table of Figure 4.

As results shows, low levels of TOC and PW are achieved. These results are in agreement with the ground measurements at several points of north of Chile (Cordero et al., 2016; Dirección Meteorológica de Chile, 2015; Galewsky et al., 2011; Kerber et al., 2014, 2012; McKenzie et al., 2015; Patat et al., 2010).

The Atacama Desert spectra derived from SMARTS and the average values of the atmospheric conditions are shown in Figure 4.

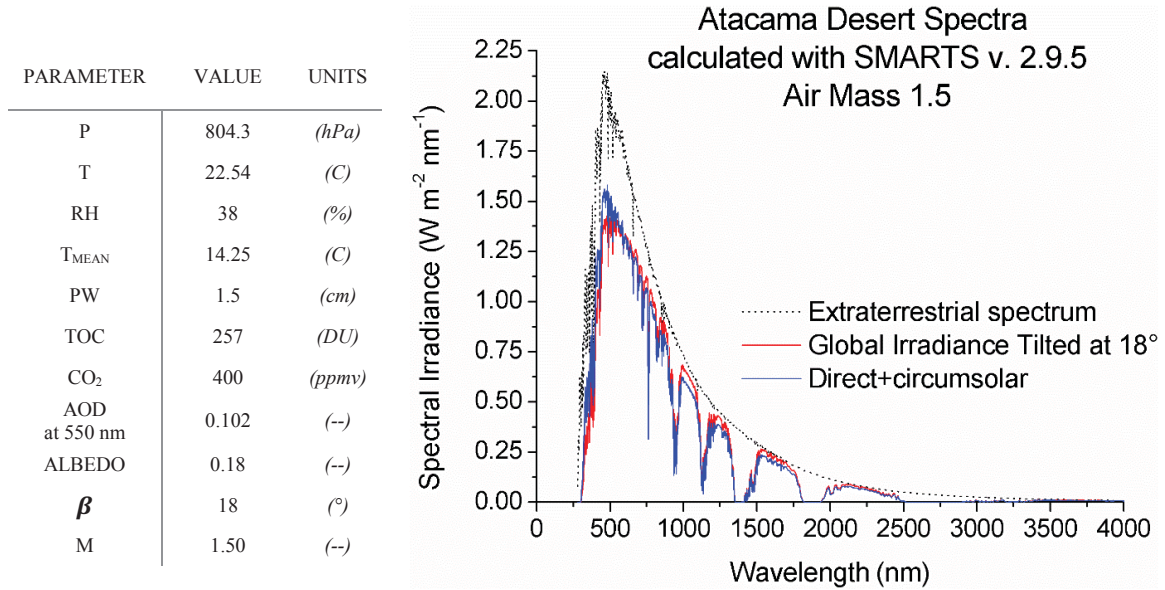| PARAMETER | VALUE | UNITS |
|-----------|-------|-------|
| P | 804.3 | (hPa) |
| T | 22.54 | (C) |
| RH | 38 | (%) |
| $T_{MEAN}$ | 14.25 | (C) |
| PW | 1.5 | (cm) |
| TOC | 257 | (DU) |
| $CO_2$ | 400 | (ppmv) |
| AOD at 550 nm | 0.102 | (--) |
| ALBEDO | 0.18 | (--) |
| $\beta$ | 18 | (°) |
| M | 1.50 | (--) |



Fig. 4: At left, a table with the inputs resulting from data processing, considered to calculate the Atacama Spectra. Right, Atacama Spectra derived from SMARTS v 2.9.5. Black line represents the extra-terrestrial solar spectrum (Gueymard, 2004), the red line is the global irradiance for a tilted surface at 18°, and the blue line represents the direct and circumsolar irradiance assuming a half aperture angle of a simulated spectroradiometer of 2.5°.

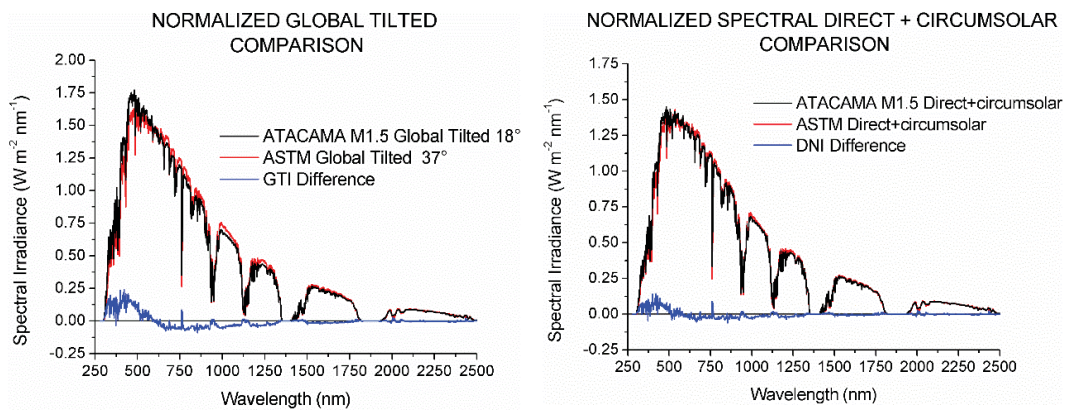### 4. Comparison with the ASTM G173-03 Reference Spectra



Fig. 5: Right, comparison of Atacama (black) and Reference (red) global spectral irradiances over a tilted surface at 18° and 37° respectively. Left, comparison of Atacama (black) and Reference (red) direct and circumsolar spectral irradiances.

Under the previously defined atmospheric and astronomic conditions, the integral values of the solar spectral global and direct plus circumsolar irradiances estimated for Atacama Desert were 893 and 903 W m$^{-2}$ respectively, while the reference spectra have 1000 W m$^{-2}$ and 900 W m$^{-2}$. The main different occurs in the global tilted spectrum and it is mainly due to the difference in the tilted angle of the surface where solar radiation is impinging on. A higher tilt angle permits a higher amount of solar radiation reflected from the ground to achieve the surface.

In order to show the differences on how the solar power is distributed along the electromagnetic spectrum, figure 5 shows the comparison of the normalized Atacama Desert spectra with the ASTM G173-03 reference for each solar irradiance component, namely Global (left) and Direct + Circumsolar (right), for M equal to 1.50. Normalization was performed to the integral values of the global tilted and direct plus circumsolar

spectral irradiances of the standard, 1000 W m$^{-2}$ and 900 W m$^{-2}$ respectively. In general, the greatest differences occur in the spectral range from 250 to 600 nm. Elevation above sea level (Pressure), AOD and TOC play an important role in light transmission at wavelengths below approximately 600 nm. The low levels of atmospheric ozone which play an important role in the atmospheric transmittance below the 340 nm, lead to higher UV-B irradiances, as ground measurements have shown, e.g. see (Dirección Meteorológica de Chile, 2015).

In the framework of solar energy technologies, the differences per wavelength do not play a role as important as the power distribution differences inside broadband ranges, excluding those processes, which occur at a given wavelength, such as for water treatment.

Figure 6 shows how much power there is in the ultraviolet (UV), visible (VIS) and near-infrared (NIR) ranges for each spectrum. In other words, it shows how the solar power is distributed for each spectral range. For that purpose, the integral of the spectral irradiance in each range was calculated and compared with the integral for the whole range in two cases: from 280 to 1200 nm (Fig. 6 left) and from 280 to 2500 nm (Fig. 6 right). Both spectral ranges were selected to provide useful information for Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies, respectively.
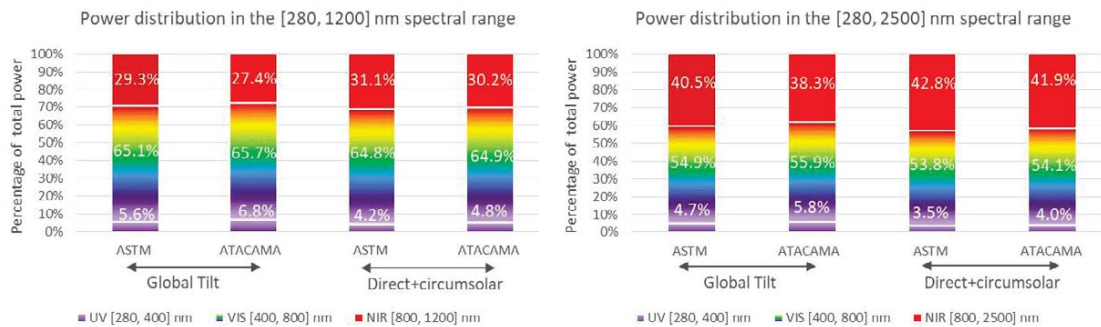


**Fig. 6: Solar power distribution for each spectral irradiance according to the UV [290, 400] nm (violet colour), VIS [400, 800] nm (rainbow colour) and NIR [800, 2500] nm (red colour) ranges. Left: results for the [280, 1200] nm spectral range. Right: results for the [280, 2500] nm spectral range.**

As figure 6 at left shows, 6.8% of the total hemispherical power received by a 18° tilted surface in Atacama Desert, is confined in the UV spectral range. Paying attention to the irradiance values in this spectral range, 58 W m$^{-2}$ for Atacama and 46 W m$^{-2}$ for the ASTM. It means that the predicted spectrum for Atacama differs 24% from the ASTM, and the difference is 93% higher if the same comparison is done in the UVB spectral range. Similar values can be obtained if the comparison is done for the direct plus circumsolar irradiance, 17% and 67%, respectively.
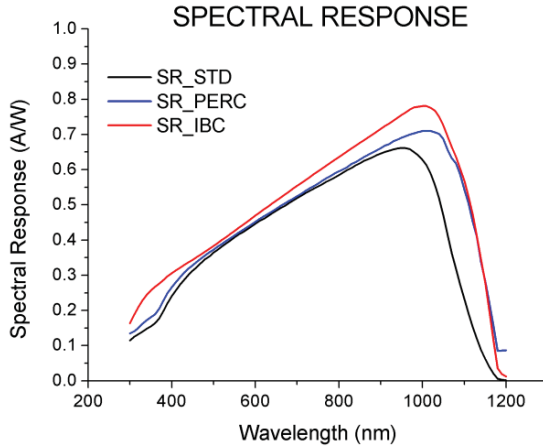
**Fig. 7 Spectral Response of standard, PERC and IBC photovoltaic technologies**

In order to know how these differences affect the development of solar technologies, three PV cells are studied under the influence of the solar global tilted reference spectrum and the average spectral irradiance estimated for Atacama Desert. The technologies used in this study were: a standard solar cell (STD), a passivated emitter and rear contact solar cell (PERC) and an interdigitated back contact solar cell (IBC) with spectral responses $(SR(\lambda))$ shown in Fig. 7.

A good indicator that helps to know about the influence of the solar spectrum shape on solar PV cells or devices is the spectral mismatch factor (MM). The MM is defined in the IEC 60904-7 norm (IEC, 2008) and describes the procedure for correcting the bias error introduced in the testing of a photovoltaic device, caused by the mismatch between the test spectrum and the reference spectrum and by the mismatch between the spectral responses (SR) of the reference cell and of the test specimen. The MM factor is defined in this work as follows:

$$MM = \frac{\int E_{ref}(\lambda)S_{Std}(\lambda)d\lambda \; \int E_{Ata}(\lambda)S_{sample}(\lambda)d\lambda}{\int E_{Ata}(\lambda)S_{Std}(\lambda)d\lambda \; \int E_{ref}(\lambda)S_{sample}(\lambda)d\lambda} \qquad \text{(eq. 2)}$$

Where $E_{ref}(\lambda)$ is the irradiance per unit bandwidth at a particular wavelength, of the reference spectral irradiance; $E_{Ata}(\lambda)$ is the irradiance per unit bandwidth at a particular wavelength, of the spectral irradiance distribution estimated for Atacama; $S_{Std}(\lambda)$ is the spectral response of the standard PV device; $S_{sample}(\lambda)$ is the spectral response of the test PV device. The relative error (ΔMM) is calculated as a deviation from 1. Results are shown in table 2.

**Tab. 2: Spectral mismatch (MM) and relative error of the spectral mismatch (ΔMM) in comparison with the reference global tilted spectrum and reference photocell**

| CELL | MM | ΔMM (%) |
|------|-----|---------|
| PERC | 0.9989 | 0.11% |
| IBC | 1.0004 | 0.04% |

The calculations show low MM values, 0.998 and 1.000, and ΔMM values, 0.11% and 0.04%, for PERC and IBC solar cells, respectively. These low ΔMM values indicate that the changes in the shape of the spectra, estimated for the specific conditions previously defined in this work, are not significant for the PV cells performance.

The photo-generated current $(J_{ph})$ is defined as the maximum theoretical current that can be generated by a PV device. It is calculated as (Ferrada et al., 2017):

$$J_{ph} = \int E(\lambda) \, SR(\lambda) \; d\lambda \qquad \text{(eq. 3)}$$

Where $SR(\lambda)$ is the spectral response of the considered PV device, $E_{\lambda}$ is the incident solar spectral irradiance, and $\lambda$ is the wavelength. The calculations were performed for both normalized and non-normalized solar spectra estimated for Atacama, and the reference solar spectrum. Results are shown in Fig. 8.
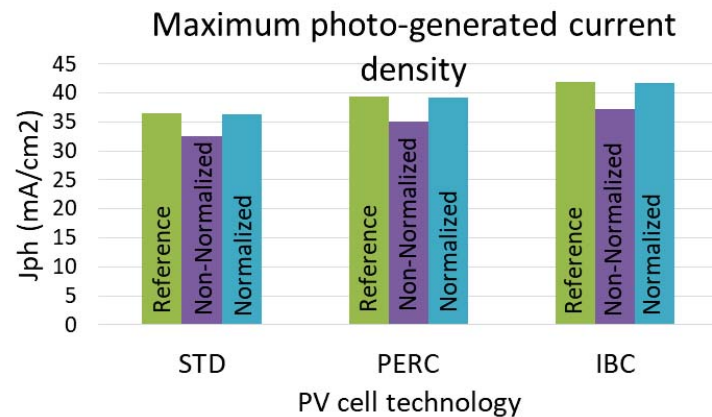
**Fig. 8 Maximum photo-generated current (Jph) for different solar cells (STD, PERC and IBC). The green bar indicates the Jph calculated with the reference global tilted spectrum, the violet bar is the Jph for the Atacama Desert global tilted spectrum without normalization, and the cyan bar represents the Jph calculated with the normalized solar spectrum estimated for Atacama Desert.**

The results indicate that the maximum difference occurs if the calculation is performed for a non-normalized spectrum, around 11%. On the contrary, the difference is minimum, less than 0.6%, if the comparison is done with normalized solar spectra. This result therefore agrees with the result of the MM comparison, indicating that the shape of the spectrum is not as important as the total amount of incident solar power, at least under the atmospheric and air mass conditions used in this work.

From the point of view of thermal processes, the differences in the energy distribution of the solar radiation do not play a major role. In CSP technologies, the aim is the production of process heat from the incident solar radiation. For this purpose, the receivers play an important role. In this context, receivers are designed to absorb the maximum of the incident solar power, which means pursuing absorptance values close to 1, usually in the 300-2500 nm spectral range. However, the aging of materials used may become a factor to be considered, especially at mirrors and receivers.

## 5. Conclusions

An estimation of the local solar irradiance spectrum for the Atacama Desert was conducted by deriving relevant atmospheric parameters from satellite databases, and then using those parameters as inputs for the SMARTS model. The atmospheric values were averaged for the area of Atacama Desert. These estimates represent a spectral distribution of the solar power for the specific conditions defined in this work.

The estimated spectra show changes with respect the world reference. These changes are in the amount of solar power and in the shape of the spectral power distribution. Changes are mainly due to the difference in the angle of the tilted surface and also because of the differences in the atmospheric parameters.

The main difference is found for short wavelengths, especially in the UV spectral range. The solar irradiance confined in the UV spectral range for the Atacama calculations resulted in 24 percentage points higher than the reference spectra for the global tilted component.

On one hand, the differences found in the shape of the solar spectrum, are not relevant for the solar technologies. The spectral mismatch calculation for three different solar cell types shown that the relative deviation from 1 is less than 0.11%. The maximum photo-generated current calculations indicates a relative error less than 0.6% respect the reference for the normalized spectrum calculated for Atacama. Both results are in agreement with themselves.

On the other hand, if the maximum photo-generated current calculations are performed with the non-normalized spectrum for Atacama, the relative error is around the 11%. This result indicates that what matters is the amount of energy and not the shape of its spectral distribution, at least under the specific conditions detailed in this paper which takes into account the same air mass than that defined for the world reference (M=1.5).

From the review of the available databases, it was noted that ground-based measurements of long-term atmospheric parameters in Atacama Desert is still necessary. The calculated spectral irradiances through SMARTS were in agreement with the spectral horizontal global measurements. However, an in-depth investigation is required in order to improve estimations, including more measurements for the improvement of the statistical methodology.

## 6. Acknowledgments

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