Analysis of the solar resource, photocurrent, electricity production and greenhouse gases emission reduction of an experimental photovoltaic power plant to be placed in a university campus

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Abstract

Solar photovoltaic power plants are expanding rapidly all over the world. We analyzed in detail the solar radiation resource at the Urcuquí region, near 0° latitude in Ecuador, the photovoltaic merit factor, the photocurrent generated by solar radiation in typical solar cells of (mono and poly) Si, Germanium and perovskite, the mean annual electric energy produced and the corresponding avoided greenhouse gases emissions. Urcuquí has an annual averaged cloud coverage of (75.7 ± 3.5) % and an annual averaged global irradiance for 2015 equal to (984 ± 57) Wm^{-2} in horizontal surface and with clear sky conditions. The photocurrent intensities calculated were: (34.9 ± 2.0) $mAcm^{-2}$, (26.9 ± 1.6) $mAcm^{-2}$, (26.5 ± 1.5) $mAcm^{-2}$ and (16.8 ± 1.2) $mAcm^{-2}$, for mono-Si, perovskite, poly-Si, and Ge solar cells, respectively. Finally, the installation of an experimental photovoltaic power plant of 1 MW_{peak}, can provide 1,410.1 MWh/year of electricity and reduce greenhouse gases emission by 483.88 $TnCO_{2eq}$/year.

Keywords: Solar photovoltaic power plant, Urcuquí, Ecuador, photocurrent, electric energy, greenhouse gases

1. Introduction

Solar energy is a clean and renewable energy source that it is available at a rather good level in Urcuquí (0.406° N, 78.172° W, 2100 m.a.s.l.), Ecuador, a high altitude site, even if the cloud coverage is important. The photovoltaic merit factor, i.e., the mean annual energy output for each kW_{peak} of photovoltaic power, is 1,640.1 kWh per kW_{peak} per year, derived from the Global Solar Atlas of World Bank Group database (Solargis). Since at this site, a University Campus (Yachay Tech) with a scientific and technological orientation is placed, we propose to install there a solar photovoltaic power plant based on solar panels made of different materials: (mono and poly) crystalline Si, Ge or perovskite, in order to have the possibility to investigate their behavior, in a geographical site with unique characteristics since it is placed at almost 0° latitude, with high global radiation, high UV radiation (related to material degradation), rather low annual mean temperature compared to desertic sites and rapid modification of solar irradiance incident on the solar photovoltaic panels, due to the particular type of clouds (mainly cumulus or similar ones) and consequently also rapid change of the electricity generated by the solar power plant.

In this work, first we present the atmospheric state, and then we present results for: a) the photocurrent produced by each solar photovoltaic material at Urcuquí University Campus, b) the electric energy that could be produced by a solar photovoltaic power plant, and c) the related reduction in the emission of greenhouse gases.

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In order to calculate the photo-generated current of each type of solar cell, it is necessary to count with the solar spectral irradiance and the quantum efficiency of the cells. The former was calculated employing the SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine) model (Gueymard, 1995).

The SMARTS model is an algorithm implemented in Fortran language that predicts the global, direct and diffuse solar intensities, and the atmospheric component transmittances in the range of 280 to 4000 nm for each wavelength, as function of different entry (atmospheric and meteorological) parameters that will be introduced later. Since their calculations are in function of input data of the site of calculation, if the data are appropriate for the site, their results are very accurate. It is important to point out that the irradiances are calculated on a horizontal plane in clear sky situation.

With regard to the solar cells in particular, the more relevant property with respect to the production of electrical energy is the *external quantum efficiency* (EQE), that is a quantum efficiency that represents the ratio of the number of charge carrier collected and the number of *incident* photons (Ananda, 2017). The photo-generated current depends on EQE of the solar cell. In the present work, the four solar cells EQE are: (mono and poly) crystalline Si and Ge (Stark and Theristis, 2015; Salum et al., 2015) and perovskite (Kim et al., 2022). Only the Ge solar cell has complete response in the infrared (IR) range, whereas the silicon solar cells have responses in the visible and IR ranges and a small fraction in the UV range. In particular, perovskite has responses in UVA, visible and a small fraction in the infrared range.

In the work of Salum et al. (2015), the results showed ozone and AOD_{550nm} having some effect on perovskite solar cell photocurrent efficiency, no significant effect on Germanium-based solar cells and some little effect on Silicon cells. The relationship between the solar cell quantum efficiency and air temperature was reported, for example, by Adeeb et al. (2019); Singh and Ravindra (2012) and Radziemska, (2003). An analysis about the influence of temperature over the solar cell efficiency was carried out by Shaban (2020). Omubo-Pepple et al. (2013) found that the emission of aerosols (natural or anthropogenic) into the atmosphere decreases the solar flux that reaches the solar panel, and Bergin et al. (2017) found that the particulate matter not only affects the incident solar radiation when it overpasses the atmosphere, but also reduces the energy production due to its deposition on the solar photovoltaic panels. Dew formation can produce reduction of the energy production of solar cells (Simsek et al., 2021); however, a novel research of 2016 analyzed the possibility of generating electricity with the fall of raindrops (Tang et al., 2016). Similarly, Ghitas (2012) performed an analysis on the effects of variation in each range of solar spectrum on the electrical parameters of mono-Si solar cell. In turn, Leitão et al. (2020) analysed the effect of spectral solar irradiance on the efficiency of different types of solar cells (including Si, Ge and perovskite). Finally, the work of Sağlam and Görgülü (2015) indicates the cloud amount produces a decrease in the generation of solar photovoltaic power, except in particular situations where it can result in an enhancement of total and UV solar irradiance (Järvelä et al., 2018; de Andrade and Tiba, 2016; do Nascimento et al., 2019; Piacentini et al.,2003; Piacentini et al., 2011; Almeida et al., 2014). In particular, Emck and Richter (2008) studied the clouds effect over the global irradiance in sites with altitude above 1900 m.a.s.l. at low latitudes and they found global irradiance values over 1800 W/m^2.

Another source of solar data consultation is the Global Solar Atlas web page of World Bank. Here, the Global Photovoltaic Power Potential by Country can been obtained. Among other parameters, the available information is about the potential solar resource enable to be used in photovoltaic power plants in the world. A factsheet for each country can be download and very useful information for the present work is showed: specific photovoltaic power output, annual mean global solar horizontal irradiation and the optimum angle of inclination for Urcuquí, Ecuador. Also, area, population, electricity consumption per capita, PV equivalent area and other parameters are published.

2. Methodology

As presented in the Salum et al. work (2016), the procedure to calculate the photo-generated current consist in the following steps:

a- Obtain the incident spectral irradiance by means of a model or a measurement.

In the present work, we used the SMARTS model to modeling the solar total spectral irradiance in a place at solar noon.

b- Obtain the meteorological input data for the SMART model.

The analysis of meteorological parameters has relevance, since the photovoltaic panels are susceptible to variables such us the air temperature at 2 meters, relative humidity, and other atmospheric components. These data were obtained from different satellite database:

i- POWER/NASA database (https://power.larc.nasa.gov/). From this database, we obtained the following data: air temperature at 10 m, relative humidity, total column precipitable water and surface albedo.

ii- OMI/NASA database. From this database, we obtained the ozone total column.

iii- MODIS-Aqua Deep Blue/NASA database. From this database, we obtained the AOD_{550m} (aerosol optical depth to 550 nm).

c- Apply the External Quantum Efficiency (EQE) for each wavelength and each type of solar cell, in order to calculate the photovoltaic current (per unit area).

This calculation requires to make the product of the spectral surface density photovoltaic current and the solar cell EQE.

Also, as a result of the spectral solar irradiance calculations made with the SMARTS model, global and total UV irradiances for each month were obtained. These irradiances are calculated integrating the spectral solar irradiances in wavelength.

From the web page of the Global Photovoltaic Power Potential by Country (Global Solar Atlas of World Bank Group), once Ecuador was chosen as country, Specific photovoltaic power output, annual mean global solar horizontal irradiation and the optimum angle of inclination were obtained.

Another result obtained in the present work is the emissions of greenhouse gases reduction caused by the hypothetical implementation of a solar photovoltaic power plant.

3. Results

3.1 Photocurrent produced by each solar photovoltaic material at Urcuquí University Campus
This objective needed to several steps. Following, each result is detailed.

3.1.1 Meteorological data
Figure 1 shows the annual evolution of average value of each month of air temperature and relative humidity at Urcuquí in 2015. The maximum (minimum) monthly average value of air temperature was 22 °C (19.9 °C) in September (January and December) 2015, and the maximum (minimum) monthly average value of relative humidity was 80.6 (50.8%) in December (August) 2015.

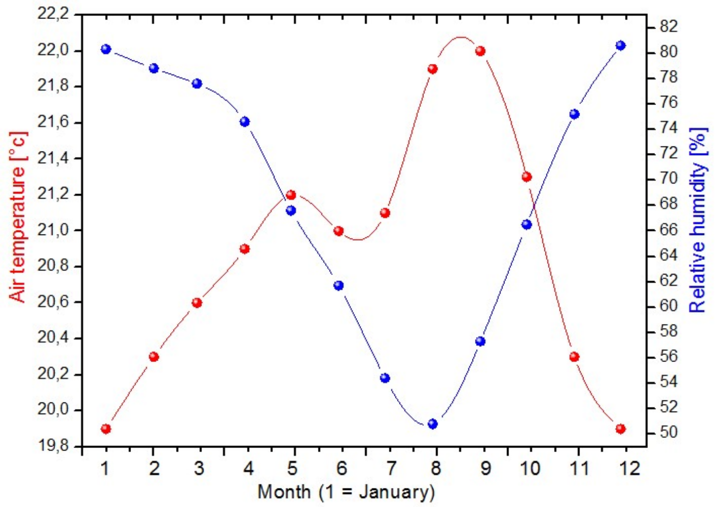

Fig. 1: Monthly mean evolution of air temperature (red line) and relative humidity (blue line) for a typical year (2015) at Urcuquí, Ecuador. Note: The line is a smoothing function connecting the points. Source: POWER/NASA.

Figure 2 shows the evolution of the monthly average total column ozone (in Dobson Units) for 2015. It can be seen that the atmospheric ozone has maximum values in August and September and maximum values in January and December. In this figure, the line represents a smoothing function.

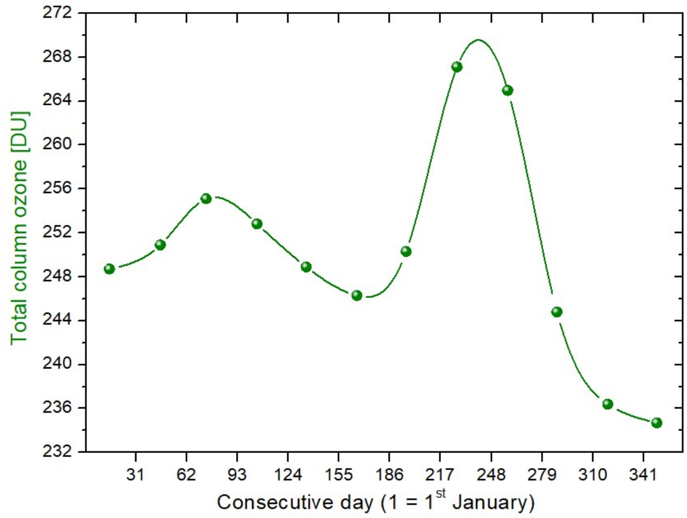

Fig. 2: Annual evolution of Total column ozone in Urcuquí for 2015. Source: Power/NASA.

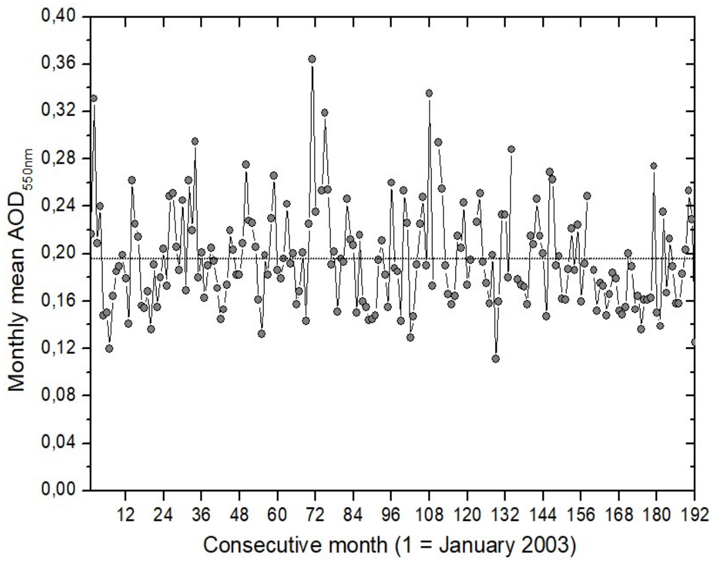

Fig. 3: Evolution of monthly average of AOD_{550nm} in the period 2003 to 2018, at Urcuquí. Source: Power/NASA

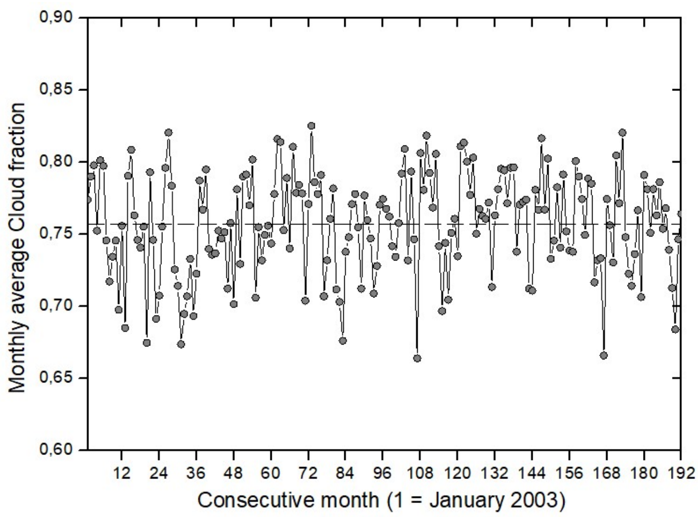

Fig. 4: Evolution of monthly average of cloud fraction in the period 2003 to 2018, at Urcuquí. Source: Power/NASA

In the case of the aerosol optical depth at 550 nm (AOD_{550nm}), it was obtained in the period 2003 to 2018 (Figure 3). The mean value is (0.196 ± 0.043), being the maximum and minimum values: 0.364 and 0.111, respectively. This parameter has a particular importance because the aerosols influence the solar irradiance mainly at lower Visible and UV wavelengths that fall over the solar panels surface and consequently decreases the corresponding efficiency.

The cloud fraction for the same period of time was obtained from the satellite data base MERRA – 2 model/NASA (Figure 4). The monthly average cloud fraction at Urcuquí, Ecuador is (0.757 ± 0.035).

According the used satellite database, the mean values of atmospheric parameters for 2015 in Urcuquí are presented in Table 1. These data were obtained in order to use the SMARTS model.

Table 1: Atmospheric parameters obtained from POWER/NASA for 2015 year for Urcuquí, Ecuador.

Parameters	Mean values
Air temperature	(20.9 ± 0.7) °C
Relative humidity	(69 ± 11) %
Total column ozone	(250.1 ± 9.6) DU
AOD_{550nm}	(0.196 ± 0.043)
Cloud fraction	(0.757 ± 0.035)

3.1.2 Solar data

According to the Global Solar Atlas of the World Bank Group, the KWh of electricity that would be generated by a photovoltaic system with each KWpeak of installed capacity is the *Specific photovoltaic power output* (or PVOUT specific). In Urcuquí, PV_{out} = 1640.1 $KWh.KWp^{-1}year^{-1}$ with an annual mean global solar horizontal irradiation of 2040.4 $kWh.m^{-2}$ and an optimum angle of inclination of 2°.

The mean annual solar global irradiance at solar noon for a typical year (2015) in Urcuquí equals to (984 ± 57) Wm^{-2} (from POWER/NASA data base).

After integrating, global and total UV irradiances were obtained, for each month in 2015 and for the same equatorial site (see Figure 5). The annual mean values of these irradiances are: (984 ± 57) Wm^{-2} and (62.9 ± 8.4) Wm^{-2}, respectively.

The small difference (of 3.9%) between the mean annual irradiance satellite value (946 W m^{-2}) and the model value (984 W m^{-2}) is mainly due to the indetermination in the cloud attenuation.

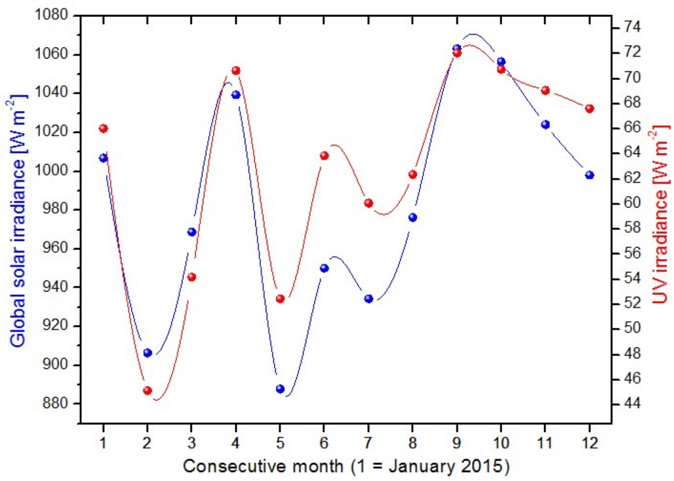

Fig. 5: Annual evolution of global (blue line and circles) and UV (red line and circles) solar irradiances in Urcuquí.

3.1.3 Solar generated photocurrent

In order to determine the potential of solar energy as a renewable source in Urcuquí, Ecuador, first, the spectral solar irradiance for Urcuquí incident on a horizontal plane for clear sky days was calculated. For this, it was used the SMARTS model with input data obtained from satellite database (aerosol optical depth, total ozone column, albedo, air temperature, and relative humidity). The spectral solar irradiance was calculated once per month (see an example for the day December 15th, 2015, corresponding to the red line in Figure 6).

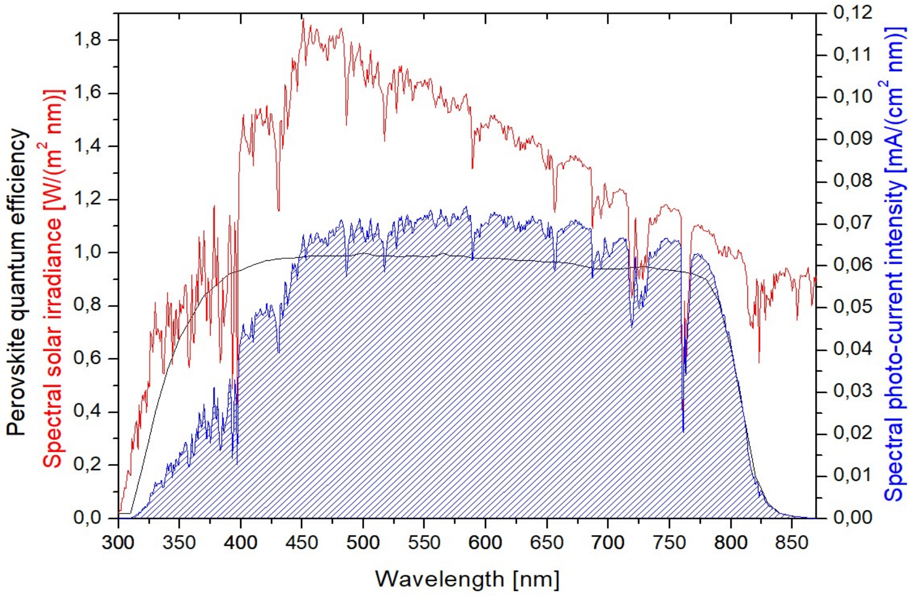

Fig. 6: Typical spectral solar irradiance for the clear sky day December 15th, 2015, as an example (from SMARTS model) (with the following values of the parameters for this particular day: O_3 = 234.5 DU, AOD_{550nm} = 0.196, Cloud cover = 0 %), incident on a horizontal surface at Urcuquí, Ecuador (red line), the EQE for a perovskite cell (black line), spectral photocurrent intensity (blue line) and integrated photocurrent intensity (grated area). Source of the perovskite data: Kim et al., 2022.

The next step was the determination of the photon density, calculating for this purpose the ratio between the solar irradiance and the photon energy, for each wavelength.

Finally, the photo-generated current for each type of solar cell is obtained as the wavelength integral of the spectral photo-current intensity (blue grated area in Figure 6). This photo-current is determined as the multiplication of the photon density by the electron charge and by the EQE (black line in Figure 6). An example of the calculation performed for perovskite solar cells is shown in Figure 6, for the typical clear sky day December 15th, 2015, at Urcuquí, Ecuador, at solar noon (=UT – 5 hours).

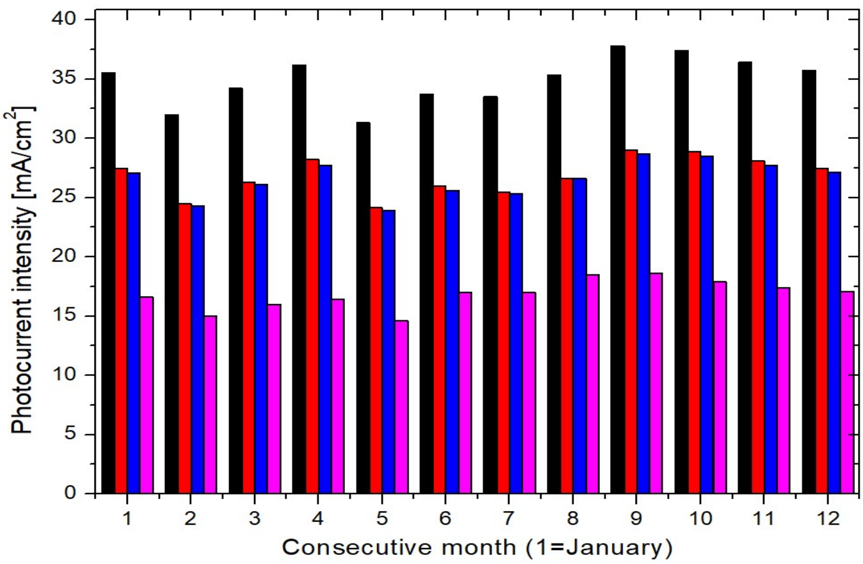

Fig. 7: Mean photocurrent of different solar cells for each month of the year (period January-December 2015), for Urcuquí, Ecuador: mono-Si (black bar), perovskite (red bar), poly-Si (blue bar) and Ge (magenta bar).

As a result of the previous calculation, we obtained one photocurrent per month. Figure 7 shows the comparison between the photocurrent generated by each of the four solar cells in different months of the year, in Urcuquí, Ecuador. As can be seen, mono-Si gives the highest mean photocurrent (34.9 ± 2.0) $mAcm^{-2}$, followed by perovskite (26.9 ± 1.6) $mAcm^{-2}$, poly-Si (26.5 ± 1.5) $mAcm^{-2}$, and finally Ge (16.8 ± 1.2) $mAcm^{-2}$. The annual mean relative percentage between each solar cell photocurrent and the mono-Si is: (76.9 ± 0.7) % for perovskite, (76.0 ± 0.3) % for poly-Si and (48.2 ± 2.1) % for Ge. The lowest value of the Germanium photocurrent density with respect to (mono and poly) Si and perovskite solar cells, is due to the particular behavior of its EQE, mainly concentrated in the infrared region of the electromagnetic spectrum, where the solar radiation is decreasing, in comparison with the visible range.

3.2 Electrical energy that could be produced by a solar photovoltaic power plant

We consider the possibility to install an experimental 1 MWpeak solar photovoltaic power plant, with panels made of different solar cells as described above, in about 1.5 Ha of the Yachay Tech University campus, at Urcuquí, Ecuador. So, the annually produced electricity will be:

$$E_{PV} = PV_{OUT} \cdot 1\, MW_{peak} = 1640.1\, MWh\ per\ year \quad \text{(eq. 1)}$$

with the PV_{OUT} value given in item *2.1.2 Solar data*. Taking into account the losses of the system as 14%, due to inverter, internal transmission lines, DC/AC transformation, etc., the electricity annually produced will be 1,410.1 MWh per year.

3.3 Related reduction in the emission of greenhouse gases.

The avoided emissions of greenhouse gases (GHG) due to the solar photovoltaic power plant, can be obtained from the conversion coefficient between a unit of mixed electric energy (renewable and non-renewable) of Ecuador and a unit of emitted GHG, which is: $f_{E,GHG(Ecuador)}=0.343\ TnCO_{2,eq}\ per\ MWh$ (Parra Narváez, 2015). Therefore, the annual mass of avoided emissions is:

$$M_{GHG,FV} = f_{E,GHG(Ecuador)} \cdot E_{PV} \cdot 0.86 = 483.8\, Tn\, CO_{2,eq}\ per\ year \quad \text{(eq. 2)}$$

were *Carbon Dioxide equivalent* ($CO_{2,eq}$) means that all other greenhouse gases (mainly Methane, CH_4 and Nitrous oxide, N_2O) are referred to CO_2.

4. Conclusions

We developed model calculations for the determination of the behavior of spectral solar irradiance (in clear sky situation) and the available annual photocurrent generated by different solar cells as part of an experimental Solar Power Plant, to be placed at an equatorial high altitude site, Urcuquí, Ecuador. The annual mean value of global solar irradiance incident at solar noon on a horizontal surface is (984 ± 57) W/m^2. A similar behavior is observed for the UV component, with an annual mean value of (62.9 ± 8.4) W/m^2.

With respect to the photocurrent intensities, the largest one corresponds to mono-Si solar cell with an annual mean value of (34.9±2.0) mA/cm^2. The annual mean relative percentage between each solar cell photocurrent and the mono-Si is: (76.9 ± 0.7) % for perovskite, (76.0 ± 0.3) % for poly-Si and (48.2 ± 2.1) % for Ge.

In particular, due to the large contribution in Urcuquí, Ecuador, of cumulus clouds to the solar radiation enhancement effect, a detailed analysis of this phenomena is of interest, taking into account that specially perovskite solar cells degrade rapidly (in several months) with time exposure.

Also, we determined the annual mean of the electricity produced by a 1 MWpeak experimental photovoltaic mini-power plant (with modules based on the 4 different cells) in a University Campus at Urcuquí, Ecuador as 1,410.1 MWh per year and the corresponding avoided emissions of CO_2, resulting in a saving of 483.88 $TnCO2_{,eq}$ per year. This mini-power plant can be employed, -besides the possibility of the electric supply of the University Campus, for doing research work and training of graduate and post-graduate students in the highly expanding field of Solar photovoltaic, -that can contribute to the world effort for mitigating the global warming (IPCC, 2013, 2018) and also in relation to solar cell degradation in an almost equatorial, high altitude site.

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