Solar Energy Materials & Solar Cells 133 (2015) 92–98

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Effects of spectral coupling on perovskite solar cells under diverse climatic conditions

S. Senthilarasu [a,*], Eduardo F. Fernández [a,b,**], F. Almonacid [b], Tapas K. Mallick [a]

[a] Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9FE, United Kingdom
[b] Centre of Advanced Studies in Energy and Environment, University of Jaen, Jaen 23071, Spain

ARTICLE INFO

Article history:
Received 16 August 2014
Received in revised form
10 October 2014
Accepted 25 October 2014
Available online 21 November 2014

Keywords:
Perovskite solar cells
Spectral effects
Climate conditions

ABSTRACT

The high conversion efficiency of perovskite solar cells has opened a potential market for solar cells based on low cost manufacturing techniques which could change the photovoltaic (PV) production road map. Although the 9% efficient 10 cm x 10 cm perovskite mini module has been reported, in depth analysis of the longevity of perovskite modules is required before being introduced to the market. Apart from the impressive demonstrated conversion efficiencies, these cells need to be tested under real climatic conditions in order to understand the integrity of their performance. This article briefly outlines significant spectral dependence at selected locations with varying parameters such as air mass, aerosol optical depth and precipitable water. Perovskite solar cells have shown significant dependence on the incident spectrum due to their strong absorption in the visible region. The influences of spectral variations on the performance of perovskite solar cells were studied under different atmospheric conditions. The demonstrated spectral losses by the perovskite solar cells in different climatic conditions are vital for the perovskite solar cell community to further improve their stability.

1. Introduction

The photovoltaics (PV) global market has experienced rapid growth in the last decade due to the renewable deployment targets and CO_2 emission control. The development of technologies and the invention of new materials could lead to the reduction of PV electricity generation cost. The most commonly used commercial PV technologies such as silicon and thin film based technologies are processed through expensive vacuum based techniques. Third generation PV technologies [1] can offer cheaper manufacturing rates compared to the existing PV technologies. Especially dye sensitized solar cells (DSSC) and perovskite materials based solar cells have attracted a great amount of attention due to their higher conversion efficiencies [2]. In recent times, DSSCs shows comparatively potential conversion efficiencies which have encouraged the scientific community to work on its inherent problems such as replacement of liquid electrolyte, durability problems, electrode corrosion and electrolyte leakage [3]. The search for alternative materials to replace the liquid electrolytes in dye-sensitized solar cells (DSSC) has led to the development of perovskite structured semiconductors based solar cells [1]. The attractions of these types of solar cells are due to their ability to increase conversion efficiencies to more than 19% [2]. Perovskite solar cells most commonly comprise of $CH_3NH_3PbI_3$ based hybrid organic-inorganic perovskite materials with an appropriate band gap (1.55 eV), high absorption coefficient, long hole–electron diffusion length ($\sim$100 nm), and excellent carrier transport [4]. Importantly, the perovskite solar cells can be deposited by low-temperature methods such as solution process (spin coating) [5] and thermal evaporation methods [6]. The advantage of the solid-state DSSCs over the liquid DSSCs will lead to a less complicated manufacturing process involved in the manufacturing process, easier production of monolithically interconnected modules, easier sealing and encapsulation of the modules which are similar to other thin film solar cells. In addition, the impressive efficiency values [7,8] reached for small-size individual solar cells can be considered to be satisfactory, and should basically provide a great commercial potential for this technology [4,6]. However, the stability and longevity of the device is yet to be ascertained. Although metal halide perovskites are cheaper than the conventional dyes, they are sensitive to temperature and humidity.

1.1. Perovskite solar cells

The device architecture of the perovskite solar cells is designed based on the function of the perovskite materials. The perovskite solar cells commonly follow three different architectures as shown

* Corresponding author Tel.: +44 (0) 1326 259486.
** Corresponding author Tel.: +34 953213518.
E-mail addresses: s.sundaram@exeter.ac.uk (S. Senthilarasu), E.Fernandez-Fernandez2@exeter.ac.uk (E.F. Fernández).

http://dx.doi.org/10.1016/j.solmat.2014.10.037
0927-0248/

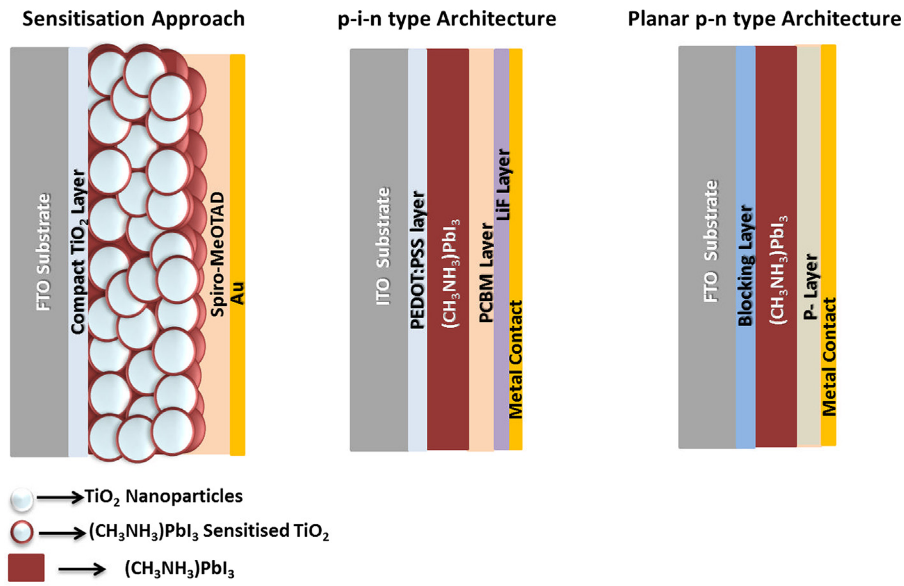

Fig. 1. Common perovskite solar cells architectures reported in the literature to date.

in Fig. 1 in order to achieve higher efficiency and increase the robustness. The high efficiency devices have been constructed with perovskite as a sensitizer, which replaces the dyes in the dye sensitized solar cells or used as a p-type [3] or n-type [9] light harvesting materials and operate efficiently in a planar p–i–n heterojunction configuration. The p-i-n based structure has been developed into 10 cm x 10 cm module with 8.7% conversion efficiency [4]. From the commercial perspective, perovskite solar cells can be compared with existing thin film photovoltaic technologies (PV) such as CdTe and CIGS solar cells in terms of efficiency and cost of production. However, perovskite solar cells are more closely comparable with CdTe thin film technologies for its lower cost of production as well as the common environmental concerns of using hazardous heavy metal [10]. The low robustness characteristic of sensitive to moist air and water vapour of the present perovskite technology is more closely related to CIGS. As there are considerable ongoing efforts to replace hazardous elements [11,12] in the perovskite solar cells, the focus needs to be shifted to overcoming the low robustness issues. However, the stability and longevity of the device is yet to be ascertained. Even though, metal halide perovskites are cheaper than the conventional dyes, they are sensitive to temperature and humidity.

1.2. Purpose of this work

The efficiencies of the emerging PV technologies are impressive in the laboratory scale efficiency (Fig. 2a). However, photovoltaic devices are spectrally selected (Fig. 2b) and their performances are influenced by the atmospheric conditions such as air mass (AM), aerosol optical depth (AOD) and precipitable water (w) [13]. Recently, there has been a considerable amount of interest in studying the influence of spectral variations in incident solar irradiance on the performance of different photovoltaic devices such as single-junction, multi-junction and concentrated PVs. The spectral effects on the performance of different PV devices have been studied as a function of the average photon energy (APE) by several authors [14–16]. A different approach has also been also used by other authors concerning the spectral factor (SF) variation under different climate conditions at different locations [17–19]. Also, the study of the spectral effects on the performance of concentrated PV devices based on multi-junction solar cells has recently been addressed. Some authors have analysed the performance of these devices as a function of the spectral parameter Z and SMR (Spectral Matching Ratio) parameters [20–22] or from the analysis of the SF variations at locations with disparate climate conditions [23]. However, the influence of spectral changes on the performance of perovskite solar cells has not been addressed and is still unknown. The analysis of perovskite solar cells under different atmospheric conditions is vital from the industrial perspective. This article focuses on the analysis of the influence of the time varying solar irradiance spectrum on the performance of perovskite solar cells. In order to address this issue, the same approach introduced by the authors to leverage our understanding of concentrated PV devices based on different optics and multi-junction cells is used [23]. For better understanding of the perovskite solar cells performance in different atmospheric conditions on spectral variations, this article aims to analyse the individual impact of atmospheric parameters such as air mass, aerosol optical depth and precipitable water. In depth analysis of the influence of the spectral variations on the performance of perovskite solar cells on an annual time scale at locations with different atmospheric conditions is crucial for a better understanding of the performance of perovskite solar cells and their potential under real operating conditions.

2. Method and computation

2.1. The spectral factor

The spectral or mismatch factor is a parameter which allows the differential performance of a PV device between the incident and reference spectrum to be evaluated [16,19,23,24]:

$$SF = \frac{\int E(\lambda)SR(\lambda)d\lambda \int E_{ref}(\lambda)d\lambda}{\int E_{ref}(\lambda)SR(\lambda)d\lambda \int E(\lambda)d\lambda} \quad (1)$$

where $E(\lambda)$ is the incident spectrum on the PV device, $E_{ref}(\lambda)$ is the AM1.5 G ASTM G-173-03 reference spectrum [25] and $SR(\lambda)$ is the spectral response of the PV device. Values of higher/lower than 1 represent spectral gains/losses with respect to the reference spectrum. Taking Eq. (1) into account, the spectral effects are finally computed as:

$$\Delta SF(\%) = \left(SF(E_b(\lambda)) - SF\left(E_{b,ref}(\lambda)\right)\right)100 = \left(SF(E_b(\lambda)) - 1\right)100 \quad (2)$$

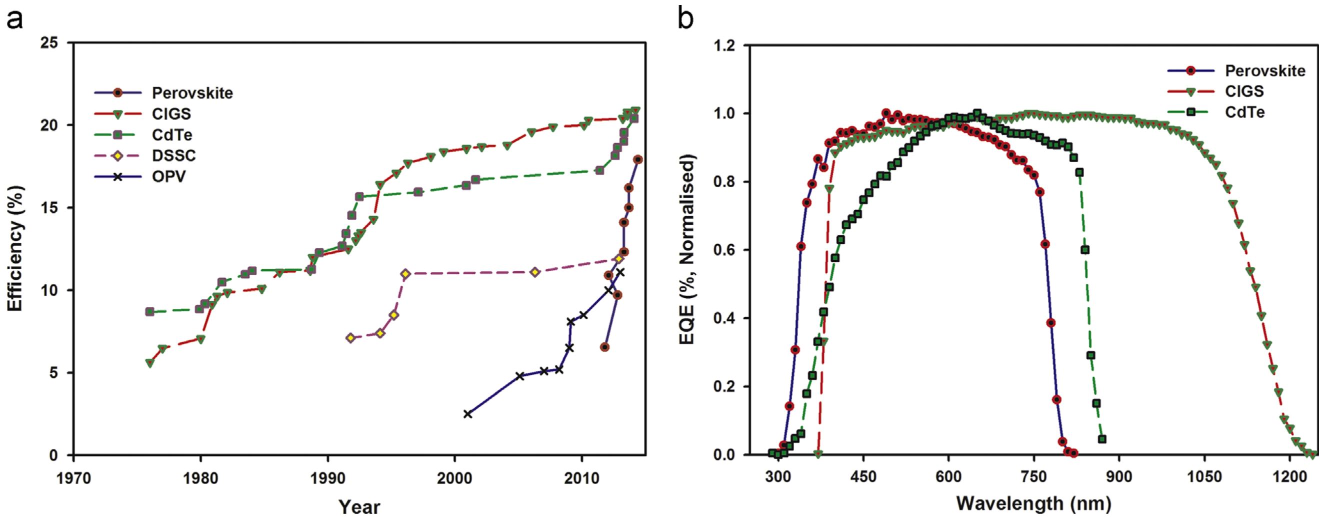

Fig. 2. (a) Efficiency chart for the emerging thin film and new generation solar cells; (b) External Quantum Efficiency (EQE) for different high efficient solar cells.

where ΔSF is defined as the relative spectral factor and expresses the percentage of gains or losses of a PV device as a function of the short-current density at operating conditions relative to the value under reference conditions. This parameter has been proven as a reliable tool to evaluate the spectral impacts in the maximum power or energy output of a PV device [26,27].

2.2. Simulation of the spectral irradiance

The spectral irradiance is simulated using the Simple Model of the Atmospheric Radiative transfer Sunshine (SMARTS [28–30]). This model accurately predicts the spectral distribution of the incident solar irradiance at any given set of atmospheric parameters.

2.3. Computation of the annual spectral losses

In order to estimate the annual spectral losses at a particular location the value of air mass (AM) is computed every minute during daylight time for a whole year using the following expression [31]:

$$AM = \frac{1}{cos\theta + 0.45665\theta^{0.07}(96.4836-\theta)^{-1.697}} \quad (3)$$

where is the sun's zenith angle.

After following this, the frequency distribution of AM (P(AM)) is obtained. Next, the global solar spectral distribution is computed for 200 AM values distributed between 1 and 38 (a sun's zenith angle around 90) using the SMARTS and the yearly average values of the atmospheric parameters based on high-quality ground-based long-term observations obtained from the Aerosol Robotic Network (AERONET [32]) data source. The spectral factor SF(AM) is then computed for 200 solar irradiance spectra using Eq. (1) and the annual spectral factor is obtained as:

$$SF_{annual} = \frac{\int P(AM)SF(AM)dAM}{\int P(AM)dAM} \quad (4)$$

Finally, once the annual spectral factor at a chosen site is obtained, the annual spectral losses are calculated using Eq. (2). Further information about the procedure followed can be found in [23].

2.4. Locations

The sites analysed here have been chosen from the Aerosol Robotic Network as they represent locations with disparate atmospheric conditions over different continents. Table 1 shows the yearly average values of AM, $\tau_{0.55}$, α and w at the six sites considered. Solar Village in Saudi Arabia (N 24°54', E 46°23') is a desert location with low annual average values of AM and medium $\tau_{0.55}$ and w values. Alta Floresta in Brazil (S 09°52', W 56°06') is a tropical location characterized by low annual average values of AM, medium values of $\tau_{0.55}$ and high values of w at any tropical site. Frenchman Flat in USA (N 36°48", W 115°56') is a desert location with medium annual average values of AM, very low values of $\tau_{0.55}$, and medium values of w values. Granada in Spain (N 37°09', W 03°36') is a non-industrialized medium-size city with medium annual average values of AM, $\tau_{0.55}$ and w. Beijing in China (N 39°58', E 116°22') is a highly polluted urban city with annual average medium values of AM, extremely high values of $\tau_{0.55}$, and medium w values. Edinburgh in Scotland (N 55°55', W 03°10') is also a non-industrialized medium-size city but with high average annual values of AM, low values of $\tau_{0.55}$, and medium values of w.

3. Results and discussion

3.1. Individual impact of atmospheric parameters

In order to understand the perovskite solar cells performance under the spectral variations, the analysis of the influence of the main atmospheric parameters (air mass, aerosol optical depth and precipitable water) has been conducted. To address this issue, several spectra are simulated with the SMARTS model. These spectra are generated varying one of the atmospheric parameters while the rest are kept constant at the reference values defined by the AM1.5 G ASTMG-173-03 reference spectrum. The spectral effects on the performance of perovskite solar cells are computed as is outlined in section 2.1.

3.1.1. Impact of air mass

The relative optical air mass or simply air mass can be defined as the ratio of the optical path length of the solar beam through the atmosphere to the optical path through a standard atmosphere at sea level with the sun at the zenith.

For dry air molecules, this parameter reduces to a purely geometrical parameter function of the zenith angle whose minimum is always 1 [31]. The influence of the air mass from AM = 1 to AM = 10 was studied and results are given in Fig. 3. The variation of spectral irradiance with different air mass values are given in Fig. 3a and relative spectral factor in Fig. 3b. The spectral factor variation over the different AM can suggest the suitability of a device in different atmospheric conditions. The reported efficiencies for perovskite solar cells are under AM = 1.5, however, the AM variations affect the distribution and magnitude of photon density in the spectrum. The observed performance loss as shown in Fig. 3b in the perovskite solar cells at different air mass conditions is due to the increase in attenuation of solar irradiance and photon density distribution. The estimated observable loss in different air mass conditions for perovskite solar cells is due to their strong absorption behaviour in the visible region. The higher AM can result in a shift of photon distribution into shorter wavelength regions which affect the perovskite solar cells. The perovskite solar cells are showing considerable loss at AM >1.5. This can be explained due to the fact that the majority of the absorption band is located in the blue part of the spectral region, as is shown in Fig. 2b, where the attenuation of AM is higher. This clearly suggests the inadequacy of perovskite solar cells in different AM conditions.

3.1.2. Impact of aerosol optical depth

Aerosols are small particles suspended in the air with diameters in the range from a few nm (nanometre) to tenths of microns. Aerosol optical depth (AOD) or turbidity is a measure of the atmospheric attenuation of solar radiation by aerosols. The value of 0.1 (at 0.5 μm) indicates a relatively clear atmosphere and 0.4 is for relatively turbid conditions [13]. Its value changes with solar irradiance wavelength. It can be represented by the Ångström law: $\tau = \beta\lambda^{-a}$, where λ is the wavelength in microns, β is the AOD at λ = 1 μm, and α is the so-called Ångström exponent [33]. It represents the spectral incidence of aerosols in the solar flux: small values of α are typically for large particles such as desert dust and large values of α are for small particles such as those found in polluted areas. According to the spectral dependence the Ångström law can be re-formulated as $\tau = \tau_{0.55}(\lambda/0.55)^{-a}$, so that the spectral dependence is now described in terms of the AOD at 0.55 μm ($\tau_{0.55}$) for the wavelength λ given in μm. The 0.55 μm is the most commonly observed value in different aerosol databases, including ground-based and remotely sensed data sources. The Fig. 4a shows the simulated solar irradiance spectra between $\tau_{0.55} = 0.1$ and $\tau_{0.55} = 0.1$. The increase in AOD will bring the changes in the incoming irradiance. As can be seen in Fig. 4b, ΔSF remains almost constant at a value of around 0% up to $\tau_{0.55} = 0.2$ which shows the aerosol in the atmosphere up to a certain level does not affect perovskite solar cell performance. Increased turbidity causes more attenuation and scattering of solar irradiance in the UV–vis spectra. Therefore, the perovskite solar cells are more affected in the turbidity conditions due to their narrow absorption band mainly located in the blue part of the spectrum. However, $\tau_{0.55}$ shows a significantly lower attenuation of the solar irradiance than AM and therefore the spectral losses are lower than in the previous case.

Table 1
Annually average values of air mass (AM), aerosol optical depth at 555 nm ($\tau_{0.55}$, Ångström exponent (α) and precipitable water (w).

Location	AM	$\tau_{0.55}$	α	w
Solar village	4.0	0.35	0.56	1.23
Alta floresta	3.1	0.31	1.27	3.92
Frenchman flat	5.0	0.07	1.15	0.89
Granada	5.0	0.15	1.07	1.27
Beijing	5.3	0.74	1.08	1.28
Edinburgh	7.5	0.09	1.00	1.14

3.1.3. Impact of precipitable water

Precipitable water (w) vapour causes absorption of solar radiation. It can be defined as the total amount of water vapour in the zenith direction, between the surface and the top of the atmosphere. However, precipitable water 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 [34]. A value of w = 1 cm is representative of a dry atmosphere and a value of w = 5 cm is for highly wet atmosphere. Fig. 5a shows the simulated solar irradiance spectra between w = 0.5 and w = 4.5. As can be seen, increased precipitable water vapour causes more absorption of solar irradiance in the near-infrared spectra. The value of ΔSF decreases by -4% for w up to 1.5 cm as shown in Fig. 5b. However, the performance of the perovskite solar cells increases with the increase of w which shows the precipitable water in the atmosphere above a certain level will improve perovskite solar cells performance. This can be explained considering that the effect of w in the spectral region of the perovskite solar cells is almost negligible. Because of this, the current of perovskite solar cells is kept almost constant as the w increase resulting in an overall increase of their performance.

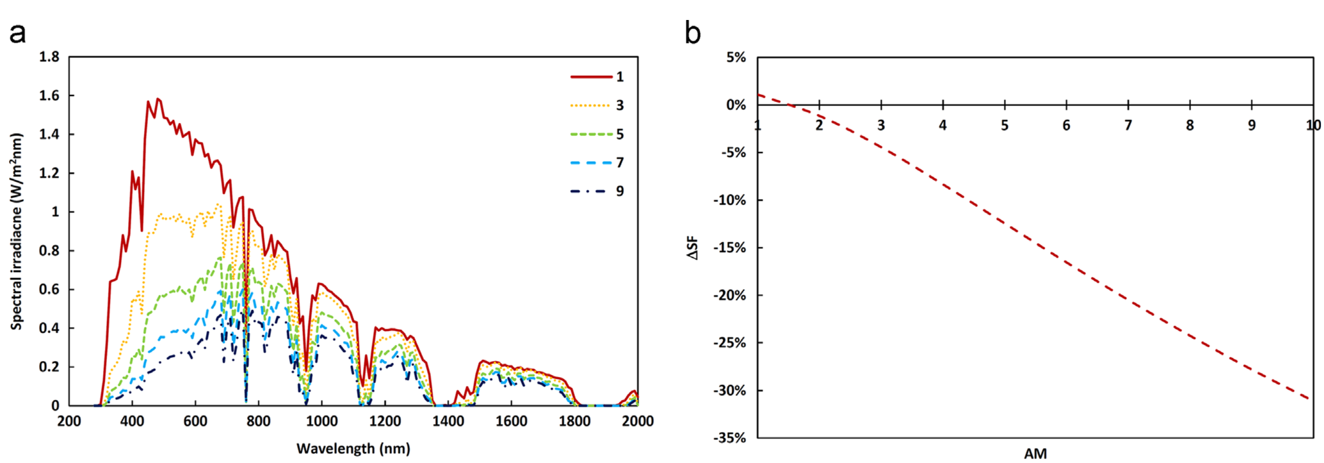

Fig. 3. Effect of air mass on the spectral irradiance (a) and on the perovskite solar cells performance (b). The other parameters are kept constant at the reference values defined by the AM1.5 G ASTMG-173-03 reference spectrum.

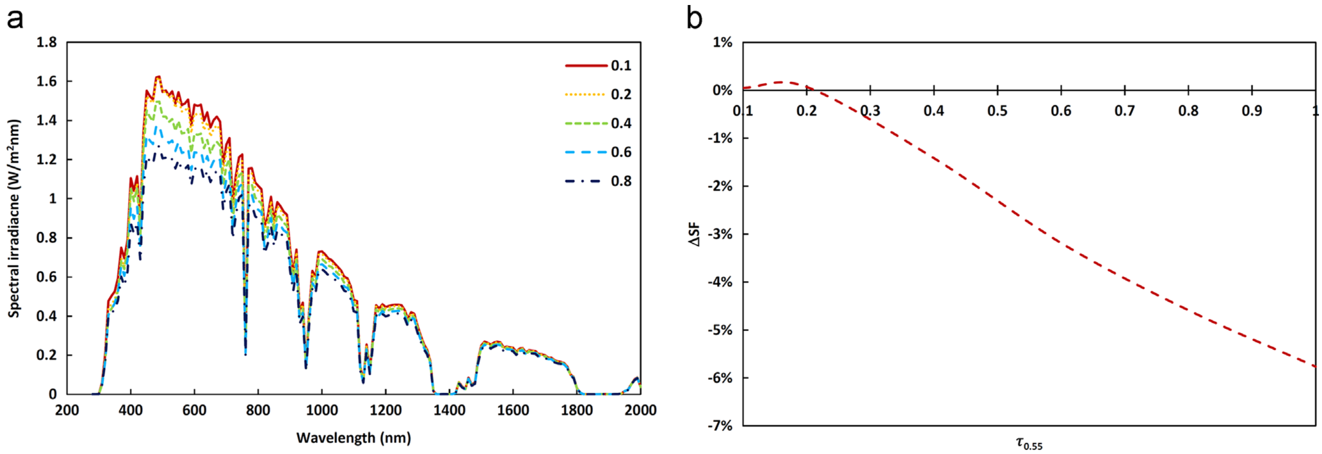

Fig. 4. Effect of aerosol optical depth on the spectral irradiance (a) and on the perovskite solar cells performance (b). The other parameters are kept constant at the reference values defined by the AM1.5 G ASTMG-173-03 reference spectrum.

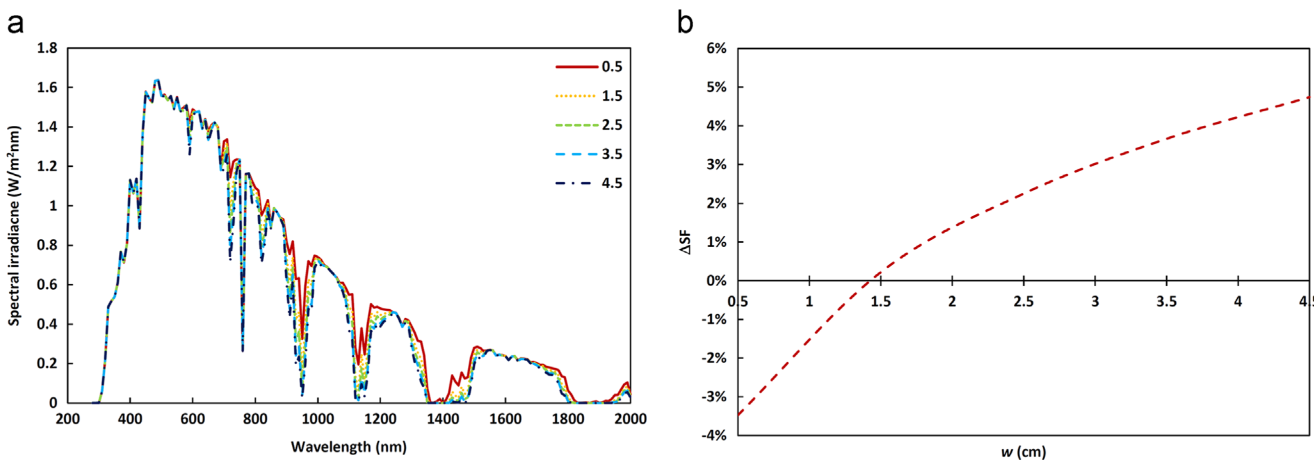

Fig. 5. Effect of precipitable water on the spectral irradiance (a) and on the perovskite solar cells performance (b). The other parameters are kept constant at the reference values defined by the AM1.5 G ASTMG-173-03 reference spectrum.

3.2. Annual impacts of the spectral variations

In order to analyse the spectral effects under different climate conditions, the spectral solar irradiance variations on an annual time scale at six different locations has been evaluated. Fig. 6 shows the annual spectral impact on perovskite solar cells at selected locations. The modules present losses with respect to the reference spectrum for all sites except for Alta Floresta. Alta Floresta shows annual spectral gains around 2% that can be explained due to the low and high annual average AM and *w* values respectively. Similar results are found at Solar Village and Granada with losses around -7%. Solar Village has a lower annual average AM value but $\tau_{0.55}$ is larger. Slightly higher annual losses are found at Frenchman Flat with a value around -8%. Frenchman Flat presents approximately the same annual average value of AM but slightly lower *w* values than Granada. Annual spectral losses around -10% are found at Edinburgh due to the high average AM value. At Beijing, although the annual average AM value is lower than Edinburgh, the extremely high $\tau_{0.55}$ values produce annual spectral losses around -13% in the perovskite solar cells.

These results suggest that this kind of solar cells are significantly more influenced by the spectral changes than other PV devices. In order to analyse this, Fig. 7 shows the difference among the annual spectral impact on perovskite and other thin film solar cells (CIGS and CdTe) at the six locations. As can be seen, perovskite solar cells present significant spectral losses with respect to CIGS and CdTe for all sites except for Alta Floresta. With

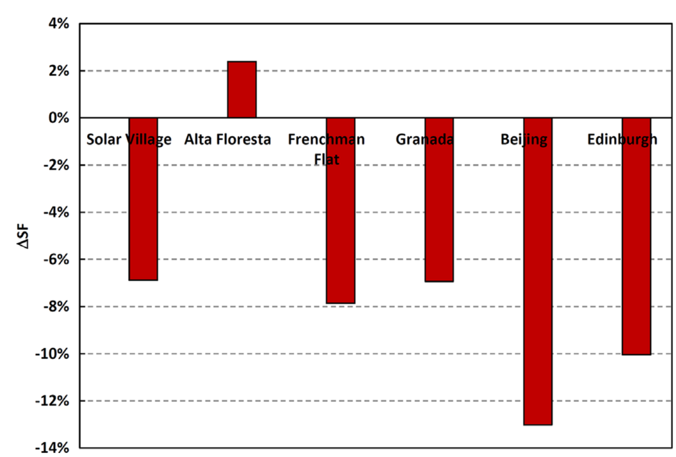

Fig. 6. Annual impacts of the spectral variations on the performance of perovskite solar cells at the six different locations.

respect to CIGS, perovskite solar cells show spectral losses ranging from 7% (Solar Village) to 11% (Beijing). With respect to CdTe, perovskite solar cells show spectral losses ranging from 2.5% (Solar Village) to 5% (Edinburgh). In Alta Floresta, perovskite solar cells show spectral gains with respect to CIGS of 3% and with respect to CdTe of 1%. This can be explained due to the low annual average AM value and the high *w* value that assist perovskite cells performance as was previously discussed. This is in agreement

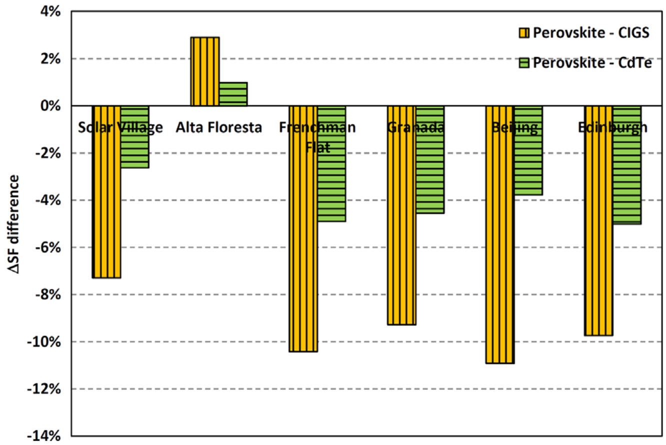

Fig. 7. Difference among the annual impacts of the spectral variations on the performance of perovskite solar cells and on the performance of CIG and CdTe solar cells at the six different locations.

with the results found in [19] where the influence of spectral variations on an annual time scale on the performance of different materials at different locations was studied. This demonstrates the high influence of spectral variations on the performance of perovskite solar cells. This can be explained due to the narrow absorption band of perovskite solar cells mainly located in the blue part of the spectrum compared with other solar cells as shown in Fig. 2b.

4. Conclusions

The critical challenge for global adoption and commercial marketing of perovskite-based solar cells is strongly based on the stable performance of the device at different atmospheric conditions. An analysis of the annual influence of spectral variations on the performance of perovskite solar cells under different climatic conditions has been conducted in Solar Village, Alta Floresta, Frenchman Flat, Granada, Beijing and Edinburgh. Also, an analysis of the individual impact of the atmospheric parameters on the performance of perovskite solar cell has been carried out in order to understand the influence of the spectral effects under real operating conditions. The following conclusions were drawn:

1. It can be concluded that the atmospheric parameters with the greatest influence on the performance is AM with spectral losses of up to -30% at AM$=$10. Also, $\tau_{0.55}$ and w have a small influence. However, $\tau_{0.55}$ yields spectra loses of around -6% at$=$1 and w can lead to spectral gains of around 5% at w=4.5 cm. This means that the spectral behaviour of a perovskite solar cell under real operating conditions is mainly given and can be explained with an acceptable margin of error taking into account only the influence of AM.
2. The spectral effects on an annual time scale influenced the performance of perovskite solar cells with spectral gains of around 2% (Alta Floresta) and spectral losses of around -13% (Beijing). Alta Floresta shows the spectral gains of around 2% due to the low and high annual average AM and w values respectively. Beijing shows extremely high spectral losses due to the medium and the extremely high average annual AM and $\tau_{0.55}$ values. The studies conducted on the performance of perovskite solar cells under real operating conditions were significantly influenced by the spectral distribution variations.
3. The perovskite solar cells absorb strongly in the visible region which leads to the 'blue-richness' of the spectrum and to higher spectral losses in the perovskite solar cells.
4. The spectral losses can be overcome by extending the absorption of the perovskite materials into the IR region.

The production of stable perovskite solar cells should consider the effect of spectral variations in different parts of the earth. The results obtained from this study are important for the perovskite solar cell community to address the issues related to the spectral losses. This leads to better understanding of the perovskite devices under real operating conditions which will impact industrial scale production processes.

Acknowledgements

This work is part of the project “Desenvolvemento de novos conceptos baseados en tecnoloxía de concentración fotovoltaica para a produción de enerxía eléctrica adaptados a distintas zonas climáticas”, through the program “formación posdoutoral do Plan galego de investigación, innovación e crecemento 2011-2015 (Plan I2C)” funded by the Xunta de Galicia and by the European Social Fund.

References

[1] Hari M. Upadhyaya, S. Senthilarasu, D. Min-Hung Hsu, Kishore Kumar, Recent progress and the status of dye-sensitised solar cell (DSSC) technology with state-of-the-art conversion efficiencies, Sol. Energ. Mater. Sol. Cell. 119 (2013) 291–295.

[2] Robert F. Service, Perovskite solar cells keep on surging, Science 344 (2014) 458.

[3] I.n. Chung, Byunghong Lee, Jiaqing He, Robert P.H. Chang, Mercouri G. Kanatzidis, All-solid-state dye-sensitized solar cells with high efficiency, Nature 485 (2012) 486–489.

[4] Jangwon Seo, Sangman Park, Young Chan Kim, Nam Joong Jeon, Jun Hong Noh, Sung Cheol Yoon, and Sang Il Seok, Benefits of very thin PCBM and LiF layers for solution-processed p–i–n perovskite solar cells, Energ. Environ. Sci. 7 (2014) 2642–2646.

[5] James M. Ball, Michael M. Lee, Andrew Hey, Henry J. Snaith, Low-temperature processed meso-superstructured to thin-film perovskite solar cells, Energ. Environ. Sci. 6 (2013) 1739–1743.

[6] Mingzhen Liu, Michael B. Johnston, Henry J. Snaith, Efficient planar heterojunction perovskite solar cells by vapour deposition, Nature 501 (2013) 395–398.

[7] Julian Burschka, Norman Pellet, Soo-Jin Moon, Robin Humphry-Baker, Peng Gao, Mohammad K. Nazeeruddin, Michael Grätzel, Sequential deposition as a route to high-performance perovskite-sensitized solar cells, Nature 499 (2013) 316–319.

[8] Jin Hyuck Heo, Sang Hyuk Im, Jun Hong Noh, Tarak N. Mandal, Choong-Sun Lim, Jeong Ah Chang, Yong Hui Lee, Hi-jung Kim, Arpita Sarkar, M.d.K. Nazeeruddin, Michael Grätzel, Sang Il Seok, Efficient inorganic–organic hybrid heterojunction solar cells containing perovskite compound and polymeric hole conductors, Nat. Photon. 7 (2013) 486–491.

[9] Hui-Seon Kim, Chang-Ryul Lee, Jeong-Hyeok Im, Ki-Beom Lee, Thomas Moehl, Arianna Marchioro, Soo-Jin Moon, Robin Humphry-Baker, Jun-Ho Yum, Jacques E. Moser, Michael Grätzel, Nam-Gyu Park, Lead iodide perovskite sensitized all-solid-state submicron thin film mesoscopic solar cell with efficiency exceeding 9%, Sci. Rep. 2 (2012) 591–598.

[10] Martin A. Green, Anita Ho-Baillie, J. Henry, Snaith, The emergence of perovskite solar cells, Nat. Photon. 8 (2014) 506–514.

[11] Feng Hao, Constantinos C. Stoumpos, Duyen Hanh Cao, Robert P.H. Chang, Mercouri G. Kanatzidis, Lead-free solid-state organic–inorganic halide perovskite solar cells, Nat. Photon. 8 (2014) 489–494.

[12] Nakita K. Noel, Samuel D. Stranks, Antonio Abate, Christian Wehrenfennig, Simone Guarnera, Amir Haghighirad, Aditya Sadhanala, Giles E Eperon, Sandeep K. Pathak, Michael B Johnston, Annamaria Petrozza, Laura Herz, Henry Snaith, Lead-free organic–inorganic tin halide perovskites for photovoltaic applications, Energ. Environ. Sci. 7 (2014) 3061–3068.

[13] P. Faine, Sarah R. Kurtz, C. Riordan, J.M. Olson, Sol. Cells, The influence of spectral solar irradiance variations on the performance of selected single-junction and multijunction solar cells 31 (1991) 259–278.

[14] T. Minemoto, M. Toda, S. Nagae, M. Gotoh, A. Nakajima, K. Yakamoto, et al., Effect of spectral irradiance distribution on the oudoor performance of amorphous Si//thin-film crystalline Si stacket photovoltaic devices, Sol. Energ. Mater. Sol. Cell. 91 (2-3) (2007) 120–122.

[15] N. Katsumata, Y. Nakada, T. Minemoto, H. Takamura, Estimation of irradiance and outdoor performance of phovoltaic modules by meteorological data, Sol. Energ. Mater. Sol. Cell 95 (1) (2011) 199–202.

[16] G. Nofuentes, B. Garcia-Dominguez, J.V. Muñoz, F. Chenlo, Analysis of the dependence of the spectral factor of some PV technologies on the solar spectrum distribution, Appl. Energ. 113 (2014) 302–309.
[17] T. Ishii, K. Otani, T. Takashima, Effects of solar spectrum and module temperature on outdoor performance of photovoltaic modules in round-robin measurements in Japan, Prog. Photovoltaics: Res. Appl. 19 (2) (2011) 141–148.
[18] T. Ishii, K. Otani, T. Takashima, Y. Xue, Solar spectral influence on the performance of photovoltaic (PV) modules under fine weather and cloudy weather conditions, Prog. Photovoltaics: Res. Appl. 21 (4) (2013) 481–489.
[19] M. Alonso-Abella, F. Chenlo, G. Nofuentes, M. Torres-Ramírez, Analisys of the spectral effects on the energy yield of different PV (photovoltaic) technologies: the case of four specific sites, Energy 67 (2014) 435–443.
[20] G. Peharz, G. Siefer, A.W. Bett, A simple method for quantifying spectral impacts on multi-junction solar cells, Sol. Energ. 83 (2009) 1588–1598.
[21] G. Peharz, J.P. Ferrer Rodriguez, G. Siefer, A.W. Bett, A method for using modules as temperatura sensors and its application to rating procedures, Sol. Energ. Mater. Sol. Cell 95 (2011) 2734–2744.
[22] B. Garcia-Dominguez, J. Aguilera, J. de la Casa, M. fuentes, Modelling the influence of atmospheric conditions on teh outdor real performance of a CPV (concentrated photovoltaics) module, Energy 70 (2014) 239–250.
[23] E.F. Fernandez, F. Almonacid, J.A. Ruiz-Arias, A. Soria-Moya, Analysis of the spectral variations on the perfromance of high concentrator photovoltaic modules operating under different real climate conditions, Sol. Energ. Mater. Sol. Cell. 127 (2014) 179–187.
[24] IEC-60904-7, Photovoltaic devices – Part 7: computation of the spectral mismatch correction for measurements of photovoltaic devices 2008.
[25] ASTM G 173-03e1 Standar tables for referecence solar spectral irradiance: direct normal and hemispherical on 37 tilted surface, *American society for testing and materials,* pp. 1-20, 2003.
[26] C. Hibberd, F. Plyta, M. Monokroussos, T. Betts, R. Gootschalg, Voltage-dependent quantum efficiency measurements of amorphous silicon multi-junction mini-modules, Sol. Energ. Mater. Sol. Cell. 95 (1) (2011) 123–126.
[27] C. Monokroussos, M. Bliss, Y. Qiu, C. Hibberd, T. Betts, A. Tirawi, Gottschalg, Effects of spectrum on the power rating of amorphous silicon photovoltaic devices, Prog. Photovoltaics: Res. Appl. 19 (6) (2011) 640–648.
[28] C. Gueymard, Parameterized transmittance model for direct beam and circumsolar spectral irradiance, Sol. Energ. 71 (5) (2001) 325–346.
[29] C. Gueymard, SMARTS. A simple model of the atmospheric radiative transfer of sunshine: algorithms and performance assesstment. Profesi, Profesional paper FSEC-PF-270-95. Florida solar energy center, Cocoa, FL1995.
[30] C. Gueymard, Simple model of the atmospheric radiative transfer of sunshine (SMARTS) version 2.9.5, 2009.
[31] F. Kasten, A.T. Young, Revised optical air mass tables and approximation formula, Appl. Opt. 28 (22) (1989) 4735–4738.
[32] Aerosol Robotic Network. 〈http://aeronet.gsfc.nasa.gov/〉, 2014.
[33] A. Ångström, Techniques of determinig the turbidity of the atmosphere I, Tellus 13 (1961) 214–223.
[34] M. Iqbal, An Introduction to Solar Radiation, Academic Press, Canada, 1983.