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1 A Theoretical Analysis of the Impact of Atmospheric Parameters on the 2 Spectral, Electrical and Thermal Performance of a Concentrating III-V 3 Triple-Junction Solar Cell

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10

11 **Abstract** — The spectral sensitivity of a concentrating triple-junction (3J) solar cell has been
12 investigated. The atmospheric parameters such as the air mass (AM), aerosol optical depth
13 (AOD) and precipitable water (PW) change the distribution of the solar spectrum in a way that
14 the spectral, electrical and thermal performance of a 3J solar cell is affected. In this paper, the
15 influence of the spectral changes on the performance of each subcell and whole cell has been
16 analysed. It has been shown that increasing the AM and AOD have a negative impact on the
17 spectral and electrical performance of 3J solar cells while increasing the PW has a positive
18 effect, although, to a lesser degree. A three-dimensional finite element analysis model is used
19 to quantify the effect of each atmospheric parameter on the thermal performance for a range of
20 heat transfer coefficients from the back-plate to the ambient air and also ambient temperature.
21 It is shown that a heat transfer coefficient greater than 1300 W/(m²K) is required to keep the
22 solar cell under 100°C at all times. In order to get a more realistic assessment and also to
23 investigate the effect of heat transfer coefficient on the annual energy yield, the methodology
24 is applied for four US locations using data from a typical meteorological year (TMY3).

25 **Keywords** — concentrating photovoltaic (CPV), III-V multijunction solar cells, integrated
26 modelling, spectral dependence, cooling requirements, electrical performance

27 **1. Introduction**

28 High Concentrating Photovoltaic (HCPV) systems use refractive or reflective optics to
29 concentrate sunlight onto a smaller area made of high efficiency multijunction (MJ) solar cells.
30 Such solar cells are made of III-V compound semiconductors and are used in both space and
31 terrestrial applications [1]. Currently triple-junction (3J) solar cells made of GaInP/GaInAs/Ge
32 are available in the market with an efficiency of up to 42% [2]. The subcells which consist a
33 3J solar cell are connected in series in a way to absorb a larger proportion of the spectral
34 irradiance and thus, to achieve higher conversion efficiencies compared to the single junction
35 cells [3]. However, the in-series connection and the different energy band-gap of each subcell
36 cause a high spectral sensitivity. It is therefore necessary to model the effect of changing
37 spectrum on the spectral, electrical and thermal performance of such devices. The HCPV
38 performance is predominantly affected by the incident direct normal irradiance (DNI) [4]
39 which in turn, is mainly determined by cloud cover [5], but also by changes in spectrum by
40 variations of air mass (AM), aerosol optical depth (AOD) and precipitable water (PW).

41 HCPV modules can be either rated indoors and outdoors [6] under Concentrator Standard Test
42 Conditions (CSTC, i.e. AM1.5D, DNI = 1000 W/m² and cell temperature $T_{\text{cell}} = 25^{\circ}\text{C}$) or
43 outdoors under Concentrator Standard Operating Conditions (CSOC, i.e. AM1.5D,
44 DNI = 900 W/m², ambient temperature $T_{\text{amb}} = 20^{\circ}\text{C}$ and wind speed $W_S = 2$ m/s). The spectral
45 conditions during the CSOC or outdoor I-V measurements for translation to CSTC [6] vary
46 significantly compared to the standard ratings depending on the location and time of year
47 because of the different atmospheric characteristics [7]. According to Muller et al. [6], the
48 spectral filtering criteria have not yet been agreed within the International Electrotechnical

49 Commission (IEC). It is important therefore, to develop models or methods to identify the
50 effects of each atmospheric parameter on the spectral and hence, the electrical and thermal
51 performance of HCPV systems. Integrated modelling is necessary to enable the quantification
52 of the spectral mismatch that will decrease the solar cell's electrical conversion efficiency
53 resulting in an increase in heat, hence higher operating temperatures which will further reduce
54 the electrical efficiency [8].

55 The majority of the commercial HCPV systems use refractive optics and passive cooling (e.g.
56 Suncore [9] and Semprius [10]). The passive heat exchangers can be different in terms of their
57 area and geometry depending on the application [11]. In order to achieve a T_{cell} below safe
58 operating limits and to avoid long-term reliability issues, the incident DNI needs to be
59 quantified because it is the dominant factor which contributes to the heat power production.
60 Due to the MJ solar cell's spectral sensitivity, analytical modelling is required to estimate the
61 cooling requirements taking into consideration the ambient and atmospheric conditions.
62 Moreover, although the temperature dependence of MJ solar cells is lower than silicon cells
63 [12, 13], it is crucial to design a robust cooling device to avoid elevated temperatures and
64 therefore possible degradation issues or even the cause of fire [14, 15]. Oversizing the heat
65 exchanger however will result in increasing the system's cost needlessly. Hence, a trade-off
66 between reliability and cost must be achieved.

67 This work focuses on the accurate quantification of heat and therefore the cooling requirements
68 using the heat transfer coefficient, h_{conv} (or the inverse thermal resistance R_{th}) from the back-
69 plate of the concentrator cell assembly (CCA) to the ambient air as a criterion. It extends on a
70 study introduced by Theristis and O'Donovan [16] where the impact of solar geometry (air
71 mass) on the electrical and thermal performance of 3J solar cells was investigated. The same
72 model is used here to assess the effect of AM, AOD and PW on the spectral, electrical and
73 thermal behaviour of 3J solar cells. The modelling procedure and methodology are presented

74 in section 2 and the results are analysed in section 3. In subsections 2.1 and 3.1, the effect of
75 AM, AOD (at 500 nm) and PW on the spectral and electrical performance of a 3J solar cell is
76 investigated at a subcell level but also as a whole device. In subsections 2.2 and 3.2, typical
77 meteorological year (TMY3) [17] data of four US locations are used in order to investigate the
78 spectral and electrical performance and also the effect of h_{conv} on the annual energy yield.
79 TMY3 data are useful for the assessment of the electrical performance of CPV systems and for
80 this work in particular, it can offer an estimate of the operating cell temperature and annual
81 energy yield. However, since these data are typical, they do not offer a real representation of
82 the system's operation under extreme conditions (i.e. worst-case scenarios) [17]. Therefore, in
83 order to be able to quantify the cooling requirements under extreme conditions, a more suitable
84 analysis is followed, in subsections 2.3 and 3.3, where the h_{conv} is quantified based on extreme
85 heat generation within the solar cell (i.e. clear-sky, low AM, AOD, PW and high T_{amb}) and is
86 compared with the h_{conv} based on the reference conditions of ASTM G173-03 [18] (AM1.5D,
87 AOD = 0.084, PW = 1.42 cm). This study models the effects on the single cell level so the
88 influence of other losses which can occur within a module can be avoided. Preliminary results
89 have been published by Theristis et al. [19] however, an extended analysis is presented here
90 incorporating individual subcell's performance along with additional case studies that enable
91 the evaluation of the impact of each atmospheric parameter.

92 **2. Modelling procedure**

93 Three models are integrated: the spectral irradiance is generated by the NREL Simple Model
94 of the Atmospheric Radiative Transfer of Sunshine, version 2 (SMARTS2) [20], an Electrical
95 Model (EM) uses a single diode model to simulate the electrical characteristics and heat power
96 of a 3J solar cell at Maximum Power Point (MPP) and a 3D Finite Element analysis Thermal
97 Model (FETM) uses the heat power as an input from the electrical model in order to predict

98 the temperature and the cooling requirements. The equations used for the EM and FETM
 99 models are presented by Theristis and O'Donovan [16, 21].

100 The spectral performance is evaluated using the spectral factor (SF) and spectral matching (or
 101 mismatch) ratio (SMR) as criteria; both of these spectral indices have been widely used in the
 102 PV community [22-25]. The SF of each subcell is given by [26]:

$$103 \quad SF_i = \frac{\int DNI(\lambda) \cdot \eta_{opt}(\lambda) \cdot SR_i(\lambda) d\lambda}{\int DNI(\lambda) d\lambda} \cdot \frac{\int DNI_{ref}(\lambda) d\lambda}{\int DNI_{ref}(\lambda) \cdot \eta_{opt}(\lambda) \cdot SR_i(\lambda) d\lambda} = \frac{J_{sc}^i}{DNI} \cdot \frac{DNI_{ref}}{J_{sc,ref}^i} \quad (1)$$

104 while the SF of the whole device, due to the in-series connection, is given by:

$$105 \quad SF = \frac{\min\left(\int DNI(\lambda) \cdot \eta_{opt}(\lambda) \cdot SR_i(\lambda) d\lambda\right)}{\int DNI(\lambda) d\lambda} \cdot \frac{\int DNI_{ref}(\lambda) d\lambda}{\min\left(\int DNI_{ref}(\lambda) \cdot \eta_{opt}(\lambda) \cdot SR_i(\lambda) d\lambda\right)} \Rightarrow$$

$$SF = \frac{\min(J_{sc}^i)}{DNI} \cdot \frac{DNI_{ref}}{\min(J_{sc,ref}^i)} \quad (2)$$

106 where $DNI(\lambda)$ is the incident spectral direct normal irradiance, $\eta_{opt}(\lambda)$ is the spectral optical
 107 efficiency, $SR(\lambda)$ is the spectral response and J_{sc} is the short-circuit current density. The
 108 subscript, “ref”, denotes the reference conditions and “i” the corresponding subcell (1 = top,
 109 2 = middle, 3 = bottom). SF values above 1 indicate spectral gains, below 1 indicate spectral
 110 losses and equal to 1 the same spectral conditions as the reference. The output current of the 3J
 111 solar cell is restricted to the minimum current of the three subcells because of the in-series
 112 connection.

113 On the other hand, the SMR of top to middle subcell is described as [27-29]:

$$\begin{aligned}
114 \quad SMR &= \frac{\int DNI(\lambda) \cdot \eta_{opt}(\lambda) \cdot SR_{top}(\lambda) d\lambda}{\int DNI_{ref}(\lambda) \cdot \eta_{opt}(\lambda) \cdot SR_{top}(\lambda) d\lambda} = \frac{\frac{J_{sc}^{top}}{J_{sc,ref}^{top}}}{\frac{J_{sc}^{mid}}{J_{sc,ref}^{mid}}} \\
115 \quad & \quad \quad \quad (3)
\end{aligned}$$

116 where $SMR > 1$ when the incident spectrum is blue rich and $SMR < 1$ when the incident
117 spectrum is red rich. The $SMR = 1$ when the incident spectrum matches the reference
118 conditions.

119 **2.1. Impact of atmospheric parameters on spectral and electrical performance**

120 Firstly, the impact of AM, AOD and PW on the spectral and electrical performance of a triple-
121 junction solar cell has been investigated for a given cell temperature. In order to achieve this,
122 an algorithm was developed to vary each parameter while keeping all others constant at the
123 reference conditions of ASTM G173-03 [18].

124 **2.2. Case studies using TMY3 data and regression analysis**

125 Case studies have been performed to determine the spectral and electrical performance and also
126 to quantify the optimum h_{conv} at four USA locations with relatively high annual direct normal
127 irradiation; Albuquerque (New Mexico), El Paso (Texas), Las Vegas (Nevada) and Tucson
128 (Arizona). A method has been developed to generate bulk spectra [19, 30] using atmospheric
129 data from a TMY3. It is worth mentioning that the use of high-quality observed data of the
130 main atmospheric parameters in conjunction with the SMARTS2 model has been widely used
131 by the scientific community and proven to be valid for the evaluation of HCPV and PV
132 performance [31-34]. To ensure clear-sky conditions, the spectral global normal irradiance
133 $GNI(\lambda)$ generated by SMARTS2 was integrated over the whole range of wavelengths and a
134 filter has been applied on TMY3 for $DNI/GNI > 0.8$. This filter is also included in the draft of

135 IEC 62670-3 [6]. Furthermore, to avoid high computational time, regression analysis has been
136 used to predict the T_{cell} as a function of P_{heat} , T_{amb} and h_{conv} .

137 **2.3. Quantification of cooling requirements**

138 In order to quantify the CCA's cooling requirements (or h_{conv}) under extreme conditions, the
139 EM and FETM have been simulated iteratively for given solar spectra generated in SMARTS2.
140 HCPV cooling requirements should be designed for $AM < 1.5$ because of the current mismatch
141 between the top and middle subcells, which subsequently contributes to greater heat, and also
142 because of the higher irradiance intensity [16]. Assuming an initial temperature $T_{cell(s)} = 25^{\circ}C$
143 (where “s” is the number of state), the EM ran the single diode model which calculated the
144 electrical characteristics and hence, the heat generated within the solar cell by [35]:

$$145 \quad P_{heat} = (CR \cdot DNI \cdot A \cdot \eta_{opt}) \cdot (1 - \eta_{cell}) \quad (4)$$

146 where CR is the concentration ratio, A is the area of the solar cell, η_{opt} is the optical efficiency
147 and η_{cell} is the electrical conversion efficiency. The heat power was then imported to the FETM
148 as a boundary condition on the solar cell's surface to model it as a heat source and hence, to
149 predict the temperature distribution. The predicted volumetric solar cell temperature was then
150 imported back to the EM and the integrated models ran iteratively until a steady state was
151 reached between them i.e. when $|T_{cell(s+1)} - T_{cell(s)}| \leq 0.002^{\circ}C$.

152 **3. Results and analysis**

153 The CCA used for this study is the C1MJ from Spectrolab [36] and the External Quantum
154 Efficiency (EQE) data at $25^{\circ}C$, $45^{\circ}C$, $65^{\circ}C$ and $75^{\circ}C$ were taken from Kinsey and Edmondson
155 [37]. The results below correspond to a $CR = 500\times$ and an $\eta_{opt} = 80\%$. All the inputs and
156 boundary conditions to the EM and FETM are similar to those presented by Theristis and
157 O'Donovan [16] unless otherwise stated.

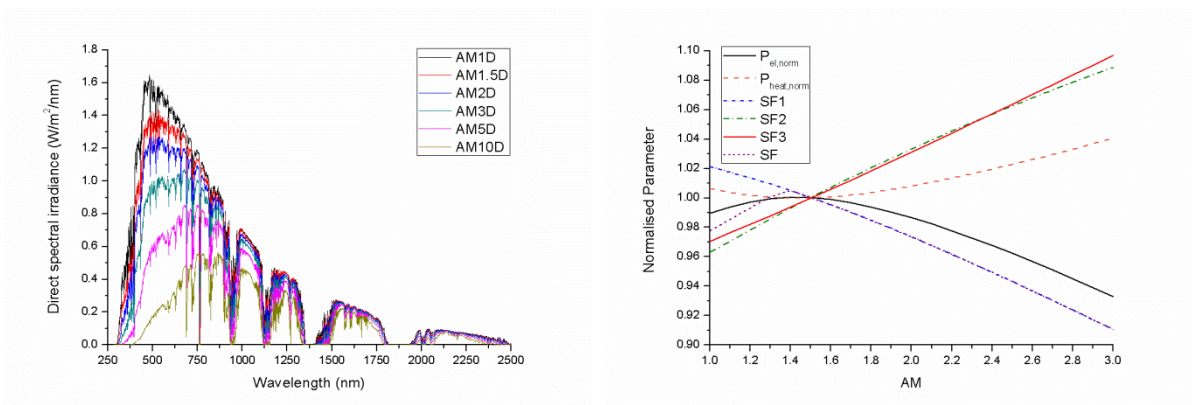
158 **3.1. Impact of individual atmospheric parameters on spectral and electrical**
159 **performance**

160 This section assesses the impact of individual atmospheric parameters (AM, AOD, PW) on the
161 spectral and electrical performance of the Spectrolab C1MJ CCA at 25°C. Realistic ranges
162 were selected ($1 \leq AM \leq 10$, $0 \leq AOD \leq 1$, $0 \text{ cm} \leq PW \leq 5 \text{ cm}$) for each atmospheric
163 parameter. Although a similar approach has been reported by Fernández et al. [26] (using only
164 the whole cell's SF as a criterion), it is also presented here in order to get a better understanding
165 of which (and to what extent) parameters contribute to the heat generated on the CCA and
166 therefore the cooling requirements and electrical energy performance of such devices for a
167 range of conditions. For this reason, it is necessary to model the SF (whole cell and individual
168 subcell), normalised electrical power ($P_{el,norm}$) and normalised heat power ($P_{heat,norm}$) as a
169 function of each atmospheric parameter by varying each one (from low to high values) at a
170 time while keeping the rest at the reference conditions of ASTM G173-03 as previously
171 considered [26, 38, 39].

172 **3.1.1. Impact of air mass**

173 Fig. 1 (left) shows the impact of AM on the spectral DNI distribution. The significant drop of
174 the spectral intensity is obvious with increasing AM. It can also be noticed that there is a shift
175 toward the longer wavelengths. The impact of changing spectrum due to variation of AM on
176 the electrical performance is also shown in Fig. 1 (right); the SF1 of the top subcell shows
177 spectral gains up to 2.1% for $AM < 1.5$ while the middle (SF2) and bottom (SF3) subcells show
178 the opposite behaviour (-3.7% (middle subcell), -3% (bottom subcell) losses for $AM < 1.5$ and
179 gains for $AM > 1.5$). The whole solar cell's spectral factor (SF) follows the top subcell for
180 $AM > 1.5$ while is close to SF2 for $AM < 1.5$. The reason for this is that at CSTC conditions
181 the middle subcell limits the current by a 1.6% difference from the top's current. Furthermore,

182 Fig. 1 (right) shows the impact of AM on the $P_{el, norm}$ and $P_{heat, norm}$; the $P_{el, norm}$ losses are $\leq 1\%$
 183 up to AM1.9D while for $AM > 2$ the losses increase significantly (6.7% at AM3D, 20.1% at
 184 AM5D and 50.3% at AM10D). The $P_{heat, norm}$ increases with the excess current mismatch (4.1%
 185 at AM3D, 12.2% at AM5D and 30.4% at AM10D) and therefore it is always greater than 0%
 186 except when the top and middle subcells are current matched; i.e. when it operates at the
 187 reference conditions. Only the AM values up to $AM = 3$ have been illustrated in Fig. 1 (right)
 188 for clarity purposes and also due to the significantly higher solar intensity, which in turn affects
 189 the thermal performance and cooling requirements of HCPV systems. Moreover, low AM
 190 values predominantly occur during the summer months at locations with a high annual direct
 191 solar irradiation.

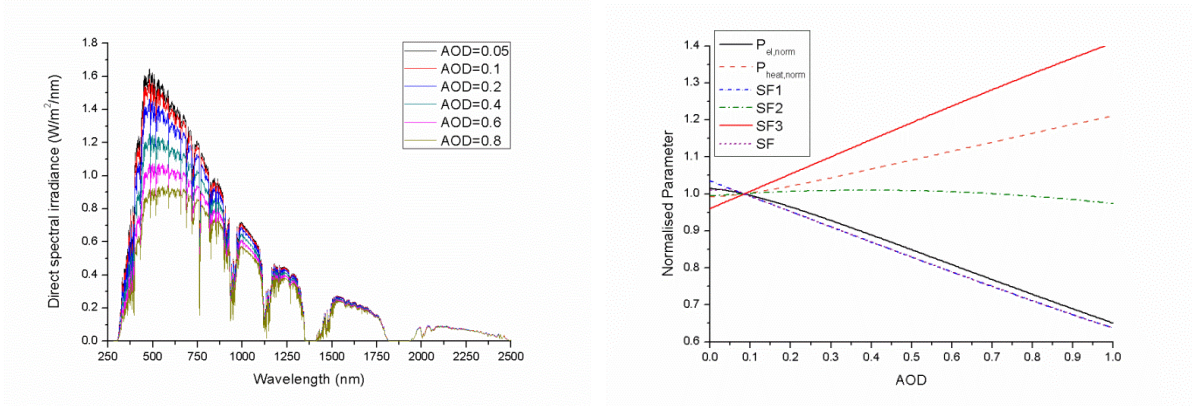


192
 193 Fig. 1. Effect of AM on the spectral irradiance (left figure) with the rest of the parameters kept
 194 constant according to the ASTM G173-03 [18]. The figure on the right shows the impact of AM
 195 on the spectral and electrical performance of C1MJ CCA.

196 **3.1.2. Impact of aerosol optical depth**

197 Increasing AOD reduces the spectral irradiance in the short wavelengths region (visible light)
 198 and to a much lesser degree in the near-infrared light (Fig. 2 left); this will have a significant
 199 influence on the current generation of the top subcell. From Fig. 2 (right) it can be seen that the
 200 middle subcell is almost unaffected by AOD (maximum losses of 1% on SF2) while the top

201 subcell shows losses of up to 36.3% at AOD = 1. However, for AOD lower than the reference
 202 value ($AOD_{ref} = 0.084$) the SF1 shows spectral gains up to 3.5%. SF3 has the opposite trend
 203 from SF1; spectral losses are down by 3.95% for AOD below reference conditions and gains
 204 up by 40.86% for $AOD > 0.084$. The SF for the whole solar cell shows the same behaviour as
 205 in the variable AM following the SF1 for values higher than the reference, since the limiting
 206 subcell is the top one. The effect of the current mismatch which was just described is evident
 207 when the $P_{heat, norm}$ and $P_{el, norm}$ are assessed; when the current mismatch between the subcells
 208 increases, the $P_{heat, norm}$ increases by up to 21.1% while the $P_{el, norm}$ is reduced by 34.9% when
 209 AOD is equal to 1.



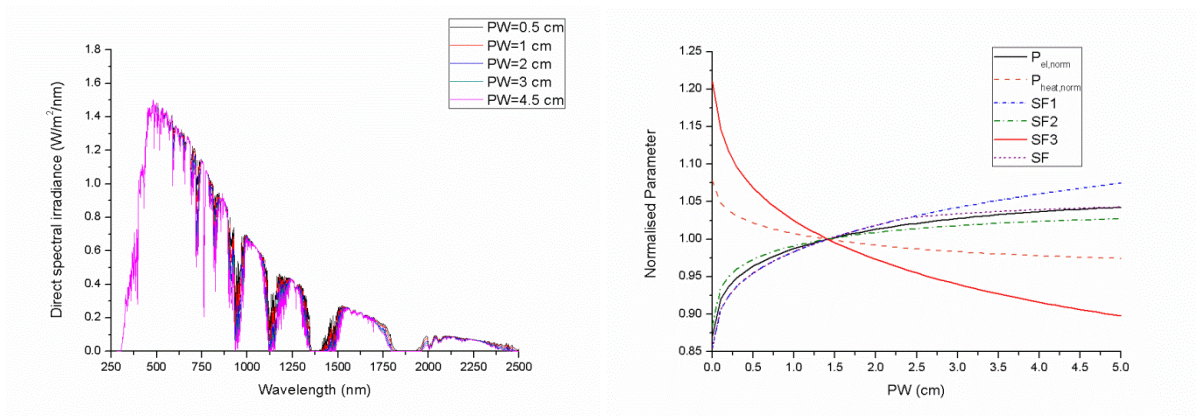
210
 211 Fig. 2. Effect of AOD on the spectral irradiance (left). The rest of the parameters are kept
 212 constant according to the ASTM G173-03. On the right figure, the impact of variable AOD on
 213 the spectral and electrical characteristics is shown.

214 3.1.3. Impact of precipitable water

215 In a similar manner to section 3.1.1. and 3.1.2., Fig. 3 (left) shows the impact of PW on the
 216 spectral DNI; in contrast to AOD, increasing PW has a minimal effect in the short wavelengths,
 217 however the longer wavelengths show a reduction. Hence, the bottom subcell, that corresponds
 218 to the infrared region will have higher spectral losses with increasing PW. The middle subcell
 219 which converts the near-infrared region will also be affected but to a lesser extent. As can be

220 seen from Fig. 3 (right), for PW values lower than 1.42 cm (reference conditions), SF1, SF2
 221 and hence, SF show losses due to the current mismatch between the top (-14.6%) and middle
 222 (-11.5%) subcells, however the SF3 shows gains of up to 21.1% and therefore increases in
 223 $P_{\text{heat, norm}}$ occur up to 7.8% with a significant drop (12.9%) in $P_{\text{el, norm}}$. For PW values higher than
 224 1.42 cm, the drop in the infrared region causes significant losses (down by 10.2%) on the
 225 bottom subcell which corresponds to the infrared proportion of the solar spectrum, hence a
 226 higher performance is noticed with $P_{\text{el, norm}}$ and SF gains up to 4.3%. This is due to the
 227 significant reduction of the excess current of the germanium subcell, therefore lower $P_{\text{heat, norm}}$
 228 by 2.6% at PW = 5 cm and a higher electrical conversion efficiency.

229 Overall, as discussed also by Fernández et al. [26], the dominant atmospheric parameters that
 230 affect the performance of 3J solar cells are the AM and AOD with losses on the $P_{\text{el, norm}}$ down
 231 by 50.3% at AM10D and 34.9% at AOD = 1.



233 Fig. 3. Effect of PW on the spectral irradiance (left). The rest of the parameters are kept
 234 constant according to the ASTM G173-03. On the right figure, the impact of variable PW on
 235 the spectral and electrical characteristics is shown.

236

237 3.2. Case Studies

238 Locations offering relatively high annual direct solar irradiation and hence applicable for CPV
239 applications were selected to investigate the effect of the heat transfer coefficient on
240 temperature and therefore, the electrical power production. Class I TMY3 hourly data have
241 been used for four locations in the USA (Albuquerque, El Paso, Las Vegas and Tucson). The
242 location characteristics are shown in Table I.

243 Table I: Sites used for the simulation along with the coordinates and elevation

Location	Latitude	Longitude	Elevation (m)
Albuquerque	35.04°N	106.62°W	1619
El Paso	31.77°N	106.50°W	1186
Las Vegas	36.08°N	115.15°W	648
Tucson	32.13°N	110.95°W	777

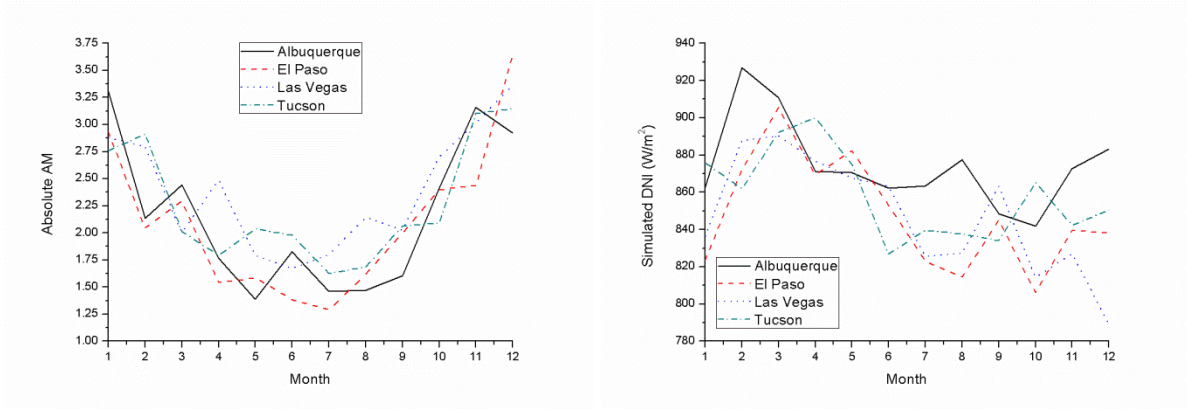
244

245 The filtering criterion resulted in 3089 hourly spectra for Albuquerque, 3180 for El Paso, 3320
246 for Las Vegas and 3300 for Tucson. Monthly average values of the filtered data are illustrated
247 below in Fig. 4 for all the locations.

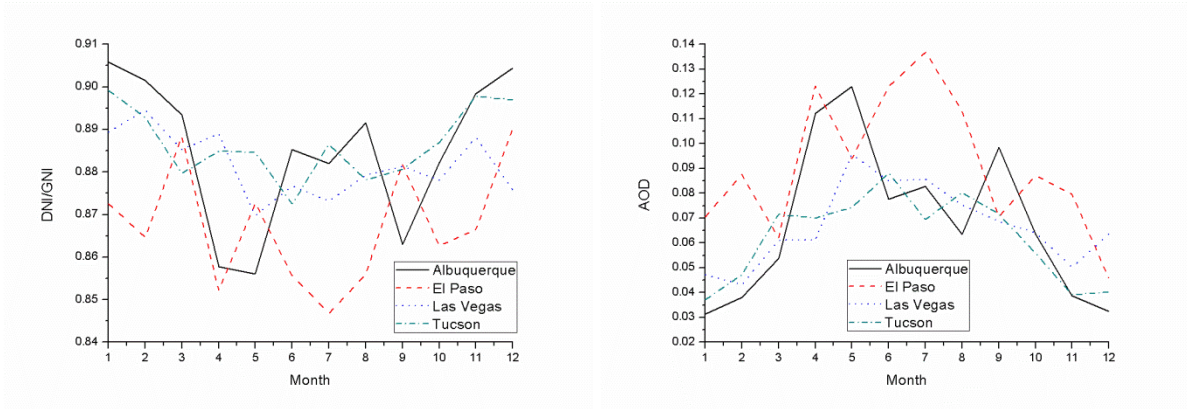
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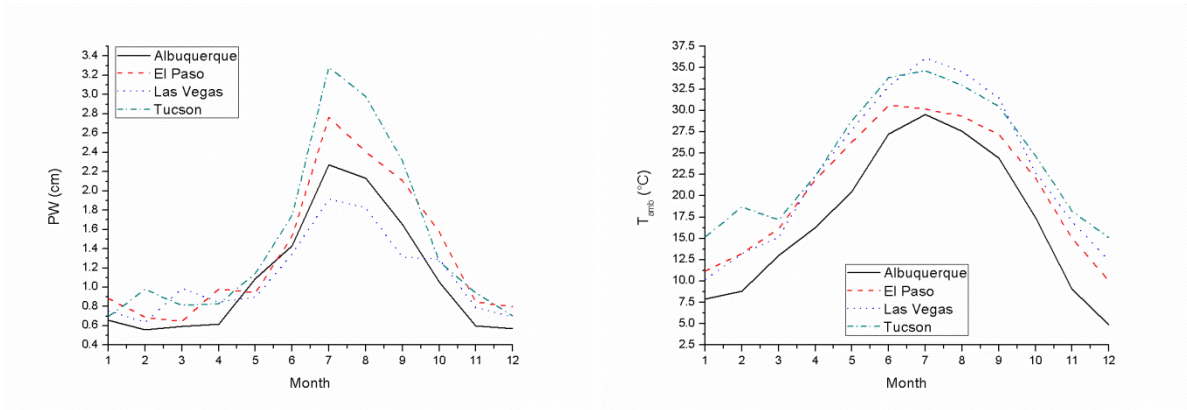
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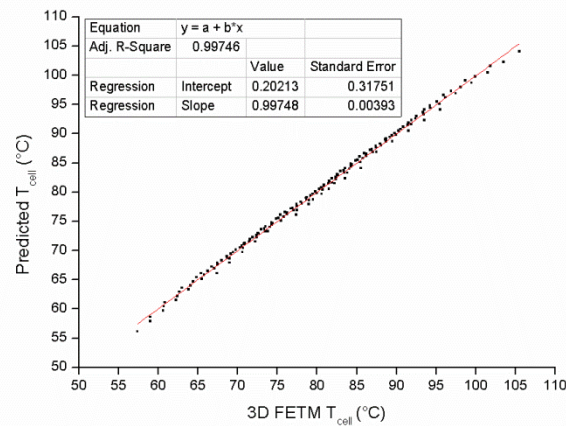
253 Fig. 4. Monthly average values of filtered data for all locations; a) absolute air mass,
254 b) simulated direct normal irradiance (DNI), c) clearness ratio (DNI/GNI), d) aerosol optical
255 depth (AOD), e) precipitable water (PW) and f) ambient temperature (T_{amb}).

256 Due to the high volume of data ($>11.5 \times 10^6$ lines of generated spectra in addition to the TMY3
257 data), regression analysis has been performed for the calculation of cell temperature. Initially

258 a parametric study was simulated in the FETM for $20 \text{ W} \leq P_{\text{heat}} \leq 30 \text{ W}$, $1200 \text{ W}/(\text{m}^2\text{K}) \leq$
 259 $h_{\text{conv}} \leq 1600 \text{ W}/(\text{m}^2\text{K})$, $15^\circ\text{C} \leq T_{\text{amb}} \leq 45^\circ\text{C}$ and the cell temperature could then be calculated
 260 using the following equation:

$$261 \quad T_{\text{cell}} = \alpha + \beta \cdot P_{\text{heat}} + \gamma \cdot h_{\text{conv}} + \delta \cdot T_{\text{amb}} \quad (5)$$

262 where the intercept and linear coefficients are $\alpha = 35.12^\circ\text{C}$, $\beta = 1.80^\circ\text{C}/\text{W}$, $\gamma = -0.02^\circ\text{C}/(\text{Wm}^{-2}\text{K}^{-1})$, $\delta = 1.00$. The R^2 between modelled (in FETM) and predicted (regression) data was
 263 0.9975 (Fig. 5). It is important to mention that the effect of W_s was not taken into consideration
 264 in equation (5) however, experimental results have proven that the effect of W_s on the
 265 estimation of T_{cell} is low, and therefore it can be neglected in a first approximation [40].
 266



267
 268 Fig. 5. Linear regression analysis of T_{cell} between simulated (in 3D FETM) and predicted data
 269 for the C1MJ solar cell.

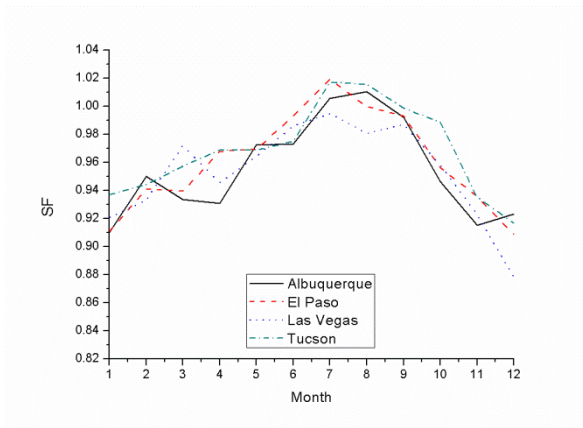
270 As mentioned in Section 2, the normalised short-circuit current or SF is a useful index to
 271 evaluate the spectral performance of a solar cell; Fig. 6a illustrates the SF for all locations. It
 272 can be seen that spectral gains occur in July and August for Albuquerque (0.6% and 1%
 273 respectively) and Tucson (1.7% and 1.6% respectively) while El Paso shows spectral gains
 274 only occur in July (1.9%). Las Vegas has spectral losses during all months of the year with the

275 lowest during December (a decrease of 12.2%). The SMR follows a similar trend to SF in Fig.
276 6b and this is because both parameters are a function of the short-circuit current; the top subcell
277 seems to be the current limiter for the whole year except when SF is above 1. This indicates
278 that spectral gains occur when the incident spectrum is blue rich.

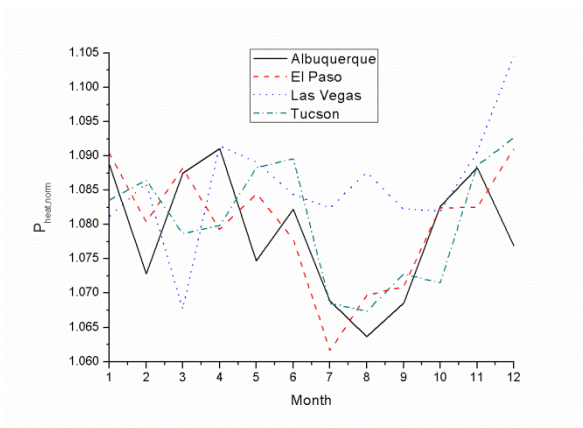
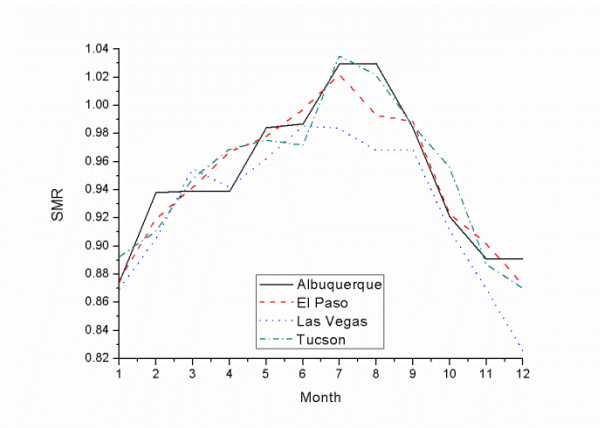
279 In Fig. 6c and 6d the normalised heat and electrical powers are shown respectively where, as
280 expected, they exhibit the opposite behaviour. All locations show $P_{el,norm}$ losses all year round
281 (as compared to the reference conditions) and therefore the $P_{heat,norm}$ shows gains; this is another
282 indication that AM1.5D is not an appropriate reference for the cooling requirements estimation
283 [16].

284 Finally, as expected, the calculated T_{cell} (Fig. 6e) peaks during the summer months for all
285 locations; this is mainly due to the higher ambient temperatures. The monthly averages show
286 temperatures of up to 88°C which are relatively high, if long term degradation issues are
287 considered [41]. The heat generated on the solar cell is mainly influenced by the system's
288 characteristics (i.e. CR, A, η_{opt}), the electrical conversion efficiency and of course the incident
289 DNI which in turn, is affected by the changes in the solar spectrum (i.e. AM, AOD, PW, etc)
290 (equation (4)). The P_{heat} , h_{conv} and T_{amb} are the parameters affecting the T_{cell} (equation (5)).
291 Since the cooling mechanism for all locations is assumed to be the same, the cell temperature
292 difference between locations is dependent on P_{heat} and T_{amb} . Tucson exhibits the highest T_{cell}
293 during the year except the months from June to September where the T_{cell} is higher in Las
294 Vegas. When Las Vegas and Tucson are compared, it can be noticed that the T_{cell} follows the
295 trend of T_{amb} except in June where although the T_{amb} is higher in Tucson, the T_{cell} is higher in
296 Las Vegas by 1°C. This can be attributed to the higher DNI in Las Vegas (by 4.2%) in
297 combination with the higher PW (by 29.9%) in Tucson, which limits the excess current on the
298 bottom subcell and therefore contributes to the heat reduction. In July, August and September
299 the T_{amb} is higher in Las Vegas (by 1.5°C, 1.6°C and 1°C respectively) and also the PW values

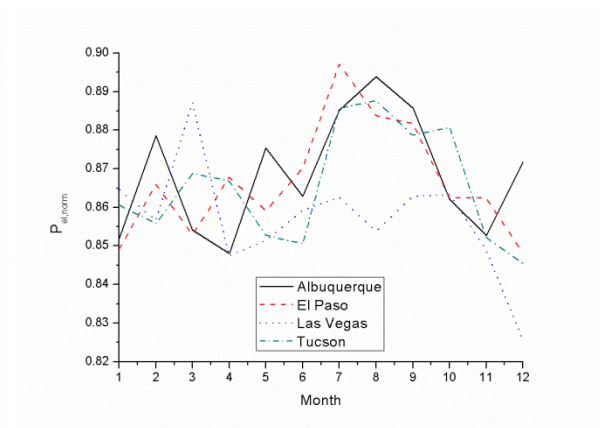
300 are much higher in Tucson (by 71.6% in July, 63.3% in August and 76.8% in September) and
 301 therefore the T_{cell} is higher in Las Vegas by 1.3°C, 1.8°C and 3°C. Although Albuquerque
 302 exhibits higher DNI than El Paso during the year (except in May), it shows the lowest T_{cell}
 303 (except in July and August) due to the lower T_{amb} . In July, the monthly average T_{cell} in
 304 Albuquerque is 1.6°C higher than El Paso due to lower T_{amb} difference (0.64°C) between them
 305 and also due to the higher PW (by 0.5 cm or 17.8%) and AOD (by 39.6%) in El Paso. In August
 306 the SMR value for Albuquerque is 1.03 whereas for El Paso is 0.99; this indicates a clearer
 307 atmosphere (lower AOD values by 43.9%) in Albuquerque and therefore higher DNI and hence
 308 higher T_{cell} even if T_{amb} is lower by 1.78°C as compared to El Paso.

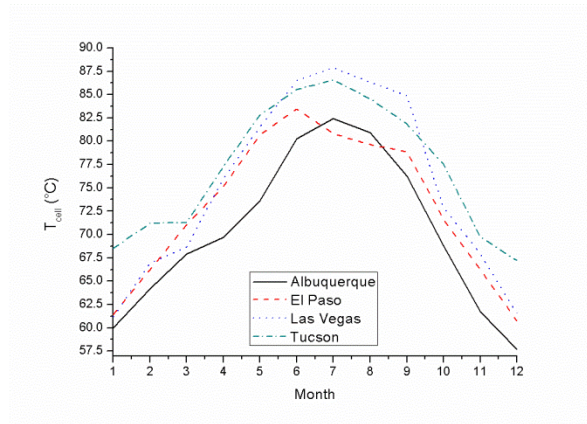


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311

312 Fig. 6. Monthly average outputs of numerical model: a) spectral factor, b) spectral mismatch
 313 ratio, c) normalised heat power, d) normalised electrical power and e) solar cell temperature.

314 Annual average inputs and outputs for all locations can be seen in Table II and III respectively.

315 Due to the relatively similar atmospheric inputs, all locations exhibit similar annual average

316 outputs; the SF ranges from 0.95 to 0.97, the $P_{el,norm}$ from 0.86 to 0.87 and the $P_{heat,norm}$ from

317 1.08 to 1.09. The T_{cell} however, ranges from 70.3°C to 77°C and follows the trend of the T_{amb}

318 inputs. Las Vegas has the highest spectral and electrical power losses of 5% and 14%

319 respectively and the highest gains in $P_{heat,norm}$ of 9%, it exhibits the second highest annual

320 average T_{cell} . The highest annual average T_{cell} of Tucson can be attributed to the higher annual

321 average T_{amb} which is 1.37°C (5.6%) higher than the one in Las Vegas. Moreover, although the

322 higher annual average PW in Tucson shows a relatively better SF (and hence lower heat) it is

323 shown that the dominant parameter for this temperature difference between locations with

324 similar location characteristics is influenced by the T_{amb} . This can also be noticed when

325 Albuquerque and El Paso are compared; although the SF, $P_{el,norm}$ and $P_{heat,norm}$ values are the

326 same, the annual average T_{cell} is 2.7°C higher in El Paso because of the higher T_{amb} .

327

328

Table II: Annual average inputs for all locations.

Location	DNI (W/m ²)	T _{amb} (°C)	AM _{abs}	AOD	PW (cm)
Albuquerque	874.25	17.21	2.16	0.07	1.10
El Paso	847.71	21.08	2.10	0.09	1.35
Las Vegas	847.37	22.97	2.39	0.07	1.11
Tucson	858.42	24.34	2.27	0.06	1.47

329

330

TABLE III: Annual average outputs for all locations.

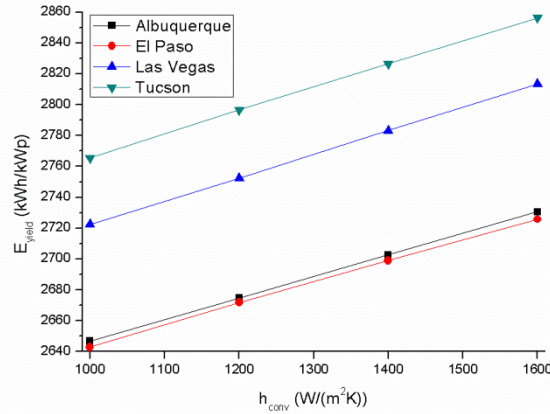
Location	SF	P _{el,norm}	P _{heat,norm}	T _{cell} (°C)
Albuquerque	0.96	0.87	1.08	70.3
El Paso	0.96	0.87	1.08	73.0
Las Vegas	0.95	0.86	1.09	75.2
Tucson	0.97	0.87	1.08	77.0

331

332 Additional simulations were conducted in order to assess the impact of h_{conv} on the energy yield
333 at each location using a range of h_{conv} within the passive cooling limits (i.e. $1000 \text{ W}/(\text{m}^2\text{K}) \leq$
334 $h_{\text{conv}} \leq 1600 \text{ W}/(\text{m}^2\text{K})$ with a step of $200 \text{ W}/(\text{m}^2\text{K})$). The results are shown in Fig. 7 and Table
335 IV for the following annual direct normal irradiation values: $2696 \text{ kWh}/\text{m}^2$ in Albuquerque,
336 $2643 \text{ kWh}/\text{m}^2$ in El Paso, $2722.4 \text{ kWh}/\text{m}^2$ in Las Vegas and $2765.5 \text{ kWh}/\text{m}^2$ in Tucson.

337 Fig. 7 shows the annual E_{yield} in kWh/kWp as a function of h_{conv} for all the locations; as
338 expected, the E_{yield} increases with the annual direct normal irradiation, since the DNI is the
339 main driver for the energy output. The E_{yield} also increases linearly with h_{conv} with the slopes
340 of the linear fit at 0.14 for Albuquerque and El Paso and 0.15 for Las Vegas and Tucson. Table
341 IV shows the annual maximum T_{cell} for four values of h_{conv} and also the annual average T_{cell} in
342 parenthesis. It can be seen that the cell temperature exceeds 100°C in Las Vegas and Tucson

343 for $h_{\text{conv}} = 1000 \text{ W}/(\text{m}^2\text{K})$. If the temperature limit is set at 90°C , the cooling requirements for
 344 Albuquerque and El Paso would be $h_{\text{conv}} > 1250 \text{ W}/(\text{m}^2\text{K})$; for Las Vegas $h_{\text{conv}} > 1450 \text{ W}/(\text{m}^2\text{K})$
 345 and for Tucson a $h_{\text{conv}} > 1350 \text{ W}/(\text{m}^2\text{K})$. The annual average T_{cell} reduction per $\text{W}/(\text{m}^2\text{K})$
 346 increase is 0.027 for all four locations.



347

348 Fig. 7. Annual values of energy yield as a function of the heat transfer coefficient.

349 TABLE IV: Annual maximum and average (in parenthesis) T_{cell} as a function of h_{conv} .

Location	$h_{\text{conv}} \text{ (W}/(\text{m}^2\text{K}))$			
	1000	1200	1400	1600
Albuquerque	96.5°C (71.4°C)	90.9°C (65.9°C)	85.4°C (60.5°C)	79.8°C (55°C)
El Paso	97.1°C (74.1°C)	91.5°C (68.6°C)	86°C (63.2°C)	80.4°C (57.7°C)
Las Vegas	102.5°C (77°C)	96.9°C (71.5°C)	91.4°C (66.1°C)	85.8°C (60.6°C)
Tucson	100°C (78°C)	94.5°C (72.5°C)	88.9°C (67.1°C)	83.3°C (61.6°C)

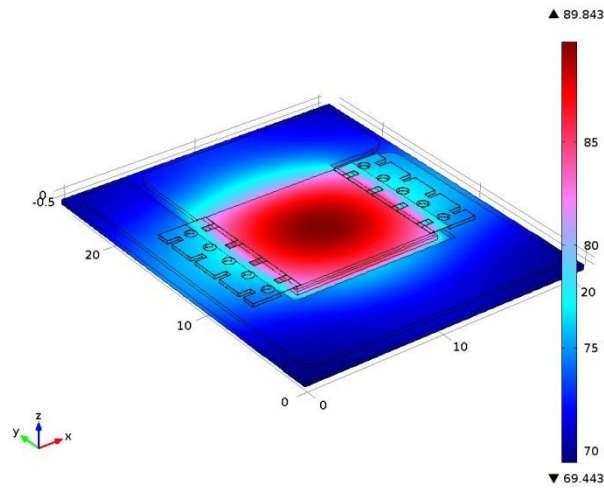
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3.3. Cooling requirements under extreme conditions

As discussed in the introduction, the study conducted in section 3.2. using TMY3 data is useful for the electrical performance and operating temperature evaluation of CPV for a particular location. However, it may have the disadvantage of not allowing the accurate quantification of the cooling requirements under extreme conditions. Hence, this section evaluates the cooling requirements of the C1MJ CCA under worst-case scenarios. The AM is fixed to $AM = 1$ and the AOD and PW have been varied for specific ranges that would trigger relatively high thermal stresses on the CCA due to additional current mismatch between the subcells and also due to higher solar irradiance intensities. Moreover, in the summer months and for latitudes lower than $40^{\circ}N$, the AM is lower than $AM = 2$ for most of the day [42]. Therefore, AM1D is considered under variable AOD and PW, for the estimation of the required h_{conv} from the back plate to the ambient air with an ambient temperature of $45^{\circ}C$. Also, the ranges of AOD ($0.05 \leq AOD \leq 0.2$) and PW ($0.5 \leq PW \leq 1.5$ cm) were chosen to simulate the thermal behaviour of CCA at relatively hot (high T_{amb}), clear (low AOD) and dry (low PW) conditions. Any cooling device designed to dissipate heat under these conditions, will be adequate for higher AM, AOD and PW values. A range of heat transfer coefficients $1200 \text{ W}/(\text{m}^2\text{K}) \leq h_{conv} \leq 1600 \text{ W}/(\text{m}^2\text{K})$ are used as a boundary condition on the back surface of the CCA. Higher heat transfer coefficients were not considered in order to stay within passive cooling limits [43]. The cell's temperature is then predicted by the FETM and the integrated volumetric temperature is then imported back to the EM. The procedure is repeated until a steady state is reached between the EM and FETM; i.e. solar cell temperature difference lower than $0.002^{\circ}C$. The solutions converge in all cases after the 3rd iteration.

The temperature distribution of the C1MJ CCA is shown in Fig. 8 for AM1D, $PW = 1.42$ cm, $AOD = 0.084$, $h_{conv} = 1600 \text{ W}/(\text{m}^2\text{K})$ (i.e. $1.22 \text{ K}/\text{W}$, area of $5.13 \times 10^{-4} \text{ m}^2$) and $T_{amb} = 45^{\circ}C$. A maximum temperature of $89.84^{\circ}C$ is observed at the centre of the cell while the temperature of

376 the top layer of the DBC board, which is not illuminated, varies from 70°C at the edges to 80°C
377 near the cell. The integrated volumetric temperature of the solar cell is 86.34°C.

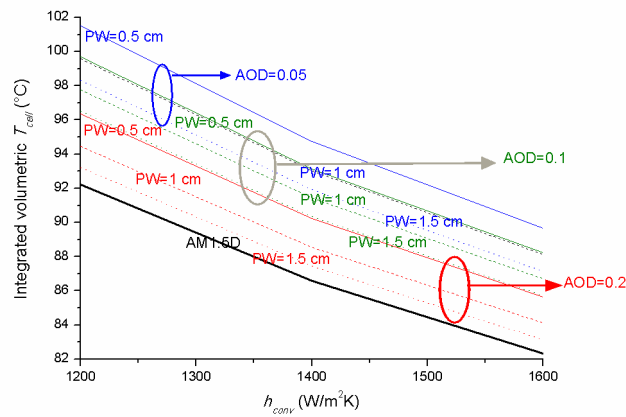


378

379 Fig. 8. Temperature distribution (°C) across the C1MJ CCA for AM1D, $h_{\text{conv}} = 1600 \text{ W}/(\text{m}^2\text{K})$
380 and $T_{\text{amb}} = 45^\circ\text{C}$.

381 The influence of the changing spectra on the calculated integrated volumetric cell temperatures
382 are illustrated in Fig. 9 for AM1D, $0.05 \leq \text{AOD} \leq 0.2$, $0.5 \text{ cm} \leq \text{PW} \leq 1.5 \text{ cm}$, $1200 \text{ W}/(\text{m}^2\text{K}) \leq$
383 $h_{\text{conv}} \leq 1600 \text{ W}/(\text{m}^2\text{K})$ and $T_{\text{amb}} = 45^\circ\text{C}$. The reference spectrum AM1.5D ASTM G173-03 is
384 also plotted (black line) for comparison. As can be seen, cooling devices designed at AM1.5D
385 will allow higher operating temperatures (by up to 9.3°C) at relatively "hot and dry" sites. The
386 elevated temperatures will cause long term degradation problems if kept for a prolonged time
387 [41]. Therefore, at sites with low AOD and PW, the h_{conv} should be higher than $1300 \text{ W}/(\text{m}^2\text{K})$
388 in order to operate at temperatures lower than 100°C.

389



390

391 Fig. 9. Integrated volumetric solar cell temperature as a function of heat transfer coefficient,
 392 aerosol optical depth (blue AOD = 0.05, green AOD = 0.1, red AOD = 0.2) and precipitable
 393 water (straight lines PW = 0.5 cm, dash lines PW = 1 cm, dot lines PW = 1.5 cm). The air mass
 394 is kept constant at AM1D. The AM1.5D ASTM G173-03 is also shown with black colour.

395 4. Discussion and conclusion

396 An integrated modelling procedure has been presented in order to evaluate the impact of
 397 atmospheric parameters on the spectral, electrical and thermal performance of a concentrating
 398 III-V triple-junction solar cell under a CR of 500×. The results show that such solar cells are
 399 mainly influenced by changes in AM and AOD with spectral losses of 51.3% at AM10D and
 400 36.3% when AOD = 1. The PW however showed spectral gains of up to 4.3% when
 401 PW = 5 cm; this is attributed to the reduction of the infrared portion of spectrum. Moreover,
 402 the $P_{el,norm}$ losses are < 1% up to AM1.9D while for AM values greater than AM2D the losses
 403 increase significantly (up to 50.3% at AM10D). The $P_{heat,norm}$ increases with the excess current
 404 mismatch between the subcells and therefore it is always greater than 0% , except when the top
 405 and middle subcells are current matched; i.e. when it operates at the reference conditions.
 406 Similarly with increasing AOD, the $P_{el,norm}$ is reduced by 34.9% when AOD = 1 while for PW =
 407 5 cm it is increased by 4.3% and therefore the $P_{heat,norm}$ is decreased by 2.6%.

408 The procedure was simplified in order to handle bulk spectra. Instead of using the 3D FETM
409 model, regression analysis has been performed for the calculation of T_{cell} using equation (5).
410 Class I TMY3 data have been used for four US locations with relatively high annual DNI
411 (Albuquerque, El Paso, Las Vegas and Tucson) in order to evaluate the performance of a CCA.
412 It was shown that Las Vegas and Tucson exhibited the highest annual average spectral losses
413 and T_{cell} respectively. $P_{\text{el,norm}}$ is always underperforming in Las Vegas while for Albuquerque
414 and El Paso gains were visible for a $h_{\text{conv}} > 1200 \text{ W}/(\text{m}^2\text{K})$; Tucson exhibited $P_{\text{el,norm}}$ gains for
415 $h_{\text{conv}} \geq 1600 \text{ W}/(\text{m}^2\text{K})$. By varying the h_{conv} at each location, its influence on E_{yield} could then
416 be determined. Because the TMY3 represent average values, a stricter T_{cell} limit was assumed
417 suggesting a different h_{conv} at each location; $1250 \text{ W}/(\text{m}^2\text{K})$ for Albuquerque and El Paso,
418 $1450 \text{ W}/(\text{m}^2\text{K})$ for Las Vegas and $1350 \text{ W}/(\text{m}^2\text{K})$ for Tucson.

419 Finally, a method was also presented in order to evaluate the cooling requirements under
420 extreme conditions; i.e. AM1D, $T_{\text{amb}} = 45^\circ\text{C}$ and a relatively clear (low AOD) and dry (low
421 PW) atmosphere. It has been shown that in order to operate at a maximum T_{cell} lower than
422 100°C , the h_{conv} should be greater than $1300 \text{ W}/(\text{m}^2\text{K})$. Future work will incorporate costs in
423 order to optimise the electrical and thermal performance at the lowest heat sink cost.

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