Impact of the temperature dependence of CPV optics transmittance on the current mismatch of multi-junction solar cells

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Impact of the Temperature Dependence of CPV Optics Transmittance on the Current Mismatch of Multi-Junction Solar Cells

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Abstract. The influence of spectra and temperature dependence of concentrator photovoltaics (CPV) optics is investigated by modelling yearly series of ambient conditions, such as typical meteorological year (TMY) data, and simulating the response of relevant CPV technologies. Results show the influence the optics have on the effective spectra available at the solar cell level. This allows us to find the limiting factors of a CPV module performance and permits energy yield predictions.

INTRODUCTION

Concentrator photovoltaics (CPV) uses very high efficiency multi-junction solar cells [1] in combination with high concentrating optical lenses [2] in order to obtain photovoltaic modules with efficiencies close to 40% for power generation. In the CPV technology an abundant amount of different solar cell technologies is used. Such as the inverse-metamorphic (IMM) solar cell [3]; lattice-matched (LM), upright-metamorphic (UMM) and current-matched solar cells [4]; and wafer-bonded solar cells [5]. In addition there are many different optical approaches such as the very common silicone-on-glass (SOG) lens [6], Poly(methyl methacrylate) (PMMA) Fresnel lens, non-imaging secondary optical elements (SOE) [7], achromatic-doublet-on glass (ADG) [8], and many more…

Power prediction studies are very common in order to study possible locations for CPV power plants [9] but also to compare different technologies [10]. Different spectral and temperature conditions around the world have a major effect on CPV system performance. The analysis and or simulation of local conditions using yearly series of ambient conditions has been done before for power analysis in publications such as S.P. Philipp et al. [11] and many more such as [10],[11]. Taking into account the spectral variability of a certain location, which varies according to spectral parameters like precipitable water (PW), aerosol optical depth (AOD) and the air mass (AM) different sites can be studied [12]. One of these yearly series is the typical meteorological year (TMY3) spectral database [13], which is used in this specific simulation. The effect of spectral variations on the solar cell has been studied by publications such as [14],[15] and the effect of the losses caused by the optical element of the CPV module has been looked at in [16]. These loss effects on the solar cell, are a very important part to consider during the design of a solar cell in order to obtain a good current matching [17].

This simulation outstands with the collection of the temperature effect, both on the external quantum efficiency (EQE) of the solar cells and the wavelength and temperature dependent transmittance for different types of CPV optics in one python [18] based simulation model. The influence of the temperature has been studied before in works such as from T. Hornung et al. [19] with a very complete simulation model, the main difference to our model is the temperature adaption of the EQE and the calculation of the cell current from the EQE. Similar to the model YieldOpt
and the theoretical analysis of M. Theristis et al. [20], the latter studies the spectral effect without the influence of the optics.

Results show both the influence the optics have on the effective spectra available at the solar cell level and the annual energy yield of the solar cell, quantified with the total current charge generated by the cells (in A·h/cm²). In contrast to typical energy yield studies simulating current-voltage (IV) curves and estimating the power output from these, such as YieldOpt [10], the current charge is more sensitive to current mismatching and expresses bigger losses due to spectral variations. This makes it possible to compare different optical systems and cell technologies under the climatic and spectral conditions of any specific site, providing the possibility of fine-tuning a CPV system for maximum current charge.

**Thermal Effects**

The effect of the temperature on the solar module can be split in two components, the effect on the solar cell and the effect on the optic. The solar cell is effected by a shift in the bandgap of the sub-cells with a temperature variation. This can be quantified using empirical constants of the bandgap shift (ΔEg), obtained from characterization reports of certain cell technologies, such as [21] for the IMM solar cell. The optic is affected by three physical properties: refractive index, thermal expansion and material absorption.

In what follows, examples will be given how these three properties influence the spot size of a SOG Fresnel lens: the refractive index varies with the wavelength and the temperature, causing both chromatic- and thermal-aberration of the concentrated light spot, this is illustrated in Figure 1a. Thermal expansion causes the facet angles of the Fresnel lens to rise at high temperatures and flatten out at low, this results an increase in focal length at higher temperatures and decrease at lower [16]. The thermal aberration is slightly compensated, but the thermal expansion of the material also results in an increase of the draft angle [22]. Causing a decrease of focusing area, therefore an optical loss. The absorption causes an additional optical loss and is dependent of the material itself, a temperature dependence of the absorption is unlikely.

![FIGURE 1.](a) Shows a SOG lens with the chromatic aberration caused by the refractive index variation over the wavelength. Similar behavior as the thermal aberration, causing larger spots at low temperatures (red traces), these type of lenses have a spot size very susceptible to temperature changes. In contrast, the achromatic doublet on glass lens (b) diminishes the chromatic aberration using two refraction levels. The materials refractive indexes are also altered by the temperature, but due to the achromatic design of the lens the effect is minor. A mirror system (c) has a subtle alteration of the spot size with the temperature, it’s only influence by the thermal expansion of the materials with a minor degree. Figures reference: (a) [23] (b) [8]

Not all optics share the same effects, therefore in the Table 1 the most widely used are compared: Figure 1a & 1b, together with an example of a new technological approach, Figure 1b. In order to get a full understanding of how the CPV module behaves in different environments it’s important to include these thermal effects in the yearly simulation.
For this a ray-tracing program is used. The program simulates the transmittance of the lens at a certain concentration, meaning that the receiver is in size inverse proportional to the concentration, being the lens size a constant \( A_{\text{Cell}} = \frac{A_{\text{Lens}}}{X} \). Using ray-tracing we can simulate the thermal effect on the spot size, setting the refraction index variation over the wavelength and temperature to the materials properties. The same can be done with the material absorption. For now we don’t have a way to simulate de thermal expansion of the material, so this effect is not taken into account yet.

<table>
<thead>
<tr>
<th>CPV Optic type</th>
<th>Effect on spot size with temperature variation</th>
<th>Reference</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror System</td>
<td>Thermal expansion, Little to no effect</td>
<td></td>
<td>1c</td>
</tr>
<tr>
<td>Silicone on glass</td>
<td>Chromatic aberration, Thermal aberration, Thermal expansion, Major effect</td>
<td>[19] [24]</td>
<td>1a</td>
</tr>
<tr>
<td>Achromatic doublet on glass</td>
<td>Hardly any chromatic aberration, Thermal expansion, Minor effect</td>
<td>[24]</td>
<td></td>
</tr>
<tr>
<td>Secondary optical element</td>
<td>Both aberrations corrected, No effect</td>
<td>[25]</td>
<td></td>
</tr>
</tbody>
</table>

**SIMULATION MODEL AND METHODOLOGY**

This work is a continuation of the studies by Victoria et al. [26] and Nuñez et al. [12] for locations others than Madrid. In Figure 2, a schematic of the simulation model is shown. The input data consists of: TMY3 data provided by NREL for different locations, measured EQE of various commercial triple-junction solar cell technologies, and simulated optical transmittance data as a function of temperature and wavelength.

![Flow chart of the simulation tool](image)
The TMY3 data is utilized to synthesize solar spectra for each sunlight hour of a year with SMARTS [27]. Air mass (AM), aerosol optical depth (AOD), humidity and precipitable water values (PW) are used for the simulation. SMARTS is the acronym for Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) [27], as this program only allows us to simulate clear sky spectra. Since the total energy yield over the whole year is higher than the Σ of DNIs from the TMY3 data, an adjustment is necessary. The artificial spectra are integrated for each minute of the year and multiplied by the ratio between the resulting value and the DNI data (TMY3). This is still a preliminary solution, as doing this causes errors on the shape of the spectra. The hourly ambient temperature from the TMY3 is adapted using a temperature delta from the Handbook of CPV for the optic (ΔT_{Optic} = +15 °C) [28] and the solar cell (ΔT_{Cell} = +40 °C) [28], better temperature estimations exist for both optics and cells such as in [19],[20] but these still haven’t been implemented into the simulation model. The adapted temperature value is then used to interpolate the appropriate optical transmittance and to shift the baseline EQE using semi-empirical ΔE_g temperature constants, for the simulated case IMM{Top:-0.43 Mid:-0.47, Bot:-0.4} meV/°C [21]. One has to consider that the EQE doesn’t shift the same for the bandgap and absorption part of the EQE-curve. The bandgap part is influenced by the subcell constant but the absorption part by the subcell above. Therefore the top subcell has no shift in the absorption part of the curve as is only influenced by the window layer which has a very minor effect on the bandgap shift [21].

Using the adjusted artificial spectra and the interpolated transmittance, the spectra on the solar cell is calculated by multiplication. Absolute photogenerated subcell-currents are subsequently estimated through DNI and the temperature adapted EQE. The resulting dataset can be divided in two parts (Figure 2): parameters characterizing the spectrum prior to entering the optics (DNI, temperature, spectral matching ratios - SMRs), and parameters describing CPV cell response: cell current density $J_{cell}$ and subcell-current-ratios $J_{top/mid}$ and $J_{mid/bot}$.

**RESULTS**

The impact of the transmittance data from different optics on the spectral distribution was studied. The presented simulation study is given for Golden, Colorado (USA) and considers an InGaP/GaAs/InGaAs inverted metamorphic (IMM) solar cell and the silicone-on-glass (SOG) lens. The simulated (ray-tracing) temperature transmittance on the focal plane was performed for a SOG lens with an f-number of 1.875 and an optical concentration of 400 X suns. The lens was optimized for a temperature of 35 °C. In the following plots, Figure 3ab, we will be looking at the results of the $J_{ratio}$ between the top and middle subcell as the middle and bottom subcell-current ratio shows a very small divergence.

![Figure 3](image_url)

**FIGURE 3.** (a) Simulation study for the location of Golden without the temperature effect on the transmittance of the silicone-on-glass lens (constant optimal temp. of 35 °C). The yearly datasets are plotted as a contour plot with the weighted element being the cell current (cell current over time = cell charge). The plot seen here is a comparison-difference between the ideal case (no optic) and the spectral variability caused by the optic. The blue regions show the areas with a deficit of cell current and the red areas a gain of cell current. The dots, indicated with dashed lines show the centroid of the yearly data. (b) Same plot for the study with temperature effect on the optic. We can see a deficit of cell charge (indicated with a red circle) in low temperature regions and therefore a stronger shift of the centroid to a $J_{ratio}$ < 1 (top limitation).
The comparative plots you can perceive in Figure 3a and 3b show the simulation without taking in account the temperature effect on the lens (a) and with taking in account the effect (b). The information obtained is: at low temperatures, there are important losses which affect how the weighted arithmetic average (or centroid) of the annual current generation is distributed in terms of ambient temperature and current ratios. In this case at low temperatures, the thermal aberration of the SOG lens causes a loss of light at short wavelengths, this means the top subcell becomes more limiting ($J_{\text{ratio}} < 1$).

In Table 2 the extracted numeric result of the study for Golden are confronted with the results of the location Lanai, Hawaii (USA) for the same lens and solar cell type. Both locations show a similar effect, due to the decrease in low wavelength transmittance of the SOG, a red shift of the spectra can be identified ($J_{\text{ratio}} < 1$). The spectra in Lanai is bluer, due to the high content of precipitable water in the air [12]. Knowing this we would expect the losses caused by the SOG to be higher, yet this is not the case. The yearly average temperature in Lanai is around 10 K above the temperature in Golden, meaning the SOG lens is operating closer to its ideal operating temperature. Resulting in less loss due to the thermal aberration, 91 % of total cell charge in contrast to the ideal case without any optic. This result claims the importance of taking in account the effect of the temperature on a CPV system.

**TABLE 2.** Numeric values extracted from the simulation study for the location of Golden and Lanai. The difference in current ratio is caused by a red-shift of the cell-level spectra, caused by the absorbance of the SOG lens. The cell charge difference can be seen as an energy yield of the system.

<table>
<thead>
<tr>
<th>Location</th>
<th>Optic</th>
<th>Avg. Current Ratio Top/Mid</th>
<th>Avg. Temperature</th>
<th>Cell Charge difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden, Co</td>
<td>None</td>
<td>1.024</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>Golden, Co</td>
<td>SOG</td>
<td>0.964</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>Golden, Co diff.</td>
<td></td>
<td>-0.060</td>
<td></td>
<td>88 %</td>
</tr>
<tr>
<td>Lanai, Hawaii</td>
<td>None</td>
<td>1.062</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Lanai, Hawaii</td>
<td>SOG</td>
<td>1.039</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Lanai, Hawaii diff.</td>
<td></td>
<td>-0.023</td>
<td></td>
<td>91 %</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The main value of this methodology lies in the comparison of the annual yield studies for different locations and different optical and solar cell technologies, which allow for more realistic fine-tuning of CPV systems as a function of the final Alternative Optics Manufacturing. At this point we are still not there. For now we only count with preliminary results as the simulation tool as a whole is still lacking certain aspects to be implemented in the near future. Nevertheless the results shown in this article unveil the importance of the thermal effect on the CPV lens system for an energy yield study. Things which are still to be included in this program are: more cell technologies with more junctions, measured transmittances for the lens materials, possibility to generate spectra using AERONET [29] + PVGIS TMY [30] for more locations, and find partners to share measured spectra. Yearly measured spectra in a periodic time-range of a few minutes would be extremely helpful in order to avoid uncertainties using artificial spectra with parameters from satellite images.

**ACKNOWLEDGEMENTS**

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