Influence of Concentration and Solar Cell Size on the Warranty Time of Triple Junction Solar Cells

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Abstract. In a previous work the warranty time of commercial lattice-matched GaInP/Ga(In)As/Ge triple junction concentrator solar cells was evaluated under real climatic conditions. The solar cells had a size of 7x7 mm operating with an efficiency of 35% at 820×. For these particular solar cells the warranty time for three locations, Golden (CO-USA), Madrid (Spain), and Tucson (AZ-USA), exhibits a 4 to 1 ratio, which affects the LCOE (Levelized Cost of Electricity) in an important way. In this work, we go a step further evaluating the influence of concentration and solar cell size on the warranty for a specific thermal design.

INTRODUCTION

In order to have a wide deployment of CPV systems, one important pending issue is to demonstrate that their reliability is competitive with other energy generation technologies [1]. Temperature Accelerated Life Tests (ALTs) [2,3] are used in order to evaluate reliability functions and parameters at a fixed solar cell temperature. However, solar cell temperature in real operation conditions is variable [4] and this variation depends on the location and time where the CPV systems are installed.

In a previous work [5] we have evaluated the solar cell reliability for different locations taking into consideration the solar cell temperature at any time for a specific solar cell and CPV module. We have observed that the influence of the location on the solar cell reliability is important and that the solar thermal design should be customized for the location where CPV module is placed.

Once we have evaluated the solar cell reliability for a given CPV module (solar cell size of 7x7 mm^2 operating at 820×) [5] we now extend the work to a wide range of concentrations and solar cells sizes. Accordingly, in this paper we evaluate the influence of solar cell size and concentration on the solar cell reliability for different locations.

MODEL

In order to evaluate the solar cell reliability parameters in a real application it is necessary to thoroughly evaluate the reliability from ALTs [3] and after that to determine the thermal behavior of the solar cell inside the CPV module [4]. The steps to extrapolate the reliability data obtained in an ALT for a given temperature to the real operation conditions of a location are the following [5]:

- To evaluate the solar cell temperature at any time (instantaneous temperature) for a specific location and year.

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- To evaluate the solar cell reliability for a specific location and year by using both the solar cell instantaneous temperature evaluated in the previous step and the reliability parameters obtained from a temperature ALT assuming a specific nominal solar cell temperature for reliability purposes [3].
- To evaluate the influence of the solar cell size and light concentration on the thermal behavior of the solar cell. Taking into account the solar cell size of 7x7mm and the operation at 820× inside the real CPV module, that we have been thoroughly characterized in previous works [3-5], the influence of solar cell size and sun concentration is analyzed by means of thermal simulations.

Solar Cell Temperature Evaluation

In order to determine the solar cell temperature from atmospheric parameters we will use a simplified equivalent thermal circuit of the CPV module, which can be described by two series connected thermal resistances, $R_{th\,c\_m}$ (thermal resistance from solar cell junction to the back of the CPV module) and $R_{th\,m\_a}$ (thermal resistance from the back of the CPV module to ambient); see Fig. 1 of reference [5]. In this model we assume $R_{th\,c\_m}$ is not affected by wind speed because all the elements affecting $R_{th\,c\_m}$ are enclosed inside the CPV module. On the other hand, the elements affecting $R_{th\,m\_a}$ are outside the CPV module and therefore, $R_{th\,m\_a}$ is highly dependent on wind speed. In the thermal circuit model of the CPV module including the solar cell [5], the temperature increment depends on both the thermal resistances and the power dissipated by means of the following equations:

$$T_{cell} - T_{mod} = P \cdot R_{th\,c\_m} \tag{1}$$

$$T_{mod} - T_{amb} = P \cdot R_{th\,m\_a} \tag{2}$$

$$R_{th\,m\_a}\left(\frac{°\mathrm{C}}{\mathrm{W}}\right) = R_{th\,m_a-nc} - Wf \cdot v_{wind} \tag{3}$$

where $R_{th\,m_a}$depends has two terms: the value of $R_{th\,m_a-nc}$ under natural convection (equivalent to a negligible wind), and the improvement due to the effect of wind velocity, being *Wf* the wind factor, and v_{wind} the wind velocity (m/s). T_{cell} is solar cell junction temperature, T_{mod} is temperature in the back of CPV module and T_{amb} is ambient temperature.

The power dissipated as heat, P , in the concentrator solar cell is:

$$P = \eta_{op} \cdot DNI \cdot A_{lens} \cdot (1 - \eta_{cell}) \tag{4}$$

where P due to the concentrated light by a lens with a size (A_{lens}) is related to the impinging irradiance (also called Direct Normal Irradiance, *DNI*) and the optical and solar cell efficiencies, η_{op} and η_{cell}., respectively. It is important to note that $A_{lens} = A \cdot C$, being A the solar cell area and C the geometrical concentration.

Therefore, the instantaneous temperature of the solar cell can be determined if the power dissipated in the solar cell, both thermal resistances and the instantaneous atmospheric data namely, ambient temperature (T_{amb}), *DNI* and wind speed, are known:

$$T_{cell} = T_{amb} + \eta_{op} \cdot DNI \cdot A_{lens} \cdot (1 - \eta_{cell}) \cdot R_{th\,c\_m} + \eta_{op} \cdot DNI \cdot A_{lens} \cdot (1 - \eta_{cell}) \cdot R_{th\,m\_a} \tag{5}$$

In Eq. (5) there are parameters related only with the CPV module design (η_{op}, η_{cell}, A_{lens} and $R_{th\,c\_m}$), parameters related with climatic conditions (T_{amb} and DNI) and finally $R_{th\,m\_a}$ which is related with both the CPV module design and the climatic conditions because $R_{th\,m\_a}$ is affected by wind speed as it has been explained in [5] and it is shown in Eq. (3).

Evaluation of the Solar Cell Reliability in Real Conditions

In this section we will show how to extrapolate the reliability parameters from an ALT, assessed for a given solar cell temperature, to the real solar cell temperature. We assume that: a) the reliability parameters are accelerated by temperature and the obtained results follow an Arrhenius law [2-3] and b) the activation energy, $E_a = 1.59\text{eV}$, has been evaluated previously in the same ALT that has provided the solar cell reliability results [3]. A failure mechanism analysis has been described in [6].

In the ALT the reliability parameters have been obtained for a nominal temperature of 80 °C [3]. Therefore, it is possible to make a relationship between the operation time in real conditions at T_{cell} $(t_{T_{cell}})$ and the time at 80 °C $(t_{T_{80}})$ by means of the Arrhenius law. This relationship is called Acceleration Factor (*AF*) of T_{cell} with respect to 80 °C, $AF_{T_{cell}/80}$:

$$AF_{Tcell/80} = \frac{t_{T_{80}}}{t_{T_{cell}}} = exp\left[\frac{E_a}{k}\left(\frac{1}{273{,}15+80} - \frac{1}{273{,}15+T_{cell}}\right)\right] \tag{6}$$

As derived from equation (6) if the solar cell temperature is lower than 80 °C, AF will be lower than 1 while if solar cell temperature is higher than 80 °C, *AF* will be higher than 1. *AF* also depends on the activation energy (E_a) obtained in the ALT and has to be known beforehand. Taking into account the hours per year at each interval (1 °C width) of solar cell temperature and the *AF* of this temperature interval with respect to 80 °C, it is possible to evaluate the equivalent time at 80 °C for each interval of temperature of the temperature histogram. Adding the heights of this histogram allows us evaluate the yearly equivalent time at 80 °C [5].

This yearly equivalent time at 80 °C value, that depends on the solar cell temperature and E_a, can be compared with the reliability results at 80 °C obtained in the temperature ALT as described in ref [3]. As an example, the yearly equivalent time at 80ºC in Tucson 2014 for the analysed solar cells corresponds to 13,464 hours [5], that compared to the warranty time measured in the ALT at 80ºC that was 206,225 hours [5], implies that in this location and year the warranty time is 206,225/13,464=15.3 years. This calculation can be done for any location and year if instantaneous atmospheric data are available.

Solar Cell Size and Sun Concentration Influence

Once we have evaluated the reliability parameters of a solar cell at a given location and year, it is very important to analyze the influence of the solar cell size and sun concentration in the reliability parameters. In order to do that, we have evaluated the thermal parameters explained in previous section by means of thermal simulations made with Finite Element Analysis (FEA), see Fig. 1. For the evaluation of the thermal parameters, we have taken the following assumptions:

- To extract the main parameters for the thermal simulations we have selected as reference a 7x7 mm solar cell area (*A*) at a geometrical concentration ratio (*C*) of 820× whose thermal and reliability parameters have been thoroughly characterized in [3-4].
- The thermal design, materials, thickness and dimension of the aluminium heat spreader [4] are the same for the different solar cell sizes and concentrations.
- The size of the rear aluminium plate will be the same than the lens size ($A_{lens} = A \cdot C$). The thickness of the rear aluminium plate is 2 mm.

Considering these assumptions and equation (4) and (5), the thermal power dissipated by the solar cell (which depends on A_{lens}) has the biggest influence on the solar cell temperature. Therefore, the higher the solar cell thermal power (*P*) the lower the warranty time. Additionally, $R_{th\,c-m}$ and $R_{th\,m-a}$ impact the solar cell temperature and thus, the warranty time. $R_{th\,c-m}$ depends mainly on both solar cell contact surface area and thermal conductivity while $R_{th\,m-a}$ depends on rear aluminum plate size, equal to A_{lens}, due to its impact on natural air thermal convection. These thermal resistances have been evaluated by FEA for different *A*, *C* and A_{lens}.

Accordingly, when *A* increases $R_{th\,c-m}$ decreases while the change of *C* has a negligible effect on $R_{th\,c-m}$. For a given A_{lens} (obtained by different combinations of *A·C*), the solar cell temperature is slightly lower for a higher solar cell area (due to $R_{th\,c-m}$ decreases). Simultaneously, since $R_{th\,m-a}$ depends on the rear aluminium plate size ($A_{lens} = A \cdot C$), a higher A_{lens} means an improvement (decrease) of $R_{th\,m-a}$, but it also results in an increase of power. This increase of power implies an increase of the solar cell temperature that is not counterbalanced by the $R_{th\,m-a}$ decrease.

In conclusion, we have evaluated both $R_{th\,c-m}$ and $R_{th\,m-a}$ for a wide range of $A_{lens,}$ $A,$ C that together with the solar cell reliability model explained in previous sections allow us to obtain the warranty time for different locations and years as described below.

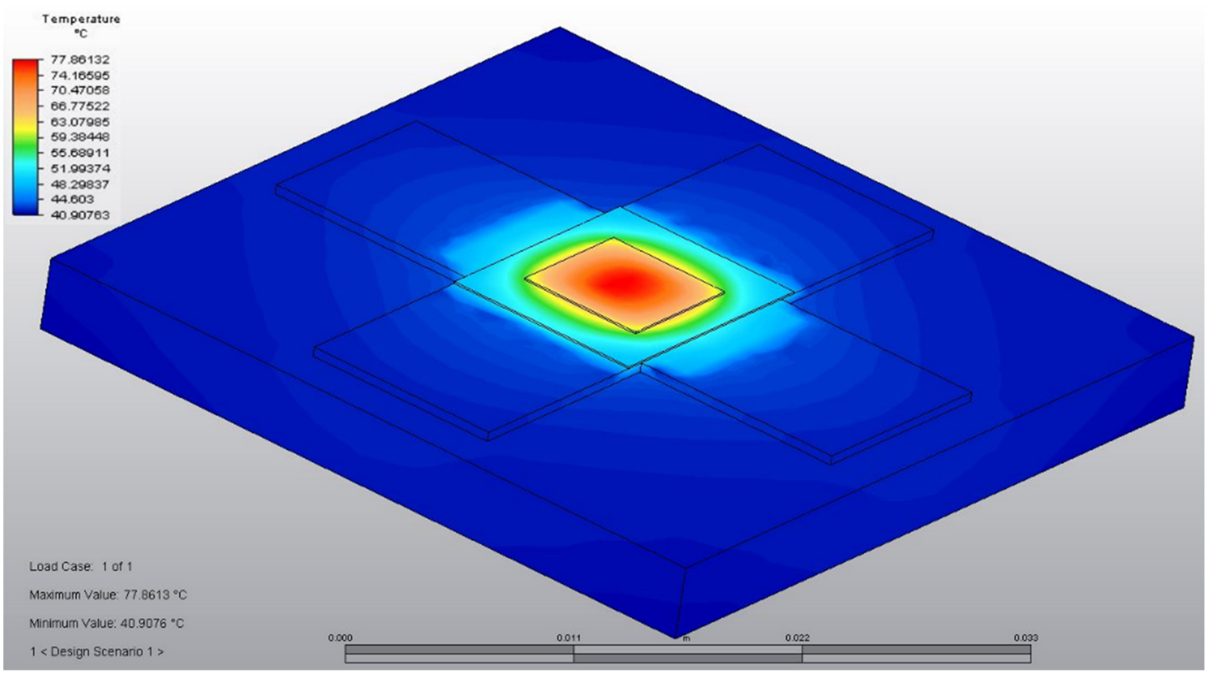


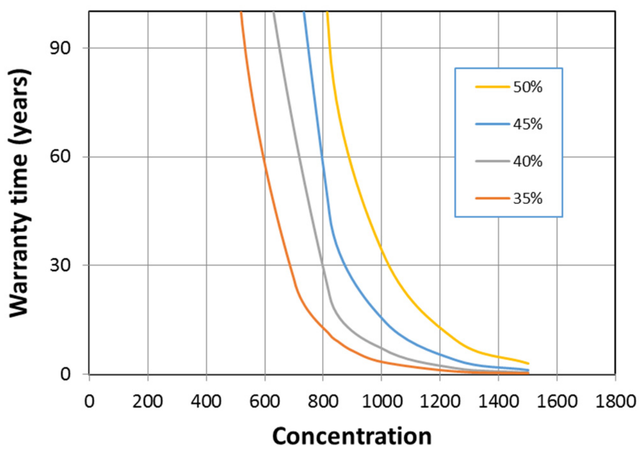
FIGURE 1. Example of one of the thermal simulations to assess the thermal resistance parameters in real conditions, for the 7x7 mm^2 triple junction solar cell at 820× at 5.5 m/s wind velocity. For the sake of simplicity, the image does not include neither the secondary optics over the cell nor rear aluminium plate and tape cell bonding.

RESULTS

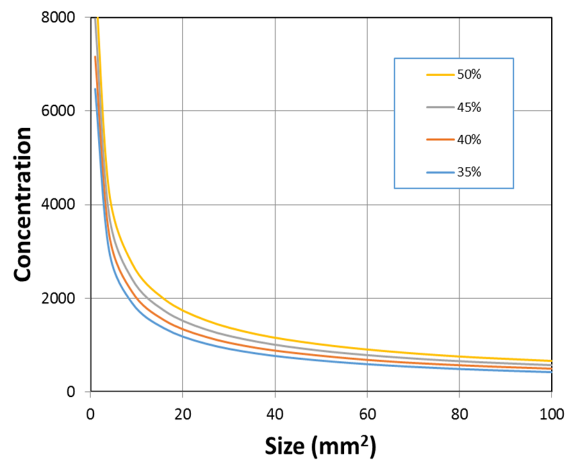
In order to analyze the influence of concentration we have carried out calculations using the 7x7 mm solar cell for different sun concentrations in a harsh environment (Tucson) with atmospheric data from 2014, Fig. 2-a. This solar cell, whose thermal dissipation was designed to work at 820× with a nominal temperature of 80ºC, does not achieve a 30 year warranty time in this location for low solar cell efficiencies (<40%).

Following with the case study of Tucson, we have also analyzed the influence of concentration, efficiency, and solar cell size to achieve a 30 year warranty time, see Fig. 2-b. This figure shows that with this thermal design, for smaller solar cell sizes the maximum achievable concentration for 30 years of warranty is very high (several thousand suns) and therefore, a cheaper and simpler thermal scheme could be used. In the other extreme, for larger solar cell sizes, the maximum concentration for 30 years warranty time is only some hundred suns and thus, a better thermal design will be required for working at concentrations above 1,000 suns

We have analyzed, in a similar way than Fig. 2-b, the solar cell size and concentration for 30 years of warranty but for different locations and years, whose results are presented in Fig. 3. As can be seen, Golden is better than Madrid and Tucson in terms of solar cell reliability. These calculations have been also done for the period 2012-2015 showing small deviations. Table 1 summarizes some the main temperature values for the three locations.



(a)



(b)

FIGURE 2. a) Warranty time vs. concentration in Tucson (Arizona) 2014 for a 7mm x 7mm solar cell with the specified thermal design for different solar cell efficiencies. b) Maximum concentration values vs solar cell size to achieve a 30 years warranty time target for different efficiencies, in Tucson (Arizona) 2014.

TABLE 1. Ambient and solar cell temperatures when DNI > 0 for Tucson; Madrid and Golden in 2014.

Temperatures, (ºC)	Tucson	Madrid	Golden
Maximum ambient temperature	42.3	38.4	35.4
Average ambient temperature	26.5	21.1	15.4
Minimum ambient temperature	6.5	-3.6	-24.8
Maximum solar cell temperature	114.2	103.8	103.4
Average solar cell temperature	73.7	66.6	59.1
Minimum Solar cell temperature	9.9	3.8	-22.8

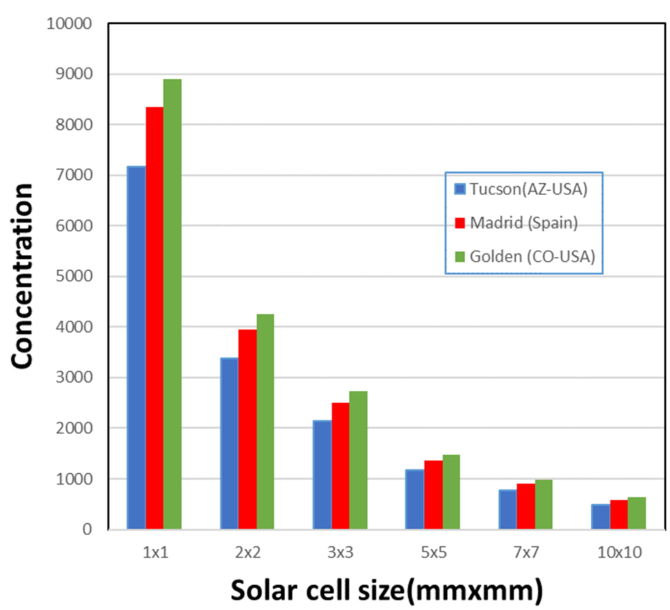


FIGURE 3. Maximum concentration values to achieve a 30 years warranty time for different locations and solar cell size with data from 2014 (assuming 40% solar cell efficiency).

The results we have obtained here are very biased by the boundary conditions of using the real thermal dissipation scheme used in the real CPV module from which we have measurements. Therefore, more realistic and useful results about recommended concentration, solar cell size and efficiency for different locations would be achieved if a customization of the thermal dissipation were done what is now ongoing in our group.

SUMMARY AND CONCLUSIONS

An analysis of the influence of solar size and concentration on warranty time of CPV solar cells that takes into account climatic conditions has been carried out. The main conclusions are:

- Solar cells below 25 mm^2 operating at 1,000× or higher are able to achieve warranty times of more than 30 years for Tucson, Madrid and Golden using the selected thermal design of this paper.
- This specific thermal design considered in this paper for 7mmx7mm solar cells is adequate for Madrid and Golden, but not for a harsher environment, such as Tucson.
- A thermal design customization for different concentration, solar cell efficiency and size has to be done is order to achieve long warranty times.

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