INTRODUCTION

To date, multijunction solar cells (MJSCs) based on III-V materials have provided the highest conversion efficiency compared to other photovoltaic technologies \(^1\)-\(^4\); nevertheless, there is still a lot of room for improvement.\(^2\),\(^5\) Particularly, III-V MJSCs are expensive, primarily due to the high cost of substrates suitable for epitaxial deposition of III-V films\(^6\); besides, manufacturing such multilayered structures can include additional microfabrication steps.\(^7\) Currently, one of the most efficient methods that have been applied for reducing the cost of CPV systems is based on MJSC designs that can operate efficiently at UHC, around >1000 suns.\(^8\)-\(^11\) It is expected that, in the near future, CPV systems become competitive for energy production market.\(^12\) They are especially advantageous for high direct-normal irradiation (DNI) regions, but they are not yet attractive for midrange and low DNI regions, where the limited acceptance angle impedes focusing the diffuse sunlight with the concentration optics.\(^13\),\(^14\) The main leverage of CPV solar cells, however, is reflected by the fact that they contribute to the cost reduction and the efficiency increase at the same time. For instance, in areas with a high
annual DNI of 2000 kWh/m² or more, the levelized cost of electricity varies between €0.08 and €0.15/kWh and the price of installing CPV power plant systems with a capacity of 10 megawatts would be between ~€700 and €1100/kWh, assuming that the installations continue to grow through 2030. Therefore, advanced architectures designed for UHC conditions are a powerful means of enabling MJSCs to be used not only in terrestrial applications but also in space applications, where watts per kilogram is a crucial requirement.

However, the performance improvement at UHC is strongly affected by three important factors, which are (a) the losses caused by the temperature increase in the solar cells (typically, about 63% of light is dissipated by generating heat in a GaInP/GaAs/Ge solar cell under concentrated light), (b) the lack of reliable optics (as a system of lenses or reflectors) and trackers that can support UHC conditions, and (c) the existence of series resistance ($R_s$) that seems to limit the efficiency at UHC when higher photocurrent levels are reached. To address the first issue, two main methods of thermal management can be used, which are active and passive cooling. As an example of passive cooling, Saadah et al demonstrated that thermal management at concentrations above 500 suns can be improved by enhancing the properties of the thermal interface materials via incorporation of graphene. Concerning the second problem, several innovative optical configurations have been proposed, such as multiple Fresnel lens primaries focusing to one central cell, allowing to increase the concentration above 3000 suns with an optical efficiency of 55%. Furthermore, Ferrer-Rodriguez et al designed a new ultrahigh CPV module based on the Cassegrain design with four optical units around a central receiver, which can reach concentrations above 1000 suns. Concerning the last issue, it seems that the energy losses are not only sensitive to the device series resistance, but they are also susceptible to the photocurrent level. To be more specific, it is the current density that turns it into the paramount hindering factor to the system performance. This is due to the fact that the resulting $R_s J^2$ power losses will scale with the square of current density. Various strategies have been proposed in order to mitigate the unfavorable effect of the resistive losses, by reducing either the series resistance or the photocurrent level. In particular, grid design should be optimized to realize the optimal balance between the contact resistance, the front metal grid, and the shading associated with the front contact metal grid. Decreasing the cell size can also reduce the series resistance losses through a drop in the area-related contribution of the series resistance. Another alternative method consists of reducing the tunnel junction-related series resistance using the highly conductive tunnel junctions that have a high current peak. In this regard, Barrigón et al reported a high peak current of 235 A/cm² for a transparent p⁺+/AlGaAs/n⁺++-GaInP tunnel junction architecture that will not electrically limit the functioning of CPV device in any practical concentration level. Furthermore, heterojunctions or band discontinuities seem to have an impact similar to that of the series resistance at high-concentration levels. This can be mitigated by increasing the doping level, hence favoring the tunneling process of carriers through the potential barriers. Another innovative design of solar cells consists of employing a vertical tunnel junction. This approach allowed a significant reduction of series resistance losses in the two p-n junctions connected in series, thereby increased the efficiency from 22.5% at 1 sun to 28.4% at an extreme concentration of 15 000 suns. Even though these strategies allow a moderate improvement in the efficiency, they require extreme concentration levels that are not easy to attain. 32 In Table S1.1 (see Appendix S1, section S1), we compared some advantages and disadvantages of the different strategies, investigated in the literature, for reducing series resistance. On the other hand, using the concept of MJSCs, which involves a combination of multiple subcells with different bandgaps, seems to be a compelling route for reducing both the generated heat, by minimizing the thermalization losses, and the photocurrent. This can be realized by splitting the solar energy spectrum over many junctions, hence significantly reducing the resistive losses power ($J^2R_s$) and, consequently, producing much useful power in the cell.

As examples of success in development of MJSCs at UHC, GaInP/GaAs dual-junction delivered an efficiency of 32% for concentrations ranging from 499 suns to 1000 suns; in addition, In$_{0.5}$Ga$_{0.5}$P/(In)GaAs/Ge three-junction showed an efficiency of 43.9% at 904 suns. Nonetheless, the efficiency of these conventional cells drops drastically beyond a certain value of concentration, which is around 1000 suns and 904 suns for dual- and triple-junction solar cells, respectively. Recently, many researches have been directed toward developments of MJSCs operating above 1000 suns condition; subsequently, module efficiency of above 35% has been reported. Other technologies capable of improving the conversion efficiency of MJSCs have been successfully developed. For instance, researchers at National Renewable Energy Laboratory (NREL) implemented four-junction solar cells, grown as inverted metamorphic multi-junctions, with efficiency close to 45.6% at 690 suns. Moreover, Friedman et al investigated high efficiency four-junction solar cells by introducing dilute nitride film. This group and others employed a layer of GaInNAs (~1 eV bandgap) between GaAs and Ge layers in the GaInP/GaAs/Ge structure. Such a design enabled equal distribution of solar spectrum over different junctions. As a result, thermalization and transmission losses in solar cells were minimized. Based on a semi-empirical model, they showed that the theoretical efficiency of GaInP/GaAs/Ge solar cells increased by 5% for AM0 at one sun and by 8% for AM1.5D at 500 suns. Despite these outstanding achievements, design and fabrication of MJSCs with high efficiency at extreme concentration levels remain a critical challenge for future solar energy systems.
conversion efficiency at UHC conditions is still an ongoing challenge that must be overcome, in order to establish a reliable and sustainable, yet cost-effective, platform for green energy production. Other complexity in MJSCs arises from the compatibility issue of the same III-V materials, in terms of lattice constant, that can be included in the solar cell.

In this work, duplicated junction solar cells (DJSCs) that can operate efficiently at UHC conditions are studied. The key principle is duplicating a given subcell (p-n junction) into 2 or more (N) similar-bandgap subjunctions, thereby creating the same optical paths that are electrically connected in series using low resistance tunnel junctions. Therefore, the optical input power can be converted into a high voltage, while maintaining current level sufficiently low, thus allowing efficient operation at higher concentrations. Furthermore, the DJSCs allow distributing the total current over multiple subjunctions. The most important advantages of this approach are as follows: Firstly, the design can be applied to single-junction solar cells as well as MJSCs; and secondly, there is no limit concerning the lattice constant compatibility, as the subcells of the same material will be duplicated. York et al.40 have presented a preliminary study of the practicality of applying such designs to CPV cells, demonstrating their ability to operate at concentrations otherwise considered high or extreme for standard cells. They mentioned that using a transparent stack of thin subjunctions in DJSCs leads to a maximum split of quasi-Fermi level that improves the $V_{OC}$ with the concentration.41 thereby improving the cell performances. However, the impact on performance and cost reduction of such designs at high concentrations has not been investigated up to now. DJSCs are conceptually comparable to the multibandgap systems investigated by Law et al.42 who demonstrated that such a design represents a very efficient strategy for achieving current matching, by selecting the suitable number of subcells.

Here, a detailed explanation of the simulation model, as well as calibration and validation of the employed model, is first presented. Then, the modeled performance of duplicated GaAs and GaInP/GaAs/Ge three-junction solar cells at UHC was compared with experimental data reported in the literature. Advantages and limitations of the new designs as well as relative cost analysis for duplicated 3XGaInP/3XGaAs/3XGe three-junction solar cells are then discussed in detail.

2 | MODELING DETAILS

Simulations were based on the detailed balance model (Shockley-Queisser limit).43 In these calculations, bandgap energies of materials and temperature were considered, whereas thickness, doping level, back-surface field (BSF), and window layer were not taken into account. For an ideal solar cell, Shockley-Queisser limit is based on certain assumptions as follows:44

1. Each absorbed photon generates absolutely one single electron-hole pair.
2. Absorption of photons with energy less than the material bandgap is null.
3. Only radiative recombination occurs within the cell and nonradiative processes (eg, Shockley-Read-Hall and Auger) are neglected.
4. The resistive losses are neglected; viz., mobility of carriers is infinite.
5. The cell temperature is equal to the ambient temperature (300 K).

A semi-empirical model was established by extending the detailed balance model in order to explicitly elucidate the impact of the resistive losses, caused by Joule effect in the electrical resistances, and the optical losses, resulted from reflection effects on the surface of the solar cells. For this purpose, a current correction factor was introduced to include the losses imposed by surface’s reflections. As a matter of fact, this can be realized using antireflecting coating (ARC) films such as ZnO45 and SiO₂/SiN.46 Lastly, the proposed model was calibrated and verified by applying it to the known reference solar cells. Simulations were conducted in the following order:

1. The photocurrent of each p-n junction was calculated by integrating the absorbed solar spectrum, assuming that each photon will create absolutely one electron-hole pair. Hence, photogenerated current density, $J_{g,k}$, became:

$$J_{g,k}(X) = X \frac{q}{hc} \int_{\lambda_k}^{\lambda_{k+1}} \lambda I(\lambda) d\lambda$$  \hspace{1cm} (1)

where $X$ is the concentration factor, $q$ is the electronic charge, $h$ is the Planck constant, $c$ is the speed of light, $I(\lambda)$ is the power density of the spectrum per wavelength $\lambda$, which is the AM1.5D spectrum in this case, and $\lambda_k (\lambda_{k+1})$ is the wavelength associated with the bandgap of the $k$th ($k+1$)th junction. It was assumed that for a stack of monolithic junctions, each junction “$k$” absorbs only a part of the spectrum. Namely, only the wavelength range between $\lambda_k$ and $\lambda_{k+1}$ was taken into account in the calculations (numbering starts at the illuminated side). The integration of $\lambda I(\lambda)$ was carried out by adopting a linear interpolation at the sampling points, referred to as “quick and dirty” method.43 Hence, Equation (1) was rewritten for the $k$th junction as:

$$J_{g,k}(X) = X \frac{q}{hc} \sum_{i=k}^{i=k+1} \lambda_i (\lambda_{i+1} - \lambda_i) I(\lambda_{i+1})$$  \hspace{1cm} (2)
The sum is on all wavelengths $\lambda_i$ between $\lambda_k$ and $\lambda_{k+1}$. Then, the full-device $J_f$ was determined through $J_f(X) = \min (J_{\lambda_k}(X))$.

2. When the subcells were duplicated, assuming that each absorbed photon generates one single electron-hole pair, each subjunction was considered partially transparent. Therefore, each subjunction could transfer a fraction of its photocurrent to the underlying subjunctions, allowing to utilize the photocurrent sharing scheme as an indicator of current preservation.\(^{11,40}\) This fraction was calculated iteratively until the photocurrent of each subjunction was almost equal and photocurrent was stabilized. In either case, the total photocurrent is conserved, because it represents the total number of absorbed photons. In the real case, thickness of each subjunction could be tuned in a way that it would absorb and convert the same fraction of the total light flux, which was normally converted in the corresponding subjunction prior to duplication. On this subject, as reported by Čičić et al.\(^ {49}\) measured the electrical resistance of the full-device, and they have been already used in solar cells. The diffusion length is related to the carrier lifetime, and $\tau$ is the carrier lifetime. As $R_S J^2$ represents the power loss caused by Joule effect. Note that the total series resistance associated with the front contact (1.93 mΩ cm\(^2\) for GaAs solar cell at 1000 suns) is the dominant term in the overall series resistance of the device and it is around $R_s=3.04$ mΩ cm\(^2\).\(^ {48}\) In addition, the series resistance is mainly influenced by the solar cell size.\(^ {49}\) Carlos Algora et al.\(^ {49}\) measured the electrical resistance of $2 \times 10^{-3}$ Ω for a 1 × 1 cm GaAs solar cell at 1000 suns, that is, $2 \times 10^{-7}$ Ω m\(^2\).

5. Finally, the efficiency $\eta(X)$ was calculated from the ratio $\frac{P_{\text{in}}}{P_{\text{out}}}$, where $P_{\text{in}}$ is the power of the incident light.

### 3 | MATERIAL CONSIDERATIONS

The designs mostly consisted of three materials, including In\(_{0.51}\)Ga\(_{0.49}\)P ($E_g \sim 1.89$ eV), GaAs ($E_g \sim 1.42$ eV), and Ge ($E_g \sim 0.67$ eV).\(^ {50}\) All these materials have been well developed, and they have been already used in solar cells. Composition of the ternary In\(_{0.51}\)Ga\(_{0.49}\)P was chosen, as it is lattice matched with both GaAs and Ge substrates.\(^ {50}\) Figure 1 shows solar cell designs based on GaAs and three-junction InGaP/GaAs/Ge solar cells. For both solar cells, each subcell was divided into $N$ subjunctions with similar bandgap (from two to five subjunctions).

In solar cell design, diffusion length is a critical parameter and it must be essentially longer than the solar cell thickness to ensure a favorable performance. In the case of DJSCs, most subjunctions will be thinned, by design, to make them transparent to a part of the spectrum; as a consequence, unabsorbed photons could be transmitted to the underneath subjunction. Since for all subjunctions the thickness will be much <1 µm, except the bottom subjunction thickness, materials with diffusion length around 1 µm are largely sufficient to distribute the current equally between all the subjunctions.\(^ {51}\) The diffusion length is related to the carrier lifetime and diffusivity according to the following equation:

$$L = \sqrt{D \tau}$$

where $L$ is the diffusion length, $D$ is the diffusivity, which is proportional to the carrier mobility, and $\tau$ is the carrier lifetime. As
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for InGaP, Schultes et al.\textsuperscript{52} measured electron diffusion length of 0.9 μm for hole concentration of $1 \times 10^{17}$ cm\textsuperscript{-3}. Moreover, they reported that the hole diffusion length in n-GaAs layers is 7 μm with an electron concentration of $1 \times 10^{17}$ cm\textsuperscript{-3}. Mintairov et al.\textsuperscript{53} measured minority carrier diffusion lengths in photoactive III-V layers of solar cells. They reported that electron and hole diffusion lengths of p-Ge and n-Ge layers were, respectively, 5 and 0.4 μm with carrier concentration of $5 \times 10^{18}$ cm\textsuperscript{-3}.

From a thermal point of view, the $V_{oc}$ can also be affected by the temperature of a solar cell, because according to the Varshini’s law,\textsuperscript{54} bandgap energy of semiconductors decreases when the temperature increases. Based on Equation (4), a little variation in the bandgap energy considerably affects the radiative recombination current. In addition, the changes in voltage can also be a result of radiative as well as nonradiative recombination processes of the charge carriers. The radiative process, however, can improve the solar cell performance through photon recycling effect.\textsuperscript{55,56} Walker et al.\textsuperscript{55} showed that the photon recycling for a GaAs solar cell increases the $V_{oc}$ by 1.8% compared to a cell with no photon recycling. Proulx et al.\textsuperscript{56} demonstrated experimentally the photon recycling effects on the performance of a thin GaAs n/p junctions, which was monolithically integrated in high-potential voltage VEHSA devices. They observed an ultrahigh efficiency exceeding 60% for very high input power of 5.87 W. The broader spectral response of the high efficiency was obtained due to the strong photon coupling effects.

Compared to classical solar cells, the DJSCs have a positive impact on the generated heat flux. In fact, the internally resistive heating in the solar cell decreases when the subcells are duplicated, because the generated current density decreases by a factor $N$.\textsuperscript{57} On the other hand, the generated heat by thermalization of carriers is not affected, since bandgap of semiconductor materials does not change when the subcells are duplicated.\textsuperscript{58}

4 | RESULTS AND DISCUSSION

4.1 | Model calibration

The calculated efficiencies vs concentration factors for single-junction GaAs and three-junction (TJ) GaInP/GaAs/Ge under AM1.5D spectrum are shown in Figure 2. These curves were calibrated by fitting the calculated data to the available experimental data provided by Fraunhofer ISE and NREL.\textsuperscript{59} Table 1

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{Figure1.png}
  \caption{Schematic representations of GaAs (A) and GaInP/GaAs/Ge (B) solar cells and their duplications that were connected in series by tunnel junctions. Dimensions are not to scale.}
\end{figure}
summarizes the results of this validation process including efficiency, $V_{oc}$, and $J$. The calculated efficiencies were matched very well with the experimental measurements; hence, they validated the parameters that were adopted in the simulations of this work. The reasonable agreement between measured and simulated efficiencies enabled extraction of the material properties relevant to the electrical component of the simulation, that is, series resistances as well as optical reflectance. The small differences are related to other limiting factors that were not considered in calculations presented here. It is important to mention that the series resistance was chosen with the intention of reaching higher concentration factor for which the efficiency is maximum ($X_{\text{peak}}$) close to that of experimentally obtained data. The value of the series resistance was set to 3.04 and 6.75 mΩ cm$^2$ for single GaAs and TJ GaInP/GaAs/Ge, respectively. These values of resistances are consistent with experimental measurements reported by Algora et al.48 Furthermore, in order to reach the efficiency values close to those of the experimental data, a current factor correction was introduced to include optical reflectance. For that purpose, it was assumed that only ~20% and ~35% of photons were reflected for single- and three-junction solar cells, respectively. These values are consistent with the reported data in Ref. 60 considering no ARC layer was applied on the solar cells. However, the reflectivity can be decreased almost 2.8% using the ARC, which can substantially improve the solar cell efficiency.

4.2 Performance of duplicated GaAs and GaInP/GaAs/Ge three-junction solar cells at UHC

As can be seen in Figure 3, the duplicated designs have efficiency peaks at higher concentration factors and present a slower drop in efficiency for increasing concentration, compared to classical single-junction GaAs and three-junction GaInP/GaAs/Ge solar cells. In the case of GaAs DJSCs, the series resistance was calculated according to the equation developed for AlGaAs/AlGaAs based tunnel junctions, as follows$^{48}$:

$$R_s (\text{mΩ cm}^2) = 3.04 + 0.17 \times N$$  \hspace{1cm} (8)

where $N (\geq 2)$ represents the number of subjunctions. However, the series resistance was kept equal to 6.75 mΩ cm$^2$ for all duplicated three-junction, as there has been no report discussing variation of series resistance as a function of p-n junction's number. Nonetheless, the total thickness of absorbing material will be approximately the same for both duplicated designs (typically ~0.65 μm for GaInP, ~3.1 μm for GaAs, and ~100 μm for Ge, including Ge substrate thickness$^{61}$); thus, it is compelling to consider that their total series resistance should also be comparable.

The drops of efficiencies, when the concentration factor increases, are related to the resistive losses.$^{28}$ In fact, the series resistance, which does not affect the efficiency at low concentration, becomes a significant problem at high concentration. As can be seen in Figure 3, the efficiency of classical single-junction GaAs cell dropped drastically for concentration factors beyond 258 suns and varied from 28.8% at 258 suns to 26.9% at 1500 suns, whereas the efficiency of duplicated GaAs cells was maintained at high levels and increased for concentration factors beyond 258 suns. For instance, the maximum efficiency increased by 0.9%, 1.3%, 1.7%, and 2.0% for 2XGaAs, 3XGaAs, 4XGaAs, and 5XGaAs, respectively, compared to classical solar cells.

In the case of duplicated GaInP/GaAs/Ge three-junction, the efficiency of the conventional solar cell considerably dropped for concentration factors beyond 956 suns and varied from 43.9% at 930 suns to 42.9% at 3000 suns. As shown in Figure 3, efficiency of GaInP/GaAs/Ge DJSCs reached 45.3% at ~3700 suns for 2X DJSCs, 46.1% at ~8300 suns for 3X DJSCs, and 46.7% at ~15k suns for 4X DJSCs. Hence, these results demonstrated the potential of the new designs for enhancing efficiency at UHC conditions. It is relevant
to mention that the most effective operating point in terms of cost reduction is not necessarily at maximum efficiency, alternatively operating at higher concentration with a maximum possible efficiency is economically attractive.

In good agreement with Ref. 62 the presented results showed that, similar to multigap systems concept, the more the number of the subjunctions increases the more the efficiency increases. However, increasing duplication steps more than five times does not provide significant enhancement of efficiency. In addition, this may impose some issues, for instance, difficulty in controlling flow of gases during growth steps and complexity of the manufacturing process during microfabrication steps that cannot be compensated by efficiency improvement.

According to Equation (6), the DJSCs are less affected by the concentration level compared to classical solar cells, because their delivered power is maximized as a result of the small-generated photocurrent. Furthermore, these new designs are attractive for several applications that require high $V_{OC}$ such as lightweight solar battery chargers. 63 The presented simulations showed that the output $V_{OC}$ delivered by 3xGaAs and 3XGaInP/3XGaAs/3XGe, at one sun, was $\sim 3.3$ V and $\sim 9.2$ V, respectively. It is important to mention that $V_{OC}$ increases roughly as a function of the logarithm of concentration factor, for concentrations lower than the efficiency peak position ($X_{peak}$).17 In fact, efficiency is theoretically proportional to the logarithm of concentration factor12 and efficiency peak position moves to high concentration according to the following equation:

$$X_{peak,duplicated} = X_{peak, classical} \frac{R_S(classical)}{R_S(duplicated)} N^2 \quad (9)$$

$N(\geq 2)$ represents the total number of subjunctions in the whole device. Equation (9) indicates that the $X_{peak}$ for DJSCs is more sensitive to changes of $N$, compared to variations of series resistance. This is considered as an important advantage for DJSC designs.

Correspondingly, it can be deduced that there is a competition between these two different phenomena. For values lower than $X_{peak}$, the efficiency increases, because it is limited by the number of absorbed photons and, generally, more concentrated light is required to generate more electron-hole pairs. In such a condition, the DJSCs are more advantageous in terms of photon absorption and, subsequently, increasing $V_{OC}$ and efficiency. For values more than $X_{peak}$, the resistive losses become dominant. These new designs provide high tolerance to the series resistance negative effect by minimizing the current density while increasing the $V_{OC}$ and efficiency.

The efficiency and the power resistive loss for both GaAs and InGaP/GaAs/Ge DJSCs are displayed in Figure 4. As it can be seen in Figure 4(A,C), when the subcells were duplicated, the efficiency at one sun increased very slightly. Therefore, these new designs do not provide more benefits in terms of efficiency for very low concentrations. Moreover, classical solar cells have significantly low efficiencies at UHCs. Typically, the efficiency in the case of classical GaAs solar cell decreases by $\sim 2\%$ in the concentration range from 258 to 1500 suns. A reduction of $\sim 1.3\%$ can be observed for GaInP/GaAs/Ge solar cell in the concentration range from 956 to 3000 suns. This can be explicated using the results shown in Figure 4(B,D), which show much higher power losses ($R_S J^2$) at high concentrations for the classical solar cell structures.

On the other hand, the efficiency of 2XGaAs as well as 2XGaInP/2XGaAs/2XGe DJSCs increased significantly for high-concentration factors. Besides the fact that the term $R_S J^2$ is proportional to $X$, it decreases by $(1/2)^2 = 1/4$ that allows to boost the efficiency at much higher concentrations than that of classical solar cells. Furthermore, in the case of duplicated designs with three or more repetitions the efficiency remained almost constant at a given concentration. According to Figure 4, the DJSCs have very low resistive losses compared to the classical solar cell. In this respect, there are considerable differences between the power losses at one sun and at UHCs. Typically, there is a difference ratio of $\frac{\Delta P_{loss}(5XGaAs)}{\Delta P_{loss}(1XGaAs)} = 4.6\%$, between one sun and 1000 suns in the case of GaAs cells, and $\frac{\Delta P_{loss}(5TJ)}{\Delta P_{loss}(1TJ)} = 4.0\%$, between one sun and 3000 suns in the case of three-junction cells.
Given that the duplicated designs require a higher number of individually deposited layers with inevitably increased number of gas-source switches during epitaxy growth, control of thickness and doping levels could become complicated. In addition, as expected, the efficiency remained almost unchanged for solar cells duplicated more than three times. These results provide confirmatory evidence that more than three-time duplication does not offer significant advantages, especially in terms of efficiency and in view of the high level of concentration required. Simulation results for more than five-time duplication are presented in the S2 (Figure S2.1 and S2.2).

As previously mentioned, the feasibility of developing high concentrator photovoltaic systems is possible and concentration factors above 3000 suns can be attained. Therefore, the high-concentration levels required for efficient performance of the three times duplicated solar cells are attainable.

4.3 | Cost analysis of duplicated three-junction

The relative cost is a qualitative measure of the rate by which the cost of energy per watt (W$^{-1}$) increases or decreases in comparison with a reference system. A simplified model of the impact of the concentration factor on the CPV system costs was performed. This model was based on the cost estimates for the components of a commercial FLATCON CPV system that was optimized for 500 suns. Vossier et al. estimated the relative cost using the following equation:

$$C(X) = \left( \frac{X_{\text{opt}}}{X} C_1 + C_2 + C_3 \cdot n \ln \left( \frac{X}{X_{\text{opt}}} \right) \right) \frac{\eta(X_{\text{opt}})}{\eta(X)}$$  \hspace{1cm} (10)$$

where $C$ is the relative cost for produced energy per watt, and $X_{\text{opt}}$ is the optimal concentration factor at which the costs $C_1$, $C_2$, and $C_3$ were estimated. This equation is only valid for concentration factors above $X_{\text{opt}}$. $C_1$ is the cost of the solar cell and its assemblies, and it represents 36.6% of the total cost of the system. This cost decreases with efficiency when the concentration factor increases. $C_2$ is the cost of electronics, module assemblies, and other indirect costs, and it represents 37.8% of the total cost. Although $C_2$ depends only on the efficiency or produced electrical power, it depends implicitly on the concentration factor as well, because efficiency varies with concentration factor. $C_3$ is the cost of optics and trackers, and it represents 25.6% of the total cost. Since DJSC designs are intended to operate at UHC factors, $C_3$ might increase. Here, four different cases were considered in calculations: $C_3$ increases by 0% ($n = 1.0$), 10% ($n = 1.1$), 20% ($n = 1.2$), and 30% ($n = 1.3$) every time the concentration factor is doubled. In the case of 0%, $C_3$ is independent of concentration factor. The optimal concentration $X_{\text{opt}}$ was set to 956 suns for which the relative cost of the reference system was set to $C(X_{\text{opt}}) = 1$. The efficiency of the three-junction solar cell was used as a reference for $\eta(X_{\text{opt}})$.

The relative costs for classical and duplicated 3XGaInP/3XGaAs/3XGe solar cell were calculated as a function of concentration factor and are illustrated in Figure 5. As expected, the classical three-junction solar cells were not
designed to operate at UHC factors. Cell cost \( C_1 \) was highly affected by the drastic drop in the efficiency for concentrations above 956 suns. Although several strategies were proposed in the literature to retain the efficiency up to several thousand suns, the efficiency could not reach values, which were high enough to reduce the cost at UHCs. In order to estimate the cost gains that would result from duplicated 3XGaInP/3XGaAs/3XGe solar cells, the relative cost for the four different cases was drawn, using the reported \( \eta(X) \).

It is worth noting that if the costs of optics and tracking could be concentration-independent (similar to the case of 0%), the DJSC leads to cost reduction at high concentration compared to classical three-junction. As can be seen in Figure 5, if 0% case is applied, the energy cost reduction will approach \(-21.5\%\) at 2000 suns and \(-31\%\) at 5000 suns for 3XGaInP/3XGaAs/3XGe. The obtained optimal values of concentration factor in this case are above 5000 suns for which the total cost approaches 0.66 W\(^{-1}\). The cost reduction reported here is a major achievement for CPV systems. The same behavior was observed for the 10% and 20% cases, which were more realistic. In fact, a reduction of energy cost in the range 22%-25% was expected for concentrations ranging from 3000 to 8000 suns. Even assuming that the optics and tracker costs increase drastically with increasing concentration factor (30% case), about 12% of reduction in energy cost can be achieved from operating at concentration of about 2400 suns. This gain, enabled by DJSCs, is the consequence of operating at UHCs, which allows producing efficiently more energy per cell. Nevertheless, the optimal values of concentration become increasingly smaller when the optics and tracking costs were supposed to increase (from \( n = 1.0 \) to \( n = 1.3 \)). In fact, \( C_3 \) is more sensitive to the concentration increase than other cost augmentations.

It can be concluded that the resulting total cost is more affected by both the cost of the cell and the cost of the optics and trackers. Given that III-V solar cells are more expensive than Si-based systems, increasing the concentration factor while keeping high efficiency seems to be an efficient strategy for minimizing the cell cost contribution in the total system cost. Moreover, reducing sensitivity of optics and tracking costs to the concentration factor increases allowing reduction of electricity cost produced by CPV. In this prospect, one can also believe that this technology has significant potential to benefit from diffuse sunlight, making CPV/PV hybrid technology more competitive by combining the high performance of DJSCs at UHC and the low costs of flat-plate PV systems.

5 CONCLUSION

In this paper, duplicated GaAs and GaInP/GaAs/Ge concentrator solar cells, designed to operate efficiently at concentrations above 1000 suns, have been proposed and modeled. Simulation results showed that these designs can operate at UHCs while maintaining a high efficiency. This is because of maintaining generated photocurrent at lower levels compared to classical solar cells. Hence, DJSCs are less affected by resistive losses. Furthermore, contrary to most commercially available solar cells, DJSC technology gives a new degree of freedom for designing cells that can withstand the elevated \( V_{OC} \) values.

The relative cost calculation for 3XGaInP/3XGaAs/3XGe has been performed. Compared to classical GaInP/GaAs/Ge solar cells, a reduction over 31% could be attained if the concentration increase does not impose extra costs. The DJSC technology does not require product redesigns, in terms of materials, surface area, microfabrication system, etc, and the same geometries can be added to any existing solar cell product line to boost the system performance at UHCs. However, one remaining technology challenge for the successful implementation of the DJSC is the development of high-band-gap tunnel junctions capable of operations at UHCs and with good optical transparency. Accordingly, further works will be focused on the optimization of duplicated cell architectures, using finite element methods, while including doping level and thickness of each layer. In the light of the presented findings, it is also intriguing to investigate the performance of other duplicated MJSC architectures under UHCs, for example, inverted metamorphic, wafer-bonded, and diluted nitride multijunction solar cells. On the basis of the results presented here, it is reasonable to suggest that these new designs give the possibility of using CPV systems in certain regions with midrange and low DNI as well as high DNI, making CPV technology accessible in a very large scale. An additional benefit of these CPV systems, however, will be
the reduction of the amounts of rare and toxic materials used to grow these cells, hence preserving the natural resources existing on earth.

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