Individual Energetic Processes Efficiencies in a Polycrystalline Silicon PV Cell Versus Electromagnetic Field

Adama Ouedraogo¹,² · Mahamadi Savadogo¹ · Prince Abdoul Aziz Honadia¹,² · Dieudonné Joseph Bathiebo¹ · Sié Kam¹

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Abstract
The Photovoltaic (PV) system is often installed near the telecommunication antenna without takes account the performance degradation that the electromagnetic field can cause. The present work provides the recognition about the greatest losses occur which can cause the overall efficiency drop. In fact, the absorption and the thermodynamic processes are more sensitive to the variation of the electromagnetic field more than FF and thermalization processes in presence of the electromagnetic field. The absorption and thermodynamic mechanism are the main cause of the degradation of the polycrystalline silicon PV cell outputs. The PV cell having height base doping level to get a better resistivity to the electromagnetic field must be chosen to improve theses outputs. Then a low electromagnetic field zones must be searched to install the PV system improving its electrical production performance.

Keywords Polycrystalline silicon PV cell · Absorption efficiency · Thermalization efficiency · Thermodynamic efficiency · Fill factor · Conversion efficiency

1 Introduction
The solar energy mainly the photovoltaic (PV) energy is a real opportunity to mitigate the climate change problems. It can be used to compensate the weakness of the electric grid in the developing countries. The Sahelian strip presents a high solar potential. However, the high level heat is a serious difficulty for the PV systems [1]. But the PV cell in silicon mainly in polycrystalline silicon can be used in this strip because of its heat resistivity [1]. Those reasons cause an proliferation of the polycrystalline PV cell use often in the great capacity PV power plant as Zagtouli in Burkina Faso [2] shown in the Fig. 1.

The Zagtouli plant has a capacity of 33MWc and uses 129 600 polycrystalline silicon PV modules of 260Wc. The energy produced presents almost 10% of the electricity needs of Ouagadougou, a city of 2.5 millions peoples environ [3]. Beside the development of the PV energy use, there is the proliferation of the technologies emitting the electromagnetic field in the environment as the base transceiver stations (BTS), the television (TV) and radios antennas, etc. Sometimes, the PV system is used in vicinity to provide the electricity for the operation of these technologies as shown in the Fig. 2.

The proximity of the PV systems and the antennas can cause the interactions between the electromagnetic field produced and the PV systems where the silicon PV cell which is a PV system basic and fundamental component. The conversion efficiency of the silicon PV cell falls down when the electromagnetic field is great. However, the electromagnetic field is not attenuated during its crossing in the PV cell [4]. The current produced by PV cell increases versus the electromagnetic field increase while the electric voltage decreases [5]. Individually the magnetic field causes the reduction of the current and the increase of the voltage due to the deflection of the carriers charge [5]. The electric field causes and increases of the current [6, 7] due to the creation of the conduction current while the photovoltage
The magnetic field of electromagnetic field from telecommunication antenna is weak but it can be not deleted as seen in some studies [8]. The electromagnetic field causes the division of the current in two components which are called leakage current and transferred current. The leakage current can cause the overheating of the \textit{pn} junction by Joule effect. Then the efficiency of the global process of the PV conversion decreases with the strong electromagnetic field strength. However, none of these studies set provides a deep explanation about the individual energetic mechanisms in the PV cell. It is then instructive to investigate the individual energetic processes in a polycrystalline solar cell versus electromagnetic field in order to recognize where the greatest losses occur and can cause the overall efficiency drop. The present work is about the efficiencies of the individual energetic processes in a polycrystalline PV cell versus electromagnetic field.

### 2 Methods and Theories

#### 2.1 Theories and Assumptions

The PV cell is the fundamental unitary component of a PV system. The low cost of the silicon and its non toxicity explained that it is the most abundant semi-conductor used in the PV cell manufacturing. The device used in this study show an emitter (\textit{n+} doping), a \textit{pn} junction, a base (\textit{p} doping) and a rear face (\textit{p+} doping). The modelling was restricted to \textit{n+}/\textit{p}/\textit{p+} PV cell. The structure of a PV cell under electromagnetic field is given in the Fig. 3.

The exponential doping gradient provides a constant strength electric field which pushes the minority carriers charge towards the \textit{p}–\textit{n} junction. The high-low \textit{p} doping junction created in the interface a strong electric field named Back Surface Field (BSF). It rejects the minority carriers back into the base of the PV cell and, thus, reduces the recombinations in the rear surface. The BSF is incorporated by assuming a \textit{p+} region in the PV cell rear surface with $W_b = 3\mu m$, and $N_B$ can reach until $5 \times 10^{18} cm^{-3}$. BSF can allow to overcome the recombination problem leading to the improvement efficiency [9]. The PV system is installed under electromagnetic field. Then we will be able to extract an unitary PV cell to investigate the influence of the electromagnetic field on the individual efficiencies. The electromagnetic wave from radio wave (9 kHz to 3000 GHz) [10, 11] has an electric field and a magnetic field which are perpendicular in planar wave assumptions. It will be assumed a monochromatic planar wave with a straight line direction polarisation following the (\textit{ox}) axis ($\vec{k} = k\hat{e}_x$) in the vacuum and according the direction of positives \textit{z}.

The expressions of the electromagnetic field components are in the vacuum [12]:

\begin{equation}
\vec{E} = E_0 \cos (\omega t - kz) \hat{e}_z
\end{equation}

and

\begin{equation}
\vec{B} = -B_0 \cos (\omega t - kz) \hat{e}_y
\end{equation}
Fig. 3 Illuminated PV cell under electromagnetic field

Where $B_0 = \frac{E_0}{c}$ and $c$ is the light free space celerity. For the distance $(r)$ from electromagnetic field emission source to the PV system is great compared to the wavelength $(\lambda)$ i.e. $r \gg \lambda$, we have the far-field matching to Fraunhofer region of the antenna pattern, the power density decreases inversely as the square of the distance. It is the region where the antenna exchanges the energy with the external zone [13, 14]. The power density, $S$, in free space is given by the following equation [13, 14]:

$$S = \frac{E_0^2}{Z_0} = H_0^2 Z_0$$  \hfill (3)

With $S$: power density ($W/m^2$) in a given direction $Z_0$: the free space intrinsic impedance, $E_0$: electric field strength ($V/m$) ($RMS$), $H_0$: magnetic field strength ($A/m$) ($RMS$), $B_0 = \mu_0 H_0$ in Tesla ($T$). The power density can be found in the far field as following at any given distance in any isotropic direction:

$$S = \frac{P_r G_i}{4\pi r^2}$$  \hfill (4)

$P_r$: power ($W$) supplied to the radiation source, assuming a lossless system $G_i$: gain factor of the radiation source in the relevant direction, relative to an isotropic radiator $r$: distance ($m$) from the radiation source. $P_r G_i$ is known as the equivalent isotropic radiated power (EIRP) which represents the power that a fictitious isotropic radiator would have to emit in order to produce the same field intensity at the receiving point [15]. The gain factor $G_i$ must be replaced by the product of $G_r G_a$ [13, 14] and some values about $G_r$ are presented in the Table 1.

Table 1 Isotropic gain factors for different types of reference antenna

| Reference antenna type | $G_r$ | Relevant applications |
|------------------------|-------|-----------------------|
| Isotropic radiator     | 1.0   | Radar, satellite, etc.|
| Half-wave dipole       | 1.64  | Television, $VHF$, etc.|
| Short monopole         | 3.0   | $LF, MF$, etc.        |

In the present case the gain of the antenna is expressed relative to a half-wave dipole: $G_d = G_a = 2.15 dB$ [16, 17]. It will be assumed a fixed polarisation direction matching to PV system orientation tilt. The electromagnetic wave reaches the solar cell when $t = 0$ and $x = y = 0$. The electric field strength created in the $d$ distance from the transmitter is

$$E_0 = \frac{1}{2r} \sqrt{\frac{P_r Z_0}{\pi}}$$  \hfill (5)

The contribution of the base in photocurrent being greater than the emitter contribution [18]. This study is carried out assuming a ideal PV cell and its base as the center of the generation and recombination phenomena. It is also carried out in the theory of quasi-neutral base ($QNB$) [19, 20]. In this theory the intrinsic electric field in the base’s region can be neglected. The radiation may be received or reflected by the semiconducting devices, or may be influenced the power conditioning electronics [21]. The effective length $L_{eff}$ and the effective relative permittivity $\varepsilon_{eff}$ can be calculated using empirical formulate as following [21].

$$L_{eff, \nu_{res}} = \frac{c}{2 \sqrt{\varepsilon_{eff}}}$$  \hfill (6)

Where $c$ is the light velocity in the free space and $\nu_{res}$ is the resonance frequency. The standard magneto-transport theory to describe the base electronic transport in PV cell provides [Betser 1995]

$$\vec{J}_n = q D_n \nabla \delta (x,y,z) - \mu_n \vec{J}_n \times \vec{B} + q \mu_n \delta (x,y,z) \vec{E}$$  \hfill (7)

The one dimensional (1D) assumptions according to the model provided by Betser et al. [22] is used to solve the mathematical equations. The base dimensions along the $x$ and $y$-axis are much larger than the base width ($H$) following the $z$ axis. Then

$$\frac{\delta \delta (x,y,z)}{\partial y} = \frac{\delta \delta (x,y,z)}{\partial x} = 0$$  \hfill (8)
Where $q$ is the electron charge, $\delta(z)$ gives the excess minority carriers charge and $D_n$ is the diffusion coefficient
\[
J_{nz} = qD_n^a \frac{\partial \delta(z)}{\partial x} + q\mu_n^a E_0 \delta(z)
\]  
(9)
With $D_n^a = \frac{D_n}{1 + (\mu_n B_0)^2}$ the electron diffusion coefficient depending to the magnetic field and $\mu_n^a = \frac{\mu_n}{1 + (\mu_n B_0)^2}$ the electron mobility coefficient depending to the magnetic field.

### 2.2 Excess minority carriers charge

The carriers charge conservation equation named continuity equation in 1D approximation of a $p-n$ junction polycrystalline silicon PV cell in steady-state is described based on one-diode model as [23–25]:
\[
\frac{\partial^2 \delta(z)}{\partial z^2} + \frac{\mu_n E_0}{D_n^a} \frac{\partial \delta(z)}{\partial z} - \frac{\delta(z)}{L_n^*} = -\frac{1}{D_n^a} \sum_{i=1}^{3} a_i e^{-b_i z}
\]
(10)
With $a_i$ and $b_i$ the coefficients deduced from modelling from the generation rate for the AM1.5 spectrum on the surface of the earth [26]. $L_n^* = D_n^a \tau_n$. It is the diffusion length depending to the magnetic field. The solution of this differential equation is given by $\delta_0(x)$ the contribution in the density of minority carriers charge in excess of the PV cell in obscurity and $\delta_1(x)$ the contribution of the PV cell under solar illumination [1, 27]. Then the definitive solution is such as
\[
\delta(x) = \delta_0(x) + \delta_1(x)
\]
(11)
The density of minority carriers charge in excess is then provided by
\[
\delta(z, S_f) = e^{\alpha z} \left[ A (S_f) \cosh (\beta z) + B (S_f) \sinh (\beta z) \right] + \sum_{i=1}^{3} \gamma_i e^{-b_i z}
\]
(12)
Where the different coefficients are given such as
\[
\alpha = -\frac{\mu_n E_0}{D_n^a}, \quad \beta = \frac{1}{2} \left( \left( \frac{\mu_n E_0}{D_n^a} \right)^2 + \frac{4}{L_n^*} \right)^{1/2} \quad \text{and} \quad \gamma_i = \frac{a_i}{D_n^a} \left[ \beta_i^2 - \frac{a_i}{D_n^a} b_i - \frac{1}{L_n^*} \right].
\]
The real constants $A$ and $B$ are provided by PV cell boundaries conditions equations [28] such as :

- In the $p-n$ junction $z = 0$
\[
D_n^a \frac{\partial \delta(z)}{\partial z} \bigg|_{z=0} = S_f \delta(0)
\]
(13)
- In the rear face $z = H$
\[
D_n^a \frac{\partial \delta(z)}{\partial z} \bigg|_{z=H} = -S_b \delta(H)
\]
(14)

The junction dynamic velocity is $S_f = S_{f1} + S_{f0}$. $S_{f0}$ provides the intrinsic junction recombination velocity related to the losses of carriers charge at the junction interface and $S_{f1}$ provides the flow of the minority carriers in excess crossing the $p-n$ junction. It is imposed by an external load and fixes the operating point of the PV cell [29]. For the ideal solar cell assumption, $S_{f0} = 0$.

### 2.3 PV cell Electrical Parameters

The photocurrent is gotten by applied of the first Fick low such as
\[
J_{ph} (S_f) = q \left[ \frac{D_n^a}{D_n^a} \frac{\partial \delta(z, S_f)}{\partial z} \right]_{z=0} + \mu_n^a E_0 \delta (0, S_f)
\]
(15)
The rear side recombination velocity is obtained after the next equation solve [30]
\[
\frac{\partial J_{ph} (S_f)}{\partial S_f} \bigg|_{S_f \to \infty} = 0
\]
(16)
In the short circuit situation
\[
J_{sc} = \lim_{S_f \to \infty} J_{ph} (S_f)
\]
(17)
The total photocurrent density is not provided to the external load. One part called leakage photocurrent is leaked in the $p-n$ junction in the parasitic resistances. But the other part is transferred to the external load and can be named the transferred photocurrent. This second component is given as following using the Eqs. 13 and 15.
\[
J_{phT} (S_f) = q S_f \delta (0, S_f)
\]
(18)
This photocurrent is taken for the next of the present study is the useful current provides by the PV cell to external load. The electrical voltage is obtained by applied of the Boltzmann low as :
\[
V_{ph} (S_f, s) = \frac{k_b T}{q} \ln \left[ N_B (s) \frac{\delta (0, S_f)}{n_i^2} + 1 \right]
\]
(19)
Where $N_B (s) = 10^{16} cm^{-3}$ is the doping level with $s$ from 14 to 18 and $k_b$, the Boltzmann constant. The accurate intrinsic carriers density ($cm^3$) depending to temperature [28, 31] is:
\[
n_i (T) = A T^{3/2} e^{-\left( \frac{E_g}{2k_b T} \right)}
\]
(20)
Where $A = 3.87 \times 10^{16} cm^{-3}, K^{-2}$. The electrical power is found by the following equation
\[
P_{ph} (S_f) = V_{ph} (S_f) \cdot J_{phT} (S_f)
\]
(21)
The conversion efficiency ($\eta_1$) is found from maximum power ($P_{ph\text{max}} (S_f)$) obtained from previous equation and taking account the incident radiation under AM1.5.
\[
\eta_1 = \frac{P_{ph\text{max}}}{P_{in}}
\]
(22)
\[ \eta_{thermo} = \frac{eV_{oc}}{(\varepsilon_e + \varepsilon_h)} \]  

In physics interpretation of this process, it can say that it provides the maximum chemical energy which can be extracted from the energy of the electron–hole pairs and it is giving the efficiency accounting for the difference between free energy and energy with a thermodynamic factor.

The last process is about the extraction of maximum electric power \( P_{\text{max}} \) compared to the ideal electric power \( (V_{\text{oc}}, J_{\text{phsc}}) \). It is named fill factor \( (FF) \). Shunt \( (R_{sh}) \) and \( (R_s) \) series resistances in the PV cell can reduce the \( FF \) below its ideal value. In the ideal condition, the PV cell has a great shunting resistance \( (R_{sh} \rightarrow \infty) \) and the series resistance tends to null value \( (R_s \rightarrow 0) \) \([23, 34]\). Then, the \( FF \) will be written as \([23, 34]\).

\[ FF = \frac{v_{oc} - \ln (v_{oc} + 0.72)}{v_{oc} + 1} \]  

With \( v_{oc} = \frac{eV_{oc}}{kT} \).  

In physics interpretation, the PV cell fill factor provides the ratio of the maximum power output of the cell to ideal electric power which is the product of the open-circuit voltage \( V_{oc} \) and the short-circuit current \( I_{sc} \) \([23, 34]\).

The product of the previous four individual efficiencies set allows to find the overall efficiency expressed by

\[ \eta_2 = \eta_{abs} \times \eta_{thermal} \times \eta_{thermo} \times FF \]  

In this study a comparison will do between \( \eta_1 \) and \( \eta_2 \) for the validation of the results obtained which will be discussed in the following section.
3 Results and Discussions

The electromagnetic field from antenna is composed by electric field and magnetic field. The different components are shown on the Figs. 5, 6 and 7.

Electric field and magnetic field decrease versus the increase of the distance between the electromagnetic field source and the PV system. For the next of this work, the behaviour of the different parameters are studies in function of the distance. The electric and magnetic fields are great for the weak distance. These fields are weak for the great value of the distance. The photocurrent which the first parameter is presented in the Fig. 8 versus junction dynamic velocity for different distances.

From the Fig. 8, the current which is strongly depending to the junction dynamic velocity presents a great value in open circuit situation due to the electromagnetic field. It is also important in short circuit state for the weak distance compared to the great distance. That can be explained by the kinetic energy acquired by the carriers charge. In fact, the magnetic being weak (around 250\(nT\)), the electric field provides a sufficient energy to the carriers charge which in linear line can cross the junction and participate to the external current. However, in open circuit situation, the junction cross by the carriers charge causes the junction heating by Joule effect. From the linear side of the Fig. 8, the rear face recombination velocity is deduced and shown in the Fig. 9.

A weakness of the rear face recombination velocity is observed when the distance is very low i.e. for the great electric field. The great magnetic field causes the deflection of the carriers charge. The direct consequence of this deflection is the increase of the rear face recombination
velocity and not its decrease when the distance is weak. It is then the electric field which is the cause of the decrease of the rear face recombination. That can explain the reduction of the rear face recombination velocity. The electric voltage obtained thanks to Boltzmann low is presented in the Fig. 10.

The voltage is important in open circuit state i.e. in low junction dynamic velocity value. However, this velocity decrease for the great electric field (low distance). This decrease is a confirmation about the important crossing of the junction by the carriers charge caused by the electric component of the electromagnetic field. However, the resistivity of the PV cell to electromagnetic field can be improved by the base doping level as shown in the Fig. 11.

For all doping level set, the open circuit voltage is weak in weak distance i.e. in great electric field. But it increase with the increase of the doping level from $10^{14} \text{cm}^{-3}$ to $10^{18} \text{cm}^{-3}$. The doping level can be then used to improve the voltage of the PV cell under electromagnetic field. The electric power is provided in the Fig. 12.

The electric power in Fig. 12 gives the influence of the electromagnetic field. The all distance values set, the electric power in the maximum power point is slightly shift from the normal operating point of the PV. That is explained by the crossing of the carriers charge in this state due to the influence of the electric field shifting the maximum power point toward the short circuit state. It is then a reason to install the PV system far to electromagnetic emission source, ideally in a distance more than $100m$ according to the assumptions of this study. The maximum powers of the different distances are extracted and presented in the Table 2.

Compared to the PV cell power without an electromagnetic field where the maximum power point is around $10^4 \text{cm.s}^{-1}$ [1], in the present work, it is beyond $10^4.5 \text{cm.s}^{-1}$. The PV conversion efficiency increase with the increase of the electromagnetic field. There is in this...
study a confirmation that an electromagnetic field mainly an electric field in low values assumptions can be used to improve the outputs of the polycrystalline silicon PV cell [25, 27]. The doping level affecting the outputs of the PV cell, some individual efficiencies are represented in the next paragraph.

The base doping level influence on the thermodynamic efficiency is shown in the Fig. 13.

The thermodynamic process is strongly depending to the open circuit voltage which also depends to the doping level. The better efficiency from conversion of the chemical energy to the electric energy is found for the greatest base doping level. However for the silicon matter, this doping level is low than $10^{19}$ cm$^{-3}$ to avoid the degeneration of the semi-conductor [35]. When the PV cell is far from electromagnetic field emission source, there is an improving of the thermodynamic process. The base doping level influence on the fill factor is provided in the Fig. 14.

From the Fig. 14, the $FF$ presents an improving far from electromagnetic field emission source. It is better also for the hight base doping level due to the improving of the open circuit voltage versus base doping level. The hight base doping level can be used to protect the PV cell against the electromagnetic wave from any source as well as against the temperature [1]. All the individual efficiencies set versus electromagnetic field are shown in the Fig. 15.

The thermalization process is not influenced by the electromagnetic field. The absorption process is improved with the great electromagnetic field. However, the $FF$ and thermodynamic are strongly affected by the increase of the electromagnetic field due to the dependence to the open circuit voltage. The absorption and the thermodynamic processes are more sensitive to the variation of the electromagnetic field more than FF and thermalization processes. The electromagnetic sensitivity of the absorption mechanism is due to the important $pn$ junction crossing by the carriers charge increasing the short circuit current. But, electromagnetic sensitivity of the thermodynamic is explained by its strongly dependence to the open circuit voltage which decreases with the increase of the electromagnetic field. The overall efficiency from the multiplication of these individual efficiencies is shown in the Table 3.

The absorption process presents an efficiency gap of 9.541% from 5m to 100m and the thermodynamic

![Fig. 13 Thermodynamic efficiency versus distance for different base doping levels](image)

![Fig. 14 Fill factor versus distance for different base doping levels](image)

![Fig. 15 Individual efficiency versus distances](image)
mechanism shows an efficiency gap of 6.051% while the FF has a gap of 1.232%. The overall efficiency decreases versus the increase of the electromagnetic field. The absorption and the thermodynamic processes are the mainly cause of the overall efficiency drop versus electromagnetic field. The overall efficiencies set are extracted and shown in the Fig. 16.

The both overall efficiencies have the same decrease slope degree when the PV cell is away from the electromagnetic field emission source. The increase observed when the electromagnetic field is great is not rentable to the PV conversion because of the Joule effect being very important in this situation. That can cause the heating of the pn junction and degrading its performance. It can be advised to install PV system in distance more than 100 m and to chose a PV cell having height base doping level to get better resistivity to the electromagnetic field. In the Table 4 the gap between $\eta_1$ and $\eta_2$ is presented.

The gap between the two overall efficiencies is very weak and the average gap is $\Delta\eta = \eta_1 - \eta_2 = Gap(\%) = 0.01311865$. That can prove the accuracy of the use of the individual efficiencies to recognize where the greatest losses occur and can cause the overall efficiency drop.

### Table 3 Individual efficiencies versus electromagnetic field emission source distance

| r(m) | $\eta_{abs}(\%)$ | $\eta_{thermal}(\%)$ | $\eta_{thermo}(\%)$ | FF (\%) | $\eta_2(\%)$ |
|------|-------------------|----------------------|---------------------|---------|-------------|
| 5    | 69.205            | 62.222               | 55.417              | 83.163  | 19.845      |
| 25   | 63.738            | 62.222               | 58.892              | 83.896  | 19.594      |
| 50   | 61.829            | 62.222               | 60.300              | 84.173  | 19.526      |
| 75   | 60.584            | 62.222               | 61.025              | 84.312  | 19.395      |
| 100  | 59.664            | 62.222               | 61.468              | 84.395  | 19.258      |

### Table 4 Overall efficiencies $\eta_1$ and $\eta_2$

| r(m) | $\eta_1(\%)$ | $\eta_2(\%)$ | Gap (\%) |
|------|--------------|--------------|----------|
| 5    | 19.857       | 19.845       | 0.01184028 |
| 25   | 19.602       | 19.594       | 0.00723963 |
| 50   | 19.538       | 19.526       | 0.01141451 |
| 75   | 19.411       | 19.395       | 0.01558440 |
| 100  | 19.278       | 19.258       | 0.01951442 |

### 4 Conclusion

The electromagnetic field influence on the individual efficiencies is presented in this work. The electric component of the electromagnetic field is the real cause of the increase of the electrical current and the decrease of the electrical voltage. The electric component cause clearly the open circuit voltage drop. That can be explained by the important increase of the $pn$ junction crossing by the generated minority carries charge in the base. The current is so increase helped by the conduction current provides by the electric field. The base doping level can be used to improve silicon PV cell resistivity to the electromagnetic field. Among the individual energetic processes, the absorption and the thermodynamic processes are more sensitive to the variation of the electromagnetic field more than FF and thermalization processes. The electromagnetic sensitivity of the absorption mechanism is caused by the important $pn$ junction crossing by the carriers charge increasing the short circuit current. But, electromagnetic sensitivity of the thermodynamic is due to its strongly dependence to the open circuit voltage which decreases according the increase of the electromagnetic field. Following these reasons, the installation of PV system in distance less than 100 m and is not advised. Then a PV cell having height base doping level to get better resistivity to the electromagnetic field must be chosen.

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### Availability of data and materials

1- The [individual energetic processes] data used to support the findings of this study have been deposited in the [A. Ouedraogo et al. (2021)] repository [https://doi.org/10.1016/j.rio.2021.100101], [P. Würfel] repository [Würfel, P., 2005. Physics of solar cells. Wiley-VCH Verlag GmbH and Co. KGaA edition, Die Deutsche Bibliothek, Berlin ] and [M. A. Green et al. (1983)] repository [M. A. Green. Accuracy of analytical expressions for solar cell fill factors. Solar cells, 7:337 – 340, 1982. Short Communication].

2- The silicon PV cell data used to support the findings of this study are included within the article of E. Seraffetin et al. 2006 https://doi.org/10.1016/j.solmat.2005.04.038 and 2008, I. Zerbo et al. 2014, https://doi.org/10.4314/gjpas.v20i2.9, A. Ouedraogo et al.2018, https://doi.org/10.4236/sgre.2018.912018, 2019.
The data about evolution of the electromagnetic field in PV cell used to support the findings of this study are included within the supplementary information file(s) are provided by [Ouedraogo et al. 2017], https://doi.org/10.3906/fiz-1703-16.

The [telecommunication antenna] characteristics used to support the findings of this work have been deposited in the [IUT]. Evaluating fields from terrestrial broadcasting transmitting systems operating in any frequency band for assessing exposure to non-ionizing radiation (question ITU-R 50/6). Technical report, IUT, ITU-R BS.2037, 2004.

The about equations solved data used to support the findings of this study have not been made available because the solution carrier transport and continuity equations are obtained manually.

Declarations

Ethics approval

This paper is the results of the contribution and collaboration of all authors. Certain authors have solved the different equation and others have provided the analysis and physics interpretations after the modelling. Some informations about the submission and the ethical Responsibilities of Authors are given in the following items:

- The manuscript is only submitted in Silicon journal.
- The submitted work should be an original and has not been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work.
- No data, text, or theories by others are presented as if they were the author’s own (‘plagiarism’). Proper citations to other works are given.
- Authors are strongly advised to ensure the author group, the Corresponding Author, and the order of authors are all correct at submission. All authors whose names appear on the submission made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work;
- drafted the work or revised it critically for important intellectual content;
- approved the version to be published; and
- agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Consent to participate

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. We are responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs Signed by all authors.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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